Dynamic Bandwidth Allocations for Extended-Reach Passive Optical Networks

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For Ian, Elizabeth and Lavinia

Life is whatever you make it.

Live whatever you see...
See whatever you want...

Zetski, circa 1998

Abstract

In recent years, the amount of global Internet traffic has been rapidly increasing as higher capacity access networks are being deployed. Passive optical networks, or PONs, are being deployed in the access network due to their high bandwidth capacity. Although currently limited to metropolitan regions due to limits on their maximum distance, recent advances in optical amplification techniques allow long-reach PONS (LR-PONs) to become commercially viable. In the upstream direction complicated scheduling mechanisms are required to schedule upstream transmissions from each subscriber to avoid contention. This mechanism is known as dynamic bandwidth allocation (DBA) and the manner in which it is implemented determines the upstream packet delay and upstream bandwidth efficiency.

This thesis examines the problem of maintaining low packet delay and high bandwidth efficiency in an LR-PON, specifically a long-reach version of the ITU-T standardised Gigabit-capable PON (GPON). This thesis describes an approach to the buffering and transmission of upstream packets using the conventional request/allocate (report/grant) implementations of DBA algorithms that rely on periodic intervals (cycle times). The round trip time (RTT) of the network is shown to be a lower interval limit for maintaining high bandwidth efficiency. With the increased RTT in LR-PONs, this issue is then addressed by determining the specific parameters responsible for the reduction in bandwidth efficiency. New DBA algorithms are developed that remove the RTT as a limitation yet still provide excellent bandwidth efficiency and low packet delay.

The second part of this thesis uses advanced simulation techniques to analyse the delay and bandwidth efficiency of the proposed DBA algorithms which are compared to existing, conventional DBA algorithms. The proposed algorithms are shown to not only produce low packet delay and high bandwidth efficiency, but in addition are capable of adapting to any fluctuations in subscriber bandwidth demand without requiring any prediction techniques.

The issue of upstream packet delay variation, or jitter, is also addressed because excessive jitter can often render real-time network services unusable. The majority of

the literature surrounding DBA algorithms often fail to incorporate jitter as a key measurable in the performance of the algorithm. This thesis examines the jitter produced by DBA algorithms and proposes new techniques for analysing the delay and jitter.

We also suggest further research directions that can be used to create comprehensive models that could facilitate the development of more advanced DBA algorithms.

Declaration

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

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Timothy G. Smith

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1 Introduction

1.1 Introduction

In 2007 there was an estimated 5 terra-bytes (TB) of global Internet protocol (IP) traffic generated every second [1]; however by 2016 this number is expected to increase to over 40 TB per second [2]. As the available bandwidth of networks increases, so too does the rate at which the traffic is generated. The majority of the global IP traffic in 2007 was generated by consumers [1], whose connections to the Internet are provided via the access network also termed the “last-mile” connection. Passive optical access networks (PONs), such as the IEEE Ethernet PON (EPON) and the ITU’s Gigabit capable PON (GPON), have been widely deployed in Asia and America and are now being deployed around the globe [3-5]. In both EPON and GPON, the signal from the optical line terminal (OLT) at the central office (CO) is split between up to 128 subscribers using a time domain multiplexed (TDM) arrangement [6, 7]. With an upstream bandwidth capacity up to 1 Gbps, PONs have become somewhat of a standard for next generation access network deployment [4, 5, 8]. While EPON only permits the transmission of Ethernet packets, GPON is designed to manage traffic of different priorities. Coupled with the higher data rates over EPON, the deployment of GPON has increased in recent years [8, 9].

From the GPON standards, the maximum distance from the OLT to the subscriber equipment, or optical network termination/unit (ONT/ONU) is 60 km [10]. An additional distance limitation, the differential distance, restricts the distance between the closest and furthest ONT (from the OLT) to 20 km [11]. This makes GPON a viable technology for metropolitan access networks. Recent additions to the GPON standard and various amplification methods [12-16] allow for what is known as long-reach GPONs (LR-GPON) which can allow deployment to regional residential clusters that reside some distance from the OLT. Research has shown that for regional deployment, long-reach PON is not

only commercially viable, but also more energy efficient than the deployment of fixed copper line or wireless alternatives [17, 18].

Upstream packet delay, or latency, is an increasingly active area of PON study [19-28]. Sufficiently large packet delays as well as variation in delay, or jitter, can render delay-sensitive services such as voice over IP (VoIP) and video conferencing, unusable [29-34]. The increased distances in LR-PONs directly translate to increased packet delay. To allow feasible long reach PONs to be commercially viable, attention must be paid to minimise the packet delay and jitter in the network. In passive optical networks the upstream direction is shared among all subscribers and complicated scheduling algorithms are used to facilitate the transfer of upstream information from the subscribers to the OLT. This thesis addresses the issues that translate to upstream packet delay in LR-GPONs by modelling the ONT buffer levels, proposing new algorithms to schedule upstream data transfer and examining new methods of analysing the delay and jitter. In the next section, the focus of the thesis is outlined.

1.2 Focus of the Thesis

In passive optical networking, multiple ONTs are connected to the same common fibre. To avoid contention and collisions, dynamic bandwidth allocation (DBA) is the key mechanism within the OLT responsible for scheduling and allocating upstream bandwidth among the ONTs [11, 35, 36]. In both EPON and GPON, the DBA mechanism is well defined by the relevant standards [6, 11], however the process by which the OLT determines the amount of upstream bandwidth to be allocated to each ONT cannot be standardized as it depends on factors such as bandwidth availability, demand and the SLAs. Many of these are dynamic and cannot be easily predicted [35]. To transmit upstream data, the OLT periodically allocates bandwidth to each ONT which in turn responds with the allowed upstream transmissions and appends a report of the remaining upstream data still be transmitted.

Although the ITU has standardized the GPON DBA mechanism, the way in which the total fixed upstream bandwidth is calculated and scheduled is a large area of research for EPON, GPON and more recently, for long-reach PONs [19, 21, 22, 24, 37-47]. The majority of DBA algorithms in the literature use an interleaved approach whereby bandwidth allocations, or grants, to one ONT can be scheduled whilst waiting for the

buffer level requests, or reports, from the next ONT. While this approach has been shown to produce low upstream packet delay in conventional PONs [19, 48], the increased RTT in an LR-PON results in an increased time between allocations from the OLT to the reception of upstream data from the ONTs [21, 23, 49].. The general outcome of this focus is that the more bandwidth that is allocated, the lower the delay [25, 27, 41, 50].

Given the fixed available upstream bandwidth, yet variable demand, this thesis investigates how the DBA mechanism from the standards can be used to maintain low upstream packet delay with the increased round trip times in an LR-GPON. We approach this problem by modelling the ONT buffer levels to determine the principle parameters responsible for the packet delay. We use this model to develop DBA algorithms that minimise the delay whilst still providing QoS support. To evaluate the performance of our proposed DBA algorithms, we use sophisticated simulation methods and compare the key measurable, the upstream packet delay, to that of conventional of DBA algorithms. We examine the jitter performance and bandwidth efficiency, both of which are often overlooked in the majority of DBA literature.

1.3 Organisation of the Thesis

This thesis examines the problem of increased packet and reporting delays in an LR-GPON using modelling and simulation techniques. In Chapters 2 through 4 we focus on the parameters of the DBA mechanism as defined in the relevant PON standards and develop mathematical models to describe the upstream buffer behaviour. Using these models, we develop some DBA algorithms that provide low upstream packet delay whilst simultaneously yielding high bandwidth efficiency. In Chapters 5 through 7 we incorporate these DBA algorithms into a custom built GPON simulator to examine the simulated packet delay, jitter and bandwidth efficiency. The organization of the thesis is as follows:

Chapter 2: Literature Review examines the PON standards and relevant literature surrounding DBA algorithms for EPON, GPON and LR-PONs. We provide an overview of the interaction between the allocated bandwidth and resulting upstream packet delay. We summarise by comparing the various DBA algorithms presented in the literature in terms of delay and QoS.

Chapter 3: Analytical Model of the GPON DBA uses the standardized DBA mechanism from the GPON standards to develop a mathematical model that quantifies the upstream packet delay as a function of the ONT buffer levels and allocated bandwidth from the OLT. This chapter shows that when conventional request-allocate algorithms are used the RTT is a limit on the time between allocations. We show that in an effort to reduce the packet delay, allocating more frequently results in a significant decrease in bandwidth efficiency.

Chapter 4: Modifying the Requested Bandwidth to construct Allocations continues the modelling from Chapter 3 to examine methods to minimise the decrease in bandwidth efficiency that occurs when allocations are made more frequently than the RTT. Two novel DBA algorithms are developed that focus on modifying the bandwidth allocations to the subscribers. The first algorithm introduces a weighting factor that proportionally reduces the allocations thereby minimising the wasted bandwidth. The second algorithm uses the difference between consecutive bandwidth requests to calculate the exact amount of required bandwidth. Both of these algorithms maintain high bandwidth efficiency and issue allocations at a time interval less than the RTT thereby allowing low packet delay.

Chapter 5: Advanced Simulation Methods for LR-GPON DBA describes a custom simulation package designed specifically for the analysis of DBA algorithms in GPON and LR-GPON. This chapter describes the various parts of the simulator that are applicable to the DBA algorithms as well as the methods by which the various categories of upstream subscriber traffic are generated. The chapter also outlines how the simulator manages the various traffic categories in terms of priority.

Chapter 6: Steady-state Delay and Bandwidth Efficiency uses the simulation package from Chapter 5 to produce steady-state average results of upstream packet delay for both short and long-reach GPON. Various DBA algorithms are analysed and the results are presented in a similar fashion to that used in the literature. The bandwidth efficiency produced by each DBA algorithm are also examined. This Chapter concludes by identifying problems with the commonly used representation of the average delay.

Chapter 7: Transient Response and Histogram Representation proposes two methods of presenting the results of the upstream packet delay and the variation in delay, or jitter. The first method looks at both the buffer occupancy and the packet delay over

time such that the effect of variations in the injected traffic rate can be observed. The second method uses a histogram-based representation that displays the normalised frequency of occurrence of the packet delay as the amount of injected traffic increases. This novel method of representation allows both the packet delay and the jitter to be analysed.

Chapter 8: Conclusion outlines the key findings of the thesis and proposes new research directions in the area.

1.4 Original Contributions

The original contributions of this thesis are:

- The derivation of a novel mathematic model that describes the ONT buffer level behaviour as a function of the bandwidth requests and allocations, the allocation interval and the injected subscriber traffic rate (Chapter 3).

- In the majority of DBA algorithms the conventional request-allocate DBA algorithms are used [19, 21, 23, 25, 40]. We identify that in this situation the RTT of the network is a limit on the allocation interval, or cycle time, beyond which the bandwidth efficiency substantially decreases (Chapter 3).

- We developing two novel DBA algorithms whose allocation intervals are less than the RTT, however high bandwidth efficiency is maintained as well as low packet delay (Chapters 4, 6).

- Network services that utilize real time traffic categories such as voice over IP (VoIP) and video conferencing have strict requirements on the jitter. We illustrate that the conventional methods of presenting and analysing the results of upstream packet delay do not provide sufficient information to analyse the variations in delay, or jitter (Chapter 6).

- We propose a novel histogram-based approach for displaying the packet delay that allows for both the packet delay and jitter to be visualized and analysed (Chapter 7)

1.5 Publications

Smith, T.G.; Tucker, R.S.; Hinton, K.; "Delay and Jitter in Long-Reach GPON," OECC 2011. 16th, vol., no., pp.184-185, September 2011

Smith, T.G.; Tucker, R.S.; Hinton, K.; Tran, A.V., "Packet delay variance and bandwidth allocation algorithms for extended-reach GPON," OECC 2009. 14th, vol., no., pp.1-2, August 2009

Smith, T.; Tucker, R.S.; Hinton, K.; Tran, A.V., "Implications of sleep mode on activation and ranging protocols in PONs," IEEE Lasers and Electro-Optics Society, 2008. LEOS 2008., vol., no., pp.604-605, 9-13 Nov. 2008

Ellershaw, J.C.; Riding, J.L.; Tran, A.V.; Guan, L.J.; Smith, T., "Economic Analysis of Broadband Access for Australian Rural and Remote Areas," ATNAC 2008. Australasian, vol., no., pp.1-4, 7-10 Dec. 2008

Ellershaw, J.C.; Riding, J.L.; Lee, A.; A.V.; Guan, L.J.; Tucker, R. S.; Smith, T.; Stumpf, E., "Deployment costs of rural broadband technologies," TJA, vol 59, no. 2, July 2009.

Tran, A.V.; Lee, A.; Ellershaw, J.C.; Riding, J.L.; Hinton, K.;Gopalakrishnapillai, B.; Smith, T.; Tucker, R.S.; "Long-reach passive optical networks for rural and remote areas," COIN, vol 9, no 1, pp.1-3, August 2010.

2 DBA LITERATURE REVIEW

2.1 Introduction

In passive optical networking, dynamic bandwidth allocation (DBA) is the key mechanism by which upstream packets are scheduled and allocated [35]. While the majority of subscriber bandwidth is currently downstream traffic, new services such as video conferencing require increased upstream bandwidth. For this reason, maximizing the bandwidth of upstream traffic and reducing its latency is essential for network operators to maximize revenue. The cost effectiveness of GPON is greatly determined by the ability for operators to sell more bandwidth than is technically available based on the premise that not all customers utilize their bandwidth rates simultaneously. This concept is known as over-subscription.

Oversubscription is only achievable if the bandwidth management is sufficient to effectively utilize the network resources. For this reason, in passive optical networking, the DBA algorithms must ensure that the required upstream packets are scheduled and transmitted with minimum latency and minimal wasted bandwidth. Delays in this scheduling can translate to increased packet latency and excessive scheduling to one ONU deprives other ONUs of bandwidth. For this reason, any DBA algorithm used should accurately handle the bandwidth demand whilst still providing an acceptable quality of service (QoS) [35].

In long-reach PONs (LR-PONs), the increased propagation delays inherent due to the increased distances translate to greater packet latency [23, 44]. In addition, the larger propagation delays also affect the DBA mechanism by introducing additional delays which, in turn, also increase packet latency. For this reason, it is essential to study how the standardized DBA mechanisms as well as DBA algorithms, respond when the physical reach of the network is increased. This will assist network operators plan for the future when longer reach PONs may be deployed. Whilst the principle mechanism that defines how the DBA operates is well defined by the relevant standards [6, 11], many

parameters are left open to the network operator. One of the most important DBA parameters is the time taken to schedule all ONUs on the network and is often referred to in the literature as the cycle time. To investigate the parameters in the DBA that contribute to packet delay and bandwidth utilization, two factors that ultimately determine the QoS, we must first examine the DBA mechanism and various implementation protocols. This chapter seeks to provide an overview of the standardized DBA mechanisms as well as research into various DBA algorithms for EPON, GPON and more recently, LR-PONs.

2.2 Dynamic Bandwidth Allocation

In a passive optical network, be it EPON or GPON, the network topology is implemented in a tree type structure as shown in Figure 2.1. Each ONU or ONT is connected to a single OLT via a common optical link. The use of passive splitters eliminates the requirement for active components in the network and gives rise to the *passive* nature of the network. The physical layer of EPON and GPON are similar in nature with each utilizing a separate wavelength for downstream and upstream transmissions.

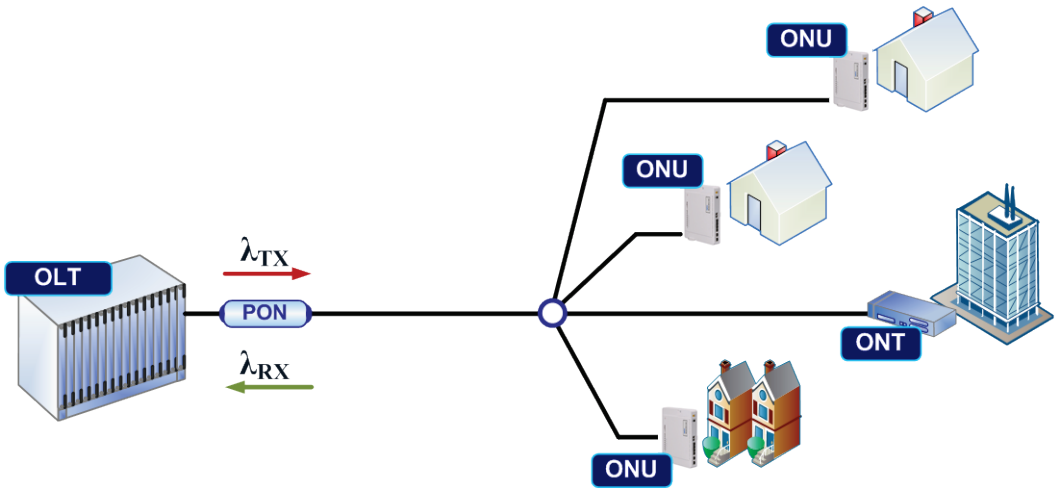

Figure 2.1 – Typical PON deployment consisting of an OLT connected to a number of ONUs/ONTs via a passive optical connection

The architecture of PON results in downstream transmissions from the OLT to the ONUs to be broadcast in nature, however the point-to-multipoint (P2MP) nature of the network means that upstream transmissions from each ONU must be appropriately timed so as not to arrive at the OLT simultaneously. Such behaviour renders any

received transmissions unrecoverable. To combat this, both EPON and GPON standards [6, 11] utilize node discovery procedures that identify the ONUs, determine their physical distance from the OLT and assign relevant network identities. Using the obtained knowledge of an ONU's physical distance, and consequently the round trip time (RTT), ranging protocols are used to time and schedule each ONUs upstream transmissions to avoid collision. Each ONU has a dedicated optical transmitter which means that the OLT must lock onto the phase of the received signal from each ONU. Between the upstream transmissions of each ONU, a small gap is left for the OLT to reset the receiver circuit. This gap is known as a guard time. While the discovery and ranging procedures ensure of collision free upstream transmissions, the DBA determines and controls the length of these transmissions.

The P2MP architecture also results in the OLT being the only entity in the network that has knowledge of all ONUs. For this reason, an ONU cannot simply transmit upstream traffic when required, instead traffic must be buffered until such time that the ONU is permitted to transmit. When requested, an ONU's buffer occupancy is conveyed to the OLT. The OLT responds by issuing messages to the ONU permitting it time slots in the upstream direction. This process forms the basic operation of the DBA and is one component of the PON media access controller (MAC). A key metric of DBA performance is that of the upstream packet latency, or delay [24] and is often analysed over varying traffic densities.

For EPON and GPON, the MAC layer components are vastly different. For EPON, both the upstream and downstream traffic and control messages are conveyed as Ethernet frames [6]. GPON, on the other hand uses a dedicated MAC layer and asynchronous transfer mode (ATM) for traffic which is fragmented into fixed size cells [11]. The Ethernet nature of EPON allows seamless integration into standard Ethernet equipment whereas GPON can facilitate a wide variety of traffic categories. Due to the difference in MAC layers of both networks, the way in which DBA is implemented is also different and is next examined in greater detail.

2.3 Static and Dynamic Bandwidth Allocation

Bandwidth allocation algorithms in passive optical networking can be categorized into two broad categories: static and dynamic [19]. In static allocations, the amount of

bandwidth that is allocated to an ONU is fixed and does not vary due to instantaneous traffic demand. Static allocations are the simplest algorithms to implement as they require little or no network traffic monitoring. The disadvantage of static algorithms is that they are very inefficient as an ONU may not have any traffic to transmit, but it is still allocated bandwidth. Dynamic allocation algorithms vary the amount of bandwidth allocated to each ONU based on demand. It has been widely observed that the traffic found in networks often exhibits a bursty nature that varies over time [51-53]. Static allocation algorithms do not vary the allocated bandwidth and result in unused allocations that lead to a reduction in throughput and increase packet delay [19]. Dynamic allocations vary the allocations to each ONU and can adapt to the instantaneous traffic demand for each ONU. As the amount of traffic varies, so too does the allocated bandwidth. Dynamic algorithms require the OLT periodically interrogate each ONUs traffic demand in order to track changes in bandwidth requests.

2.4 EPON and the Cycle Time

The EPON standard was announced in 2001 and finalised in 2004 by the IEEE as part of the 802.1ah task force [6]. Prior to the finalization, some research took place to understand how Ethernet could work in a P2MP environment [19, 37, 54-56]. EPON is a passive optical network with full Ethernet interoperability with downstream and upstream line rates of up to 1.25 Gbps. An EPON with line rates of 1.25Gbps is referred to as GEPON, however 8B/10B encoding is used that reduces the data rates to 1 Gbps. Once the standard was finalized, deployment of Gigabit EPON (GEPON) commenced, particularly in Asia [57]. The majority of research on DBA algorithms for PONs has been on EPON/GEPON as this is the most widely deployed PON to date [58, 59]. As a consequence, the terminology used in literature of EPON has carried forward, however the DBA algorithms also apply to GEPON.

In the EPON standard, standard Ethernet frames are transmitted for both traffic and control messages [60]. There are two control messages used for DBA; GATE and REPORT, as shown in Figure 2.2 (a) where a single ONU is connected to the OLT. The OLT issues gate messages to the ONU which responds with a report message. Once the report is processed, a new gate message is issued allowing the ONU to transmit data and append a new report. The process continues in this fashion. The gate message issued by the OLT

contains a time synchronization marker along with start and stop times indicating the length of time that particular ONU, identified by a logical link identifier (LLID), can transmit in the upstream direction. In EPON terminology, the gate message is commonly referred to as a bandwidth grant. The start and stop times in the gate message are relative to the synchronization marker which allows the OLT to coordinate the timing of all ONUs. Upon receiving a grant, an ONU transmits Ethernet frames according to the allowed time and appends a report message. This report message notifies the OLT of impending transmission requests for the ONU due to incoming subscriber traffic.

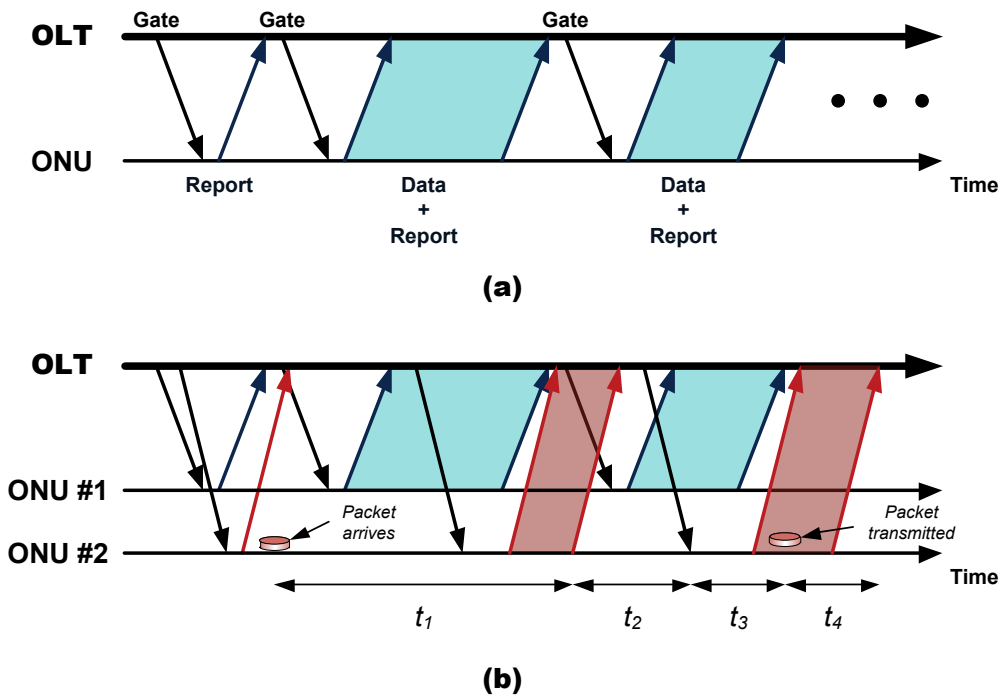

Figure 2.2 – (a) Principle operation of polling based DBA in EPON and (b) principle of interleaved polling and elements of packet delay due to a packets arrival and transmission

In EPON, the OLT does not issue a gate message to an ONU until a report message from that particular ONU is received [19, 61, 62]. The time between report messages is no less than the RTT and during which no other transmissions can be made between the ONU and the OLT. This polling gives rise to two problems. Firstly, bandwidth is under utilised during the wait periods as can be seen in Figure 2.2 (a) where a period of non-utilization exists between the two DATA + REPORT events. Secondly, during the time after a report is issued, and a grant is received, traffic continues to arrive at the ONU and must wait until the next polling cycle until its presence is reported. This is shown in

Figure 2.2 (b) where a packet arrives at ONU2 after a report is sent. The packet's presence is not reported until after time t_1 when the next report is sent. The packet then waits a time of t_2 until the ONU receives the next grant. After time t_3, sometime during the next data + report, the packet can be transmitted. After time t_4, which is equal to RTT/2, the packet arrives at the OLT. The total packet delay is the sum of these times.

Kramer et al. in [19] proposed a method whereby the wait times are reduced. In [19], an algorithm is proposed, - called interleaved polling with adaptive cycle time (IPACT) – in which the OLT polls the ONUs in an interleaving fashion. After a gate message is transmitted to one ONU, the OLT schedules the gate message to the next ONU such that its response arrives just after the response from the first ONU. This concept is shown in Figure 2.2 (b) where the data + report from ONU2 are scheduled to arrive just after the end of the data + report from ONU1. Kramer et al. also introduced the concept of a cycle time, i.e. the time taken to poll all ONUs on the network. The cycle time is adaptive and dependent on the amount of traffic on the network. This time varies due as the overall traffic density on the network changes. At low traffic density, fewer packets are required to be transmitted, and consequently less time is taken to serve all ONUs and hence a shorter cycle time. As traffic density increases, more bandwidth must be granted to the ONUs, thereby increasing the cycle time. The adaptive nature of the cycle time allows the algorithm to adapt to fluctuations in traffic patterns [19].

One important aspect Kramer et al. consider is the concept of fairness. If a straight forward granting process is applied whereby each ONU is granted the same level of bandwidth in the reports, ONUs with excessive volumes of traffic can dominate the network. IPACT imposes maximum window sizes on the grants to prevent this from occurring. The ith ONU is granted bandwidth based on the amount that has been reported, B_R^i, and the maximum window size for that ONU, $W_{\max}^i$. A decision is then made to determine the allowed bandwidth, B_A^i. The actual granted bandwidth, B_G^i, is therefore given by

$$B_G^i = \begin{cases} B_R^i, & B_R^i < W_{\max}^i \\ W_{\max}^i, & B_R^i \geq W_{\max}^i \end{cases} = \min \begin{cases} B_R^i \\ W_{\max}^i \end{cases} \tag{2.1}$$

This method ensures that heavily-loaded ONUs do not monopolize the available bandwidth as well as imposing upper limits on the cycle time as too long a cycle time can lead to increased packet delay [19]. Kramer et al. also offer several methods for determining the allowable bandwidth, B_A^i. These methods include fixed grants, where $B_A^i = W_{\max}^i$ regardless of reports, limited grants where $B_A^i = B_R^i$ and grants with additional credit where $B_A^i = B_R^i + x^i$, where x^i is either constant or a proportion of B_R^i. As seen in Figure 2.2 (b), subscriber packets that arrive at the ONU after a report is sent to the OLT must wait for an entire cycle until the next grant is received. This can produce significant delay in situations where high volumes of traffic are present as the delay is dependent on the cycle time. The credit schemes allow for this additional traffic. Analysis of the proposed methods indicate that all exhibit similar delay properties except for the fixed allowance method [19]. From IPACT we can see that if the grants can vary dynamically in an effort to match the variation of the input traffic, better results are achieved than that of fixed grants. The interleaved polling method is an effective algorithm in preventing an ONU from monopolizing the upstream frame, however no significant reduction in average packet delay was displayed when credit schemes were used as opposed to without [19].

Kramer et al. also incorporate a realistic network traffic model based on previous work [51, 53] that identifies network traffic as self-similar and displays long range dependency. This traffic can be generated by aggregating multiple smaller streams of Pareto on/off traffic models to generate realistic Ethernet traffic that also exhibits bursty behaviour [51].

In [19], three classes of bandwidth granting algorithms were considered;

1. Constant, or static, window sizes where the OLT grants the maximum window size regardless of the reported queue size. This static granting method could be considered the simplest of algorithms as the OLT does not require any complex decision processes to issue grants, however static grants do not account for any variation in subscriber traffic.
2. Limited window sizes where the OLT grants the reported bandwidth up to the maximum window size. This algorithm does allow for fluctuations in subscriber traffic; however it does not take into account any traffic that has arrived between when a report is sent to when the gate message arrives.

3. Credit based schemes where the OLT can increase the granted bandwidth above the reported bandwidth up to a maximum size. The idea behind credit is to account for the additional traffic. Kramer et al. describe various methods for generating the excess; constant credit, linear credit or elastic credit. Regardless of the credit method, all employ some form of traffic estimation or prediction.

This now enables DBA schemes to be defined into two groups, those that try to predict traffic usage and those that do not (the static granting method does not allow any dynamic variation to the grants and therefore cannot be considered a *dynamic* bandwidth allocation algorithm).

IPACT does not specify the order in which the ONUs are granted bandwidth. If a simple pointer mechanism is used to schedule, then the ONUs could be allocated in numerical order according to each ONUs unique identifier. The OLT could schedule the ONUs according to distance, since it is unlikely that an ONU should alter physical location. The OLT could also schedule according to queue size. Zheng et al. [63] present two approaches to varying the OLT scheduling order; schedule in terms of decreasing queue size and schedule in terms of traffic arrival times at the ONUs [63]. Zheng et al. propose that the ONU with the longest queue would otherwise experience the longest packet delay and therefore should be granted earlier. Their other proposed method, whereby the ONU with the earliest packet is granted first, requires that the ONU modify the report message to include information regarding the arrival time of the first packet in the buffer. The OLT can then determine the scheduling order. Both methods display a small improvement in average packet delay over round-robin schemes [63]. One major disadvantage to the earliest packet first scheme is that the report message at the ONU must be modified becoming non-standard equipment which can limit interoperability amongst vendors.

Bhatia et al. in [26], also proposed to alter the scheduling to be performed in terms of queue length, but the queue lengths are scheduled in ascending order. The approach taken requires an initial grant sufficient to only send a report whereby the OLT can construct a scheduling list. Afterward, the OLT can continue to schedule the ONUs according to queue length however limits on maximum scheduling times are imposed. Bhatia et al. use the limited window size as described in [19] and generate self-similar traffic in their modelling. This approach displays some reductions in cycle time and average packet delay as compared to IPACT, however at low traffic density little or no

benefit is observed [26]. ONUs that have no packets to transmit are not scheduled first, as this may un-necessarily increase the delay of other ONUs. Rather these ONUs are scheduled as if the queue length was the average of all ONU reports. In situations of low traffic density more zero length queues are reported and consequently no benefit is observed.

Hee-Jung et al. [64] proposes an algorithm based on IPACT whereby the OLT employs a control based traffic prediction method to increase the grants to allow for additional traffic arriving at the ONUs. This prediction scheme calculates the difference between the current reported queue size at the ONU and the previously reported queue size and increases the size of the grant accordingly. A control parameter is also used to prevent system instability. Delay results of this algorithm display a significant improvement over IPACT [64], although the traffic model used assumed traffic was piecewise-constant with fast settling and therefore did not exhibit a high degree of burstiness.

Another credit-based DBA algorithm was proposed by Miyoshi et al. in [65]. This scheme identifies that Ethernet frames cannot be fragmented and must be transmitted as a whole. If insufficient credit is provided to an ONU such that it cannot transmit en entire Ethernet frame, this frame must remain in the buffer and a portion of the grant is considered wasted [65]. To eliminate this problem, Miyoshi et al. propose to allow the ONU to include in the report information pertaining to both the absolute queue length as well as the frame boundaries. While this process displays higher throughput, the DBA often requires an additional cycle to grant according to the frame boundaries and modification is made to the reporting mechanism which again results in non-standard equipment.

In the EPON DBA algorithms discussed in [19, 26, 63, 64] interleaved polling has proven to be an effective method of granting bandwidth to ONUs. Kramer et al. show that interleaving works well with the P2MP EPON standard and by allowing the grants to vary dynamically with traffic density, average upstream packet delay is lower than that of fixed, or static, grants [19]. Varying the order by which the OLT schedules and interleaves grants to the ONUs, either in ascending or descending queue size, can also lower packet delay [26, 63]. From this we can deduce that the order itself is not important, rather the fact that the scheduler is varying the order.

In the previous examples of IPACT and variations thereof, all ONUs were given the same maximum transmission window, however in the next section we will examine DBA algorithms for EPON where variations on the bandwidth requirements of individual ONUs are included.

2.5 EPON and Service Level Agreements (SLAs)

In practice, network operators issue service level agreements (SLAs) to subscribers allowing higher bandwidth for premium subscribers. In EPON, the upstream bandwidth capacity is fixed to 1 Gbps after encoding, although overheads and guard times reduce the actual data capacity to below this amount. These overheads include the DBA control messages and are therefore dependent on the traffic density and number of active users. With 32 ONUs, the average upstream bandwidth per user could be calculated at just over 30 Mbps, however using over-subscription, network operators can provide upper limits on the achievable bandwidth to well above this rate. Recall that over-subscription works on the premise that not all subscribers will utilize the network at their specified limit at any given time. Over-subscription will therefore only work if a DBA algorithm is used is capable of adapting to traffic fluctuations and can also differentiate between SLAs [35].

Ma et al. in [55] and Yongqing et al. in [56] allow for different SLAs amongst subscribers by grouping the ONUs into two sets. One set provides bandwidth guaranteed services and the other does not. ONUs in the bandwidth guaranteed group are allocated multiple entries in a table that holds all ONUs bandwidth requirements. The lager the number of entries in the table, the more bandwidth is allocated. Using this technique SLAs can be met for these ONUs, however results indicate that the packet delay for the non-guaranteed ONUs increases significantly at low traffic densities [55, 56]. A logical conclusion drawn from these algorithms is that the packet delay is inversely proportional to the amount of bandwidth granted.

As shown in [55, 56], increasing the grant to an ONU can reduce the packet delay for that particular ONU. A clear disadvantage to this is that it deprives other ONUs of bandwidth, thereby increasing their packet delay. One solution is to allow bandwidth that is not required by some ONUs to be re-distributed amongst other ONUs that may

have exceeded their maximum limit [66]. By summing up bandwidth requests in the reports, the OLT can calculate the excess bandwidth, B_{excess}, given by:

$$B_{excess} = C(t_c) - \sum_{i=1}^{N} B_R^i \tag{2.2}$$

where $C(t_c)$ is the total capacity of the network for the current cycle time, t_c, i is the ONU index, N is the total number of ONUs and B_R^i is the amount requested by ONU_i. This enables some of this excess bandwidth to be added to the grant, B_G^i, of a heavy traffic ONU:

$$B_G^i = B_R^i + B_{excess}^i \tag{2.3}$$

where

$$B_{excess}^i = \frac{B_{excess}}{F_i} \tag{2.4}$$

and F_i is a factor based on the ONU's SLA. The re-distribution factor can be assigned according to the excess requested [19], or according the SLA [66].

Bandwidth redistribution allows for a fairer scheduling scheme whereby the grants to some ONUs can be increased, but not at to expense of other ONUs. Lee et al. [66] prove that a reduction in average delay can be seen at high traffic densities.

One problem encountered with bandwidth redistribution algorithms is that the OLT requires knowledge of all the ONUs reports prior to allocating the excess bandwidth. This creates a delay in allocating the excess, or what is referred to as an idle-time delay, and can result in in-efficient frame usage [67]. Shown in Figure 2.3 are two DBA cycles; the current *cycle (n)* and the previous *cycle (n-1)*. The previous cycle concludes when all the last report from that cycle is received at the OLT, and the current cycle begins when the first grant of the current cycle is sent. The idle time occurs when the OLT waits to issue the first grant after the last report is received, thus leaving a period of unused, or idle, upstream frame time. During this idle time, the upstream frame is not utilized and this leads to a decrease in throughput.

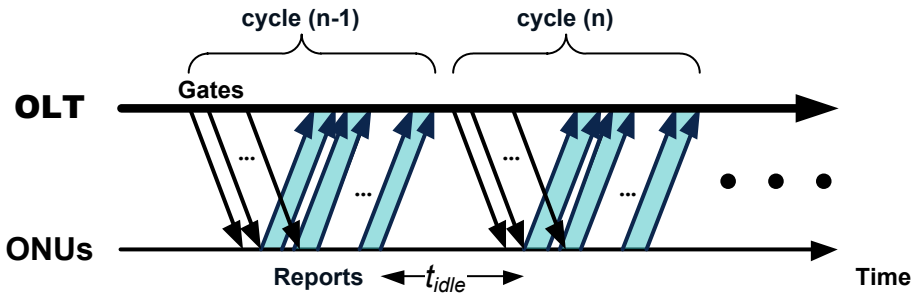

Figure 2.3 – Idle time created in interleaved polling

The idle-time can be minimized by allocating ONUs that do not require excess bandwidth immediately, and delaying the ONUs that require excess bandwidth allowing for their reports to be received [68]. This may perform favourably at low network loads, but at high network load the effectiveness decreases as more ONUs may require additional bandwidth [67, 68]. Typically a minimum bandwidth limit is determined by a weighting factor set by the SLA for each ONU. Bursty traffic produced by self-similar modelling results in some ONUs not requiring their minimum bandwidth limit so a bandwidth redistribution approach similar to [66] can be used. ONUs with low traffic volumes can then be scheduled immediately and a tally of the excess is accumulated. The OLT keeps track of when the next available slot on the upstream is available and schedules ONUs with high traffic volumes such that no idle period should occur [67, 68]. The excess bandwidth is re-distributed amongst these ONUs as required. The results of this method indicate that by reducing, or even eliminating any idle periods, average traffic delay can be reduced, however only at high traffic densities [67, 68].

The idle time can directly impact throughput as shown in Figure 2.3. As observed in the previous section, the more bandwidth that is granted, the lower the packet delays. The idle time reduces the amount of bandwidth that can be utilized; hence packet delays may increase. By redistributing bandwidth amongst the ONUs, throughput can be increased and the average packet delay can be reduced; however the effectiveness of bandwidth redistribution is generally increased only for the ONUs with a premium SLA. This allows another key relationship to be identified in that the higher the throughput, the lower the average delay.

In the following section we will examine how EPON behaves with not only ONUs with varying priorities, but different categories of traffic with varying delay requirements within each ONU.

2.6 QoS in EPON

With new and emerging internet services becoming available every day, it is important for an access network to be able to efficiently handle traffic of different categories. Some traffic, such as voice over IP (VoIP) has strict delay and jitter (delay variance) requirements which if not met, the service quality can degrade or risk disconnection [69]. In the EPON standard, provision exists for the OLT to provide grants for up to eight priority queues within a single ONU. IPACT is only capable of allocating an ONU a single grant and the ONU must aggregate and shape any traffic into this grant. Whilst this is an efficient method of allocation from a throughput perspective, room for improvement exists in order to allow for differentiation of the different categories of traffic classes. Figure 2.4 shows the basic concept of an EPON ONU with three traffic categories of varying rates and priorities being queued and aggregated prior to transmission. To incorporate QoS into a DBA algorithm, the OLT must assign some bandwidth to the ONUs not only based on the SLA requirements, but also on the traffic class as well.

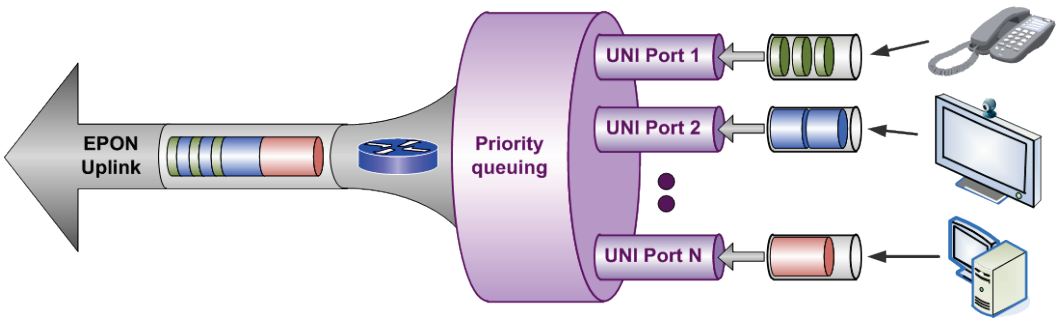

Figure 2.4 – QoS with three traffic services in an EPON ONU. Incoming traffic is queued according to priority prior to upstream transmission.

From the previous section, the DBA algorithm grants bandwidth to the ONUs based on simply the reports or a combination of reports and SLAs. This behaviour, where no variations of traffic class are considered, can be referred to as *inter-ONU* scheduling and is performed by the DBA process within the OLT. When QoS, and traffic of different

priorities is considered, traffic classification and prioritizing that occurs within the ONU is referred to as *intra-ONU* scheduling [57, 62]. Figure 2.5 displays these concepts with N ONUs connected to a single OLT and up to three queues within each ONU.

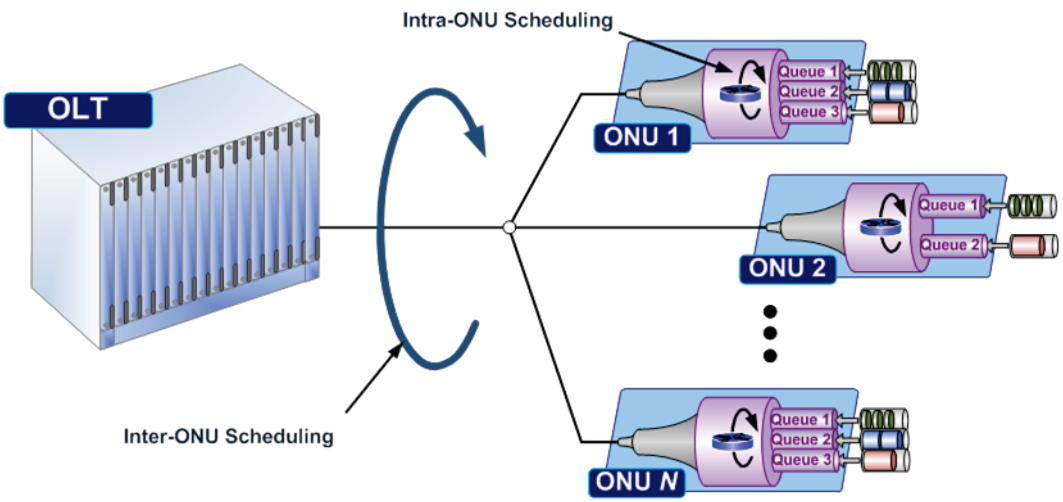

Figure 2.5 – intra-ONU and inter-ONU scheduling in EPON.

The simplest approach to intra-ONU scheduling utilizes the different priority queues in a report message to convey priority information to the OLT [40, 70]. Maode et al. in [71] account for QoS by allowing the ONU to perform intra-ONU scheduling according to descending queue priority and inter-ONU scheduling is performed according to descending ONU total queue size, similar to that described in [63].

Other proposed schemes continue the approach of grouping the ONUs into bandwidth guaranteed and non-bandwidth guaranteed groups, but also allow for different traffic classes in the ONUs [72, 73]. Although the two classes of ONUs have different SLAs, the ONU still utilises intra-ONU scheduling. Biao et al. in [72] use a max-min fairness scheme for inter-ONU scheduling combined with bandwidth redistribution, as discussed in [66-68], to account for the SLAs. Xiaofeng et al. [73] take a similar approach; however the ONU calculates the required bandwidth to transmit the high priority traffic, denoted as minimum bandwidth, and the additional bandwidth to transmit the remainder, denoted as maximum bandwidth. These two bandwidth requirements are included in the ONU's report and the OLT then employs the bandwidth redistribution approach [73]. Results for both of these similar schemes show that while the throughput for high priority traffic is high and the delay is low, similar to the other bandwidth redistribution approaches, this benefit comes at a cost. In this scenario it is the lower priority traffic suffers low

throughput and consequently high delay [72, 73]. The low priority traffic delay is much higher than a simple interleaved polling algorithm such as in [19].

Miyoshi et al. [65] allow for QoS by employing a two-part report consisting of queue levels for delay sensitive traffic (denoted as high priority) and best-effort traffic (denoted as low priority). A max-min fairness scheme is also used to redistribute bandwidth; however a satisfaction parameter is used that is calculated based on the difference between an ONUs total report and the amount granted [65]. If a grant to an ONU is considerably less that the total requested, the satisfaction is said to be low and if the grant equals the report the satisfaction is high. This parameter is then incorporated into the max-min redistribution in an effort to reduce queue sizes. The result is that delay sensitive traffic displays less delay than best-effort traffic [65], however no other DBA schemes are considered.

Kramer et al. [62] use both inter-ONU and intra-ONU scheduling with the incoming traffic sharing a common buffer at the ONU. As the ONU classifies incoming traffic, a higher priority packet is allowed to displace a packet of lower priority in the buffer. This allows high priority traffic to be transmitted sooner and experience lower delay. A drawback is that at low traffic densities low priority traffic suffers high delay [62]. This is due to higher priority traffic arriving after a report was sent to the OLT requesting bandwidth for lower priority traffic. Under the proposed scheme, the newly arrived higher priority traffic can displace the lower priority traffic, thereby essentially taking its place when the next grant arrives. To overcome this, Kramer et al. propose either an additional queue to hold traffic after buffer-displacement has occurred and the packets cannot be rearranged or a credit system to account for the additional packets [62].

A similar DBA algorithm is proposed by Assi et al. in [37], but also uses SLA based bandwidth redistribution and addresses the idle time commonly seen by such redistribution. This scheme also allows higher priority packet to displace lower priority packets as in [62]. The OLT applies bandwidth redistribution according to the SLAs when scheduling the grants and the idle time is reduced by granting ONUs with low traffic volume as in [67]. This scheme addresses most of the common problems seen in EPON DBA, and the results display a common trend. High priority traffic experiences low average packet delay at the expense of lower priority traffic.

2.7 Summary of EPON DBA Literature

In summary, we have seen that although simple interleaved polling is an effective method of scheduling multiple ONUs on the network [19], it does not account for ONUs with varying SLAs or traffic with degrees of priority. To overcome this, bandwidth redistribution can be used, but a side effect is an idle time that reduces network utilization, but can be reduced [67, 68]. When considering QoS in EPON, it is often left to the ONU to utilize intra-ONU scheduling to determine the priority of traffic prior to issuing report messages [57, 62]. Packet displacement has been proposed to better serve traffic of higher priority, however this can lead to low priority traffic being further delayed at the expense of higher priority traffic [37, 62].

To compare the results presented by the various algorithms, we consider the network traffic density over the total capacity of the network. Such parameter is often referred to as network load or offered network load. A comparison of approaches taken by and delay results for some of the EPON DBA algorithms are presented in Table 2.1:

Table 2.1: Comparison of EPON DBA Algorithms

Authors	Zheng et al. [63]	Ma et al. [55]	Fan et al. [68]	Yuanqiu et al. [40]	Assi et al. [37]
Inter-ONU scheduling	Longest queue first Earliest packet first	Table based	Bandwidth redistribution with immediate scheduling	Round robin	Bandwidth redistribution
Intra-ONU scheduling	Aggregation	Aggregation	Priority queuing	Priority queuing	Packet displacement
Traffic model	Self-similar fixed length packets	Exponential distribution Fixed length packets	Self-similar variable length packets	Self-similar variable length packets	Self-similar, variable length packets Poisson, fixed length packets
ONU buffer sixe	10 MB	10 MB	10 Mb	10 MB	10 Mb
Maximum cycle time	2.0 ms	Not provided	2.0 ms	Not provided	2.0 ms
Network load delay benefit	0.4 to 0.8	High priority beneficial: 0.0 to >1.0 Low priority adverse: 0.2 to >1.0	0.9 to >1.0	0.5 to 0.7	High priority beneficial: 0.0 to >1.0 Low priority adverse: 0.4 to >1.0 Medium priority adverse: 0.8 to >1.0

In all of the literature, a similar concept arises. The more bandwidth a source can be given (either an entire ONU or a priority queue), then a packet from that particular source will encounter lower delay. The obvious drawback of this is that the bandwidth allocated to packets outside that source is reduced and suffer an increased delay.

While those papers that focus on DBA in EPON have demonstrated that EPON is a suitable architecture for an access network, a similar architecture, GPON, was also standardized at a similar time. In the next section we will discuss the workings of dynamic bandwidth allocation in GPON and examine some of the GPON DBA literature.

2.8 GPON DBA

The international telecommunication union (ITU) which had previously standardized asynchronous PON (APON) and broadband PON (BPON), finalized the Gigabit-capable PON (GPON) in 2004, with amendments in 2006 and 2008 [7, 10, 11, 74]. GPON is another promising access network architecture consisting of an OLT connected to a number of ONUs by means of a passive optical network. As such, the physical architecture is almost identical to that of EPON/GEPON; however the downstream line rate is 2.488Gbps; double that of EPON, while the upstream line rate is close to that of EPON at 1.244Gbps. Unlike EPON, GPON does not use encoding resulting in line rates equal to the data rates. The physical distance that the network can span is also different to EPON. EPON has an unlimited logical (maximum) reach and differential reach (the differential reach being the distance between the furthest and closest ONU to the OLT); however in practice both these distances are limited by the power budget. The GPON standard limits to the logical reach to 60 km for power budget reasons and 20 km for the differential reach due to restrictions in the MAC protocol [11]. Figure 2.6 shows two ONUs connected to the OLT with ONU1 located at 60 km from the OLT and ONU2 located 20 km from ONU1. In EPON, the OLT uses the report/gate message mechanism to determine the physical distance of each ONU. In GPON, the OLT performs activation and ranging procedures periodically that detects ONUs on the network, measures their physical distance and assigns an equalization delay parameter (EqD) to each ONU. The ONUs use this parameter to create a virtual buffer to store upstream traffic prior to actual transmission such that the effective distance of all ONUs becomes equal. This

concept is shown in Figure 2.6 where the ONU2 uses the EqD to appear at a transmit location identical to that of ONU1.

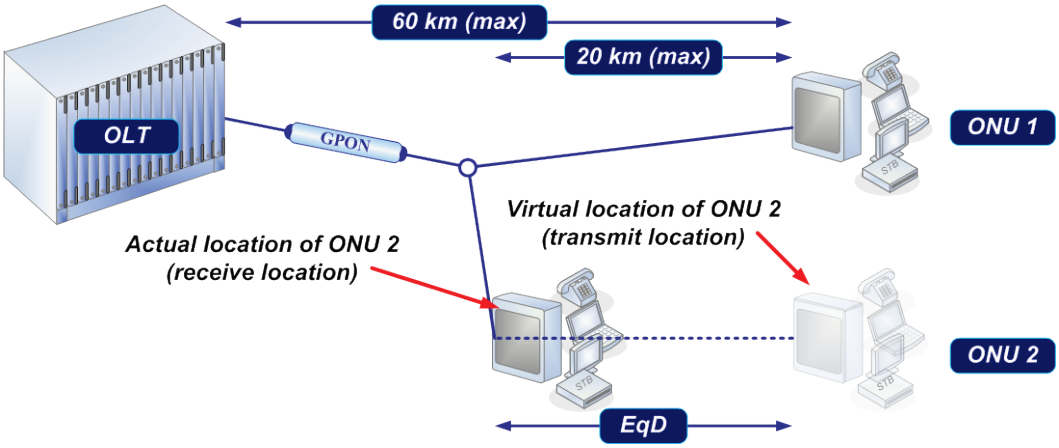

Figure 2.6 – Equalization of two ONUs in GPON with logical and differential reaches also shown.

While the architectures are virtually similar, the MAC layer for GPON is vastly different. EPON traffic consists of only Ethernet frames, whereas GPON traffic is fragmented and encapsulated into fixed size cells using the GPON encapsulation method (GEM) and therefore has the capability to carry any category of traffic.

The DBA mechanism used in GPON also is responsible for the granting of bandwidth according to an ONU's report. The terminology is different however as GPON uses allocations and requests in place of grants and reports respectively. While the principle of DBA in GPON is the same as in EPON in that upstream packets must be scheduled prior to being transmitted, the way in which the DBA is executed is vastly different. Upstream traffic in GPON is encapsulated in traffic containers (T-CONTs) of which there can be multiple associated within a single ONU and can also be dynamically created and destroyed [11]. This structure allows traffic of different priorities to be carried in one or more T-CONTs, each with a pre-assigned priority. The OLT allocates each T-CONT independently, thus making QoS an inherent component of GPON. Unlike EPON, which transmits Ethernet frames when required, GPON broadcasts continuous, consecutive downstream frames of 125 µs in length. The components of a single downstream frame are shown below in Figure 2.7.

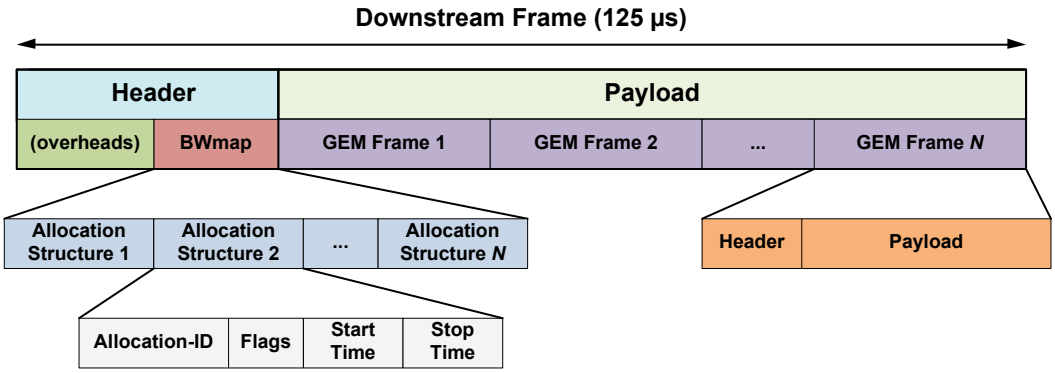

Figure 2.7 – Downstream framing Structure of GPON.

Figure 2.7 shows the basic elements of a GPON downstream frame with header and payload components. The payload contains fragmented traffic with fixed size cells and the header contains overheads, including physical layer information and physical layer operation and administrative messages (PLOAMs), and a bandwidth map (BWmap) that is used to provide allocations to the T-CONTs. ONUs are allocated bandwidth periodically using the BWmap. The BWmap consists of a number of allocations structures, each with a specific ID (Alloc-ID) for an associated T-CONT along with flags, start and stop times. The flags are used to indicate options, and the start/stop times contain the T-CONT's available transmission time for the next upstream frame. While the DBA in EPON granted bandwidth to an ONU using a single LLID, GPON allows multiple T-CONTs in each ONU [11]. This provides more flexibility over the DBA mechanism of EPON as different priorities within an ONU can be addressed individually. An ONU that has multiple T-CONTs allocated in the same BWmap will combine the packets from the T-CONTs into a single upstream transmission. In order to convey information regarding the T-CONT's buffer status, an upstream dynamic bandwidth report (DBRu) can be included to the T-CONT's transmission. The DBRu contains the number of GEM frames still occupying the T-CONTs buffer and is therefore similar to that of an EPON report. GPON allows for two types of DBA methods; status reporting and traffic monitoring. The former dictates that a DBRu be issued upon request and the latter requires that no DBRu is issued and the OLT monitors the amount of empty, or idle, GEM frames to determine if the allocations should be increased or decreased.

The upstream frame structure is shown in Figure 2.8 with *N* ONUs transmitting upstream bursts. Each burst consists of a physical layer overhead (PLOu) and a number of

allocation intervals containing the upstream data from the various T-CONTs within that ONU. The PLOu contains a syncing pattern to allow the receiver at the OLT to lock onto the phase of the burst, ONU information and administrative messages (PLOAMu). The allocation intervals of ONU2 in Figure 2.8 are expanded to show that up to *N* intervals can be present, each containing a DBRu and a number of GEM frames.

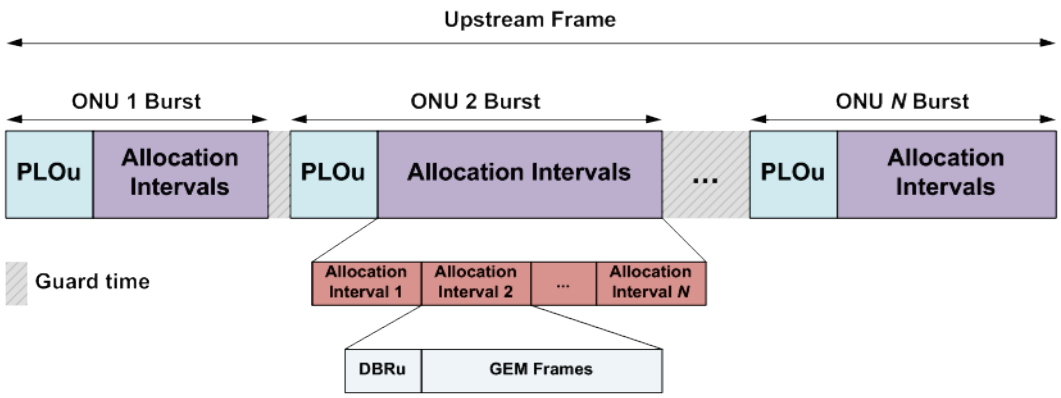

Figure 2.8 – GPON upstream frame showing three ONUs, with ONU2 transmitting packets from multiple T-CONTs

The T-CONTs are divided into five types, each designed to carry different categories of traffic such as delay-sensitive or best-effort [11]. These types are:

1. Fixed bandwidth. Bandwidth that is always allocated, regardless of request or demand. Static allocation DBA type.
2. Assured bandwidth. Bandwidth that is allocated in full if requested and given the highest priority over other traffic.
3. Assured and non-assured bandwidth. Contains an element of assured bandwidth that is allocated in full if required, and an element of non-assured bandwidth that is allocated if remaining bandwidth is available.
4. Best-effort bandwidth. Bandwidth that is allocated only if remaining bandwidth is available after all other T-CONT types have been allocated.
5. Super-Set: Bandwidth is allocated based on multiple components of the other four T-CONT types.

By using these types of T-CONTs, network operators can provision the network based on a specific user's SLA and expected QoS. In addition, as the T-CONTs can be created and destroyed, services can be added on an as-needed basis. Figure 2.9 shows a conceptual diagram of upstream QoS in GPON with four T-CONTs of varying types. Priority is assigned from fixed, down to best-effort depending on the requirements of the T-CONTs. Fixed bandwidth is always allocated and is essentially a static allocation. Assured

bandwidth is allocated to the full amount requested, and for this reason no traffic shaping need be performed on incoming traffic streams, only prioritizing using strict priority (SP). With non-assured and best-effort types, bandwidth is only allocated if there is sufficient bandwidth remaining. For this reason, weighted-round-robin (WRR) shaping and prioritizing (SP) are still required at the ONU. These concepts are also shown in Figure 2.9.

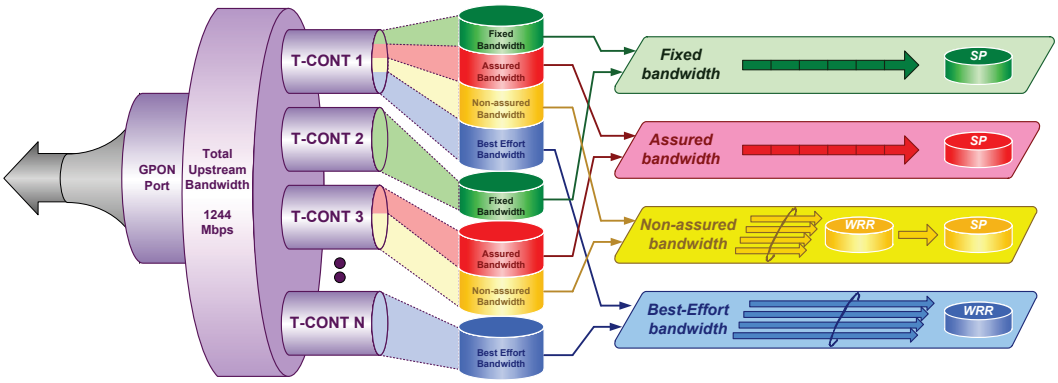

Figure 2.9 – Conceptual diagram of QoS in GPON. Four T-CONTs of varying types are shown in the upstream path of GPON.

The DBA reporting mechanism in GPON is different to that of EPON in that the allocations are sent as part of the downstream frame header. Flags indicate if the associated T-CONT is required to append a DBRu to the upstream transmission. In the following section we will examine the literature regarding DBA and its role in GPON.

2.9 Literature on DBA for GPON

The DBA mechanism, as outlined in the previous section, is more complicated in GPON than in EPON. However the actual implementation is vendor specific meaning that the size and frequency of the allocations are not defined in the standard. There has been some research into various DBA algorithms for GPON, specifically focusing on similar aims to that of EPON; specifically maximizing throughput and minimizing upstream packet delay.

A general implementation of the GPON DBA mechanism with different types of T-CONTs (types 2, 3 and 4) and traffic priorities was examined by Angelopoulos et al. in [41] and

delay outcome at two different network loads (under-loaded and over-loaded) was observed. A tri-modal packet generator is used to inject traffic into the ONUs and determine the packet delay. Angelopoulos et al. conclude that for under-loaded conditions, the typical packet delay can be under 1 ms, however for an over-loaded system, T-CONT types 2 & 3 experience a mean delay of 0.5 ms and the delay for type 4 (best-effort bandwidth) increases over time. Angelopoulos et al. note that while this delay increases without bound, eventually packets will be dropped and higher layer protocols are assumed to adjust the traffic rate.

The behaviour of prioritized traffic in GPON DBA algorithms results in semi-asymptotic delay behaviour where the lower priority traffic experience a sharp increase in packet delay as the network load increases [28]. This is due to the higher priority traffic being allocated over the lower priority. As traffic requests continue to increase, the next lowest priority traffic queue will experience the same result, and so forth. Fixed type traffic has shown to exhibit predictable characteristics and whilst generally not examined, it is often included in some analysis [28, 41]. Once the combined requested traffic levels of an ONU increase beyond the capacity of the allocations, i.e. congestion has occurred, lower priority queues are buffered thereby increasing their packet delay as higher priority traffic is scheduled first [27, 28, 41]. This is a similar effect as seen in EPON with bandwidth redistribution schemes. The amount of bandwidth allocated and the frequency at which it is done, affect both the throughput and the delay. If the time between allocations (allocation interval) is large, traffic throughput can be increased as less bandwidth is consumed by overheads such as DBA messages and guard times; however packet delay increases due to the increased time between allocations. Conversely, if the allocation interval is reduced, packet delay decreases; however the traffic throughput decreases as bandwidth is consumed by additional overheads [27].The OLT allocates bandwidth using the BWmap on a periodic basis; however the GPON standard does not mandate that all T-CONTs be allocated in each BWmap. This allows for service, or allocation, intervals to be defined for each T-CONT [25, 27, 44, 75]. By allowing each T-CONT to be allocated independently, those with higher priority types can be scheduled more frequently, and as we have seen this can reduce the packet delay. Bandwidth redistribution in GPON has also been seen to reduce variations in average delay [48, 76].

Investigation into the scheduling according to service intervals was done in [25] where fixed type T-CONTs were allocated every downstream frame and flexible type T-CONTs (such as assured and non-assured types) were allocated according to a variable interval. Minimum limits were imposed on the flexible intervals based on RTT and processing delays, which were then rounded up to be an integer multiple of the frame time [25]. Traffic prediction is also used to estimate traffic rates by comparing a current DBRu to the previous ones. The allocations intervals were determined by the OLT based on variation in traffic densities between the T-CONTs. A parallelization is drawn between the scheme and IPACT as the allocation interval in the proposed scheme is also adaptive similar to the cycle time in EPON [25]. The results presented in their literature are simulated for a 10-Gbps network; however the concepts presented still hold true for a 2.5/1.25-Gbps GPON network.

Whilst the DBA mechanism of GPON is implemented in a different manner to that of EPON, some principle parameters and concepts can be used such as the cycle time, which in the case of GPON is denoted the allocation or service interval and is specific to each T-CONT. Whilst the MAC for GPON does not support a direct implementation of interleaved polling as in EPON, an adaptation of IPACT was examined in [42] and bandwidth redistribution was used to account for SLAs, similar to that described in [37]. The throughput was almost identical in its behaviour to that of EPON and the delay of lower priority traffic increased at lower network loads than that of higher priority. While this can confirm the bandwidth redistribution penalty present in EPON also affects GPON networks, no information was given as to how IPACT was adapted for GPON and for this reason a direct comparison should not be made. Recall that the BWmap is sent as part of every downstream frame which has exact timing requirements, whereas interleaved polling requires that grants be issued on an irregular basis. Traffic prediction has also been investigated in GPON [25, 50, 75] where bandwidth allocated to a T-CONT is predicted to account for discrepancies that arise due to traffic arrivals after a DBRu has been issued.

Other similarities are drawn from investigation into EPON such as credit, bandwidth redistribution, SLA partitioning and inter-ONU/intra-ONU scheduling [20, 50]. Partitioning also allows for idle time elimination as while one group of T-CONTs is being allocated, DBRus from the other group are processed. Any remaining bandwidth after the first group has been allocated is added to the available bandwidth of the second

group. Groups are partitioned according to T-CONT types, with types one and two in one group and the remainder in another. As expected, these concepts have similar results as seen in EPON with the higher priority group exhibiting less packet delay that the other group [50]. While this concept relies on similar aspects as seen in EPON, network provisioning as outlined in the ITU-T standard dictates that intra-ONU scheduling need not occur between T-CONTs, only within a T-CONT. If traffic of multiple priorities is to be placed into a common T-CONT, then scheduling may be required; however as multiple T-CONTs can be created and managed right through from user to OLT [74], the ONU need only classify incoming traffic and place the traffic into the appropriate T-CONT buffer.

We saw in the previous sections that traffic prediction and credit schemes were often used in EPON DBA to increase the size of the grants to allow traffic that may have arrived after a report was sent to be transmitted sooner [19, 64]. However Skubic et al. [77] identify that the use of inefficient prediction schemes in GPON can lead to an inconsistency which results in bandwidth being allocated that is not required, leading to a reduction in throughput. If traffic prediction is to be used, the accuracy of the traffic prediction scheme must be high in order to minimize the wasted bandwidth that is not required. Skubic et al. [77] use a scheme whereby the DBRu of the current interval is compared to the allocation of the previous interval to estimate the T-CONT's traffic rate [77]. This allows for a more accurate estimation scheme thereby reducing the wasted bandwidth.

The authors in [27, 28, 41] all examine a fairly general implementation of the GPON DBA mechanism and conclude that GPON is effective in handling QoS and produces comparable results to EPON when SLAs and QoS are considered. These schemes do not propose any modification to the GPON DBA standard; rather utilize the allocation intervals to provide QoS to the traffic queues. Using these schemes, correlations are seen between the amount allocated to a T-CONT and the resultant packet delay. Some proposals have been made to modify the DBA standard to allow the ONUs to report the *incremental* buffer level to the OLT since the last allocation [78, 79]. The OLT then uses this information to allocate bandwidth to different queues within the ONUs. While this mechanism displays reduced queue sizes and increased throughput, the DBRu format that each ONU transmits becomes non-standard, thereby reducing market compatibility. Others point out that this scheme has drawbacks due to a lack of robustness against frame dropping [75] which may lead to missed reporting of packets which will

consequently create imbalance between requests and allocations. While there is a very small probability of this occurring, there are sufficient mechanisms, such as error checking (CRC) and bit interleaved parity (BIP), in the GPON framing structures to detect the majority of bit-errors [11]. If errors are detected, or even an entire missed upstream transmission from and ONU, the OLT can issue a variety of administrative PLOAMs to detect possible faulty ONUs and seek to reconnect [11].

2.10 Summary of Literature on DBAs in GPON

The GPON standard regarding DBA and traffic management, focuses on encapsulating both the upstream and downstream traffic and carrying the upstream traffic in individual T-CONTs rather than an aggregation system commonly seen in EPON. The GPON OLT allocates upstream bandwidth to the T-CONTs instead of the ONUs and as the T-CONTs have varying priority types, the upstream traffic can be assured of QoS. In the papers examining DBAs in GPON, we observe that the common approach is to allocate bandwidth based on strict priority according to the type of T-CONTs. Higher priority types are allocated first with lower priority and best-effort T-CONTs to follow [27, 28, 41]. Parameters such as allocation intervals and minimum/maximum bandwidth limits are imposed on the individual T-CONTs directly and not on the ONUs as a whole allowing for excellent QoS capability. The resulting packet delays produced indicate a direct correlation between the amount of bandwidth allocated and packet delay with larger allocations producing lower packet delay.

Some schemes proposed in the literature for GPON borrow concepts that are predominantly from EPON, such as bandwidth redistribution [48, 76] and credit or traffic prediction [25, 77]. While bandwidth redistribution in GPON has shown that it can improve the packet delay for higher priority T-CONTs, it comes at the expense of the packet delay for the lower priority T-CONTs. Traffic prediction can also improve throughput and utilization, however this can lead to wasted bandwidth [77]. A comparison of some of the GPON DBA algorithms examined in the above section is presented in Table 2.2:

Table 2.2: Comparison of GPON DBA algorithms

Authors	Angelopoulos et al. [28]	Chang et al. [42]	Hwang et al. [50]	Kanonakis et al. [44]	Jiang et al. [79]
T-CONT types	1 x 2, 3 & 4	1 per ONU	1 x 2, 3 & 4	1 x 2, 3 & 4	1 x 2, 3 & 4
Traffic model	Exponential tri-modal 64, 500 1500 lengths	Self-similar, variable length packets	Exponential tri-modal 64, 500 1500 lengths	Exponential tri-modal 64, 500 1500 lengths	Self-similar, variable length packets
ONU buffer sixe	Not given	Not given	10 MB	Not given	1 Mb
Number of ONUs	32	16	32	16	32
Network load delay benefit	Type , 3: 1.0 Type 4: 0.65	0.85	Type 2, 3: 0.8 Type 4: 0.5	Type 2: no increase Type 3:0.8 Type 4: 0.45	Type 2: 1.4 Type 3: 0.8 Type 4: 0.9
Maximum interval	10 GPON frames	16 GPON frames	10 GPON frames	Not given	Not given

Of the algorithms presented in Table 2.2, all but [50] use multiple T-CONTs within each ONU and the network load at which the delay increases for each T-CONT type appears similar across the algorithms. One exception is that used in [79] where T-CONT type 2 does not begin to increase until after a network load of 1.0. This implies that even just after full congestion no increase in packet delay is observed. Whilst the majority of literature presented in the preceding section examine DBA implementations that operate within the bounds of the ITU-T standards, some literature propose that small modifications can be made to the way in which an ONU requests bandwidth [78, 79]. If the requesting mechanism within an ONU is modified, then interoperability between equipment vendors may become an issue.

2.11 DBAs for Long Reach PON

The literature for DBA has shown that existing DBA methods are effective in allocating ONU bandwidth in both EPON and GPON using various methods as described in the previous sections. While there is no distance limitation in EPON, physical parameters such as laser transmit power, split ratios and receiver sensitivity limit deployment to within 20 km. As the optical power budget is affected by all three of these parameters, if

the budget can be extended, by means of optical amplification or repeaters, then the deployment distance could be greatly increased. GPON, on the other hand, has distance limitation imposed by the standards that limit deployment to a maximum distance of 60 km provided that the ONUs are grouped within 20 km of one another [10], although a recent ITU-T amendment to the GPON standard allows for a 40 km differential reach [16]. Even with the highest class optics specified in the standards (class C [10]), deployment with a maximum reach of 60 km would be difficult with 32 ONUs. If the split ratio was reduced then the possibility improves, but at some point reducing the split ratio becomes too costly [80]. There has been significant research on how to increase the optical power budget in PON using amplification techniques [12, 13, 15] and other techniques such as using unique wavelengths for each ONU (WDM) [14, 81]. While these methods achieve sustainable error free transmission, until recently there has been surprisingly little research into DBA algorithms for LR-PON.

As the physical distance between the OLT and ONUs is increased, the propagation delay also increases. All transmissions on the PON are subject to the propagation delay, including the allocations/grants and the requests/reports and therefore the time between a packet's arrival and when bandwidth is requested also increases. If we recall the elements constituting packet delay from Figure 2.2 (b), all of the times t_1 through t_4 are increased.

Another problem that arises in LR-PONs due to the increased propagation delay is the allocations from the OLT take longer to arrive at the ONUs. This has the result that the idle time, as shown in Figure 2.3, increases. Group partitioning, as outlined in [55, 56], has been proposed for LR-PONs by Vahabzadeh et al. in [82] where ONUs are arranged into groups. This allows the OLT to issue allocations to one group while collecting the reports from the previous group. As with most partitioning schemes, bandwidth redistribution is used to schedule the allocations [82]. Using this scheme the idle time can be reduced and throughput increased; however packets are still subject to longer delays than that of conventional PON.

One common technique for long reach EPON is that of multi-threading as proposed in [23, 46, 47, 83] where additional grants and reports are issued. The concept is shown in Figure 2.10 where a single ONU is connected to the OLT. Two interleaved threads, A and B, are shown where the first gate message (Gate A) is sent to the ONU prior to receiving the first report (Report A). Also shown is a packet arriving at the ONU just after the

report of thread A. Due to the multi-threading, its presence is reported in thread B unlike regular interleaved algorithms in which the packets presence is not reported until the next report A. The interleaving therefore reduces time t_1.

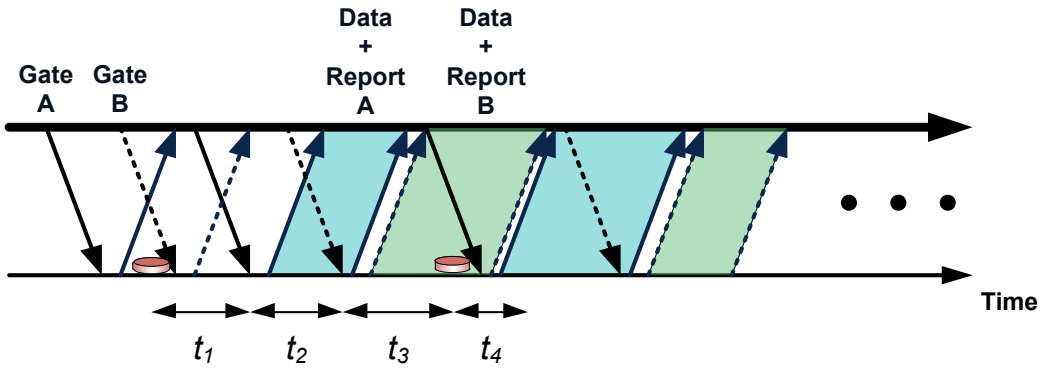

Figure 2.10 – Multi-threaded interleaved polling in EPON

The number of threads used can vary from an additional thread [47], to defining the number of threads based on the RTT between the ONU and the OLT [23]. A longer RTT denotes that more threads can be used or adaptive thread numbers depending on the traffic volume [49].

While multi-threading has proven to reduce packet delay, the problem or SR-inconsistency arises as discussed in [77] whereby a packets presence can be reported in multiple reports. The result is that the packet is still present in the buffer when the data + report of thread A is transmitted and thus bandwidth may be also granted in thread A that actually not required. This excess bandwidth constitutes waste and can degrade throughput [77]. The issue is overcome in [47] whereby the ONU deducts the reported level from the buffer after each report is sent. While this can eliminate the SR-inconsistencies, it is essentially the same method as described in [78, 79] in which the ONU requests the incremental buffer level leading to a non-standard approach.

For multi-threading to function, synchronization between threads must be maintained otherwise wasted bandwidth can lead to a significant degradation in throughput. One approach is to segregate the DBA processes that occur within the OLT and allow each process to allocate bandwidth using a single thread. Synchronization is performed by comparing the bandwidth requested in one thread against the requested bandwidth of

the next thread [22]. This allows the OLT to calculate the actual bandwidth demand for each thread.

2.12 Summary of Literature on DBAs for Long-Reach PON

When the reach of a PON is extended, both the traffic and DBA messages suffer increased propagation delay. The combined effect is that the time taken for the DBA process to be executed increases which adds to the overall propagation delay. Whilst ONU segregation can improve throughput by eliminating the idle time, additional methods must be used to reduce the packet delay. Multithreading is the common approach taken whereby the OLT issues the next allocation before receiving a bandwidth request. This leads to a reduction in the buffering time a packet experiences prior to being requested, however unless synchronization is used to co-ordinate bandwidth requests between threads, bandwidth can be allocated that is not required, thereby reducing throughput. The majority of methods proposed to provide this synchronization rely on the ONU to request bandwidth according to the accumulated traffic between threads. While this approach is non-standard and can potentially limit vendor interoperability, long-reach GPON as a whole is also non-standard. Only EPON allows for long reach to be compliant with the standard as no maximum reach is specified.

2.13 Conclusions

In this chapter we have examined the standards as well as the literature concerning the DBA in EPON, GPON and LR-PON. DBA algorithms have been proposed where the principle aim is to reduce the average upstream packet delay and to provide throughput close to the maximum capacity of the network. Various concepts such as bandwidth redistribution, ONU partitioning and traffic prediction schemes have been proposed to reduce the average delay, however the majority of the literature examined neglects to elucidate further on the specifics that contribute to the delay. While some papers have identified components of upstream packet delay, no modelling has yet been observed that explicitly defines the transport of packets from the ONU/T-CONT buffers to the OLT using the DBA mechanisms. This creates a significant void in the research field that this thesis aims to cover.

The principle focus of many of the papers examine is also on the *average* upstream packet delay, yet delay is only one component that contribute to QoS. Real-time traffic services impose limitations as to the variation in packet delay, or jitter. The jitter that a DBA algorithm produces cannot be inferred by examining the average delay produced by the algorithm. In some published works, the maximum delay is included; however in most cases the number of packets used to produce the average delay is omitted from the results. The common approach also seems to be to display the packet delay with the independent variable being network load. While this provides an indication of what the average delay is at varying traffic volumes, network traffic has been seen to exhibit bursty behaviour and analysis of the behaviour of the DBA algorithm under transient behaviour is often omitted.

In the following chapter, we will derive a mathematical model that defines how packet delay is produced in GPON of arbitrary length. GPON is chosen due to the inherent ability to handle QoS and the higher traffic rates over that of EPON. The model also provides insight into how packet delay increases as the length of the GPON is also increased. Wasted bandwidth and delay is then modelled when additional threads are included.

3 Analytical Model of the GPON DBA

3.1 Introduction

As we have seen in the previous chapter, the DBA algorithm in any PON is the primary mechanism responsible for the transport of the various categories of upstream traffic from the subscribers to the OLT. We also saw that in most DBA schemes the ONU determines the category and priority of the injected traffic, places the traffic packets into one or more buffers, or queues, and transmits the occupancy of the buffers to the OLT. The OLT assesses the requests and issues bandwidth allocations to the ONUs. The PON standards, however, do not specify how often this procedure must be performed and by what method the OLT makes its decisions on how the allocations are constructed. Such things are left to the network implementer; however we have seen in the previous chapter that varying the allocation interval, or cycle time, can have an impact on the resulting packet delay [19, 26]. Whilst packet delay in any network is unavoidable, measures should be taken to minimize the delay within the access network as the upstream packets may be required to transverse and be processed at multiple network nodes. This adds additional packet delay and to ensure a low total end-to-end packet delay a low packet delay within the access network is required.

Varying the size of the allocations also plays a key role in determining the packet delay [19]. Increasing the size of an allocation to one entity reduces the delay to that entity; however the packet delay for other entities is increased [55, 56]. In long-reach PON, the common approach is to introduce additional threads in an attempt to minimize the time a packet spends in the buffer prior to being requested [23]. This is referred to as the reporting delay and is the key motivation behind multi-threading in LR-PON. While multi-threading can reduce the average packet delay, thread synchronization must be maintained otherwise excessive bandwidth is allocated leading to wasted bandwidth [77].

The two key parameters of a DBA algorithm identified in the previous chapter are the duration of the allocation interval and the amount allocated to each entity. The former is determined solely by the DBA algorithm, but the latter is also determined by the traffic demand and any service level agreements (SLAs) that might be in effect. In the previous chapter some schemes were proposed for DBA algorithms that focused on minimizing the packet delay or maximizing throughput or both, however a thorough analytical model of the packet delay has not yet been published. Without such a model, a clear understanding of exactly how these parameters are responsible for upstream packet delay is not possible.

In this chapter, we will focus on identifying how the parameters of a DBA algorithm are responsible for packet delay and wasted bandwidth in the upstream traffic flow of GPON. We derive a model for the upstream packet delay by analysing the T-CONT buffer behaviour with packet arrivals due to subscriber traffic and packet departures due to bandwidth allocations. We develop the model using the standardized DBA mechanisms and identify key parameters responsible for packet delay. We then investigate the consequence to both traffic delay and wasted bandwidth when the reach of the GPON is increased and when an approach similar to multi-threading is incorporated into the model.

3.2 Analytical Model

The analytical model presented in this chapter begins by assuming that only one T-CONT is present in each ONU and each T-CONT is injected with only a single category of traffic. Although GPON has the ability for up to 4096 T-CONTs in total [11], it is the intention of this model to gain an understanding as to how the packet delay and wasted bandwidth occur in a single T-CONT per ONU all with equal priority. Chapter 6 examines the delay and wasted bandwidth behaviour of GPON and LR-GPON through advanced simulation methods when multiple T-CONTs and multiple traffic categories and priorities are used.

In this model, in some cases, we impose limitations on the incoming traffic rates which, when imposed, keep the number of injected traffic bytes below the maximum window sizes. This is done to prevent congestion. Congestion occurs when the total injected traffic bytes in one allocation interval exceed the total GPON frame capacity over the same duration. As congestion is determined primarily by the injected traffic rate, in

actual network implementations this is beyond the control of the network operator without the use of traffic rate shaping which can introduce additional delay. In chapter 6 we will examine the delay and throughput behaviour of DBA algorithms when these limitations are removed. The model in this chapter also assumes that subscriber traffic is injected into the ONU buffers with no additional rate shaping and no additional protocols exist to limit the rate of injection. Such protocols are beyond the scope of this work as they exist beyond the boundary of the access network.

In GPON, upstream traffic arriving at an ONU from subscribers is classified according to delay/QoS requirements and fragmented into fixed length frames using the GPON encapsulation method (GEM). These GEM frames are then buffered until they can be transmitted upstream to the OLT. On a basic level, the DBA mechanism operates as follows:

- Each ONU transmits a DBRu containing the number of GEM frames in the buffers of each T-CONT.
- The OLT uses the received DBRus to compile and transmit a BWmap that instructs any number of T-CONTs the number of GEM frames that can be transmitted in the next upstream frame.
- Upon receiving an allocation in the BWmap, each ONU transmits the allocated GEM frames from the T-CONT buffers and appends new DBRus, one for each T-CONT, to the upstream transmission.

A simplified depiction of these processes is shown in Figure 3.1 where a single ONU is connected to the OLT and the first BWmap is compiled such that the ONU is allocated sufficient bandwidth to only transmit a DBRu. A single packet is shown arriving at the ONU and departing. Only one ONU is depicted as the ranging protocol in GPON provides all ONUs with a unique equalization delay (EqD) which results in all ONUs being the same virtual transmission distance from the OLT.

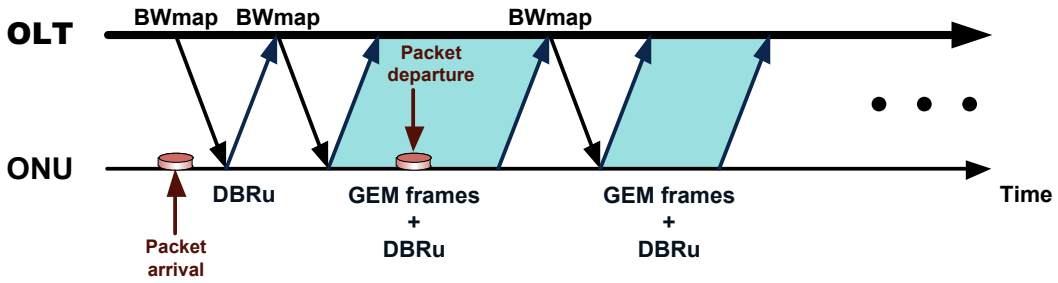

Figure 3.1 – basic operation of DBA in GPON with one ONU

As the subscriber packets are fragmented using the GEM, the bandwidth allocated by the OLT is sufficient to transmit a number of complete GEM frames as well as a DBRu if required [11]. The use of GEM allows arbitrary traffic to be encapsulated; however the injected traffic packets may not necessarily be evenly divisible by the GEM frame length. As a result, the encapsulation may result in some partially filled GEM frames. Once the packet is injected into the ONU it is classified and placed in a first-in first-out (FIFO) buffer and from Figure 3.1 we can see that the time between the arrival of a packet and its departure is dependent on the time between the DBA events. As packets can arrive at any time, packets may already exist within the FIFO which will be sent first. Once the packet leaves the buffer, it is transmitted through the optical fibre to the OLT.

A conceptual schematic of a GPON is shown in Figure 3.2 where *N* ONUs are connected to the OLT. The nth ONU has a single upstream traffic profile, $T_n(\rho)$, which is a time dependent function that increases the buffer occupancy by a variable number of bytes over the time period, ρ. It is assumed that once a packet exits the FIFO classification buffer the propagation delay to the OLT consists of the ONUs EqD delay and the propagation delay through the fibre. Due to the ranging protocol the sum of these two delays is constant for all ONUs [11].

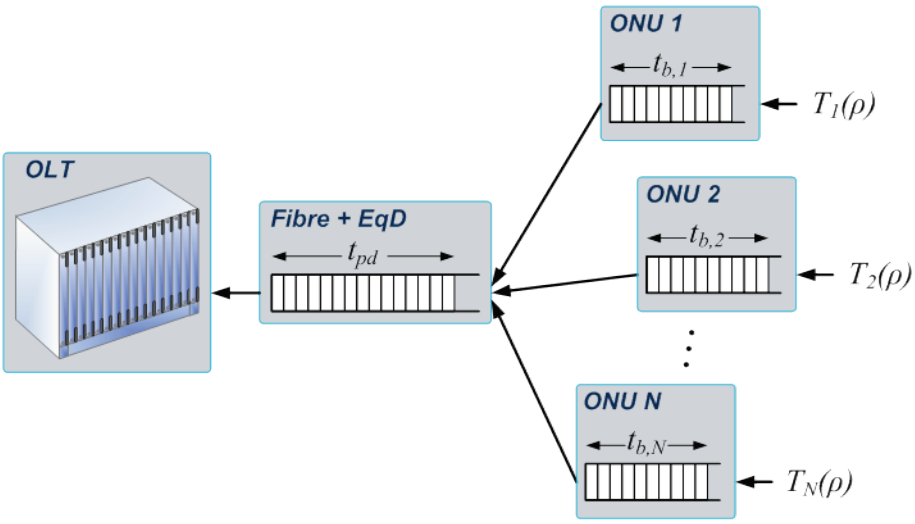

Figure 3.2 - Delay model of upstream transmission in GPON.

Using this concept, the total packet delay of a given packet for the nth ONU, $t_{p,n}$, can simply be expressed as

$$t_{p,n}(t) = t_{pd} + t_{b,n}(t) \tag{3.1}$$

where $t_{b,n}$ is the buffering delay and t_{pd} is the total propagation delay, or sum of the EqD and the fibre propagation delay. The total propagation delay is constant, however the buffering delay component is dependent on the DBA process. To reduce the total packet delay attention should be focused on reducing $t_{b,n}$.

The buffering delay is duration of time the packet resides in the FIFO buffer. The delay behaviour of FIFO buffers is well studied [84, 85] and can be determined by the rate at which bytes leave the buffer and the number of bytes in the buffer, B_{fifo}. The injection rate into the buffer is known as the ingress rate, $T_n(\rho)$, and in the case of GPON, it is dependent on the subscriber traffic. The rate at which packets leave the buffer is known as the egress rate, $T_e(\rho)$, and this is dependent on the DBA as packets can only leave as dictated by the BWmap. Using these parameters, $t_{b,n}(t)$ is given by

$$t_{b,n}(t) = \frac{B_{fifo}}{T_e(\rho)} \tag{3.2}$$

where B_{fifo} has units bytes and $T_e(\rho)$ has units of bytes/sec. In GPON $T_e(\rho)$ and B_{fifo} are both dependent on the subscriber traffic and are very much interrelated. The number of bytes in the buffer determines the allocations which determine the egress rate. The

subscriber traffic and the egress rate determine the number of bytes in the buffer. To model the packet delay, the buffer occupancy due to the injected traffic must first be analysed.

In GPON, both downstream and upstream frames have a fixed time duration of 125 µs. The time taken to allocate all ONUs on the network we denote as the allocation interval, t_c, and should be a fixed multiple of the GPON frame duration [11]. We use c as an index of these allocation intervals. We begin the model by taking the scenario when t_c is greater than the RTT of the GPON which reflects the majority of single-threaded DBA algorithms.

3.2.1 Modelling delay for $t_c \geq RTT$

As we saw in the previous chapter, the majority of DBA algorithms reported in the literature do not allow an ONU to transmit any additional upstream transmissions until the next DBRu is received and processed. Likewise, the OLT only allocates bandwidth to an ONU once this DBRu has been received [41, 42]. This *request-allocate* process gives rise to periodic procedure that depends on the RTT of the GPON. These periodic allocations can be performed within a few frames depending on the network activity [44].

To determine the buffering delay component for a given ONU, $t_{b,n}$, we must first derive an expression for the occupation (or buffer level), in bytes, of the buffer for that ONU. The injected traffic into ONU_N from a subscriber, represented by $T_n(\rho)$, adds a number of bytes into the buffer over a certain time period. The number of bytes added to the buffer, $B^{+}_{B,n}(t)$, over time period $t=0$ to $t=t_1$, is therefore

$$B^{+}_{B,n}(t_1) = \int_0^{t_1} T_n(\rho)\, d\rho \qquad (3.3)$$

$T_n(\rho)$ is given in units of bytes per time period and the integral of this function is over time variable ρ. The number of bytes departing the buffer due to the allocation at time $t=t_2$, $B_{A,n}(t_2)$, is provided by the BWmap. As the process is periodic, a BWmap arrives at each allocation interval, Mt_c, where M is a positive integer used to index the allocation intervals. At each interval a DBRu is also sent to the OLT containing the buffer occupancy

at that time. The number of bytes departing the buffer at time $t=Mt_c$, $B^-_{B,n}(Mt_c)$, is therefore

$$B^-_{B,n}(Mt_c) = B_{A,n}(Mt_c) \tag{3.4}$$

The total buffer occupancy over time, $B_{B,n}(t)$ is the difference between the total incoming bytes up to time t, $B^+_{B,n}(t)$ and the total allocated bytes transmitted up to time t, $B^-_{B,n}(Mt_c)$, where $Mt_c \leq t$, added to the occupancy at time $t=0$ and is given by

$$B_{B,n}(t) = B^+_{B,n}(t) - \sum_{m=0}^{M} B^-_{B,n}(mt_c) + B_{B,n}(0) \tag{3.5}$$

where $B_{B,n}(0)$ is the initial buffer occupancy at $t=0$.

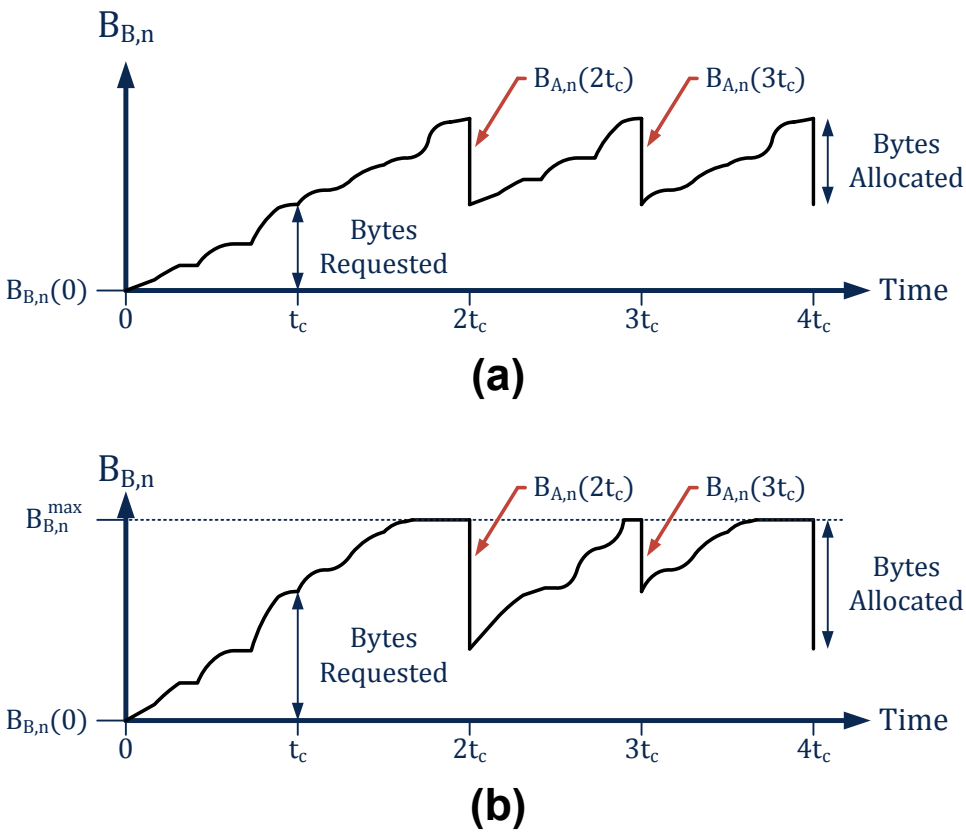

Figure 3.3 - Buffer occupancy against time for ONU$_n$ for (a) below congestion and (b) above congestion

Figure 3.3 (a) schematically shows the behaviour of the buffer occupancy over the allocation intervals. Also shown is the initial buffer occupation level, $B_{B,n}(0)$ and two

allocations, $B_{A,n}(2t_c)$ and $B_{A,n}(3t_c)$. Figure 3.3 (b) shows the buffer occupancy for the case of when the injected traffic rate exceeds the maximum egress rate of the buffer. When this occurs, the buffer reaches maximum occupancy, $B_{B,n}^{\max}$ and any further injected packets are rejected, or dropped.

The allocation interval is implemented from a time $t=0$. The traffic buffers used in ONUs are commonly RAM based and therefore we assume the occupancy is zero upon power-up. We therefore assume that at $t=0$ the buffer is empty giving $B_{B,n}(0)=0$. We can also define $t=0$ as any time where a packet arrives at an ONU, when the ONUs buffer has been previously requested as empty for a period of time greater or equal to the RTT. We define this as a "t_0 event". Due to the bursty nature of network traffic [51], t_0 events can occur at times other than just upon power-up.

For both cases shown in Figure 3.3, the buffer occupancy increases due to $T_n(\rho)$. At $t=Mt_c$ the ONU issues a DBRu requesting bandwidth equal to the buffer occupancy at that time, $B_{B,n}(Mt_c)$. When the next allocation interval occurs, the ONU receives and processes an allocation from the BWmap and is then allowed to transmit a number of bytes, $B_{A,n}(Mt_c)$, from buffer. The number of bytes in the buffer is reduced as the ONU transmits this data along with a new DBRu equal to the number of bytes remaining in the buffer, $B_{B,n}((M+1)t_c)$. If the allocations issued by the OLT are limited by the SLAs, they will not be sufficient to prevent the buffer occupancy from increasing; the buffer occupancy may eventually reach $B_{B,n}^{\max}$ which sets the maximum delay for that ONU.

The buffer occupancy, at the time of the first allocation interval is therefore given by

$$B_{B,n}(t_c) = B_{B,n}(0) + \int_0^{t_c} T_n(\rho)\, d\rho \tag{3.6}$$

By our definition of a t_0 event, at $t=0$, $B_{B,n}(0)=0$ and the buffer occupancy for $t < 0$ can be ignored. This also means that $B_{A,n}(t_c)=0$.

At the second allocation interval, $t=2t_c$, the ONU will receive a BWmap and process an allocation, $B_{A,n}(2t_c)$, from the OLT that is derived from $B_{B,n}(t_c)$. A portion of the ONUs buffer will be emptied and the buffer occupancy at a time $t=2t_c$ is then given by

$$
\begin{aligned}
B_{B,n}\left(2t_c\right) &= \int_0^{t_c} T_n\left(\rho\right) d\rho + \int_{t_c}^{2t_c} T_n\left(\rho\right) d\rho \\
&\quad - B_{A,n}\left(2t_c\right) \\
&= \int_0^{2t_c} T_n\left(\rho\right) d\rho - B_{A,n}\left(2t_c\right)
\end{aligned} \tag{3.7}
$$

The number of bytes in the allocation, $B_{A,n}(2t_c)$, is left to the discretion of the OLT. As we have seen in the last chapter, the allocations can be subject to a wide variety of conditions including, but not limited to, limited window and credit schemes [19]. Regardless of the DBA scheme, all the allocations to all N ONUs are bound by

$$
\sum_{n=1}^{N} B_{A,n}\left(Mt_c\right) = B_{PON}^{\max}\left(Mt_c\right) \tag{3.8}
$$

where $B_{PON}^{\max}\left(Mc\right)$ is the maximum number of bytes available to be allocated in the current interval as per the GPON capacity. This limit is interval dependent as the number of available bytes depends on overheads and guard times [11].

This model applies a limited window scheme such that the generalized form of $B_{A,n}(Mt_c)$ is

$$
B_{A,n}\left(\left(M+1\right)t_c\right) = \min\begin{bmatrix} B_{B,n}\left(Mt_c\right) \\ B_{A,n}^{SLA}\left(\left(M+1\right)t_c\right) \end{bmatrix} \tag{3.9}
$$

where $B_{A,n}^{SLA}\left(Mt_c\right)$ is the maximum number of bytes that can be allocated in the interval and is set by the network operator according to that ONU's SLA. It should be noted that the SLAs are both ONU and interval dependent and therefore subject to change depending on time [86]. A common example of this is when a subscriber has exceeded their traffic quota and their internet service provider (ISP) reduces their downstream and upstream traffic rates. As long as the allocations to an ONU are below the limits imposed by the SLAs, the buffer occupancy for that ONU will not reach $B_{B,n}^{\max}$.

Using (3.7) and (3.9) a general expression for the buffer occupancy at an arbitrary time, t, can be obtained

$$B_{B,n}(t) = \min\left[\begin{array}{l} \int_0^t T_n(\rho)\, d\rho - \sum_{m=2}^{M} B_{A,n}(mt_c)\theta(t - mt_c) \\ B_{B,n}^{\max} \end{array}\right. \qquad (3.10)$$
$$0 < t \le Mt_c; M \ge 2$$

where $\theta(t)$ is the Heavyside step function defining the time at which $B_{A,n}(mt_c)$ is processed.

Now that an expression for the buffer occupancy has been obtained, we recall that (3.2) can be used to determine the delay in a FIFO buffer. In the case of an arbitrary FIFO buffer, the egress rate can be given in units of bytes/sec. However in the case of GPON, varying size allocations arrive once per interval, c, and are therefore the egress rate is given in units of allocations/c. For this reason, a direct application of (3.2) will not provide us with the buffering delay. Instead, we use the fact that after a packet arrives, at each interval, the allocations remove bytes ahead of the packet until such time that the packet can be transmitted.

A packet that is transmitted from the ONU cannot be said to have arrived at the OLT until the last bit of the packet is received. GEM allows packets to be fragmented and split over one or more upstream transmissions. As a result, in determining the delay, the packet length must also be included in $B_{B,n}(t)$ as we are in fact determining the delay of the last bit of the packet.

Two additional factors that must also be considered are the arrival and departure times of the packet. We define the arrival time, $\Delta t_{a,i}(t)$, as the time between the arrival of the packet at the ONU and the next DBRu in which the presence of the packet is reported. The departure time, $\Delta t_{d,i}(t)$, is the time between the packets departure from the ONU and the allocation that permitted its transmission.

Let us consider that a packet arrives just after a DBRu has been transmitted. In this situation the newly arrived packet must wait for an entire allocation interval before being requested in the next DBRu. The maximum arrival time of any packet is then equal to t_c. The departure time however is dependent on number of packets transmitted due to the corresponding processed allocation. The maximum time for $\Delta t_{d,i}(t)$ is therefore set by the maximum allowable allocated bandwidth. In the previous chapter we examined buffer-displacement methods that manipulate the queuing order in the ONU

buffers which, if used, potentially increase the maximum times for $\Delta t_{a,i}^{\max}(t)$ and $\Delta t_{d,i}(t)$ [37, 62].

Using (3.10) as well as the arrival and departure times, the buffering delay for a packet arriving at an ONU at time t is then expressed as

$$t_{b,n}(t) = \left[k : \sum_{j=1}^{k} B_{A,n}(t + j.t_c) \geq \left(B_{B,n}(t) + B_{p,i} \right) \right] t_c + \Delta t_{a,i}(t) + \Delta t_{d,i}(t) \tag{3.11}$$

where $B_{p,i}$ is the number of bytes in packet i.

From examining (3.11), we can see that the buffering delay for the ith packet is the minimum number of whole allocation intervals taken to empty the buffer occupancy, including the packet size, at the arrival time of that packet plus the arrival time and departure time of the packet. Note that the variable k cannot be bounded as it depicts the number of allocation intervals required to deplete the buffer. As the OLT can allocate zero bytes, the variable k can be infinite.

Using (3.1) and (3.11), the total propagation delay of a particular packet arriving at the buffer at time t can be expressed as

$$t_{p,i}(t) = t_{b,n}(t) + \frac{t_{RTT}}{2} \tag{3.12}$$

where $t_{RTT}/2$ is the total propagation delay from the ONU to the OLT including the EqD time.

When we examine the parameters in (3.11), the injected traffic rate determines the buffer occupancy which, in turn, determines the requested bandwidth. Assuming that the SLAs are satisfied, the allocated bandwidth is equal to the requested bandwidth which then continues to determine the buffer occupancy combined with the injected traffic. The arrival time is dependent on the injected traffic and t_c and the departure time is dependent on the buffer occupancy and the allocated bandwidth. In fact, all of the factors in (3.11) except for the duration of the allocation interval, t_c, are dependent on $T_n(\rho)$ and therefore beyond the network operator's control.

To reduce the buffering delay, there is no option than to either increase the allocations, $B_{A,n}\left(Mt_c\right)$, or reduce t_c. Increasing the allocations can be done using credit or traffic prediction schemes [25, 65], however this cannot be done to one ONU without directly affecting other ONUs on the network. By reducing t_c, not only is the buffering delay reduced, allocations and requests are issued more often which results in the DBA algorithm having a greater ability to adapt to fluctuations in network traffic [87].

In the previous chapter we saw a common occurrence in the literature whereby the OLT waits to receive a DBRu from each ONU before issuing bandwidth allocations to that ONU. In these cases, the allocation interval must be set to greater or equal than the RTT of the network [21, 23]. This imposes a lower bound for t_c equal to the RTT. In multi-threading, the duration of the allocation interval is reduced below the RTT [23, 47]. From the GPON standards, the allocation interval must be an integer multiple of the GPON frame time [11] and this then imposes an absolute minimum limit on t_c to be 125 µs, or one GPON frame. In the following section we will examine when t_c is reduced below the RTT.

3.2.2 Modelling Delay for $t_c < RTT$

From (3.11) we can see the duration of the allocation interval, t_c, is an integral component of the buffering delay. For LR-PONs, the increased RTT will increase the allocation interval thereby increasing the buffering delay as per (3.11). The common approach to minimize delay in LR-PONs is to introduce additional threads, thereby effectively reducing t_c below the RTT value.

To model the effect of reducing t_c, we use a similar approach taken in the previous section. We also assume that the SLAs are satisfied and that the time between a DBRu and the corresponding BWmap is equal to the RTT such that

$$B_{A,n}\left(\left(M+1\right).RTT\right) \propto B_{B,n}\left(M.RTT\right) \tag{3.13}$$

We also introduce a new parameter, W, that is the number of allocation intervals in an RTT giving us $Wt_c = RTT$.

Figure 3.4 shows the buffer occupancy over the allocation intervals when t_c is reduced below the RTT and $W=4$. Also shown are the first two allocations, $B_{A,n}(RTT+t_c)$ and

$B_{A,n}(RTT+2t_c)$. For simplicity, the injected traffic shown in Figure 3.4 ceases after $t=RTT$.

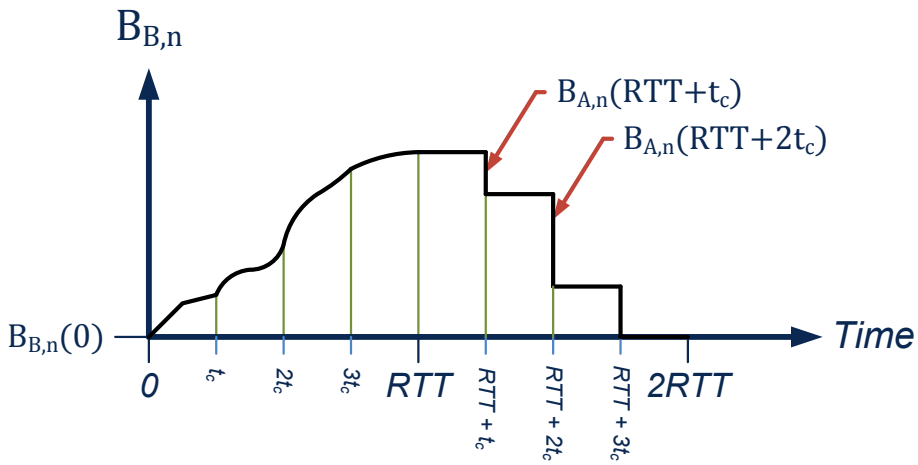

Figure 3.4 - Buffer occupancy over time where $t_c < RTT$.

As in the previous section, the buffer fills at a rate given by $T_n(\rho)$ and the analysis begins at a t_0 event so that $B_{B,n}(0)=0$ which results in $B_{A,n}(RTT)=0$.

The buffer occupancy at the time at which the first allocation is processed, $t=RTT+t_c$, is given by

$$B_{B,n}\left(RTT+t_c\right)=B_{B,n}\left(0\right)+\int_0^{RTT+t_c}T_n\left(\rho\right)\,d\rho-B_{A,n}\left(RTT+t_c\right) \qquad (3.14)$$

By the time $t=2RTT$, the number of allocations processed is equal to W. At this time the buffer occupancy is

$$B_{B,n}\left(2RTT\right)=\int_0^{2RTT}T_n\left(\rho\right)\,d\rho-\sum_{w=1}^{W}B_{A,n}\left(RTT+wc\right) \qquad (3.15)$$

The expression for the total allocations in $M.RTT$ periods, $B_{A,n}^{T}\left(M.RTT\right)$ is

$$B_{A,n}^{T}\left(M.RTT\right)=\sum_{m=1}^{M-1}\sum_{w=1}^{W}B_{A,n}\left(mWt_c+wc\right) \qquad (3.16)$$

As packets may arrive at any time we must also consider the time at which a packet arrives mid-RTT. In this case, there will not be exactly W allocations in the last RTT; therefore these last allocations are given by

$$B_{A,n}^{L}\left(t_c\right)=\sum_{w=1}^{\operatorname{int}[W-w]} B_{A,n}\left(wt_c\right) \tag{3.17}$$

Using (3.15), (3.16) and (3.17), an expression for the buffer occupancy at an arbitrary time, *t*, as

$$\begin{aligned} B_{B,n}\left(t\right) &= \min\left[\begin{array}{l} \int_0^t T_n\left(\rho\right)\, d\rho - \left(B_{A,n}^{T}\left(MWt_c\right)+B_{A,n}^{L}\left(t_c\right)\right) \\ B_{B,n}^{\max} \end{array}\right. \\ M &= \operatorname{int}\left[\frac{t}{RTT}\right] \end{aligned} \tag{3.18}$$

When $t_c \geq RTT$ (3.11) was used to determine the packet delay from the buffering delay. For $t_c = RTT$ the minimum buffering delay becomes equal to RTT. Recall that (3.13) states that the minimum time between the transmission of a DBRu to the processing of the corresponding BWmap is equal to the RTT. Therefore the minimum buffering delay for a requested packet is still equal to the RTT, or Wt_c. Once a packet has been requested, and the corresponding allocation received, the remaining buffering delay is the number of additional allocation intervals taken to empty the buffer should the previous allocation be insufficient.

The buffering delay for $t_c < RTT$ is therefore given by

$$t_{b,n}\left(t\right)' = \left|\begin{array}{ll} Wt_c + \Delta t_{a,i}\left(t\right)+\Delta t_{d,i}\left(t\right); & \left[B_{B,n}\left(t\right)+B_{p,i}\right] \leq B_{A,n}\left(t+t_c\right) \\ Wt_c + \left\{k : \sum_{j=1}^{k} B_{A,n}\left(t+j.t_c\right) \geq B_{B,n}\left(t\right)+B_{p,i}\left(t\right)\right\} t_c & \\ +\Delta t_{a,i}\left(t\right)+\Delta t_{d,i}\left(t\right); & \left[B_{B,n}\left(t\right)+B_{p,i}\right] > B_{A,n}\left(t+t_c\right) \end{array}\right. \tag{3.19}$$

From (3.19) we can see that should the initial allocation be insufficient to transmit the buffer contents, including the ith packet, the buffering delay consists of an additional k allocation intervals. We can also see that the minimum buffering delay is Wt_c and this can be validated against (3.11) by setting t_c in (3.11) to RTT. As t_c is reduced below the RTT, the minimum delay does not change as the RTT sets a lower bound on the delay of a requested packet. By reducing the duration of the allocation interval the number of bytes available in each allocation interval also decreases. This means that a greater number of the additional k allocation intervals might be required to transmit a packet when $t_c < RTT$ as opposed to $t_c \geq RTT$. Although more allocation intervals may be

required, the duration of the allocation interval has decreased thereby potentially offsetting the increase. As t_c reduces, the maximum arrival waiting time, $t_{a,i}^{\max}(t)$ is also reduced thereby also potentially lowering the buffering delay.

The buffering delay in (3.19) can be used with (3.12) to determine the total packet delay. We can also validate (3.18) against (3.10), by setting $W=1$ and $t_c=RTT$. From (3.16), the total number of allocations, in a discrete number of RTT periods, is greater than (3.10) by a factor of W.

Reducing t_c does not reduce the fundamental limit imposed on the network due to the propagation delay. All transmissions on the GPON are still subject to the propagation delay and consequently reducing the allocation interval cannot change this. We saw in the previous chapter that the principle behind increasing the number of allocations per RTT was to reduce the time between when a packet arrives and the next DBRu, or $t_{a,i}(t)$. As the packet arrival times are dependent on $T_n(\rho)$ they are beyond the scope of this model and will be examined in Chapters 6 and 7.

The model presented in this section for $t_c < RTT$, has no synchronization between allocation intervals. From [77], improper synchronization can lead to an inefficient use of bandwidth which will be examined in the following section.

3.3 Wasted Bandwidth

In the previous chapter we saw that a commonly used measure for DBA performance in a PON is throughput; however it is rarely defined. An accepted definition is the total number of bytes transmitted by all ONUs over the total capacity of the PON for a certain length of time [65, 88]. This definition does not differentiate between traffic bytes and null bytes. Null bytes are bytes that are transmitted but not required [11]. We consider any null bytes as wasted bandwidth and they can potentially deprive other ONUs of required bandwidth thereby increasing the packet delay to these deprived ONUs.

Figure 3.5 (a) shows the scenario where the number of bytes in $B_{A,n}(t_c)$ is not sufficient for the ONU to transmit the number of bytes generated due to $T_n(\rho)$. In this situation the ONU can only transmit the number of bytes according to $B_{A,n}(t_c)$ and as these bytes consist of injected traffic no null bytes are transmitted. Figure 3.5 (b) shows the scenario

where the number of bytes in $B_{A,n}(t_c)$ exceeds the number of bytes injected due to $T_n(\rho)$. As per the GPON standards, the ONU must transmit a number of bytes equal to $B_{A,n}(t_c)$. Once the injected traffic bytes are transmitted, the ONU transmits null GEM frames which constitute wasted bandwidth.

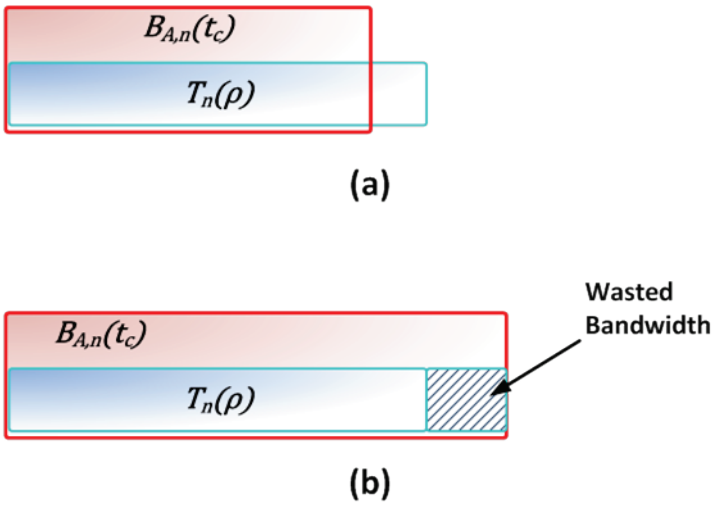

Figure 3.5 – $B_{A,n}(t_c)$ with respect to $T_n(\rho)$ for the case where (a) $T_n(\rho) > B_{A,n}(t_c)$ and (b) $T_n(\rho) < B_{A,n}(t_c)$.

As the size of the GEM frames is fixed, the length of an incoming traffic packet may not be an exact multiple of the GEM frame length. In GPON, the DBRu transmitted by the ONUs contains the number of GEM frames residing in the buffer. The OLT allocates bandwidth in multiples of the GEM frame length and as a result, the last GEM frame transmitted by the ONU may only be partially filled by the data within the traffic packet. Any leftover bytes within the GEM frame that are transmitted are considered wasted.

To provide maximum bandwidth efficiency, the DBA algorithm needs to ensure that only the required bandwidth is allocated with minimal wasted bandwidth. This means that the number of bytes allocated to an ONU should be as close as possible to the number of bytes generated by the customer traffic. The fixed length of GEM frames implies that the wasted bandwidth is unlikely to be zero; however for the purposes of the model developed in this chapter, we shall not consider the impact of partially filled GEM frames as these will be a product of the injected traffic. When considering the impact of GEM and partially filled frames, the number of wasted bytes due to partially-filled GEM frames is related to the length of the injected packets. This will be considered in Chapter 6.

The traffic in one RTT is not allocated until the following RTT as per the offset in (3.9). Figure 3.6 shows a schematic of buffer occupancy in an ONU subject to injected traffic and allocations received and processed. The RTT offset stipulates that the bytes due to the traffic added to the buffer from *M.RTT* to *(M+1)RTT* are not fully allocated until *(M+2)RTT* and therefore the wasted bandwidth due to the aforementioned traffic cannot be calculated until this time.

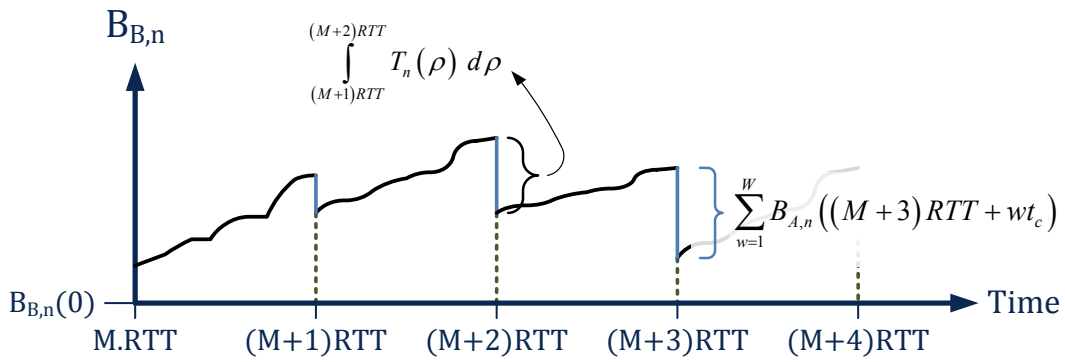

Figure 3.6 – Accumulated traffic in an RTT and allocations in the following RTT

Using the RTT offset from (3.9), wasted bandwidth, $B_{W,n}(t)$, for a given RTT is given by

$$B_{W,n}\left((M+2)RTT\right) = \max\left[\begin{array}{l} \sum_{w=1}^{W} B_{A,n}\left((M+1)RTT + w.t_c\right) - \int_{M.RTT}^{(M+1)RTT} T_n(\rho)\, d\rho \\ 0 \end{array}\right. \tag{3.20}$$

By making the differentiation between required and non-required transmitted bits also allows us to define the bandwidth efficiency, B_{eff}, as the ratio of used bandwidth to wasted bandwidth. That is

$$B_{eff} = \frac{\int_{M.RTT}^{(M+1)RTT} T_n(\rho)\, d\rho}{\int_{M.RTT}^{(M+1)RTT} T_n(\rho)\, d\rho + \sum_{w=1}^{W} B_{W,n}\left((M+1)RTT + w.t_c\right)} \tag{3.21}$$

Using (3.20) the wasted bandwidth can be determined for the scenarios where $t_c \geq RTT$ and $t_c \leq RTT$.

3.3.1 Wasted bandwidth when $t_c \geq RTT$

In this section, we consider the situation where $t_c \geq RTT$ and assume that $T_n(\rho)$ is such that the traffic generated within an allocation interval is less than the limit imposed by the SLA such that

$$\begin{aligned}\int_{(M-1)t_c}^{Mt_c} T_n(\rho)\, d\rho &= B_{B,n}(Mt_c) \\ &\leq B_{A,n}^{SLA}\left((M+1)t_c\right)\end{aligned} \tag{3.22}$$

Using (3.22) allocations are then given by

$$B_{A,n}\left((M+1)t_c\right) = B_{B,n}(Mt_c) \tag{3.23}$$

which also implies that

$$B_{A,n}\left((M+2)t_c\right) = B_{B,n}\left((M+1)t_c\right) \tag{3.24}$$

To model the wasted bandwidth, (3.24) and (3.10) can be used to obtain an expression for the allocations in terms of traffic generated, when (3.22) is satisfied,

$$\begin{aligned}B_{A,n}\left((M+2)t_c\right) &= B_{B,n}\left((M+1)t_c\right) \\ &= \int_0^{(M+1)t_c} T_n(\rho)\, d\rho - \sum_{m=2}^{M+1} B_{A,n}(mt_c) \\ &= \int_{Mt_c}^{(M+1)t_c} T_n(\rho)\, d\rho\end{aligned} \tag{3.25}$$

Using (3.20) and (3.25), when (3.22) is satisfied the wasted bandwidth is

$$\begin{aligned}B_{W,n}\left((M+2)t_c\right) &= B_{A,n}\left((M+2)t_c\right) - \int_{Mt_c}^{(M+1)t_c} T_n(\rho)\, d\rho \\ &= \int_{Mt_c}^{(M+1)t_c} T_n(\rho)\, d\rho - \int_{Mt_c}^{(M+1)t_c} T_n(\rho)\, d\rho \\ &= 0\end{aligned} \tag{3.26}$$

Equation (3.26) states that by setting $t_c \geq RTT$, in any allocation interval the sum of the bytes allocated is equal to the sum of the bytes generated resulting in no wasted bandwidth. An earlier assumption made is that the traffic generated in an allocation interval is less than the SLA for that interval. If the traffic rate increases such that the condition in (3.22) is violated, (3.24) goes to

$$B_{A,n}\left(\left(M+2\right)t_c\right)' = B_{B,n}^{SLA}\left(\left(M+1\right)t_c\right) \tag{3.27}$$

which then modifies (3.25) to become

$$B_{A,n}\left(\left(M+2\right)t_c\right)' \leq \int_{Mt_c}^{(M+1)t_c} T_n\left(\rho\right)\ d\rho \tag{3.28}$$

and the wasted bandwidth from (3.26) becomes

$$\begin{aligned} B_{W,n}\left(\left(M+2\right)t_c\right)' &= \max\left[\begin{array}{l} B_{A,n}\left(\left(M+2\right)t_c\right)' - \int_{Mt_c}^{(M+1)t_c} T_n\left(\rho\right)\ d\rho \\ 0 \end{array}\right. \\ &= 0 \end{aligned} \tag{3.29}$$

Even if the traffic generated due to $T_n(\rho)$ exceeds the limits imposed by the SLAs, every byte that is allocated is occupied with the injected subscriber traffic thereby the wasted bandwidth is still zero.

We will now derive the wasted bandwidth for the case when $t_c < RTT$.

3.3.2 Wasted bandwidth when $t_c < RTT$

For the case with W allocation intervals per RTT and $t_c < RTT$, each DBRu transmitted by the ONU still contains the buffer occupancy at the time of the request. Equation (3.13) stipulates that the allocations derived from these requests do not arrive, and are therefore are not processed, until one RTT after the requests were sent. From the definition of a t_0 event, the buffer begins empty and therefore no allocations are processed until $t=Wt_c$. As no allocations are processed, the buffer occupancy does not decrease, and by the GPON standards this occupancy is requested each interval [11].

During the first RTT the buffer occupancy at each interval equals the sum of the traffic from $t=0$ as no allocations have been received to reduce the buffer. We can write the occupancy of the buffer up until this time as

$$B_{B,n}\left(Wt_c\right)=\int_0^{Wt_c} T_n\left(\rho\right)\ d\rho \tag{3.30}$$

Again assuming that the injected traffic and resultant allocated bandwidth are less than the maximum windows set by the SLAs, using (3.13) the buffer levels from (3.30) are allocated one RTT later giving

$$\begin{aligned}\sum_{w=1}^{W} B_{A,n}\left(RTT+wt_c\right) &= \sum_{w=1}^{W} B_{B,n}\left(wt_c\right)\\ &= \sum_{w=1}^{W}\left[\int_0^{wt_c} T_n\left(\rho\right)\ d\rho\right]\\ &= W\int_0^{t_c} T_n\left(\rho\right)\ d\rho\\ &\quad +\left(W-1\right)\int_c^{2t_c} T_n\left(\rho\right)\ d\rho\\ &\quad +\\ &\quad \ldots\\ &\quad +\int_{(W-1)t_c}^{Wt_c} T_n\left(\rho\right)\ d\rho\\ &= \sum_{w=0}^{W-1}\left[\left(W-w\right)\int_{wt_c}^{(w+1)t_c} T_n\left(\rho\right)\ d\rho\right]\end{aligned} \tag{3.31}$$

The wasted bandwidth at *t=2RTT* can be obtained using (3.20) and (3.31) and is expressed as

$$\begin{aligned}B_{W,n}\left(2RTT\right) &= \sum_{w=1}^{W}\left[B_{A,n}\left(RTT+wt_c\right)\right]-\int_0^{RTT} T_n\left(\rho\right)\ d\rho\\ &= \sum_{w=1}^{W}\left[\int_0^{wt_c} T_n\left(\rho\right)\ d\rho\right]-\int_0^{RTT} T_n\left(\rho\right)\ d\rho\\ &= \left(W-1\right)\int_0^{t_c} T_n\left(\rho\right)d\rho\\ &\quad +\left(W-2\right)\int_{t_c}^{2t_c} T_n\left(\rho\right)d\rho\\ &\quad +\left(W-3\right)\int_{2t_c}^{3t_c} T_n\left(\rho\right)d\rho\\ &\quad +\ldots\\ &\quad +\int_{(W-2)t_c}^{(W-1)c} T_n\left(\rho\right)d\rho\\ &= \sum_{w=1}^{W}\left[\left(W-w\right)\int_{(w-1)t_c}^{wt_c} T_n\left(\rho\right)d\rho\right]\end{aligned} \tag{3.32}$$

From (3.31) we can see that the allocated bandwidth exceeds the required traffic by an amount dependent on W. From (3.32) that the wasted bandwidth is also dependent on W potentially giving rise to large amounts of wasted bandwidth for all $W > 1$. We refer to this effect as the *reduced-interval waste* effect.

While previously we have assumed that the traffic rate satisfies the SLAs, in this situation the allocated bandwidth exceeds the required traffic and may be limited by the maximum window size from the SLA. To model this, let us assume that the traffic rate is constant over ρ and adds the same number of bytes in each interval and that the traffic rate is sufficiently small such that each allocation satisfies the SLA

With these assumptions, (3.31) becomes

$$\begin{aligned}
\sum_{w=1}^{W} B_{A,n}\left(RTT + wt_c\right)' &= \sum_{w=1}^{W} B_{B,n}\left(wt_c\right) \\
&= W\int_0^{t_c} T_n(\rho)\ d\rho \\
&\quad + (W-1)\int_0^{t_c} T_n(\rho)\ d\rho \\
&\quad + \\
&\quad \ldots \\
&\quad + \int_0^{t_c} T_n(\rho)\ d\rho \\
&= \sum_{w=0}^{W-1}\left[(W-w)\int_0^{t_c} T_n(\rho)\ d\rho\right] \\
&= \left(0.5W^2 + 0.5W\right)\int_0^{t_c} T_n(\rho)\ d\rho
\end{aligned} \tag{3.33}$$

Using (3.33), the buffer level at $t=2RTT$ becomes

$$\begin{aligned}
B_{B,n}\left(2RTT\right)' &= \int_0^{2RTT} T_n(\rho)\ d\rho - \sum_{w=1}^{W} B_{A,n}\left(RTT + wt_c\right) \\
&= 2W\left(\int_0^{t_c} T_{r,n}(\rho)\ d\rho\right) - \left(0.5W^2 + 0.5W\right)\int_0^{t_c} T_n(\rho)\ d\rho \\
&= \left(2W - 0.5W^2 - 0.5W\right)\int_0^{t_c} T_n(\rho)\ d\rho \\
&= \max\left[\begin{array}{l}\left(1.5W - 0.5W^2\right)\int_0^{t_c} T_n(\rho)\ d\rho \\ 0\end{array}\right.
\end{aligned} \tag{3.34}$$

which results in a buffer occupancy of zero for all $W \geq 3$. Once the buffer occupancy drops to zero any further allocations result in wasted bandwidth and the buffer remains at zero. For all $W \geq 3$ the ONU buffer will be empty for a period of time greater or equal

to the RTT which produces a t_0 event. The transient dynamics of this situation will be examined in Chapter 7.

From (3.33) we can see that the allocated bandwidth exceeds the required traffic by an amount proportional to W. When $t_c < RTT$ and the allocations are made according to $B_{A,n}(t) = B_{B,n}(t\text{-}RTT)$ the allocated bandwidth exceeds the traffic bandwidth thereby producing wasted bandwidth. If the allocated bandwidth is not made according to $B_{A,n}(t) = B_{B,n}(t\text{-}RTT)$ and the traffic rate is not constant, then the allocated bandwidth may be reduced thereby reducing the wasted bandwidth.

In the GPON standards, the ONU compiles each DBRu according to the number of GEM frames residing in the corresponding T-CONT buffer [11]. The ONU cannot distinguish which frames have been previously requested. When allocations are issued at the OLT, the OLT does not differentiate between required bytes and wasted bytes. Packets within the ONU buffers continue to egress and are transmitted upstream regardless of whether these packets have been requested. From our model above, when $t_c < RTT$ we have shown that this methodology results in the allocated bytes exceeding the required traffic bytes.

In Chapter 2 we saw that credit schemes as described in [25, 65] intentionally increase the allocated bytes above the required traffic bytes in an attempt to reduce the packet delay. This intentional increase is only performed should sufficient bytes be available that are otherwise not required to be allocated. This approach differs to the result from the model above when $t_c < RTT$. In the model, the increase in allocated bytes is unintentional and is due to the multiple requests for the same packets within an ONUs buffer. In this situation, the increase of allocated bytes to one ONU may be performed at the expense to other ONUs. The overall result of reducing t_c below the RTT, in terms of bandwidth efficiency, is that both traffic throughput and efficiency are dramatically reduced.

We now present a simple validation of the model developed above and conclude with a summary of the key findings.

3.4 Validation

To validate the model against other PON average delay results, we use a simple simulation of the model using equations (3.11) and (3.19) to calculate the packet delay for $t_c > RTT$ and $t_c < RTT$ respectively, neglecting packet arrival time. Equations (3.10) and (3.18) are used to determine the buffer occupancy for $t_c > RTT$ and $t_c < RTT$ respectively. To calculate the average packet delay, one packet injection per ONU was simulated per allocation interval over 30,000 allocation intervals and 32 ONUs. The delay of each packet was calculated and averaged over all received packets. The size of the packets varied using a simple pseudo-random number generator [89]. The network load was calculated as the sum of the total injected traffic bytes generated in the simulation over the sum of the total upstream capacity in the 30,000 intervals.

The results of our model are compared with the results from the literature using both a single and multiple threaded approaches for a PON for both 20 km and 100 km maximum reach [23, 79]. Recall that reducing t_c below the RTT is comparable to multi-threading.

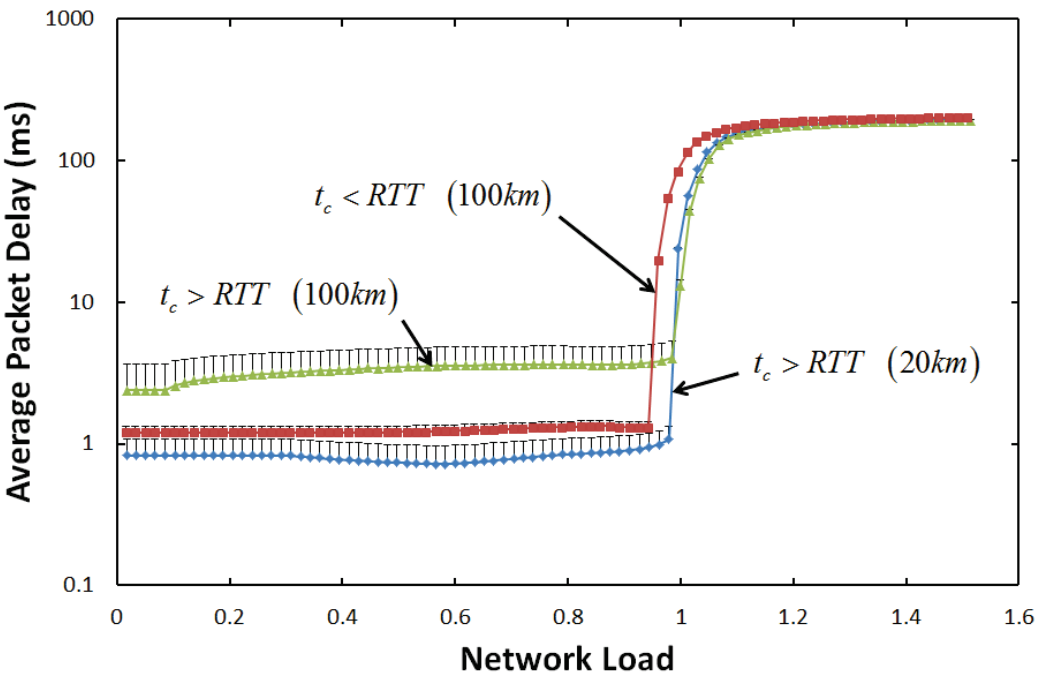

Figure 3.7 – Model results for average packet delay against network load for 20 km and 100 km reach GPON with $t_c > RTT$ and $t_c < RTT$.

Using our model, Figure 3.7 shows the average packet delay from the model for the case where $t_c > RTT$ in both a 20 km and 100 km reach GPON as well as when $t_c < RTT$ in a 100 km reach GPON. The RTTs for 20 km reach and 100 km reach are 0.1 ms and 0.4 ms respectively and allocation intervals of 3 and 10 GPON frames are used respectively. Positive error bars are included to reflect a maximum addition to the average delay of one allocation interval due to the arrival times as this was not included in the simulation environment.

We can see from Figure 3.7 that at as network load increases the average packet delay maintains a steady value for network loads below 1.0. We define this value of network load as network saturation. This occurs when the total amount of traffic generated in the simulation is the same as the total GPON capacity. Prior to network saturation, the allocated bandwidth is equal to the amount of requested bandwidth. Above network saturation the buffers begin to fill and approach maximum occupancy. The average delay drastically increases towards an upper limit and all three curves approach a maximum delay value.

Figure 3.7 also shows that the difference between the delay of the 20 km and 100 km reach curves below network saturation differs by the ratio of the duration of the allocation interval, t_c. We can also see that in the 100 km scenario by reducing the duration of the allocation interval to less than the RTT, the average delay is reduced. This is because the larger allocated bandwidth due to the reduced-interval waste effect results in lower packet delay. When $t_c < RTT$ network saturation occurs at a lower value of network load than when $t_c > RTT$. This is because the bandwidth required for overheads increases as t_c reduces.

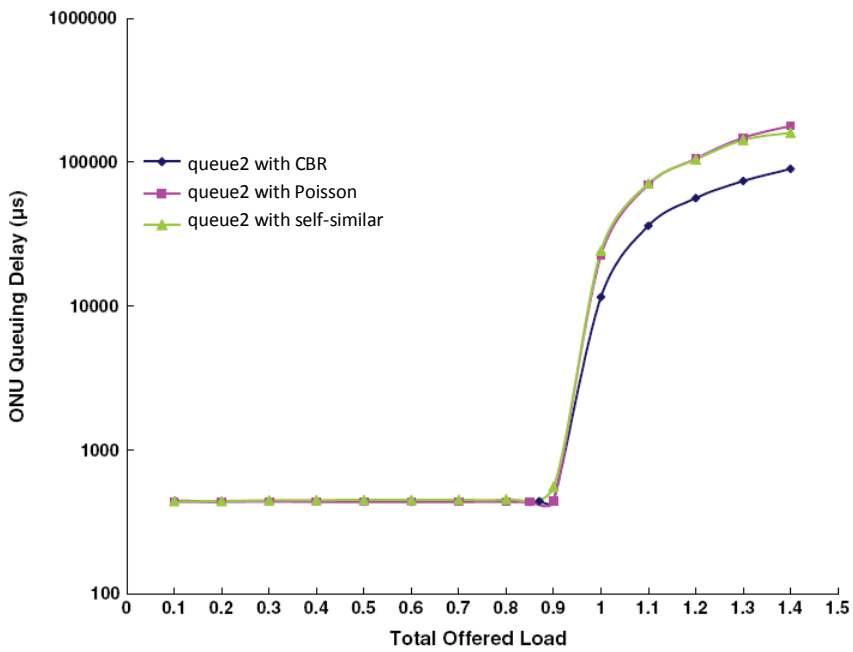

Figure 3.8 – ONU queuing delays for 20 km reach GPON using type 4 T-CONTs and various injected traffic models from [79].

Figure 3.8 shows the queuing delays for a 20 km reach GPON using three traffic injection models for a type 4 T-CONT carrying best-effort traffic as presented in [79]. Queue 2 is defined in [79] as lowest priority traffic assigned to type 4 T-CONTs and treated as best effort.

We can see that the general trend of the delay curves in Figure 3.8 are quite similar to that of the model, however the average delay below network saturation is less than shown in Figure 3.7 as only the queuing delay is represented and not the total packet delay. Above network saturation, the curves approach an average maximum delay that is set by the maximum buffer level although the rate of delay increase is less in Figure 3.8 which may be due to the number of packets used to obtain the results which is not disclosed in the literature. Network saturation also occurs earlier in Figure 3.8 as other T-CONT types and overheads were used whereas these were not considered in the simulation of our model.

Figure 3.9 shows the average packet delay for (a) 20 km reach PON and (b) 100 km reach PON using a single thread and multiple threads as presented in [23].

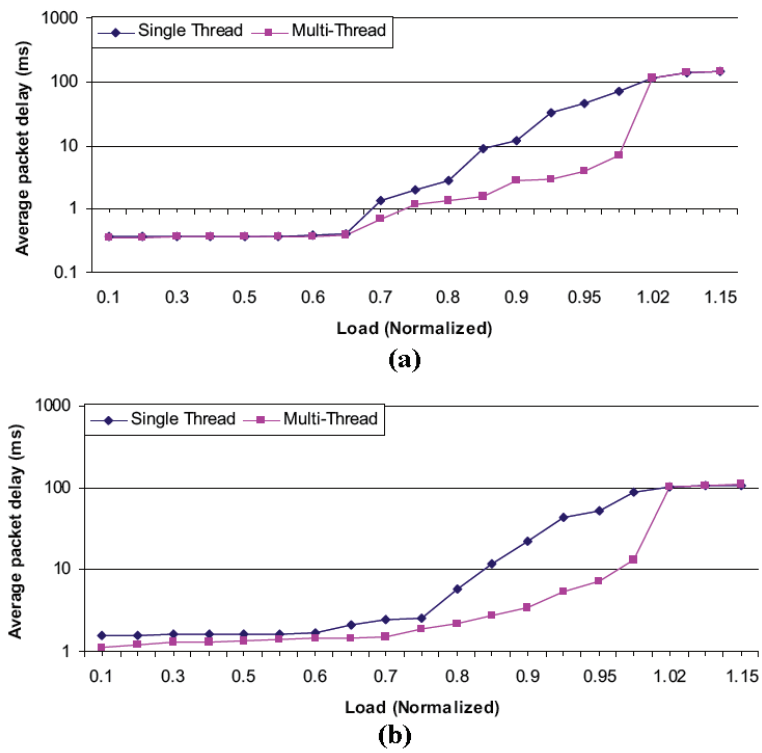

Figure 3.9 – Results of multi-threaded approach for (a) 20 km reach and (b) 100 km reach from [23]

When comparing the results of the model, shown in Figure 3.7, to that of [23], we note that when $t_c > RTT$ the average delay values for low network load are very much comparable. Likewise, as the network load increases the average delay given in [23] increases at similar values of network load before starting to settle at the maximum delay value. For the case where $t_c < RTT$ the delay calculated using our model shown in Figure 3.7 differs from the delay given in [23] shown in Figure 3.9. This is because we have assumed the maximum number of threads per RTT as opposed to an EPON based cycle-time approach. While the delay values at lower network loads are almost directly comparable in both cases when $t_c < RTT$, this similarity diverges as the network load increases as the number of packets used as well as the SLAs and traffic variation patterns begin to have an effect on the individual packet delay. For this reason a direct comparison cannot be made at high network loads unless the same parameters and traffic patterns are used.

3.5 Conclusion

In this chapter we have seen that the total delay an upstream packet experiences is influenced by three factors: the packet arrival and departure times, the buffering delay and the total propagation delay. The first two components are affected by the DBA algorithm however the characteristics of the injected traffic also contribute to the arrival time. The total propagation delay is only affected by the physical distance that the GPON spans. From analysis based upon FIFO buffers, the occupancy of the buffer and the egress rate are key parameters that influence the buffering delay. A model for the buffer occupancy has been developed and when allocations and requests are made in a periodic fashion the buffer egress rate is determined by both the size and the rate of the allocations from the OLT. A principle parameter responsible for the buffering delay in GPON was shown to be the duration of the allocation interval, t_c.

The analytical model developed in this chapter has shown that the parameters B_B and B_A are a direct consequence of the injected subscriber traffic and are consequently beyond the network operator's control. In contrast, the duration of the allocation interval, t_c, is in direct control of the operator. In this chapter we have shown analytically that reducing the interval reduces the average delay. This is not without consequence however as the reduced-interval waste effect degrades the bandwidth efficiency.

The RTT has also been identified as a fundamental limit on all transmissions on the GPON. This limit provides insight into why simply reducing the duration of the allocation interval is not sufficient in reducing the average delay. We have shown that while $t_c < RTT$ reduces the average delay, large amounts of wasted bandwidth cause network saturation to occur at a lower network load that when $t_c \geq RTT$.

From here we can draw a conclusion that while t_c is an important parameter in reducing the average packet delay, the allocations issued by the OLT also play an important factor. In the following chapter, we use the model developed above to manipulate the allocations made by the OLT in an effort to reduce both the wasted bandwidth and the average packet delay.

4 Modifying the Requested Bandwidth to construct Allocations

4.1 Introduction

The model developed in the previous chapter shows that when allocations and requests in GPON are made on a periodic basis, the duration of the allocation interval, t_c, is a key parameter in determining the upstream packet delay. Conventional request-allocate DBA algorithms often set the duration of the allocation interval greater than the RTT of the GPON [41, 42]. The model shows that when the duration of the allocation interval is decreased to below the round trip time (RTT) of the GPON the allocated bandwidth, $B_{A,n}(t)$, increases and the average packet delay decreases for low traffic densities. We also saw that the RTT is a fundamental lower limit on the delay of all requested packets on the PON. Therefore, injected customer traffic will experience a minimum delay equal to the RTT unless the bandwidth allocations are increased.

In this chapter we examine two algorithms whereby $t_c < RTT$ and the relationship between the requested bandwidth and the allocated bandwidth is modified by the OLT to minimize both the wasted bandwidth and packet delay. We then examine the impact of these algorithms by means of a simple simulation. We compare their performance to the DBA algorithms studied in the previous chapter.

4.2 Allocation reduction

In Chapter 3 we showed that by reducing the duration of the allocation interval below the RTT the reduced-interval waste effect reduces bandwidth efficiency. We recall that the wasted bandwidth at $t=2RTT$, as given by (3.32), is

$$B_{W,n}(2RTT) = \sum_{w=1}^{W}\left[B_{A,n}(RTT + wt_c)\right] - \int_0^{RTT} T_{r,n}(\rho)\, d\rho$$
$$= \sum_{w=1}^{W}\left[(W - w)\int_{(w-1)t_c}^{wt_c} T_{r,n}(\rho)\, d\rho\right] \tag{4.1}$$

where $B_{W,n}(t)$ is the wasted bandwidth, $B_{A,n}(t)$ is the allocated bandwidth, $\int_0^{RTT} T_{r,n}(\rho)\, d\rho$ is the injected customer traffic bytes due to $T_{r,n}(\rho)$ and W is the number of allocation intervals per RTT.

To reduce the wasted bandwidth, one possible solution is to incorporate a factor whereby the allocated bandwidth is reduced, thereby reducing the potential wasted bandwidth. To display the effect of such a factor we can assume that the total customer traffic over any allocation interval, t_c, is approximately constant such that

$$\int_{wt_c}^{(w+1)t_c} T_{r,n}(\rho)\, d\rho \approx \int_{(w+1)t_c}^{(w+2)t_c} T_{r,n}(\rho)\, d\rho \approx K \quad : \forall w \tag{4.2}$$

and the allocated bandwidth satisfies the service level agreements (SLAs)

$$K \le B_{A,n}^{SLA}(wt_c) \quad : \forall w \tag{4.3}$$

where $B_{A,n}^{SLA}(t)$ is the upper limit, or maximum window size, on the number of bytes allocated in a given interval as determined by the SLAs.

In the previous chapter we showed that when $t_c < RTT$ the buffer occupancy drops to zero at $t=2RTT$ for $W \geq 3$ creating a t_0 event at which the process repeats. Once the buffer occupancy is at zero, any further allocations result in wasted bandwidth. To reduce the wasted bandwidth, the OLT must reduce the allocations so that the buffer occupancy either drops to zero at a slower rate, or reaches zero with no further allocations that will otherwise result in wasted bandwidth. In order for this to occur, the DBA algorithm must be aware of both the RTT, which is possible due to the ranging protocol [11], and the duration of the allocation interval, t_c. Using this information, we will now show that the DBA algorithm can reduce the allocated bandwidth to minimize the wasted bandwidth.

We recall that the relationship between the allocated bandwidth and requested buffer occupancies is given by

$$B_{A,n}\left(M.RTT\right) = B_{B,n}\left(\left(M-1\right)RTT\right) \tag{4.4}$$

We propose to modify this relationship to reduce the allocated bandwidth such that (4.4) is re-written as

$$\begin{aligned} &B_{A,n}\left(M.RTT\right)' = B_{B,n}\left(\left(M-1\right)RTT\right)\times\frac{1}{\delta_{e,n}\left(W\right)} \\ &\delta_{e,n}\left(W\right)\geq 1 \end{aligned} \tag{4.5}$$

where $\delta_{e,n}(W)$ is an allocation reduction factor intended to reduce the amount of bandwidth allocated to an ONU in the given RTT. From (3.32) we can see that the wasted bandwidth is dependent on W and therefore we make the reduction factor also dependent on W. As more allocations are made per RTT, the higher the wasted bandwidth and thus a larger reduction factor is be required.

Using (4.4) and (4.5) the wasted bandwidth at $t=2RTT$ is given by

$$B_{W,n}\left(2RTT\right)' = \max\left[\begin{array}{l}\displaystyle\sum_{w=1}^{W}\left[\frac{\left(W-w\right)}{\delta_{e,n}\left(W\right)}\int_{(w-1)t_c}^{wt_c} T_{r,n}\left(\rho\right)\,d\rho\right] \\ 0\end{array}\right] \tag{4.6}$$

From (4.6) we can see that the higher the allocation reduction factor, the lower the wasted bandwidth. By incorporating this reduction factor into the DBA algorithm, the OLT can allocate less bandwidth to the ONUs thereby decreasing the wasted bandwidth. As $\delta_{e,n}(W)$ increases, less bandwidth is allocated per interval which also reduces the rate at which the buffer occupancy drops to zero.

The reduction factor is dependent on W and it is therefore desirable to determine an optimal value such that the wasted bandwidth is minimalized or eliminated. To determine this optimal value, we retain the assumptions in (4.2) and (4.3) and use (4.6) to give us the modified wasted bandwidth at $t=2RTT$ as

$$
\begin{aligned}
B_{W,n}(2RTT)' &= \sum_{w=1}^{W}\left[\frac{B_{B,n}(wt_c)}{\delta_{e,n}(W)}\right] - \int_0^{RTT} T_{r,n}(\rho)\ d\rho \\
&= \left(0.5W^2 + 0.5W\right)\left[\frac{\int_0^{t_c} T_{r,n}(\rho)\ d\rho}{\delta_{e,n}(W)}\right] - W\left[\int_0^{t_c} T_{r,n}(\rho)\ d\rho\right] \qquad (4.7) \\
&= \int_0^{c} T_{r,n}(\rho)\ d\rho\left(\frac{\left(0.5W^2 + 0.5W\right)}{\delta_{e,n}(W)} - W\right)
\end{aligned}
$$

In (4.7) we assume that the injected customer traffic is not zero and therefore an optimum value for $\delta_{e,n}(W)$ can be obtained

$$
\begin{aligned}
&\int_0^{t_c} T_{r,n}(\rho)\ d\rho\left(\frac{\left(0.5W^2 + 0.5W\right)}{\delta_{e,n}(W)} - W\right) = 0 \\
&\therefore \delta_{e,n}(W) = \left(\frac{W+1}{2}\right)
\end{aligned} \qquad (4.8)
$$

This value is the minimum required $\delta_{e,n}(W)$ to produce zero wasted bandwidth at $t=2RTT$ when the conditions (4.2) and (4.3) are satisfied. If the condition (4.2) is removed, the injected customer traffic rate is no longer constant. This will then require the reduction factor to be interval dependent. If the condition (4.3) is removed, the requested bandwidth may exceed the maximum window size set by the SLA. In this situation, the wasted bandwidth is determined by a combination of the SLA and the reduction factor.

4.2.1 Simulated wasted bandwidth using allocation reduction

To determine the effect that the proposed reduction factor has on the wasted bandwidth we use the same simple simulation scenario as outlined in Chapter 3. We examine a LR-GPON with maximum logical reach set to 100 km which has an RTT of 8.0 GPON frames. We keep the duration of the allocation interval, t_c, at 0.125 ms, corresponding to a single GPON frame. This value of t_c is the smallest possible value and corresponds to $t_c < RTT$. We vary the value for $\delta_{e,n}(W)$ from 1.0 to 5.0 in increments of 1.0. We also consider $\delta_{e,n}(W)=10$ to examine the case where $\delta_{e,n}(W)$ is very high.

The simulated average wasted bandwidth against network load is shown in Figure 4.1. The average wasted bandwidth is given in Mbps per ONU. The network load was calculated as the sum of the injected customer traffic bytes over the sum of the GPON frame capacity over the duration of the simulation.

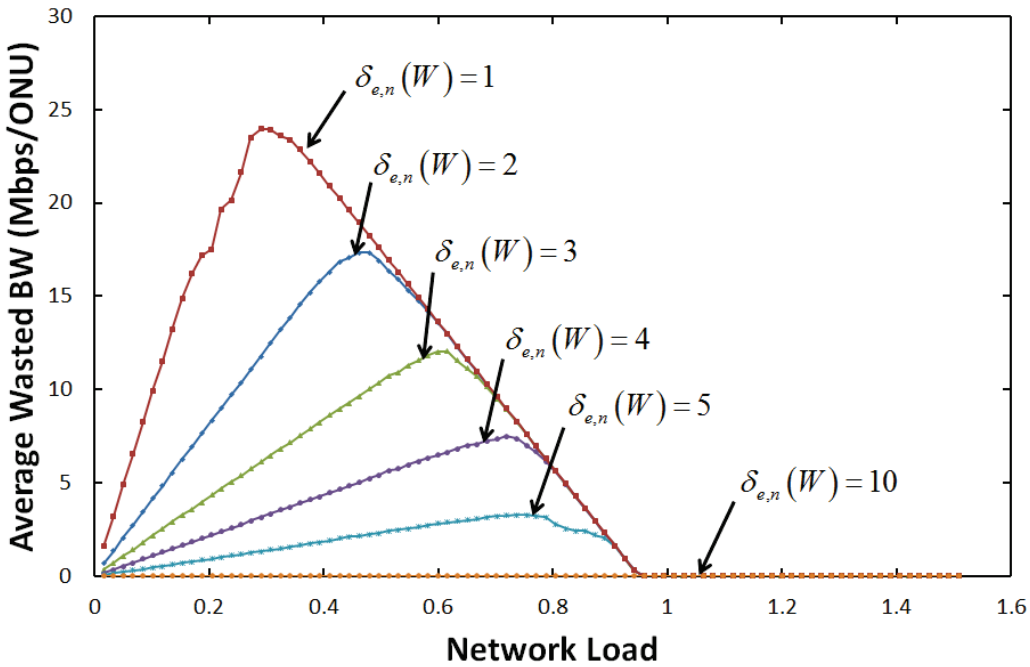

Figure 4.1 – Average wasted bytes per ONU per interval against network load for $\delta_{e,n}(W)=1, 2, 3, 4, 5$ & 10.

All curves in Figure 4.1 display a similar characteristic shape. As the network load increases, the average wasted bandwidth increases to a maximum value then decreases towards zero. When $\delta_{e,n}(W)=10$, the average wasted bandwidth produced is only in the order of a few kbps for all network load values.

As the traffic rate increases, the combined bandwidth requests (required bandwidth and wasted bandwidth) increase. At higher network loads the SLAs begin to limit the allocated bandwidth and so progressively reduces the wasted bandwidth as the network load approaches unity. If we examine the case where $\delta_{e,n}(W)=1$, the peak wasted bandwidth occurs when the network load is 0.3 thereby resulting in an total injected customer traffic rate of approximately 375 Mbps. The wasted bandwidth at that network load is nearly 25 Mbps per ONU, or 800 Mbps in total. The combined wasted and required bandwidth is then 1.175 Gbps which is close to the total GPON upstream frame capacity of 1.25 Gbps. The difference is about 36 bytes per ONU per frame which

corresponds to the overheads. At the network load where the peak wasted bandwidth occurs, from the OLTs perspective the network has reached saturation as the total requested bandwidth equals the total available bandwidth. We refer to this condition as *apparent* network saturation as opposed to *actual* network saturation which occurs at a network load of 1.0. Above the apparent network saturation the wasted bandwidth decreases as the allocations become limited by the SLAs. When this occurs, less total bandwidth is allocated to each ONU thereby decreasing the wasted bandwidth.

We can see that as $\delta_{e,n}(W)$ increases the network load at which the peak wasted bandwidth occurs also increases. From (3.32) we see the wasted bandwidth is derived from the allocated bandwidth. Using a reduction factor, less bandwidth is allocated due to $\delta_{e,n}(W)$, and so less wasted bandwidth is allocated. This means that the network load at which the SLA limitation becomes apparent increases thereby increasing the network load at which the *apparent* network saturation occurs.

From Figure 4.1 as $\delta_{e,n}(W)$ increases, less bandwidth is allocated to each ONU using the allocation reduction factor and as a result more allocation intervals may be required to empty the buffers. Therefore the effect of $\delta_{e,n}(W)$ on the average packet delay must also be considered.

4.2.2 Simulated average delay using allocation reduction

We saw from the model developed in Chapter 3 that the buffering delay corresponds to the number of allocation intervals taken to empty the buffer once the customer packet is injected. The allocation reduction factor discussed in the previous section reduces the allocated bandwidth which means additional intervals may be required to empty the buffer thereby increasing the packet delay. To assess the impact of $\delta_{e,n}(W)$ on the average upstream packet delay we used the same simple simulation environment as the previous section. Equations (3.11) and (3.19) were used to calculate the average delay over all the injected customer packets.

Figure 4.2 shows the average packet delay against network load for the same values of $\delta_{e,n}(W)$ considered in the previous section. We can see that regardless of the allocation reduction factor, the average upstream packet delays are very similar for $\delta_{e,n}(W) \in \{1,2,3,4,5\}$. There is only a slight increase in average delay at low network

loads as $\delta_{e,n}(W)$ increases up to 5.0; the increase is only in the order of a few ms. When $\delta_{e,n}(W)=10$, the average delay is slightly higher as significantly less bandwidth per interval is allocated thereby increasing the average delay.

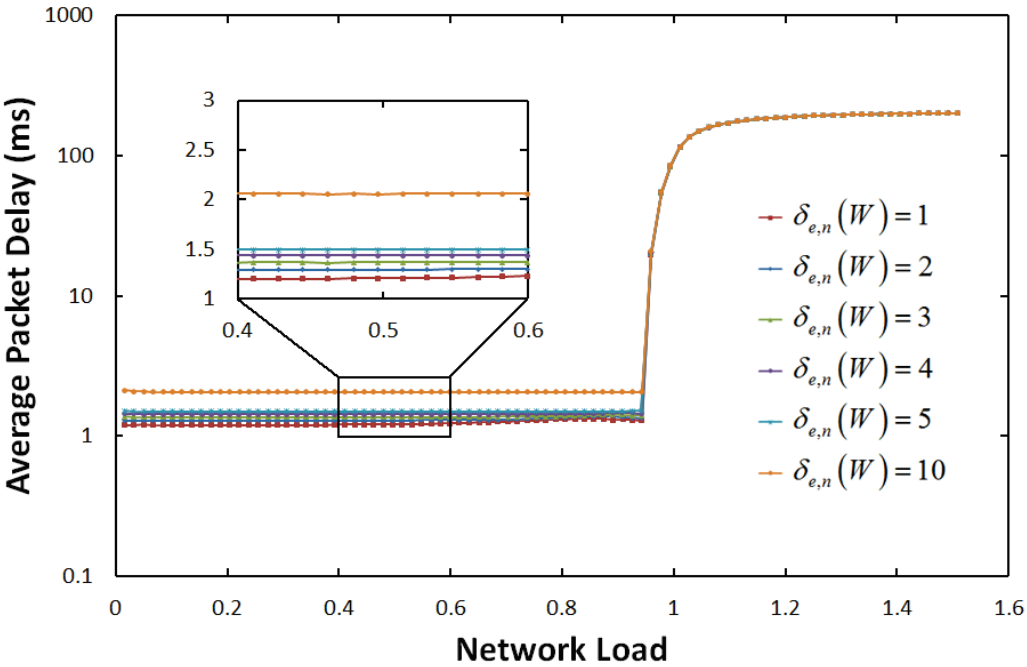

Figure 4.2 – Average packet delay against network load for $\delta_{e,n}(W)=1, 2, 3, 4, 5$ & 10.

Once network saturation occurs the average delay for all $\delta_{e,n}(W)$ is effectively the same because the SLAs are limiting the allocations rather than the modification factor. As seen in the previous chapter, once saturation occurs the average delay approaches the maximum delay value as set by the buffer size. In Figure 4.2 the actual network saturation occurs for the same network load for all $\delta_{e,n}(W)$. In Figure 3.7 we saw that the network load at which the simulated average delay began to increase was lowest when $t_c < RTT$ as the additional overheads required each GPON frame decreased the available bandwidth. In the simulated results shown in Figure 4.2 the increase in delay occurs at the same value of network load as the amount of bandwidth required for the overheads is the same.

4.3 Allocation reduction – Discussion

From the simulated results in Figure 4.1 and Figure 4.2 we can see that while the reduction factor has a significant impact on the wasted bandwidth per ONU, little impact is observed on the average delay. Only a very slight increase in average delay is observed as $\delta_{e,n}(W)$ increases. This leads us to conclude that incorporating an allocation reduction factor into the DBA, the wasted bandwidth can be reduced with minimal increase in the average packet delay. This re-iterates the effect outlined in the literature examined in Chapter 2 whereby the average upstream delay is inversely proportional to the amount of bandwidth allocated [37, 66]. Allocation reduction is an example of how the OLT can manipulate the amount of bandwidth allocated without violating the operation of the DBA given by the GPON standards.

In the following sections we will examine a more advanced DBA algorithm in which the OLT tracks the behaviour of the injected customer traffic operating at an allocation interval below the RTT ($t_c < RTT$) without compromising bandwidth efficiency and still resulting in low average packet delay.

4.4 Delta-Buffer Allocation

Several DBA schemes examined in Chapter 2 utilise traffic prediction to increase the OLTs bandwidth allocations in an effort to reduce the buffering delay. Traffic prediction has yielded some promising results in terms of reducing average upstream packet delay, however network traffic has been widely demonstrated to exhibit bursty behaviour [51, 53]. For this reason the behaviour of the traffic becomes difficult to predict [79]. Allocation reduction can reduce the wasted bandwidth, but increases the average upstream delay. Both traffic prediction and allocation reduction are methods of manipulating the allocations made by the OLT in an effort to reduce the average upstream packet delay.

The bursty nature of customer traffic results in fluctuations in the arrival times of the subscriber traffic at the ONUs. By reducing t_c, the impact of these variations on the packet delay can be reduced [35, 79]. To take full advantage of this the DBA algorithm must operate at the shortest possible interval which is set by the duration of a GPON frame [11]. In an LR-GPON this is well below that of the RTT and the problem of

excessive wasted bandwidth must be eliminated in order to provide good bandwidth efficiency.

When the duration of the allocation interval, t_c, is reduced below the RTT, we saw from (3.32) that the wasted bandwidth is caused by the reduced-interval waste effect. If the injected customer traffic satisfies the SLAs and the requests are equal to the buffer occupancy at the time the request is made, when $t_c < RTT$ the first allocation after a t_0 event is given by

$$B_{A,n}\left(RTT + t_c\right) = B_{B,n}\left(t_c\right) = \int_0^{t_c} T_{r,n}\left(\rho\right)\, d\rho \tag{4.9}$$

and the second allocation is given by

$$\begin{aligned} B_{A,n}\left(RTT + 2t_c\right) &= B_{B,n}\left(2t_c\right) \\ &= \int_0^{2t_c} T_{r,n}\left(\rho\right)\, d\rho \\ &= \int_0^{t_c} T_{r,n}\left(\rho\right)\, d\rho + \int_{t_c}^{2t_c} T_{r,n}\left(\rho\right)\, d\rho \end{aligned} \tag{4.10}$$

The allocation at $t=RTT+t_c$ accounts for the traffic during the interval 0 to t_c. The allocation at $t=RTT+2t_c$ accounts for the traffic during the interval t_c to $2t_c$, but also includes the customer traffic bytes that arrived during the interval 0 to t_c because no allocation arrived at $t = t_c$ to reduce the buffer occupancy. The injected customer traffic bytes over 0 to t_c, $\int_0^{t_c} T_{r,n}\left(\rho\right)\, d\rho$, will be allocated at $t=RTT+ t_c$ and need not be allocated at $t=RTT+ 2t_c$ which would result in wasted bandwidth.

Figure 4.3 shows the buffer occupancy over time when the duration of the allocation interval is reduced below the RTT. In the time between 0 and RTT, the buffer occupancy increases due to the injected customer traffic, but no allocation arrives to reduce the buffer level. Also shown are the buffer occupancies for $t=t_c$ and $t=2t_c$. As the buffer occupancy increases, Figure 4.3 shows the components of the buffer content representing the newly arrived customer traffic and the previously arrived traffic.

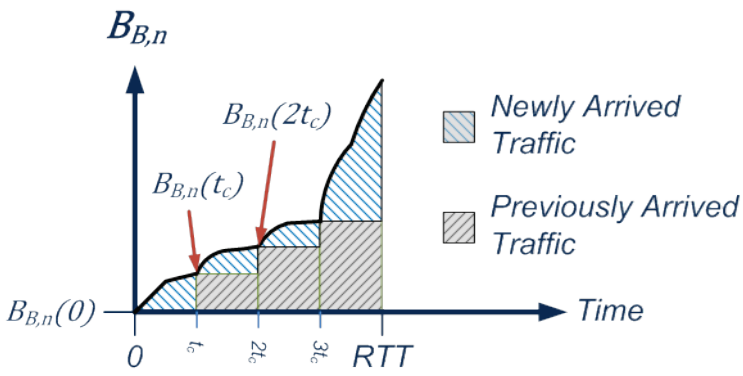

Figure 4.3 – Buffer occupancy over time when t_c<*RTT* with traffic and wasted bandwidth components of the buffer.

From examination of Figure 4.3 we can see the components of the buffer that correspond to the previously arrived traffic, but are still allocated translate to wasted bandwidth.

From (4.10) the traffic rate integrals over time can be broken into piecewise integrals over the allocation intervals. Using this concept, the general statement for the buffer occupancy at any given allocation interval, t_c, is

$$\begin{aligned} B_{B,n}\left(M.RTT+i.t_c\right) &= B_{B,n}\left(M.RTT+(i-1)t_c\right) \\ &+ \int_{M.RTT+(i-1)t_c}^{M.RTT+i.t_c} T_{r,n}(\rho)\, d\rho \\ &- B_{A,n}\left(M.RTT+i.t_c\right) \end{aligned} \tag{4.11}$$

where i is a positive integer used to index the allocation intervals and has a maximum value W equal to the number of allocations over an RTT. Equation (4.11) is true for all M and i and from this we can express the customer traffic as

$$\begin{aligned} \int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}(\rho)\, d\rho &= B_{B,n}\left((M-1)RTT+i.t_c\right) \\ &- B_{B,n}\left((M-1)RTT+(i-1)t_c\right) \\ &+ B_{A,n}\left((M-1)RTT+i.t_c\right) \end{aligned} \tag{4.12}$$

In the Chapter 3 we showed that when the duration of the allocation interval, t_c, is less than the RTT wasted bandwidth was produced. To eliminate this, we set the allocation in

one allocation interval, $B_{A,n}(M.RTT+i.t_c)$, to be equal to the customer traffic from the previous RTT, $\int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}(\rho)\, d\rho$. Using this approach and (4.12) we get

$$\begin{aligned} B_{A,n}(M.RTT+i.t_c) &= \int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}(\rho)\, d\rho \\ &= B_{B,n}((M-1)RTT+i.t_c) \\ &\quad -B_{B,n}((M-1)RTT+(i-1)t_c) \\ &\quad +B_{A,n}((M-1)RTT+i.t_c) \end{aligned} \tag{4.13}$$

For the OLT to implement allocations according to (4.13), the OLT is required to remember the previous request, $B_B((M-1)RTT+(i-1)t_c)$, and therefore additional memory is required. To assess the feasibility of such an implementation, we examine the additional memory requirements.

From the GPON standards, only 3,840 T-CONTs can be utilised to carry GEM traffic and a maximum of three bytes is used to convey the DBRu [11]. This requires a 36 bit binary vector to store both the T-CONT identification number and the previous number of GEM frames requested. To store the previous buffer occupancy for all 3,840 T-CONTs an additional 17 KB of memory is required.

From (4.13) we can see that the OLT is also required to remember the number of bytes allocated in the same allocation for a maximum of one RTT. From the GPON standards, each allocation structure consists of 8 bytes [11]. For a 100 km reach LR-GPON the RTT equals 8 GPON frames. For 3,840 T-CONTs and 8 frames, the OLT requires 250 KB of memory to store 8 RTTs worth of previous allocations. To fully implement (4.13), 17 KB is also required to store the previous buffer occupancies from the previous DBRu. The total memory requirement is therefore only 267 KB.

By examining (4.13), the OLT allocates bandwidth based on the difference between the ONUs bandwidth requests. We therefore denote the algorithm displayed in (4.13) as the *Delta-Buffer* DBA algorithm. We will now consider the amount of wasted bandwidth that this algorithm produces.

In determining the wasted bandwidth we use (4.13) to express the allocations in terms of customer traffic injected as

$$B_{A,n}\left(M.RTT+i.t_c\right)=\int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}\left(\rho\right)\ d\rho \tag{4.14}$$

From (4.14) and the general term for wasted bandwidth from (3.20), the wasted bandwidth produced by the Delta-Buffer algorithm is

$$\begin{aligned}
&B_{W,n}\left(\left(M+2\right)RTT\right)\\
&=\max\left[\begin{array}{l}\sum_{i=1}^{W} B_{A,n}\left(\left(M+1\right)RTT+i.t_c\right)-\int_{M.RTT}^{(M+1)RTT} T_{r,n}\left(\rho\right)\ d\rho\\ 0\end{array}\right.\\
&=\max\left[\begin{array}{l}\sum_{i=1}^{W}\left[\int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}\left(\rho\right)\ d\rho\right]-\sum_{i=1}^{W}\left[\int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}\left(\rho\right)\ d\rho\right]\\ 0\end{array}\right.\\
&=0
\end{aligned} \tag{4.15}$$

From (4.15) the wasted bandwidth produced by the Delta-Buffer algorithm should be zero provided the SLAs are satisfied as in (4.2) and (4.3). To fully assess the Delta-Buffer algorithm, we also calculate the wasted bandwidth when this assumption is removed. Doing this, the allocations from (4.14) are limited by $B_{A,n}^{SLA}$. That is

$$\begin{aligned}
B_{A,n}\left(M.RTT+i.t_c\right)&=\min\left[\begin{array}{l}\int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}\left(\rho\right)\ d\rho\\ B_{A,n}^{SLA}\left(t\right)\end{array}\right.\\
&=B_{A,n}^{SLA}\left(t\right)
\end{aligned} \tag{4.16}$$

When the SLAs are not satisfied we have more customer traffic per allocation interval than can be allocated by the OLT. That is

$$B_{A,n}^{SLA}\left(t\right)<\int_{(M-1)RTT+(i-1)t_c}^{(M-1)RTT+i.t_c} T_{r,n}\left(\rho\right)\ d\rho \tag{4.17}$$

Therefore the wasted bandwidth is

$$
\begin{aligned}
& B_{W,n}\left((M+2)RTT\right) \\
& = \max\left[\begin{array}{l} \sum_{i=1}^{W}\left[B_{A,n}^{SLA}(t)\right] - \int_{M.RTT}^{(M+1)RTT} T_{r,n}(\rho)\, d\rho \\ 0 \end{array}\right. \\
& = 0
\end{aligned}
\tag{4.18}
$$

We can see that even if the injected customer traffic increases such that the SLAs limit the bandwidth allocated, the wasted bandwidth is still zero.

To assess the performance of the Delta-Buffer algorithm we will now examine the average packet delay as produced through simple simulation methods.

4.4.1 Simulated average delay using Delta-Buffer DBA

By contrast to the algorithm described in Chapter 3 where t_c was less than the RTT, the Delta-Buffer algorithm has the potential to allocate less bandwidth per interval thereby possibly increasing the average packet delay. To determine the average packet delay produced by the Delta-Buffer DBA algorithm, the same simulation environment is used as in the previous section. Figure 4.4 shows the simulation results for average packet delay against network load for a 100 km reach GPON using the Delta-Buffer DBA with $t_c = 1$ GPON frame (t_F). Also shown are the average delay simulation results for the case where the OLT allocates bandwidth according to (3.9) with $t_c = 10T_F$ and $t_c = t_F$. We denote the latter algorithm as the *Reduced-Interval* DBA.

We can see that the average upstream packet delay below network saturation for the Delta-Buffer DBA with $t_c = t_F$. is less than the delay when $t_c = 10t_F$, however the Delta-Buffer DBA exhibits a greater average delay than the Reduced-Interval DBA.

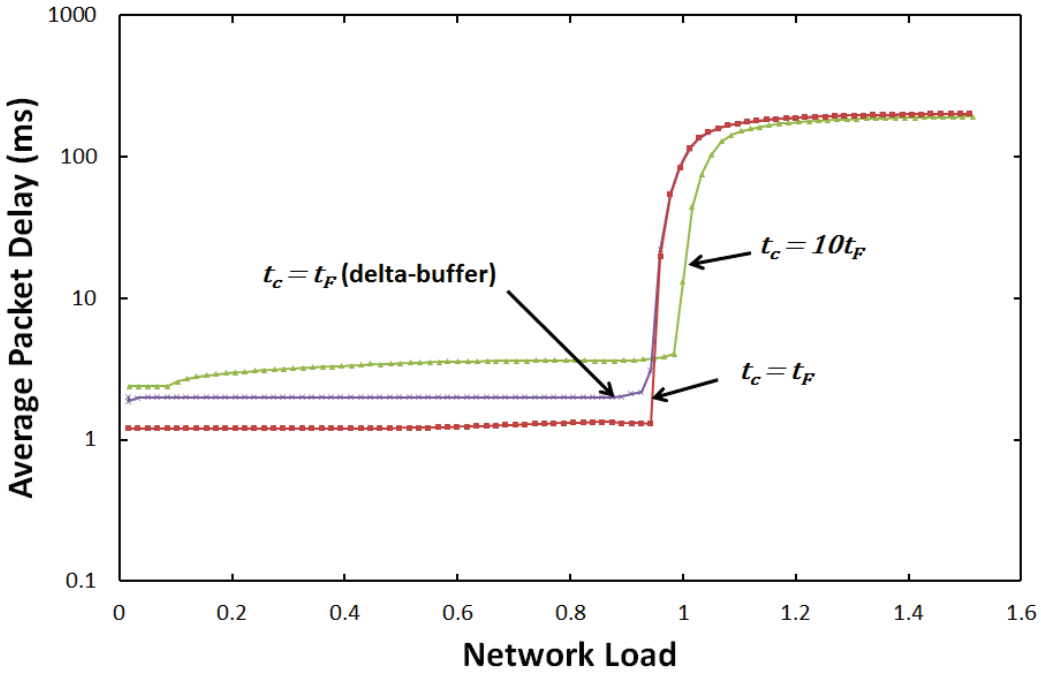

Figure 4.4 - Average packet delay against network load in a 100 km reach GPON using the Delta-Buffer DBA with $t_c = t_F$ as well as DBAs with $t_c = t_F$ and $t_c = 10t_F$

Below network saturation, the average delay produced by the Delta-Buffer DBA algorithm is fairly constant as all injected customer packets are only buffered for the minimum number of allocation intervals as per (3.19). We can also see in Figure 4.4 that network saturation using the Delta-Buffer DBA begins to occur at a slightly lower network load than the Reduced-Interval DBA. This is because the bandwidth requests in some intervals for the Reduced-Interval DBA exceed the injected customer traffic rate. This allows some packets to be transmitted with a lower delay thereby decreasing the average delay. Because no wasted bandwidth occurs when the Delta-Buffer algorithm the variations in the injected customer traffic produce a slightly higher buffering delay for some injected customer packets when the network load is close to the network saturation point. Above network saturation, both the Delta-Buffer and the Reduced-Interval DBA algorithms display the same average delay and converge to the same maximum delay.

4.5 Delta-Buffer DBA – Discussion

We have shown that using the Delta-Buffer DBA algorithm does not result in wasted bandwidth even though $t_c < RTT$. By calculating the difference between two bandwidth requests and accounting for the previous allocations, the resulting allocated bandwidth is adequate for the required traffic bandwidth with no wasted bandwidth. Although the average delay of the Delta-Buffer DBA is observed to be higher than when the OLT uses the Reduced-Interval DBA, the Delta-Buffer DBA algorithm gives zero wasted bandwidth whereas the Reduced-Interval DBA algorithm wastes bandwidth. In addition, below network saturation, minimal variation, or jitter, in the average traffic delay was observed. This is especially beneficial for upstream traffic that has tight jitter requirements and will be explored in further detail in Chapter 7.

4.6 Conclusion

The primary function of any DBA in GPON is to enable information to be carried from the ONUs to the OLT. This is done by means of the DBA which is currently specified by the GPON standards [11]. In LR-GPON the increased propagation increases the RTT of the network thereby increasing the average time a packet must be buffered prior to upstream transmission. We have shown that in an attempt to reduce the packet delay by allowing the DBA to be executed at faster intervals excessive wasted bandwidth is produced. While wasted bandwidth can aid in reducing the average packet delay experienced by upstream packets, it represents a reduction in bandwidth efficiency and can have a significant impact on the quality of service [22, 35].

In this chapter we have shown that by manipulating the algorithm used by the OLT to allocate bandwidth to the ONUs, the amount of wasted bandwidth can be reduced. This manipulation can be done by employing an allocation reduction scheme in which the OLT reduces the allocated bandwidth to reduce wasted bandwidth. Using simple simulation we have shown that this method produces less wasted bandwidth than DBA algorithms that do not employ this method. Using the allocation reduction method there is also little impact to average upstream packet delay so long a suitable reduction factor is used. As the modification factor relies heavily on the dynamics of the injected customer traffic which is difficult to predict, the choice of a suitable reduction factor may be a difficult task for network operators.

The Delta-Buffer DBA algorithm is designed to completely eliminate the wasted bandwidth while still allowing the duration of the allocation interval to be less than the RTT. To implement this algorithm the OLT must have knowledge of previous DBRu requests and allocations. While this can be seen as an additional memory requirement, we have shown that this increase is only in the order of a few KB. From the simple simulation results the Delta-Buffer algorithm displays higher average delay than the Reduced-Interval DBA, but lower average delay than when the duration of the allocation interval is greater than the RTT.

In the following chapter we will examine a more complicated simulation environment whereby many of the assumptions made in this chapter will be removed. This allows us to gain deeper insight into how the DBA algorithms in GPON and LR-GPON behave under more realistic scenarios with multiple T-CONTs and traffic categories as well as self-similar bursty network traffic.

5 Advanced Simulation Methods for LR-GPON DBA

5.1 Introduction

As networks become increasingly complex in order to facilitate the increasing diversity of traffic categories and priorities, the use of network simulation and emulation methods is beneficial to plan and research network behaviour [90]. Simulations enable manipulation and re-configuration of aspects of the network that may be difficult to modify once the network hardware is in production or deployed in the field [90]. Network simulators and hardware emulators can be used to model scenarios whose occurrence in deployment is either limited, difficult to predict or involves complicated network architectures [91]. Simulations allow network operators to plan for worst case situations such as network overload [90].

Network emulation tools are commonly implemented in hardware, but can also include the use of software, to analyse the network behaviour under various operating conditions [92, 93]. Hardware emulation tools can consist of the required network physical architecture, but offer additional functionality such as increased configuration options and management ability. Hardware emulators are required to be physically integrated into existing networks that are either being, or have been deployed. As they require both network infrastructure and additional hardware, the ability to be upgraded as new technology emerges may be limited.

To analyse the packet delay and bandwidth characteristics in LR-GPONs using hardware emulation requires that both the GPON network and the emulation tools capable of operating over a long reach. GPON emulation tools are currently limited to operating within the distance limitations of the GPON standard and therefore cannot be used to emulate or analyse LR-GPONs [92, 93].

Software simulation packages often have the ability to be upgraded as well as the ability to incorporate scenarios that hardware emulation tools cannot [94]. Software

simulation tools also provide a modular approach thereby allowing either re-use in other scenarios or a customizable simulation environment [95]. Software also appears to be the choice in published literature when analysing DBA algorithms for both EPON and GPON [20, 25, 27, 42, 45, 48, 75, 76, 78, 83, 94, 96-98]. The most widely used optical network simulator for EPON and GPON networks in the literature is OPNET Modeller [99]. While OPNET offers an array of features, at the time this research commenced, OPNET had limited support for complete flexibility in configuring a DBA algorithm and LR-GPON.

In the models developed in Chapter 3 and Chapter 4 many assumptions were made regarding the nature of the injected traffic, the number of traffic containers (T-CONTs) and service level agreements (SLAs). In order to examine the packet delay and bandwidth behaviour of the network when these assumptions are removed, the use of a simulation tool is required. In order to assess the delay and bandwidth efficiency performance of DBA algorithms for LR-GPON, a “purpose built” package was developed. Developing a purpose built simulation package provides complete customization of the package; however there is the possibility of errors in the results. Therefore, in an effort to validate the simulator, the results produced were compared to that of existing DBA literature and found to be in agreement with them. A validation of the simulator was presented in Chapter 3 using the analytical model and an appropriate configuration of the simulator.

In this chapter we provide a brief overview of the simulation environment developed for the work in this thesis. A detailed explanation of how the DBA algorithms are handled in the simulation as well as various simulation parameters used is provided in Appendix A.

5.2 Simulation Environment

The simulation environment was designed and developed using object orientated C# and is a discrete event simulator. Discrete event simulation allows for complex simulations to be performed with minimal computational complexity [100]. The environment simulates only the packet structure of GPON. It does not account for any physical layer effects such as dispersion, bit-errors and ONU phase differences. Figure 5.1 shows a basic overview of the simulation environment.

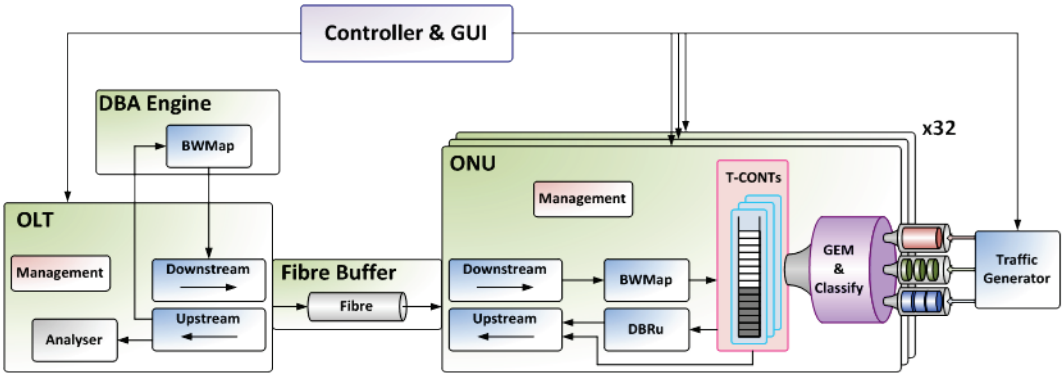

Figure 5.1 – Overview of simulation environment

The simulation environment consists of six main systems:

- A traffic generator module that has the capacity to generate an unlimited number of traffic streams of varying traffic categories.
- An ONU module that contains a classifier and GEM framer, a number of T-CONTs as assigned by the configuration and an ONU management framework that operates in accordance with the GPON standards [11].
- An OLT module containing an upstream packet analyser and an OLT management module that also operates according to the GPON standards [11].
- Optical fibre which is represented as a FIFO buffer.
- DBA Engine responsible for the DBA algorithms, scheduling and BWmap construction.
- Simulation controller and graphical user interface (GUI).

The simulator can simulate two distance variants of GPON; a standard network with a maximum reach of 20 km and a LR-GPON with a maximum reach of 100 km. These distances cannot be modified once the simulation is operating as such a situation would be unlikely to occur in a deployed GPON.

We will now describe some of the simulator modules in more detail

5.2.1 Traffic Generator

The traffic generator is responsible for the customer traffic streams injected into the ONUs T-CONT buffers. The traffic generator in the simulation generates customer packets according to the specified traffic category. The customer packets are then injected into the ONU once per GPON frame according to the utilization rate. Once the packet is created, the back end of the packet is time-stamped in µsec with the current simulation time, derived from a global counter. The time location of the last byte in the packet can also be used in the calculation of the arrival time.

The single traffic generator module is responsible for the generation of simulated traffic to all ONU modules in the simulation. The generator is capable of generating six categories of traffic and the simulator assigns a T-CONT type depending on the pre-determined priority of the traffic category.

The traffic categories capable of being injected will now be described in more detail.

5.2.1.1 TCP-IP Network Traffic

The nature of network traffic has been widely observed as self-similar as well as exhibiting bursty characteristics [51, 53]. In the majority of literature examined in Chapter 2 the simulated model for the injected traffic used a publicly available self-similar Ethernet packet creator from [101] using Pareto distribution derived from the work in [52]. As this method of generating Ethernet packets has become widely accepted, we adopt the same method to generate our Ethernet TCP-IP packets. The packet generator creates a specified number of packets, each with a size (between 64 and 1500 bytes) and an inter-frame gap with a minimum of 20 bytes. When injected into the simulator, the generated packet rate is set to attain a specified target network load between 0 and 1.0. Ethernet traffic has demonstrated a Hurst parameter of 0.8 [36] which requires an alpha (α), or traffic shaping parameter of 1.4 [101]. The inter packet gap is used to determine the time between the end of one packet and the arrival of the next.

The TCP-IP traffic generated is considered to be best-effort (BE) and is injected into the ONU module at a set rate ranging from 0.0 Mbps to 60.0 Mbps. In accordance with the

GPON ONT management control interface (OMCI) standards, an end-to-end connection is set up and this category of traffic is transported using a dedicated type 4 T-CONT [74].

5.2.1.2 VoIP Traffic

Voice traffic is simulated using the ITU G.711 standard [102]. A single voice packet of 160 bytes is simulated every 20 ms, or 160 GPON frames. Once Ethernet and 802.1Q overheads are added, the total packet size becomes 192 bytes. We assume that 802.1Q tagging is used as VoIP is as delay sensitive so that routers can forward the traffic with high priority.

This category of traffic is considered as high priority and is transported using a dedicated T-CONT of type 2 to ensure low delay and jitter.

5.2.1.3 UDP Datagrams

User datagram protocol (UDP) packets are a common form of traffic used in applications such as file transfer, media streaming and text based messaging. It is an unreliable form of packet transfer as no handshaking or rate alteration is performed by the application layers unlike other IP protocols such as TCP-IP. We assume that subscribers may utilize UDP packets for instant messaging services consisting of only ANSII characters and therefore assign it as low priority. For this category of traffic, we use the self-similar packet generator from [101] with low utilization.

This traffic is considered as BE and is transported using a dedicated T-CONT of type 4.

5.2.1.4 Online Video Gaming

The popularity of online video gaming has increased as new technology improves the graphics and sound quality of video games. From the Cisco visual networking index (VNI) in 2011, online gaming totaled 68 petabytes per month of global internet traffic [1]. The specific network protocol traffic used to convey gaming information varies according to game and platform; we assume that HTTP traffic is used with low data rate, but high utilization.

This traffic is considered as high priority and is transported using a dedicated T-CONT of type 3 to ensure low delay and jitter.

5.2.1.5 HD Video

For video conferencing, we assume that the video traffic is MPEG-2 H.264 video data as this is becoming the industry standard for video such as Blu-Ray and HDTV [103]. When transported over a network, the video packets are often fragmented using the real-time transport protocol (RTP) which are then encapsulated in UDP datagrams [104, 105]. The packet size of H.264 video can be up to 65,535 bytes which exceeds the maximum Ethernet frame size of 1500 bytes. As UDP does not provide mitigation against lost packets and congestion, the use of H.264 packets with smaller sizes has been demonstrated to provide better performance [104]. For this reason, we set the total RTP packet size to 256 bytes and once UDP and IP overheads are added, the total frame size is 296 bytes. The bit-rate of the video stream depends on the quality of the video and the compression in the codec. An upstream bandwidth of 2-3 Mbps is required for a 1280 x 720 pixel, progressive, video stream (720p) at 30 frames per second for home video conferencing [106]. We therefore use a variable bit rate (VBR) traffic stream for HD video at 2.0 Mbps with variance of 1.0 Mbps.

This traffic is considered as high priority and is transported using a dedicated T-CONT of type 2 to ensure low delay and jitter because excessive delays can deteriorate the video experience

5.2.1.6 Peer to Peer Traffic

The popularity of Peer to Peer (P2P) traffic has increased in recent years, mainly due its use in content distribution and file sharing. Whilst the majority of P2P traffic is multimedia sharing [1], other applications such as real-time voice and video transfer, scientific and defence research also utilise P2P services. Similar to online gaming, the specific network traffic protocol varies according to application and we therefore assume that P2P traffic is Ethernet traffic with moderate load and utilization.

This traffic is considered as medium priority and is transported using a dedicated T-CONT of type 3 to achieve low delay and jitter.

5.2.2 ONU Module

The ONU module in the simulation is replicated 32 times to simulate 32 individual ONUs on the GPON network. Each ONU module contains a series of T-CONT buffers, framing management as well as other modules that although required, do not directly affect the DBA and upstream packet behaviour.

5.2.2.1 ONU T-CONT Buffers

Each ONU contains four T-CONTs to carry subscriber traffic and an additional T-CONT to convey management information. As packets are injected from the traffic generator, a framing function breaks the packets up into 48 byte GEM fragments which are then stored in a buffer as shown in Figure 5.2. A unique identifier (port-ID) within the GEM header defines both the specific traffic category and stream of the fragment as multiple traffic streams can be injected into each T-CONT.

The total buffer size for each T-CONT is set to 1 Mbytes; however the structure of the buffer is that each address holds a GEM frame. Using the default GEM payload length of 48 bytes provides a maximum of 18,867 GEM frames that can be contained in each T-CONT buffer.

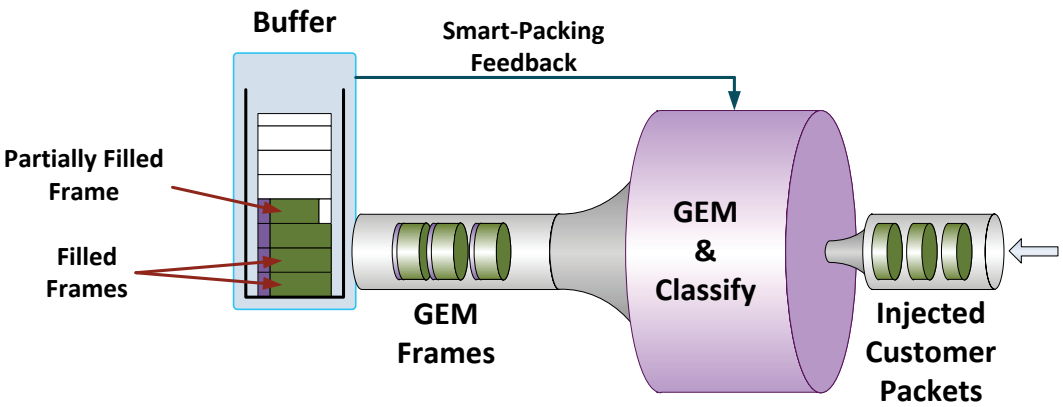

Figure 5.2 – GEM framing and buffering of injected packets

Another feature included we refer to as smart-packing. From Figure 5.2 we can see that the last utilised GEM frame is only partially filled as the injected customer packet length was not a multiple of the GEM frame length. Smart-packing allows any partially filled frames to be completely filled as long as the injected traffic is of the same category. The result is that buffer utilization can be improved and the transmission of partially-filled GEM frames reduced. This not only reduces delay, but also reduces the number of wasted bytes.

5.2.2.2 ONU Framing Management

The ONU framing sub-module processes the received downstream frames from the OLT and examines management information as well as the allocations within each BWmap. If an allocation is identified for any T-CONTs within the ONU, the allocation structure from the BWmap is extracted and forwarded to the T-CONT sub-module for further processing.

The framing management sub-module also compiles upstream GEM frames from the T-CONT buffers and assembles the full upstream burst according to the BWmap. The burst is then placed into the EqD buffer as specified by the GPON standards [11]. Once the burst departs the EqD buffer, it is then copied into the fibre module according to the start and stop times dictated in the BWmap. The simulated physical distance and possible contention issues are detected and managed by the fibre module.

5.2.3 OLT Module

The OLT module in the simulation is constructed according to relevant sections of the GPON standards that concern the DBA, activation and GEM framing. The OLT module handles the downstream frame compilation, upstream frame reception and upstream packet analysis. In each simulation event a single downstream frame is compiled with a frame header, a PLOAM if required, a BWmap, but no downstream GEM frames are transmitted as these do not relate to or affect the DBA. The OLT also analyses an upstream frame in each simulation event to extract upstream packets and record the packet delay.

The OLT module comprises of a downstream frame management module, upstream frame receiver and upstream packet analyser. While other functions exist that are related to activation, ranging and management, these are not directly related to the DBA and are not discussed.

5.2.3.1 OLT Downstream Frame Management

When the simulation controller generates an event handler, the OLT downstream frame management sub-module generates a partial downstream frame and BWmap structures compiled from the DBA engine sub-module. Once compiled, the downstream frame is sent to the optical fibre module.

5.2.3.2 OLT Upstream Frame Receiver

In each simulation event, an upstream frame is received and processed. The BW map that corresponds to the previous received frame is used to extract the individual ONU bursts which are then processed. The DBRus and GEM frames are extracted, DBRus are passed to the DBA engine and the GEM headers and payloads are forwarded to the packet analyser sub-module.

5.2.3.3 OLT Upstream Packet Analyser

Each GEM frame contains a 5-byte header and GEM payload which is by default, 48-bytes. Although the GPON standards permit longer GEM payload lengths, the simulation only considers lengths of 48 bytes. The port-ID within the header is used to determine the specific traffic stream within the payload.

The received GEM frames are processed and sorted into unique packets according to the port-ID. For each unique stream, the OLT creates a separate array in which to store the packet. Once the complete packet has arrived, the time stamp of the packet is used to calculate the total packet delay. The upstream frame analyser also records the number of utilized and empty bytes for each T-CONT such that the wasted bandwidth and bandwidth efficiency can be calculated. Once the utilization and packet delay for each

packet is recorded the array holding the packet is destroyed. No further processing need occur.

5.2.4 Optical Fibre Module

The optical fibre module consists of two FIFO buffer elements. One holds the downstream frame structures from the OLT, the other holds the upstream frames from the ONU modules. Both the downstream and upstream frames are held as an array of structures in the FIFO buffer. The maximum length of the buffer is calculated by the maximum propagation time, in GPON frames, for the maximum network reach. In our case this is set to 5 GPON frames and 2 GPON frames corresponding to a maximum reach of 100 km and 20 km respectively.

5.2.5 DBA Engine

The DBA engine is the module responsible for allocating bandwidth to the T-CONTs in the ONU modules based on the information in each received DBRu. There are three primary functions of the DBA engine; receive and process the DBRus from the ONU modules, determine the number of bytes to allocate to each T-CONT in the next allocation interval and to assemble the BWmap for each downstream frame. The DBA engine keeps a record of the buffer occupancy of all T-CONTs as each DBRu is received. The number of GEM frames requested in the previous interval and the BWmap from one RTT prior are used by the DBA engine to calculate the Delta-Buffer DBA algorithm as given by (4.13).

The DBA engine allocates the T-CONTs on a priority basis according to the type of T-CONT. Figure 5.3 shows the basic order in which these T-CONTs are allocated. Management, type 1, type 2 T-CONTs and the assured bandwidth component of type 3 T-CONTs are not oversubscribed, therefore the total amount of bandwidth allowed for all of the T-CONTs cannot exceed the total upstream frame capacity [11]. The non-assured components of type 3 T-CONTs and the type 4 T-CONTs are only allocated if sufficient bandwidth remains in the allocation interval. Therefore these can be oversubscribed.

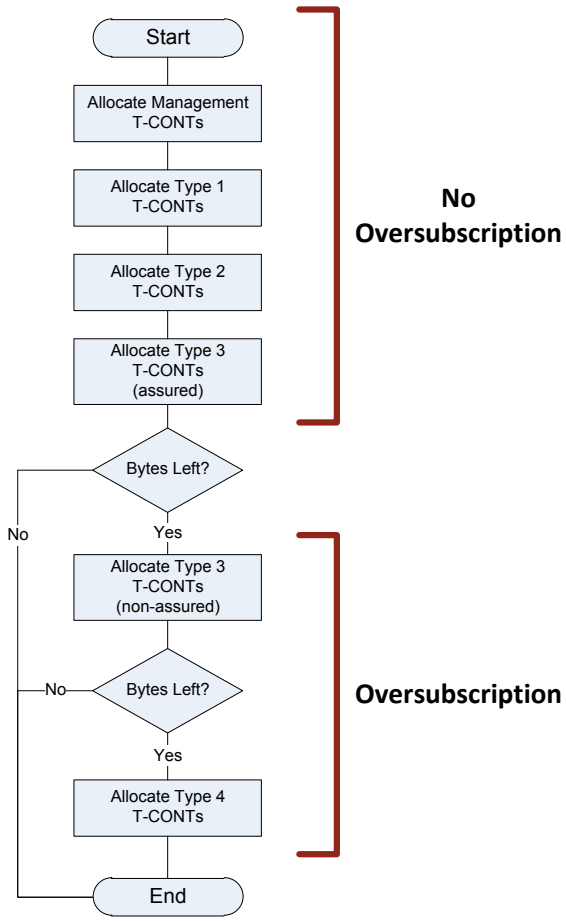

Figure 5.3 – Basic DBA process

In allocating the non-assured bandwidth a min-max scheduling scheme is utilised. A flowchart of this procedure is shown in Figure 5.4 where the number of bytes available for use in the proportional bandwidth for the ith T-CONT is $P_{r,i}$, the requested bytes for the T-CONT is $B_{R,i}$ and the maximum bytes for the T-CONT is $B_{i,\max}^{SLA}$.

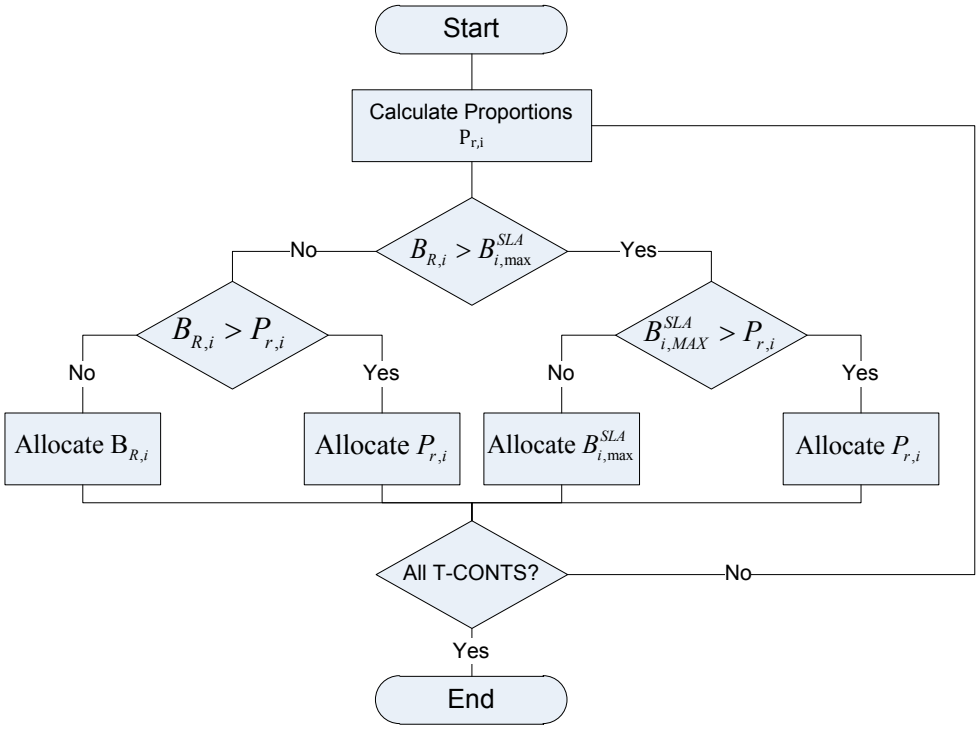

Figure 5.4 – Allocation of non-assured bandwidth according to Min-Max scheduling

The number of bytes for proportional bandwidth for the ith T-CONT is calculated by

$$P_{r,i} = B_{remain} \times W_i \tag{5.1}$$

where B_{remain} is the number of bytes remaining in the allocation interval and W_i is a weighting factor based on the ith T-CONTs maximum bandwidth field and calculated by

$$W_i = \left(\frac{B_{i,\max}^{SLA}}{\sum_{n=1}^{N} B_{n,\max}^{SLA}} \right) \tag{5.2}$$

where $B_{i,\max}^{SLA}$ is the maximum allowable bandwidth for the ith T-CONT and N is the number of remaining T-CONTs of type 3 to be allocated.

By including the weighting factor in the calculation of the bytes for proportional bandwidth, the OLT can allocate higher amounts of bandwidth to higher priority T-CONTs within the same T-CONT type.

5.3 Long Reach Modification

Although the simulator is designed to the GPON standards, some modifications have been made. The most notable of the standard violations is that of the ability for the program to simulate GPON networks with a maximum logical reach of 100 km. The GPON standards only permit a maximum reach of up to 60 km, however the purpose of this thesis it to examine DBA algorithms when implemented in a 100 km reach LR-GPON.

In addition to an extension to the logical reach, the simulator removes the limitations on the differential reach that exist in the GPON standards. The simulation allows a differential reach equal to that of the logical reach, whereas the GPON standards specify that the differential reach can only be a maximum distance of 40 km [16]. The main reason for this violation is to remove any limitation on ONU location as the deployment applications for LR-GPONs may also require increased differential reach.

5.4 Conclusion

In this chapter we have discussed the benefits of network simulation methods and presented an overview of the software simulation package developed for this work. The principle components of the simulation environment have been also described. The purpose of the simulation is to examine the delay, bandwidth and throughput behaviour of upstream packets under various conditions, packet types and DBA algorithms. By developing a custom purpose simulation package, the key performance parameters in GPON and LR-GPON such packet delay, framing and bandwidth efficiency can be investigated.

The simulator has been designed in accordance with the GPON standards and allows the analysis of various parameters related to the upstream traffic. By eliminating the unrequired layers, additional processing operations can be eliminated for aspects of the GPON that are either not required or do not affect the aspects of particular interest. Additional modifications have also been designed into the simulator to enable it to simulate the GPON under long-reach conditions. While the use of amplification or repeater technology may be required for actual LR-GPONs to be deployed, the simulation does not include such methods.

In the following chapter we will use the simulation to analyse the steady-state, or averaged, packet delay and ONU/T-CONT bandwidth behaviour when the DBA algorithms from Chapter 3 and Chapter 4 are used in conjunction with the DBA mechanism defined by the GPON standards. In Chapter 7 we will use the simulation environment to simulate the transient response under various injected packet situations to analyse the delay and jitter behaviour.

6 Steady-state Delay and Bandwidth Efficiency

6.1 Introduction

In the previous chapter we described the simulations designed to assess the packet delay and bandwidth efficiency parameters of DBA algorithms in GPON and long-reach GPON (LR-GPON). The same simulations are used in this chapter to obtain the steady-state results and long-term averages of these parameters so we can gain an understanding of how the DBA algorithms we have proposed perform under varying conditions and long-reach applications. We use simulations to record the upstream packet delay over a pre-set network run time to determine how the packet delay varies as the amount of injected customer traffic increases or changes. The long-term average results are presented as this is the most widely accepted method of publishing DBA results in the literature [19, 25, 37, 44, 55, 67, 68, 73, 79]. In Chapter 2 we discussed various PON DBA literature and the majority of these use the long-term average delay results to validate the proposed DBA algorithms. While the average delay has become a common metric for comparing DBA algorithms, we will show that the length of the simulation, and consequently the number of values within the data set, can impact the assessment of the algorithms.

In this chapter we simulate both GPON and LR-GPON using the DBA mechanisms defined in the model presented in Chapter 3. The principle focus of this thesis is on DBA algorithms for LR-GPON, for 20 km reach GPON we restrict consideration to the Reduced-Interval and Delta-Buffer DBA algorithms (developed in Chapter 4) and only analyse best-effort traffic (using a single type 4 T-CONT). For 100 km reach LR-GPON we simulate the network using all the DBA algorithms from Chapter 3 and Chapter 4. We also analyse the network behaviour when varying categories of customer traffic is injected with varying priorities using multiple types of T-CONTs. The relationship between the traffic category and priority to the type of T-CONTs used was discussed in Chapter 5.

The long-term average results are presented as a function of the total network load which we defined in Chapter 3 as the sum of the injected traffic divided by the sum of the total upstream frame capacity. By studying the long-term average results, an estimation of the expected delay can be obtained, given a particular traffic category and network load, by averaging the delay of all packets received over the simulation.

6.2 Average Delay and Bandwidth Efficiency of 20 km GPON

The GPON used in the simulation considered in this section has a maximum reach of 20 km corresponding to the original standardized differential reach limit of 20 km [10, 11]. To simulate the delay and bandwidth efficiency behaviour for 20 km reach GPON we inject 30,000 packets of simulated TCP-IP traffic into each ONU over time. The resulting upstream packet delay for each packet is recorded along with the bandwidth efficiency. The simulation is run until the first ONU has transmitted 30,000 packets. Once this occurs, the resulting delay, bandwidth efficiency and network load parameters are saved and the target load of each TCP-IP traffic stream is increased. The simulation is then repeated until the network load over the course of a simulation run is ≥ 1.5.

6.2.1 Average Packet Delay

Figure 6.1 shows the average packet delay over network load for a 20 km reach GPON with only TCP-IP traffic injected into 32 ONUs. Three DBA algorithms are used; $t_c = 3t_F$, (RTT-Based DBA) $t_c = t_F$ (Reduced-Interval DBA) and the Delta-Buffer algorithm also with $t_c = t_F$.

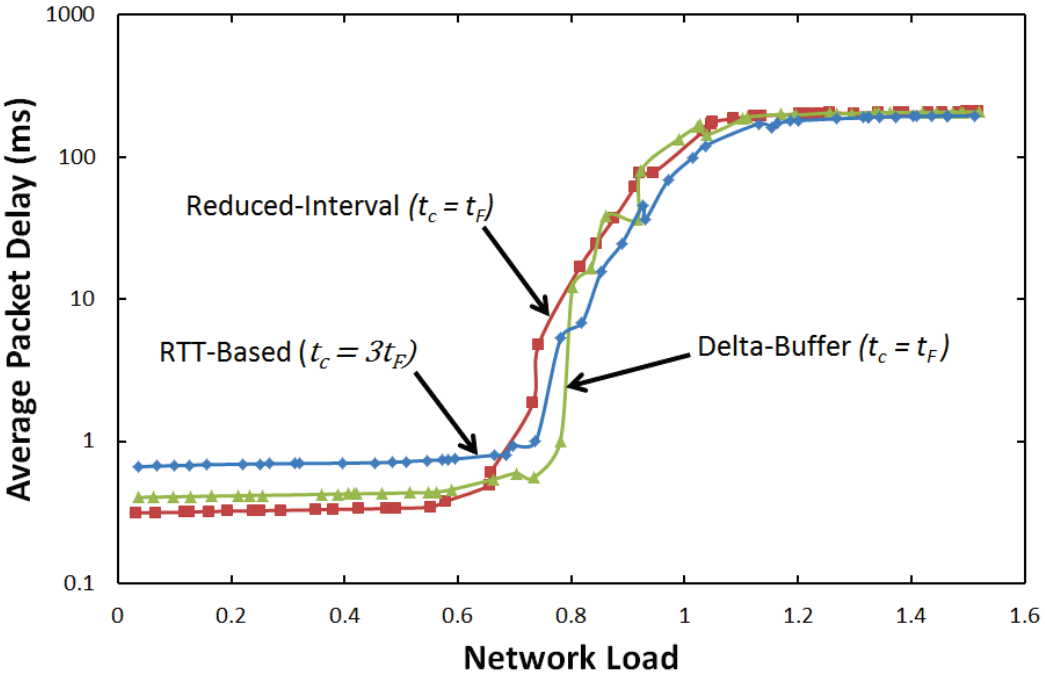

Figure 6.1 – Average TCP-IP packet delay for 20 km GPON with the RTT-Based DBA, Reduced-Interval DBA and the Delta-Buffer DBA algorithms

We can see from Figure 6.1 that all curves display three distinct characteristics as the network load increases. Below a network load of approximately 0.6 the average packet delay marginally increases with network load. Between network loads of 0.6 to 1.1 the increase in average delay becomes greater and above a network load of 1.1 the average delay converges to a common value. We denote these three regions as pre-congestion, transition and saturation respectively.

We define network congestion as the situation when the total bandwidth requests in a single allocation interval exceed the total GPON frame capacity, less any overheads. We define saturation as being when the total injected traffic equals the total upstream frame capacity over the simulation run time. At saturation, the network load is 1.0. By this definition, congestion can occur well before saturation because the injected traffic is dynamic and exhibits bursty characteristics [51]. When congestion begins to occur, in some intervals certain packets cannot be transmitted upstream in the corresponding allocation and must be buffered. The result is an increase in the delay for these packets which contributes to an increased average packet delay. The transition region is where congestion begins to occur, however over the duration of the simulation run time the total injected traffic is less than the total upstream frame capacity. During this region

the dynamics of the injected traffic produce fluctuations in the average delay as is evident from all curves in Figure 6.1. We can also see that the average delay of the Delta-Buffer DBA in the transition region quickly exceeds the average delay of the RTT-Based DBA above a network load of 0.8. This is because the duration of the allocation interval, t_c, is less than that of the RTT-Based DBA, resulting in less available bandwidth per interval due to the bandwidth overheads. This means that compared to the Reduced-Interval DBA, less injected customer traffic bytes are transmitted per GPON frame, thereby increasing the average delay.

In the pre-congestion region the increase in average delay for each DBA algorithm in Figure 6.1 for increasing network load is minimal. This increase in average packet delay occurs due to some packets being transmitted during later sections of the allocation interval. The upstream channel in GPON is a single channel whereby only one ONU can transmit at any given time [10]. In the previous chapter we described how the OLT in the simulations compiles the BWmap according to the allocation order. As the number of packets required to be transmitted upstream in any given allocation interval increases, the instantaneous packet delay for ONUs allocated later in the allocation interval increases. This effect is depicted in Figure 6.2.

Figure 6.2 (a) shows the distribution of upstream bursts in an allocation interval for low network load. All *N* ONUs transmit within the earlier portion of the allocation interval. Figure 6.2 (b) shows the same *N* ONUs transmitting upstream bursts, however the increased length of each burst due to an increase in network load requires more time to transmit all *N* bursts. The overall result is that the average packet delay for the load in Figure 6.2 (b) will be greater than for the load Figure 6.2 (a).

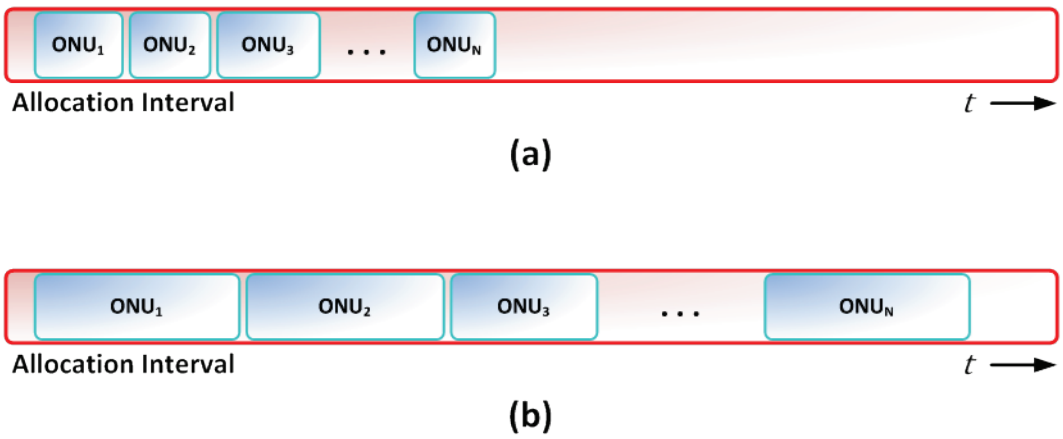

Figure 6.2 – Distribution of ONUs upstream bursts during a single allocation interval for (a) low network load and (b) higher network load.

When we examine the individual curves in Figure 6.1, the average packet delay in the pre-congestion region varies between algorithms. The RTT-Based DBA algorithm, having the largest allocation interval, exhibits the highest average packet delay which is consistent with (3.11). The Reduced-Interval algorithm produces the lowest average packet delay in the pre-congestion region. From (3.19), the minimum buffering delay for a packet that is requested in a DBRu is still equal to the RTT of the network. What (3.19) does not take into account are packets that are transmitted prior to being requested. As we showed in Chapter 3, when $t_c < RTT$ the presence of some packets is requested multiple times leading to excessive bandwidth allocations. These allocations can exceed the actual traffic requirements and allow additional packets to be transmitted with lower delay. The Delta-Buffer DBA algorithm displays higher average delay in this region than the Reduced-Interval algorithm but lower delay than the RTT-Based DBA algorithm. This is because no excessive allocations occur that allow packets to be transmitted prior to being requested, and the duration of the allocation interval is kept to a minimum thus preventing portions of the allocation interval being unused.

Figure 6.1 also shows that there is a slight variation in the network load at which network congestion begins to occur for all three algorithms. The excessive allocations produced using the Reduced-Interval algorithm result in bandwidth being deprived of some ONUs during some allocation intervals. The result is that congestion begins to occur at a lower network load in comparison with the other algorithms. Congestion begins to occur at a later value of network load for the RTT-Based DBA and the Delta-Buffer algorithms. This is because these algorithms do not produce any excessive allocations.

In the saturation region the buffer occupancy increases until full at which point any incoming packets are dropped. The result is that the average delay approaches a maximum value at which all curves in Figure 6.1 converge. As the injected traffic is dynamic and varies from one ONU to another, the rate at which the buffers fill may vary across the ONUs. This results in some fluctuation in the average delay, however as the network load increases, these fluctuations decrease as all buffers reach maximum occupancy and some packets are dropped rather than transmitted.

The maximum average delay is determined by the size of each T-CONT buffer, the buffer egress rate and the propagation delay. The buffer size is independent of these two factors and the saturation egress rate at time Mt_c, $T_{e,n}(Mt_c)$, is given by

$$T_{e,n}\left(Mt_c\right)=\frac{B_{A,n}\left(Mt_c\right)}{t_c} \tag{6.1}$$

The SLAs for all ONUs, n, are identical, and the saturation condition dictates that the injected customer traffic bytes of all ONUs approaches a value greater than allocated bandwidth. Therefore $B_{A,n}(Mt_c)$ goes to

$$B_{A,n}\left(Mt_c\right)\rightarrow\frac{B_{PON}^{\max}\left(Mt_c\right)-B_{A,n}^{\zeta}}{N},\quad \forall n \tag{6.2}$$

where $B_{PON}^{\max}\left(Mt_c\right)$, defined in (3.8), is the maximum number of bytes available to be allocated in the Mth allocation interval, $B_{A,n}^{\zeta}$ is the number of bytes allocated to higher priority T-CONTs and N is the number of ONUs on the network. From (6.2) we can see that the number of bytes allocated to each ONU approaches a constant value because both $B_{PON}^{\max}\left(Mt_c\right)$ and $B_{A,n}^{\zeta}$ are constant. This implies that the egress rate approaches the same constant value for all ONUs. With a default GEM frame size of 53 bytes, the maximum buffer size of each ONU is 999,951 bytes. Using (3.11), the maximum buffering delay for the RTT-Based DBA algorithm can be calculated. Using (3.19) the maximum buffering delay for the RTT-Based DBA and the Delta-Buffer DBA can be calculated. Equation (3.12) can then be used to calculate the maximum packet delay. The calculated and simulated maximum delays for 20 km reach GPON are given in Table 6.1 which shows that there is little difference between the calculated and simulated values.

Table 6.1: Calculated and Simulated Maximum Packet Delays for 20 km GPON with TCP-IP traffic.

Algorithm	Calculated Maximum Delay	Simulated Maximum Delay
RTT-Based DBA	212 ms	214 ms
Reduced-interval DBA	236 ms	235 ms
Delta-Buffer DBA	236 ms	235 ms

6.2.2 Average Wasted Bandwidth

The average wasted bandwidth as a function of network load for the DBA algorithms defined in section 6.2.1 is shown in Figure 6.3. Two vertical axes have been used because the average wasted bandwidth produced by the Delta-Buffer DBA and RTT-Based DBA algorithms is significantly less than the Reduced-Interval algorithm.

All curves in Figure 6.3 show similar characteristics. Prior to network saturation, each DBA algorithm produces a region of increasing and decreasing wasted bandwidth. At a network load close to, and above, network saturation, all curves produce minimal wasted bandwidth. The shape of these wasted bandwidth curves is consistent with the simulation results in Chapter 4.

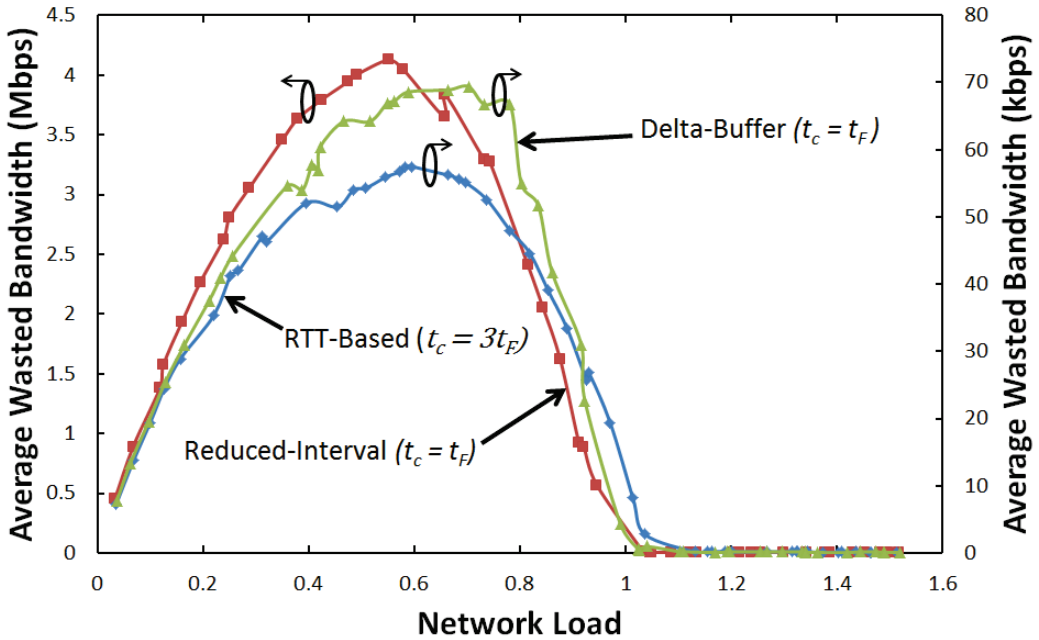

Figure 6.3 – Average TCP-IP wasted bandwidth for 20 km GPON with $t_c = 3t_F$, $t_c = t_F$, and the Delta-Buffer DBA algorithms.

When the injected traffic, $\int_{Mt_c}^{(M+1)t_c} T_n(\rho)\, d\rho$, is less than the maximum allowable allocated bandwidth, $B_{A,n}(M.t_c)$, the service level agreements (SLAs) are said to be satisfied. We showed that using this assumption, as given by (3.22), the wasted bandwidth produced by the RTT-Based DBA algorithm was zero. When this assumption was removed, the wasted bandwidth was still zero. Figure 6.3 shows that the RTT-Based DBA produces positive wasted bandwidth. In Chapter 3 we assumed that the exact

number of customer bytes injected into the ONU was allocated by the OLT in the corresponding BWmap. In the GPON standards the ONU compiles the DBRu according to the number of completely, or partially, filled GEM frames [11]. To generate the simulated results in Figure 6.3 the traffic generator, as described in Chapter 5, injects variable size packets. In some allocation intervals the number of injected customer traffic bytes does not equal an exact multiple of the default GEM frame size (48 bytes). When these GEM frames are received at the OLT, any portions of a partially filled GEM frame are included in the wasted bandwidth. This results in positive wasted bandwidth for the RTT-Based DBA. The same argument also holds true for the Delta-Buffer DBA algorithm. We can also see from Figure 6.3 that the Delta-Buffer algorithm produces more wasted bandwidth than the RTT-Based DBA algorithm. This is because the duration of the allocation interval in the Delta-Buffer algorithm is lower resulting in fewer packets buffered before being transmitted upstream. The longer duration of the allocation interval means that more customer packets can be buffered thereby providing a higher GEM frame utilization than the Delta-Buffer algorithm.

The shape of the wasted bandwidth of the curves in Figure 6.3 for RTT-Based DBA and the Delta-Buffer DBA algorithms is understood by noting that the number of customer traffic bytes injected into each T-CONT increases as the network load increases. As previously discussed, some of these GEM frames are only partially filled with injected customer bytes. As the network load increases, due to an increased amount of injected customer bytes, the number of partially filled GEM frames also increases thereby increasing the amount of wasted bandwidth. When the network load reaches 0.7, corresponding to the transition region the wasted bandwidth produced by both the RTT-Based DBA and the Delta-Buffer DBA algorithms in Figure 6.3 begins to decrease. This is due to the increased injection of subscriber traffic resulting in fewer partially-filled GEM frames, thereby reducing the wasted bandwidth.

The average wasted bandwidth for the Reduced-Interval algorithm is significantly higher than the other two DBA algorithms. In Chapter 3 we defined the reduced-interval waste effect, as indicated by (3.32). This effect can clearly be seen in Figure 6.3 as the ONU must transmit empty, or null, GEM frames if the buffer is empty but allocations are still received [11].

6.3 Average Delay and bandwidth efficiency of 100 km GPON

As the length of the GPON is increased, not only does the propagation delay of a customer packet increase, as shown in Chapters 3 & 4, the increase in reach also affects the DBA mechanism. We also showed in Chapter 3 that the RTT plays a fundamental role in determining the minimum delay for a packet that has been requested via a DBRu. With a 100 km reach LR-GPON, the increase in RTT will therefore not only increase the propagation delay of the injected customer packets, but also that of the DBRu and BWmap components of the DBA mechanism.

To understand the effect of increased reach on traffic with varying priorities, we use simulations with the maximum distance set to 100 km. We begin by using the simulation with only TCP-IP traffic in order to understand how increasing the reach of the GPON impacts the average upstream customer packet delay.

6.3.1 100 km LR-GPON with Best Effort Traffic

For an LR-GPON with only TCP-IP traffic, we assume that the SLAs for all 32 ONUs are identical. We follow the same simulation conditions used for the 20 km GPON by injecting 30,000 customer packets per ONU over time. When the first ONU has transmitted 30,000 packets the delay, load and bandwidth efficiency results are saved, the target load of each ONU TCP-IP traffic stream is then increased and the simulation repeats. Again, we continue this procedure until the average network load is greater, or equal, to 1.5.

6.3.1.1 Average Packet Delay

Figure 6.4 shows the average packet delay as a function of network load for a 100 km LR-GPON using the Delta-Buffer DBA algorithm as well as the RTT-Based and Reduced-Interval DBA algorithms. For 100km reach $t_c = 10t_F$ for the RTT-Based DBA algorithm. We can see from Figure 6.4 that the average delay curves for all three DBA algorithms follow the same characteristics observed in the 20 km GPON, as shown in Figure 6.1.

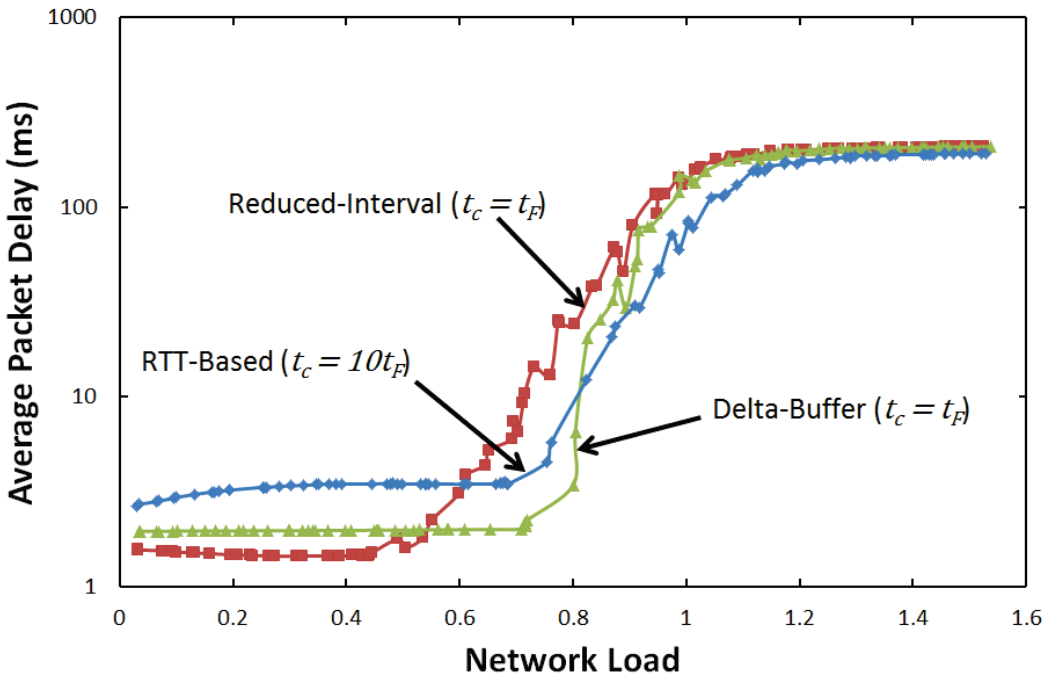

Figure 6.4 – Average TCP-IP packet delay for 100 km LR-GPON with $t_c = 10t_F$, $t_c = t_F$, and the Delta-Buffer DBA algorithms

During the pre-congestion region, the RTT-Based DBA clearly displays higher average packet delay than both the Reduced-Interval and the Delta-Buffer DBA. During this region the average packet delay for the RTT-Based DBA actually displays a notable increase in average delay whereas this is not observed for the 20 km GPON and occurs due to the increased length of the allocation interval. With low densities of injected customer traffic, much of the longer allocation interval is unused thereby increasing the arrival delay for some newly arrived packets. As the amount of injected traffic increases, the utilization of the allocation interval increases hence the average delay plateaus in the pre-congestion region.

The average delay produced by the Reduced-Interval DBA in the pre-congestion region is lower than both the RTT-Based DBA and the Delta-Buffer DBA. We also can see the average delay decreases slightly in this region as the network load increases. This is due to the reduced-interval waste effect increasing the allocations thereby allowing more packets to be transmitted. As in the case of 20 km GPON, the transition region for the Reduced-Interval DBA in 100 km LR-GPON occurs at a lower network load than that of either the RTT-Based DBA or Delta-Buffer DBA algorithms. This is due to the wasted bandwidth allocated to some ONUs depriving other ONUs of required bandwidth

thereby increasing their packet delay. For the 100 km LR-GPON the transition region occurs at a considerably earlier network load as compared to the 20 km GPON.

During the pre-congestion region of the Delta-Buffer DBA, we can see that from Figure 6.4 the average delay is quite uniform but higher than the Reduced-Interval DBA and lower than that of the RTT-Based DBA. Only in the transition region does a change in the average delay begin to occur for the Delta-Buffer DBA algorithm.

There is also some variation in the average delay in the transition regions of the three DBA algorithms in Figure 6.4. This is because the random nature of the injected traffic results in slightly different values for the long-term average delay. We can also see that in the transition region the average delay for the Delta-Buffer DBA algorithm exceeds the average delay for the RTT-Based DBA algorithm. This is due to the reduced allocation interval resulting in additional overheads thereby reducing the available traffic bandwidth. The average delay of the Delta-Buffer DBA algorithm also converges to that of the Reduced-Interval DBA algorithm in the saturation region.

The average delay of the RTT-Based DBA algorithm in saturation region approaches a maximum value that is slightly less that for the Reduced-Interval DBA and Delta-Buffer DBA algorithms. This is because there are less overheads consuming bandwidth in the case of the RTT-Based DBA.

Table 6.2 shows the calculated and simulated values for the maximum delay using the same buffer size as in section 6.2.1 and a 100 km network reach.

Table 6.2: Calculated and Simulated Maximum Packet Delays for 100 km LR-GPON with TCP-IP traffic.

Algorithm	Calculated Maximum Delay	Simulated Maximum Delay
RTT-Based DBA	208 ms	210 ms
Reduced-interval DBA	236 ms	236 ms
Delta-Buffer DBA	236 ms	236 ms

As for the 20 km network, the calculated values and simulated values are very similar.

6.3.1.2 Average Wasted Bandwidth

The average wasted bandwidth over network load for the RTT-Based DBA, the Reduced-Interval DBA and the Delta-Buffer DBA algorithms are shown in Figure 6.5. As with Figure 6.3, two vertical axes are used to display the average wasted bandwidth as the Reduced-Interval DBA produces large amounts of wasted bandwidth.

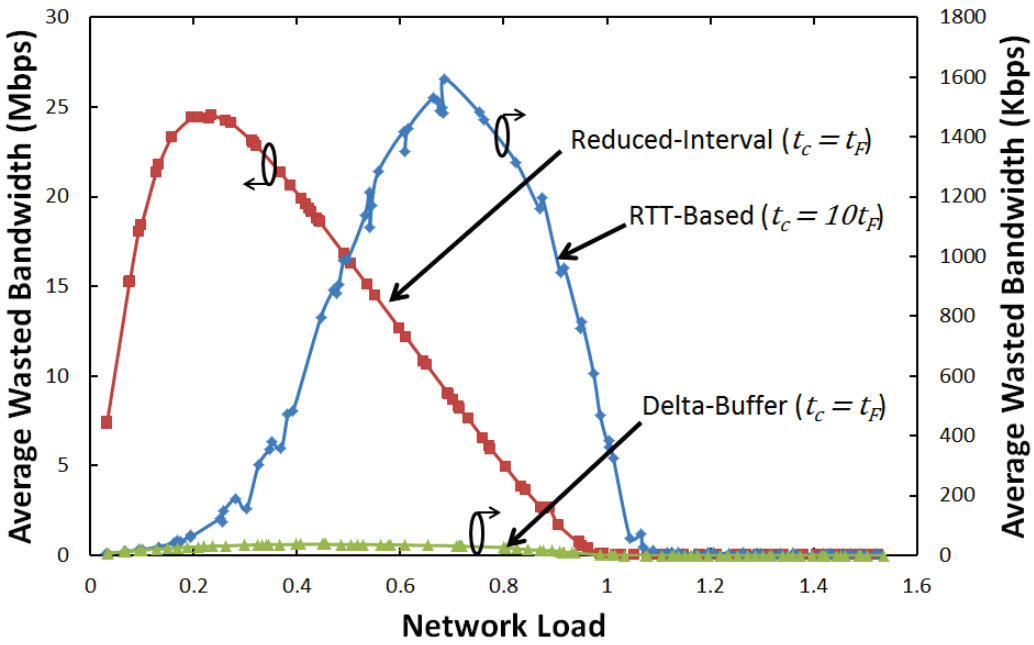

Figure 6.5 – Average TCP-IP wasted bandwidth for 100 km LR-GPON with $t_c = 3t_F$, $t_c = t_F$, and the Delta-Buffer DBA algorithms.

At a network load of 0.2 the average customer traffic bandwidth, per ONU is approximately 6.5 Mbps. However Figure 6.5 shows that for the Reduced-Interval DBA algorithm the average wasted bandwidth is in almost 25 Mbps. This is a direct result of the reduced-interval waste effect as described in (3.32). The peak wasted bandwidth produced by the Reduced-Interval DBA exceeds the customer traffic rate by almost a factor of 4.0. As the network load increases, the average wasted bandwidth produced by the Reduced-Interval DBA decreases towards zero as the SLAs begin to limit the allocations.

From Figure 6.5 we can see that positive wasted bandwidth is produced for the RTT-Based DBA with a peak occurring at a network load of 0.7. This value of network load correlates to the beginning of the transition region as is evident from Figure 6.4. We can also see that the peak average wasted bandwidth produced by the RTT-Based DBA in

Figure 6.5 is significantly higher than that shown in Figure 6.3 for a 20 km GPON. This is because although the RTT-Based DBA algorithm only allocates each ONU once per allocation interval, t_c, the nature of the BWmap compilation means that in some situations the time between allocations to one ONU across two consecutive intervals may be less than the RTT. Figure 6.6 shows two consecutive allocation intervals with allocations to ONUs distributed throughout the intervals.

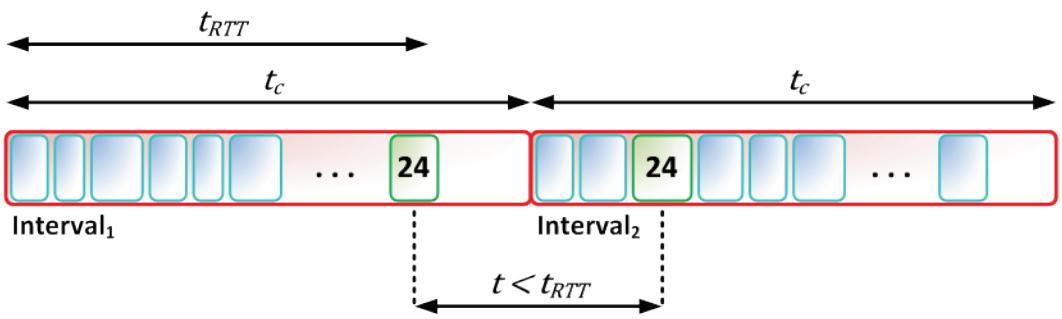

Figure 6.6 – Allocations for ONUs with $t_c > RTT$.

The allocation to a specific ONU, in this case ONU #24, is marked at two different locations in each interval, t_c. Although the duration of the allocation interval is greater than t_{RTT}, we can see that the nature of the BWmap compilation results in the time between the two allocations to ONU #24 being less than the RTT. We refer to this time as the *allocation time differential*. In this situation the DBRu transmitted by this ONU in the first interval will not have been processed by the OLT prior to compiling the BWmap for the second interval. As a result, the DBRu transmitted by the ONU in the second interval will re-request bandwidth already requested in the first interval giving rise to the reduced-interval waste effect that was discussed in Chapter 3. The time between allocations to a specific ONU is determined by the duration of the allocation interval and the number of allocations present within the BWmap. Due to the statistical nature of the injected customer traffic, in some instances, the allocation time differential of the same ONU may be less that the RTT and consequently wasted bandwidth will occur.

In Chapter 4 we showed that the wasted bandwidth produced by the Delta-Buffer DBA algorithm should be zero, however positive wasted bandwidth is produced by the Delta-Buffer DBA algorithm as can be seen in Figure 6.5. The average wasted bandwidth is extremely low because only the required bandwidth is allocated each interval. Although the allocation time differential is less than the RTT, the very nature of the Delta-Buffer

DBA algorithm eliminates the reduced-interval waste effect. The only wasted bandwidth produced by the Delta-Buffer DBA algorithm is due to the injected customer traffic not being an exact multiple of the GEM frame length thereby resulting in some GEM frames being under-utilized.

Figure 6.4 shows that the Reduced-Interval DBA produces the lowest average delay in the pre-congestion region; however from Figure 6.5 the wasted bandwidth produced by this algorithm can far exceed the injected customer traffic rate. The RTT-Based DBA algorithm produces the highest average delay in the same region; however the wasted bandwidth is significantly less than that of the Reduced-Interval DBA. The Delta-Buffer DBA algorithm produces lower average delay than that of the RTT-Based DBA, but slightly higher average delay than the Reduced-Interval DBA. The use of the Delta-Buffer DBA results in minimal wasted bandwidth and therefore can be considered the most bandwidth efficient DBA algorithm.

6.3.1.3 Allocation Reduction

In Chapter 4 we proposed a DBA algorithm whereby the OLT reduced the allocated bandwidth to each ONU using a reduction factor. This algorithm allows the OLT to allocate a portion of the requested bytes in each DBRu which results in less wasted bandwidth as described in (4.6). Recall that the bytes allocated to an ONU using the allocation reduction algorithm is given by

$$B_{A,n}\left(M.RTT\right)' = B_{B,n}\left(\left(M-1\right)RTT\right)\times\frac{1}{\delta_{e,n}\left(W\right)} \qquad (6.3)$$
$$\delta_{e,n}\left(W\right)\geq 1$$

where $\delta_{e,n}(W)$ is the reduction factor and is greater than 1.0.

The simulated upstream packet delay for the Reduced-Interval DBA using the reduction factor, $\delta_{e,n}(W)$, is shown in Figure 6.7. Reduction values of $\delta_{e,n}(W)$ = 1, 2, 3, 4, 5 & 10 are used in the simulation and an enlargement of the delay during a section of the pre-congestion region is shown as an inset. The duration of the allocation interval for all cases of $\delta_{e,n}(W)$ is set to 1 GPON frame. The $\delta_{e,n}(W)$ = 1 curve in Figure 6.7 is generated from the same data as that of the Reduced-Interval DBA curve in Figure 6.4.

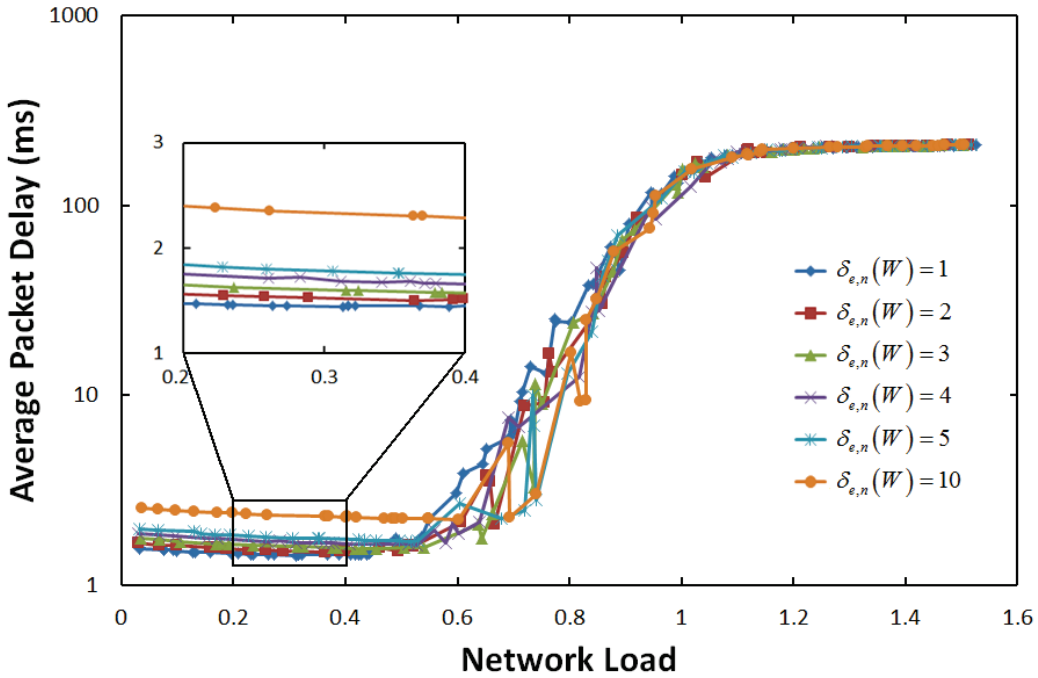

Figure 6.7 – Average packet delay against network load for $\delta_{e,n}(W)$=1, 2, 3, 4, 5 & 10.

From the inset in Figure 6.7 we can see that, during the pre-congestion region, as the allocation reduction value increases, so too does the average packet delay. Equation (4.5) shows that as the reduction factor, $\delta_{e,n}(W)$, increases the allocated bandwidth decreases and the average packet delay, being inversely proportional to the allocated bandwidth, will therefore increase. We can therefore conclude that the average delay, during the pre-congestion region, is proportional to the reduction factor, $\delta_{e,n}(W)$.

In the post-saturation region, all curves in Figure 6.7 converge to the same maximum average delay value. In all three regions, the average delay is still dependent on the number of bytes allocated by the OLT. In the pre-congestion region the allocations are mainly determined by the relationship between the requested bytes and the reduction factor, $\delta_{e,n}(W)$. In the post-saturation region the number of bytes requested in a DBRu exceeds the maximum window set by the SLA, therefore the SLA defines the relationship. As all ONUs have the same maximum window across all curves in Figure 6.7, it is clear that all curves will converge to the same maximum delay value.

The objective of the allocation reduction DBA algorithm was to reduce the wasted bandwidth produced by the Reduced-Interval DBA algorithm. We showed in (4.6) that the number of wasted bytes was inversely proportional to the reduction factor $\delta_{e,n}(W)$. The average wasted bandwidth over network load for the Reduced-Interval DBA algorithm using a reduction factor of 1,2,3,4,5 & 10 is shown in Figure 6.8.

From Figure 6.8, each curve displays a peak wasted bandwidth which then decreases towards zero as the network load increases. The amount of wasted bandwidth decreases as $\delta_{e,n}(W)$ increases as described in (4.6). The network load at which the peak wasted bandwidth occurs also increases as $\delta_{e,n}(W)$ increases. The variation in peak wasted bandwidth is due to the varying network load at which the *apparent* network saturation occurs, as discussed in Chapter 4.

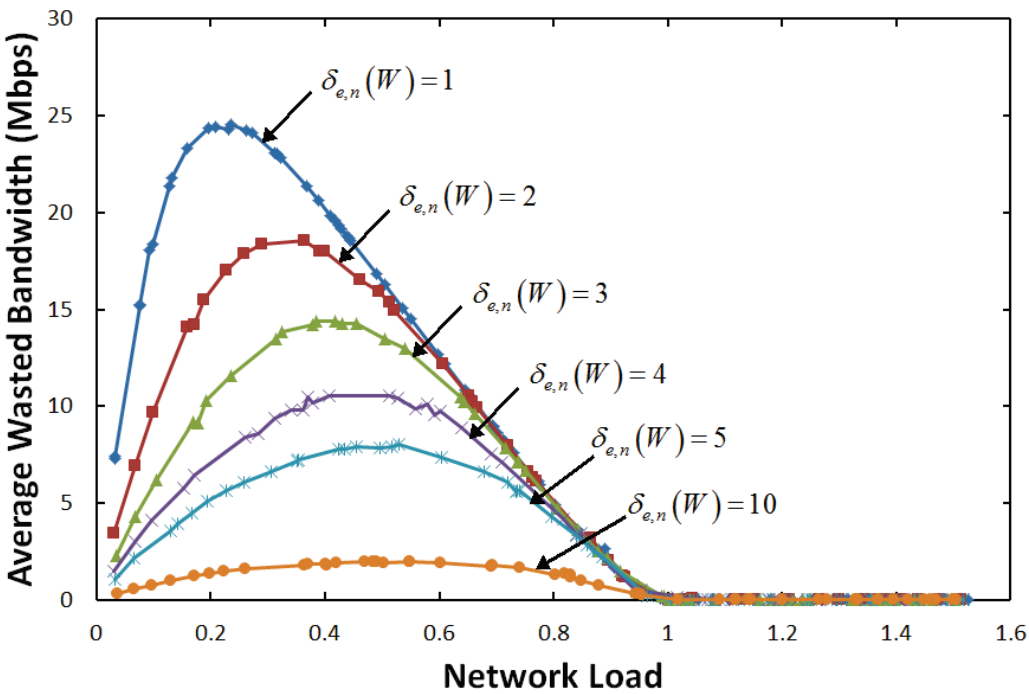

Figure 6.8 – Average wasted bandwidth against network load for $\delta_{e,n}(W)$=1, 2, 3, 4, 5 & 10.

Figure 6.8 shows that the greater the value of the reduction factor, $\delta_{e,n}(W)$, the greater the value of network load at which the *apparent* network saturation occurs and the lower the average wasted bandwidth. We can therefore conclude that the allocation reduction DBA is indeed effective at reducing the wasted bandwidth. When we consider the effect that $\delta_{e,n}(W)$ has on the average packet delay, Figure 6.7 shows that the

greater the reduction factor, higher average delay during the pre-congestion region. Although a larger delay is observed over $\delta_{e,n}(W)$, this increase in average delay is only in the order of a few ms.

We will now examine the average packet delay of a 100 km LR-GPON when multiple categories of customer traffic with varying priorities is injected in the ONUs.

6.3.2 100 km LR-GPON with Varying Traffic Priorities

ITU-T GPON was standardized to facilitate the transport of multiple traffic categories with varying priorities. The use of T-CONTs in the upstream direction allows for QoS support as each T-CONT can be allocated with different priority according to the traffic category. Coupled with GEM fragmentation, a GPON can transport customer packets of any category thereby providing improved network performance over that of EPON [87]. In this section, we examine the average packet delay of an LR-GPON when six customer traffic categories are injected into the ONUs. In Chapter 5 we discussed these traffic categories and the associated T-CONT types that transport the upstream packets.

To obtain the average delay results with multiple traffic categories in the network, we only consider the impact on the network when the injected rate of traffic using type 3 and type 4 T-CONTs is increased. This is because in order to provide oversubscription the maximum allowable bandwidth for these T-CONT types exceeds the available GPON bandwidth. We do not investigate the impact when traffic using type 2 T-CONTs is increased as these T-CONT types are not oversubscribed. We also do not consider the effect on wasted bandwidth or bandwidth efficiency as this was examined directly in the previous sections of this chapter.

6.3.2.1 Type 3 T-CONTs

We examine the packet delay when category 3 traffic, such as HD Gaming, dominates the network by configuring the network simulator to inject a single stream of all six categories of traffic into each ONU. The injected rate of the HD Gaming traffic into each ONU is increased in 1.0 Mbps increments until the average network load exceeds 1.5. As

stated previously, we do not increase or alter the allowable bandwidth rates at the OLT to account for the additional injected customer traffic bytes.

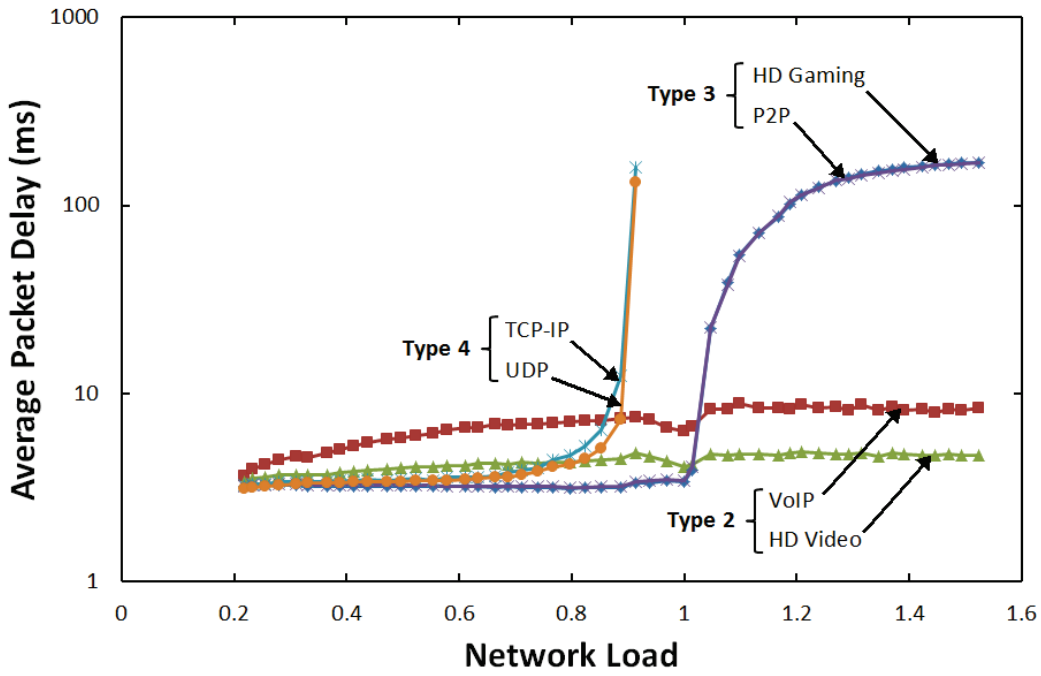

Figure 6.9 – Average packet delay for 100 km LR-GPON using RTT-Based DBA with $t_c = 10t_F$, various traffic categories and HD Gaming traffic as input variable.

Figure 6.9 shows the average packet delay for all six traffic categories when the RTT-Based DBA algorithm is used in a 100 km LR-GPON and the injection rate of the HD Gaming traffic is increased. We can see that no congestion occurs for type 2 traffic (VoIP and HD Video). This is because this traffic is treated with the highest priority and, because the injection rate of this traffic category does not increase, the requested bandwidth does not exceed its allowable bandwidth. Although Type 2 T-CONTs have been treated with the highest priority, from Figure 6.9 we can see that both the VoIP and HD Video traffic experience the highest average traffic delay below a network load of 0.8. This is because, unlike the self-similar traffic packets, the packets for Type 2 T-CONTs are not injected as often. This increases the average traffic arrival waiting time and consequently the total average delay. Although the average packet delays for both VoIP and HD Video traffic display the same characteristics, the average delay for VoIP is higher than that of the HD Video as the VoIP packets are injected less frequently than the HD Video packets.

Type 4 T-CONTs are only allocated should sufficient bandwidth remain and we can see in Figure 6.9 that at a network load of approximately 0.9 the average packet delay for traffic in the Type 4 T-CONTs dramatically increases. This is because the combined bandwidth requirements for the higher priority traffic results in insufficient available bandwidth for Type 4 T-CONTs. Although the average delay obtained from the simulation results continues to increase, it is not shown in Figure 6.9 as eventually the available bandwidth for Type 4 T-CONTs drops below the minimum amount required to transmit complete GEM frames. Once this occurs, no traffic in Type 4 T-CONTs can be transmitted and the delay approaches infinity. Once no available bandwidth is allocated to Type 4 T-CONTs, a small increase in available bandwidth for higher priority traffic occurs, thereby reducing the average packet delay. This effect can be seen in Figure 6.9 just below a network load of 1.0. As the injection rate of the HD Gaming traffic increases, we can see that from Figure 6.9 the average delay of traffic in Type 3 T-CONTs increases and approaches a maximum delay value.

Figure 6.10 shows the average packet delay for all six traffic categories when the Reduced-Interval DBA algorithm is used in a 100 km LR-GPON and the injection rate of the HD Gaming traffic (Type 3) is increased. We can see that the average delay for Type 4 T-CONT traffic increases at very low network loads due to the wasted bandwidth produced by the Reduced-Interval DBA algorithm.

The average delay for Type 2 T-CONT traffic remains very similar regardless of network load as the wasted bandwidth allows the ONUs to transmit this traffic with minimal buffering delay. The transition region of traffic in Type 3 T-CONTs does not occur until a network load of just above 0.8. At this load the injection rate begins to exceed the allowable bandwidth, including the wasted bandwidth.

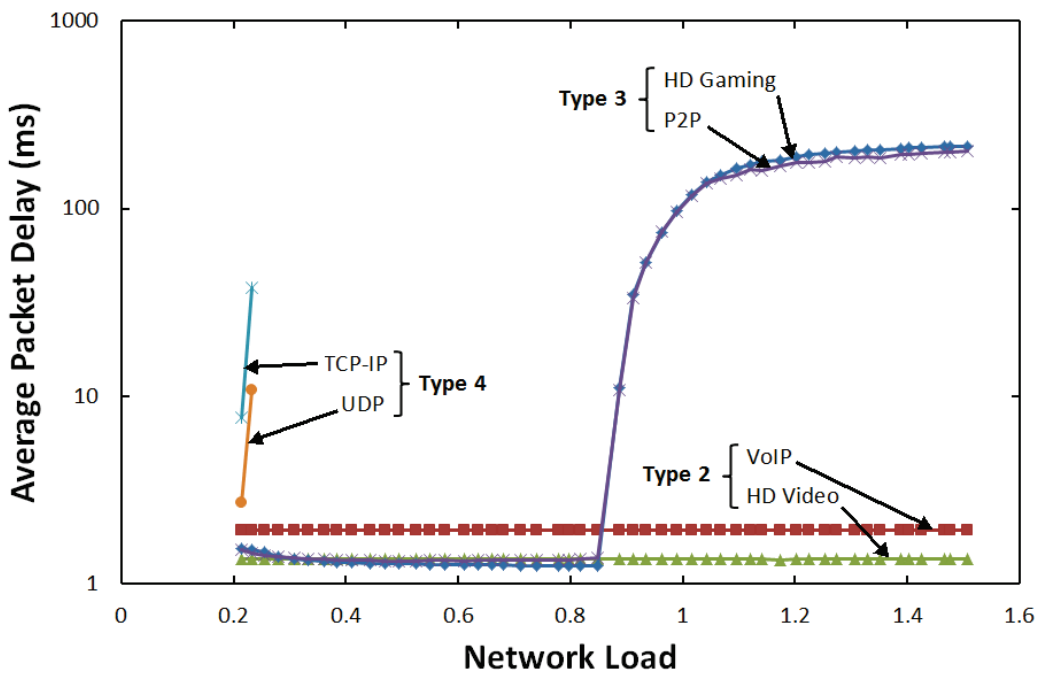

Figure 6.10 – Average packet delay for 100 km LR-GPON using Reduced-Interval DBA with $t_c = t_F$, various traffic categories and HD Gaming traffic as input variable.

From Figure 6.10 we can see that Type 4 T-CONT traffic cannot be accommodated in the network when the Reduced-Interval DBA algorithm is used. The average delay for higher priority traffic is considerably lower than when the RTT-Based DBA algorithm is used due to the wasted bandwidth produced by the Reduced-Interval DBA algorithm. VoIP traffic displays the highest average delay due which is again to the low injection rate of customer packets.

The average delay for all six traffic categories is shown in Figure 6.11 when the Delta-Buffer DBA algorithm is used with $t_c = t_F$, again with the HD Gaming traffic increased in 1.0 Mbps increments.

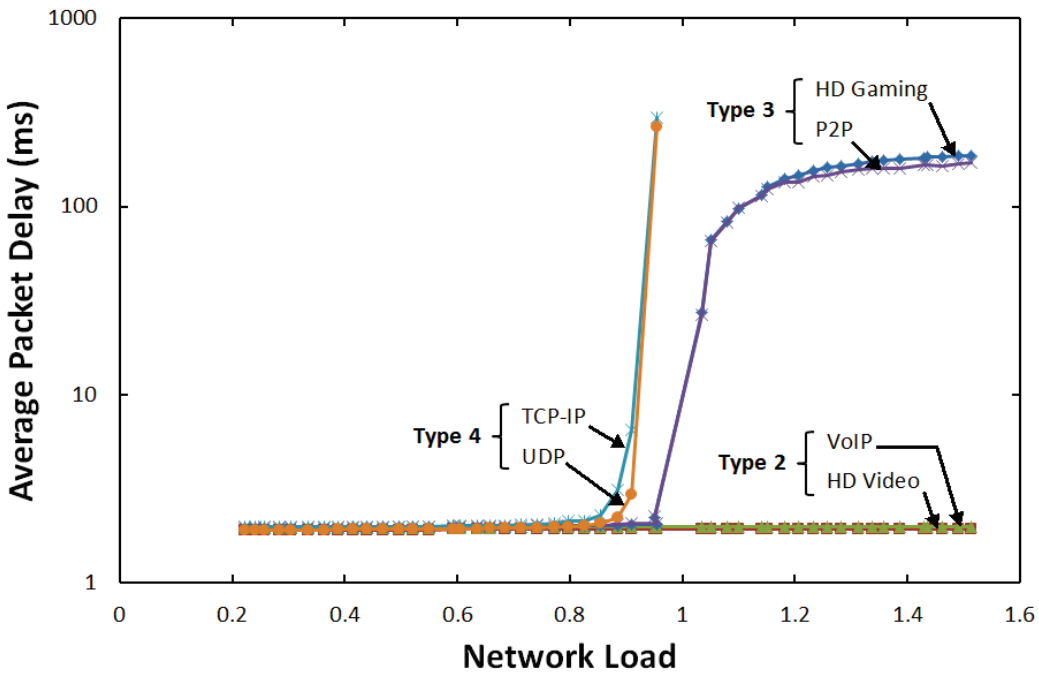

Figure 6.11 – Average packet delay for 100 km LR-GPON using Delta-Buffer DBA with $t_c = t_F$, various traffic categories and HD Gaming traffic as input variable.

We can see that the traffic in Type 2 T-CONTs experiences a near constant delay regardless of network load and VoIP and HD Video traffic experience the same delay. In fact, all traffic categories display similar average delay until the transition regions of Type 3 and Type 4 T-CONTs. The average delay of Type 4 T-CONT traffic, having the lowest priority, does not increase until a network load of just above 0.8 at which load the delay increases beyond the scale displayed in Figure 6.11.

The beginning of the transition region for Type 3 T-CONT traffic occurs just prior to a network load of 1.0 at which point the average delay approaches a maximum value. The average delay for both VoIP and HD Video is very much the same over all values of network load because the Delta-Buffer DBA algorithm is only allocating the required bandwidth at the fastest possible interval, one GPON frame. By allocating using this DBA algorithm, the OLT can allocate according to the change in buffer level and the allocation of bandwidth therefore does not depend on injection rate or packet size.

6.3.2.2 Type 4 T-CONTs

To determine the average packet delay of all traffic categories when the traffic in Type 4 T-CONTs dominates the network, we use the same simulator configuration as described in section 6.3.1 where a single traffic stream of all six traffic categories is also injected into each ONU; however in this scenario, the amount of TCP-IP traffic is increased.

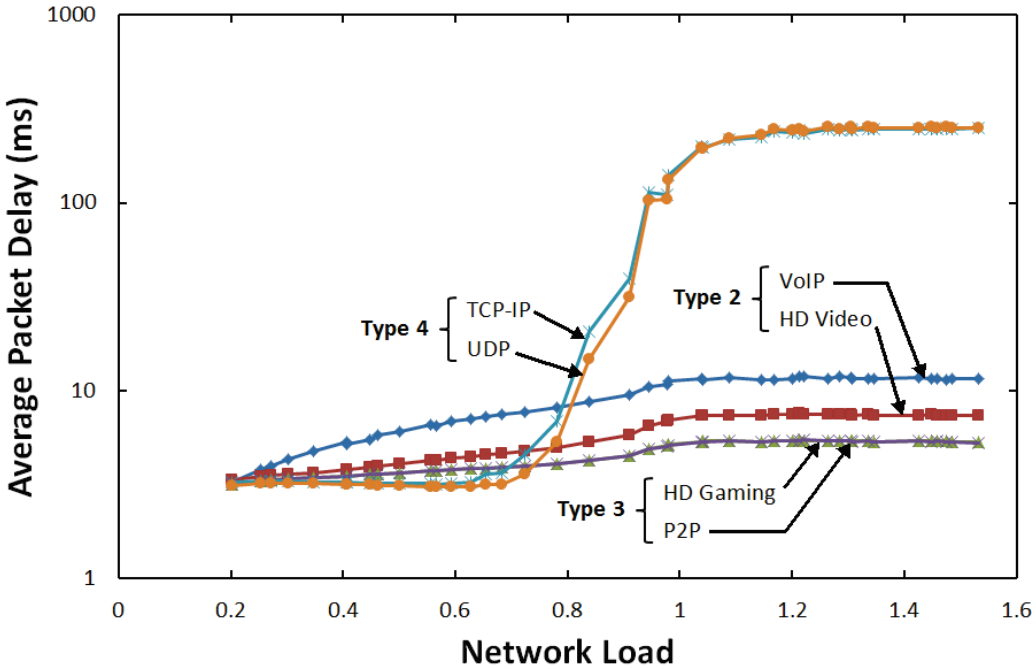

Figure 6.12 – Average packet delay for 100 km LR-GPON using RTT-Based DBA with $t_c = 10t_F$, various traffic categories and TCP-IP traffic as input variable.

Figure 6.12 shows the average packet delay for a 100 km LR-GPON for all six traffic categories when the RTT-Based DBA algorithm is used and the target load of each TCP-IP traffic stream is increased. We can see the traffic in Type 4 T-CONTs displays the lowest average delay of all traffic categories in the pre-congestion region. This occurs because as more bandwidth is allocated to the Type 4 T-CONTs of one ONU, allocations to the other T-CONT types of other ONUs occur later in the allocation interval. In Figure 6.12 the transition region for the traffic in Type 4 T-CONTs begins at a network load of 0.6 which is slightly less than that observed for the RTT-Based DBA algorithm in Figure 6.4 when only TCP-IP traffic was present. The addition of higher priority traffic categories have the effect of reducing the available bandwidth that can be allocated to Type 4 T-

CONTs. As the amount of injected higher priority traffic does not increase, the remaining bandwidth available for Type 4 T-CONTs is less in Figure 6.12 than in Figure 6.4.

From Figure 6.12 we can see that the highest priority traffic, VoIP and HD Video, displays higher average packet delay than that of the P2P and HD Gaming traffic which is again due to the frequency of packet injection. We also notice that the average delay for the traffic in both Type 2 and Type 3 T-CONTs increases until the network load where the saturation region of the Type 4 T-CONT traffic begins. At this point, the SLAs for the Type 4 T-CONTs limit the allocated bandwidth thereby minimising any variation in allocations to the Type 2 and Type 3 T-CONTs.

The average packet delay for all six traffic categories when the Reduced-Interval DBA algorithm is used in a 100 km LR-GPON with the target load of the TCP-IP traffic increased is shown in Figure 6.13.

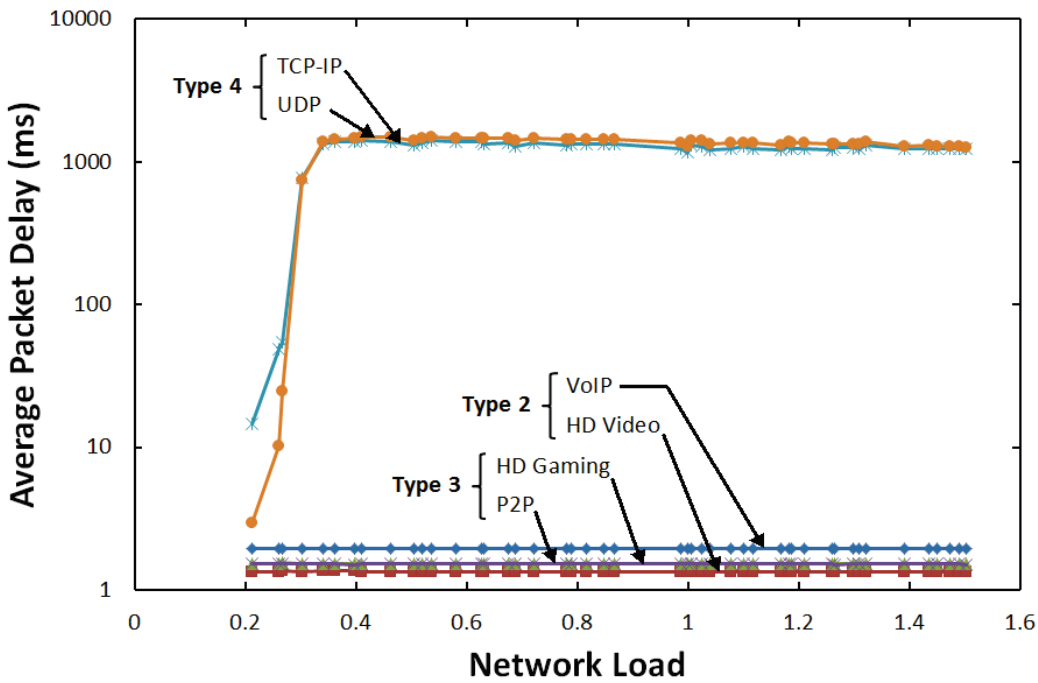

Figure 6.13 – Average packet delay for 100 km LR-GPON using Reduced-Interval DBA with $t_c = t_R$, various traffic categories and TCP-IP traffic as input variable.

With the large total bandwidth allocated to higher priority traffic, insufficient bandwidth is allocated to the Type 4 T-CONTs. As a result, no pre-congestion region is observed for the average delay of the Type 4 T-CONT traffic. We can also see that the maximum

average delay of the Type 4 T-CONT traffic is in excess of 1,000 ms which is nearly an order of magnitude above when the RTT-Based DBA algorithm is used. With such high average packet delay of Type 4 T-CONT traffic within the access network, transport of some TCP-IP based services that require strict end-to-end delay requirements would not be feasible.

Although the wasted bandwidth produced by the Type 2 and Type 3 T-CONTs deprives bandwidth allocations to lower priority traffic, the high levels of wasted bandwidth results in sufficient bandwidth being allocated to Type 3 and Type 4 T-CONTs to transmit the injected traffic. This is evident from Figure 6.13 as the average packet delay of this traffic is almost uniform for all values of network load.

Figure 6.14 shows the average packet delay for the same six traffic categories in a 100 km LR-GPON when the Delta-Buffer DBA algorithm is used and the load of each TCP-IP stream is increased.

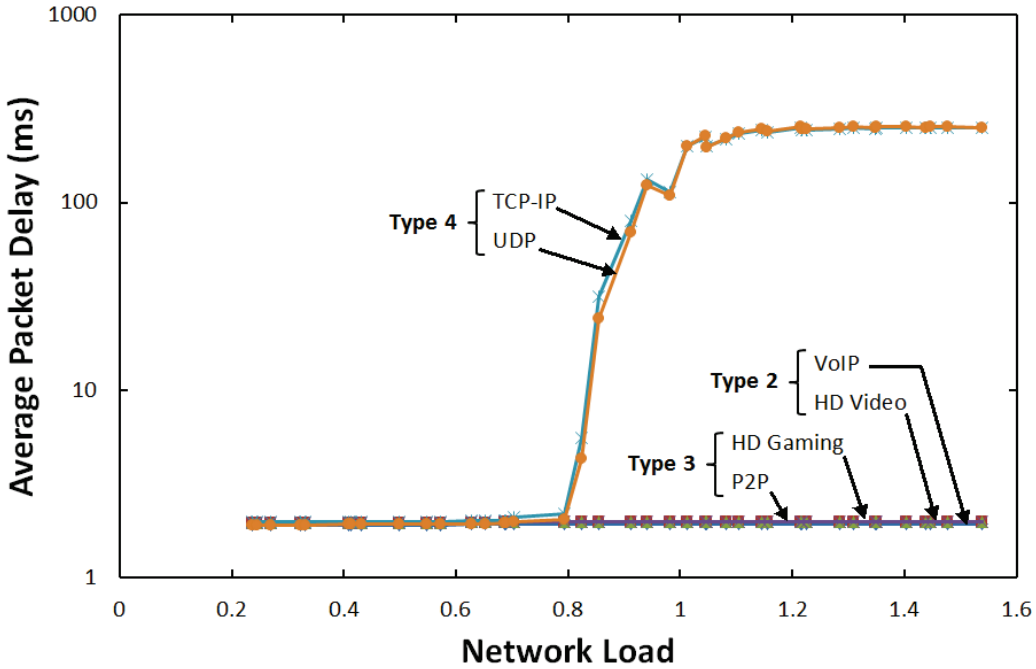

Figure 6.14 – Average packet delay for 100 km LR-GPON using Delta-Buffer DBA with $t_c = t_F$, various traffic categories and TCP-IP traffic as input variable.

We can see that below a network load of 0.8 the average delay for all traffic categories is very similar and only does the traffic in Type 4 T-CONTs show any discernible increase in average delay. This is because as the number of bytes comprising the traffic in Type 4

T-CONTs increases above the capacity of the LR-GPON, the OLT must limit the remaining allocated bandwidth thereby increasing the average packet delay. As the traffic in Type 2 and Type 3 T-CONTs are allocated prior to the Type 4 T-CONTs, and the number of injected bytes in these higher priority traffic streams is not increased, no increase in average delay is observed for both Type 2 and Type 3 T-CONTs.

Once network saturation occurs in Figure 6.14, the average delay for the Type 4 T-CONT traffic approaches a maximum value of just over 250 ms. This is similar to the maximum delay values calculated and shown in Table 6.2 for a 100 km LR-GPON and significantly less than when the Reduced-Interval DBA algorithm is used.

6.4 Problems Associated with Averaging

We saw in Chapter 2 that the majority of the DBA literature discussed presented results in the form of average packet delay; however the specific number of packets used, or simulation run times for which these averaged results were obtained, are often not defined [19, 25, 27, 37, 41, 63, 65, 78]. The majority of the DBA literature uses the self-similar traffic model to inject packets into the simulations and this model has proven to be the most representative of network traffic [36, 51, 53, 84, 91, 101]. The bursty nature of this form of traffic model results in variation in the buffer levels at the ONUs, thereby producing variations in the packet delay. When examining the results of the packet delay using the average values the number of packets used to obtain the average values may affect the representation of the average results due to the bursty nature of the injected customer traffic [23].

Earlier in this chapter we defined the three regions for the average delay curves. We then proceeded to characterize the performance of the DBA algorithms based on the network load at which these regions occurred; specifically the beginning of the transition region. We defined this point as the network load at which the network begins to suffer congestion and some packets must be delayed. It is important to understand how the simulation run-time affects this particular characteristic because when examining the performance of a DBA algorithm using the average delay, the network load at which the transition region begins may vary.

To understand how the simulation run affects the presentation of the average delay we use the simulator to generate the average delay in a 100 km LR-GPON for varying simulation run-times. In section 6.2 we specified that the end of each simulation run occurred when the OLT received 30,000 packets from one ONU (P = 30,000). We will now examine the average delay when the number of packets is 100, 1000, 30,000 and 100,000. We use the RTT-Based DBA algorithm with $t_c = 10t_F$ and inject only a single stream of TCP-IP packets into each ONU.

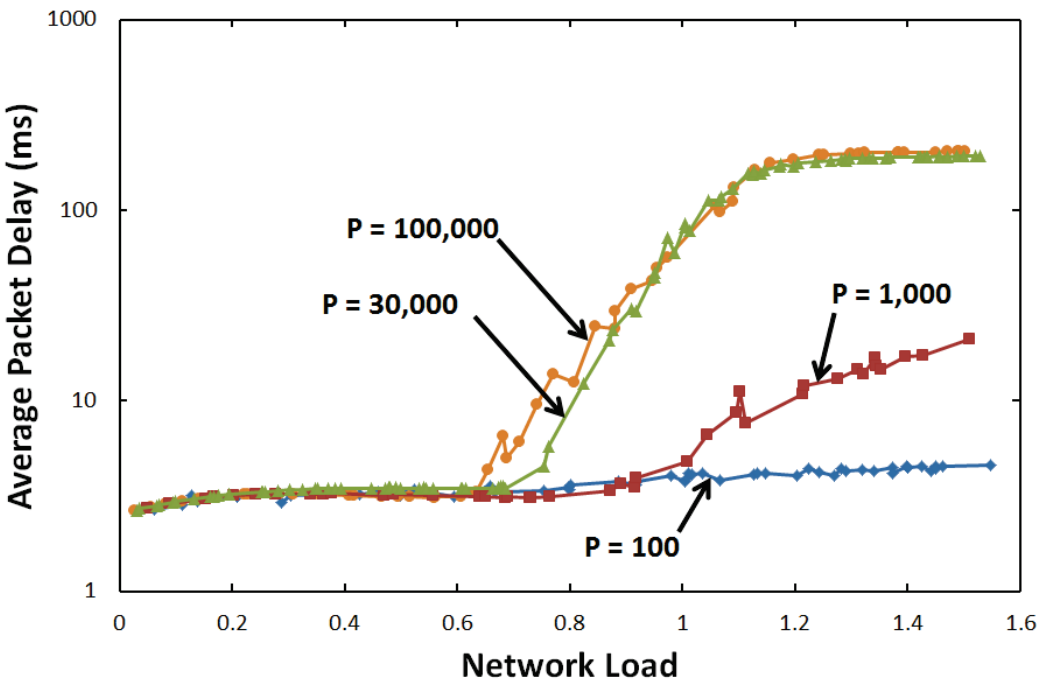

Figure 6.15 – Average packet delay for 100km LR-GPON with TCP-IP traffic, $t_c = 10t_F$ and varied simulation run-times.

From Figure 6.15 we can see that calculating the average delay when fewer packets are received, the regions of the curves become less pronounced. When only 100 packets are received, there is almost no visible change in the average delay over the network load. This is because even at high loads, the simulation does not run for long enough to allow the accumulated packets within the buffers to be transmitted. Although the number of bytes generated exceeds the frame capacity, thereby creating a total network load greater than 1.0, at the end of the simulation packets remain within the buffer that are not transmitted. As these packets are never received at the OLT, they do not contribute to the average packet delay.

As the number of packets received increases, we can see that the regions of the curves become more pronounced; however when P = 1,000, the beginning of the transition region occurs just below a network load of 1.0. This can give the impression that this algorithm performs well until this value of network load. The maximum average delay for P = 1,000 is also much lower for when P = 100,000 as some packets remain in the buffers at the end of each simulation run.

When we examine the curves where P = 30,000 and P = 100,000, we can see that the transition regions occur at a network load of 0.6 and the maximum average delay levels out at just over 200 ms. As the number of packets used to generate the average delay increases we can see that the network loads at which the regions occur appear to converge. By allowing the simulation to run for a longer time, the delay of more packets are used to calculate the average and as can be seen from Figure 6.15, the average delay curves take on a more consistent shape.

6.5 Conclusion

In this chapter we have presented and analysed the steady-state average packet delay and wasted bandwidth in both 20 km GPON and 100 km LR-GPON. We have also described how the DBA algorithms developed in Chapters 3 and 4 have been used with the simulator to analyse the relationship between network load and average packet delay for these algorithms.

When examining the average upstream packet delay against network load, we see three distinct regions for the average delay; pre-congestion, transition and saturation. By examining the network load at which these regions occur, we can assess the performance of the DBA algorithm in terms of average packet delay. The most critical point on the average delay curve is when the transition region begins. At this network load, the network starts to suffer from congestion during some allocation intervals. Once this occurs, some ONUs must delay the transmission of upstream packets, thereby increasing the average packet delay. The network load at which this occurs is dictated by the relationship between the number of bytes allocated and the number of injected customer traffic bytes and is therefore heavily dependent on the particular DBA algorithm used. The allocations are limited by both the maximum window sizes and the total available traffic bandwidth in each allocation interval. With bursty injected traffic,

the random nature of the traffic results in some allocation intervals being congested. It is the responsibility of the DBA algorithm to allocate only the required bandwidth thereby maximizing the utilization of the upstream frame in terms of packet transport.

We saw in Figure 6.1 and Figure 6.4 that during the pre-congestion region the Reduced-Interval DBA algorithm produces the lowest average packet delay when only one category of traffic is present in the network. While the average delay is low, this is a result of the large amounts of wasted bandwidth produced by this algorithm. This has the effect of reducing the network load where the transition region begins. We also see from Figure 6.3 and Figure 6.5 that the Reduced-Interval DBA algorithm produces extremely large amounts of wasted bandwidth. The Delta-Buffer DBA algorithm produces lower average delay in the pre-congestion region that that of the RTT-Based DBA. Once congestion begins to occur this delay exceeds that of the RTT-Based DBA due to the larger overheads associated with a lower allocation interval. In both 20km GPON and 100km LR-GPON the network load at which the transition region begins to occur is higher using the Delta-Buffer DBA. This implies that more network traffic can be handled with lower delay using this algorithm.

In Chapter 4 we proposed the Allocation Reduction DBA algorithm that reduces the wasted bandwidth produced by the Reduced-Interval DBA by incorporating a reduction factor, $\delta_{e,n}(W)$. We have shown that the average wasted bandwidth can be reduced by increasing the reduction factor with little compromise to the average delay. Although the average delay increases as the wasted bandwidth is reduced, this increase is marginal.

When multiple categories of traffic with various priorities are injected into the ONUs, the average delay can be used to determine the effectiveness of a DBA algorithm's ability to handle QoS. Type 2 traffic, possessing the highest priority, can be viewed as simply a reduction in the available bandwidth for the lower traffic priorities because this traffic is managed and therefore cannot be over-subscribed. When the amount of injected customer traffic bytes of traffic that can be over-subscribed is increased, the general result is that the average delay of lower priority traffic increases. This is consistent with the GPON QoS model in that traffic is allocated in order of priority. When the Reduced-Interval DBA algorithm is used with varying traffic priorities, the result is that the lowest priority T-CONT, Type 4, suffers extremely large average delay due to the large amounts of wasted bandwidth allocated to the higher priority traffic.

Although the RTT-Based DBA algorithm does not produce large amounts of wasted bandwidth, the highest priority traffic actually produces the highest average delay in the pre-congestion region. With the models used for the VoIP and HD Video traffic streams, a longer interval means that the arrival waiting time of these packets is larger therefore contributing to the higher average delay. Whilst this is an artifact of the traffic model used, the DBA algorithm in any PON should be capable of handling a wide variety of traffic behaviour [35].

The ability of a DBA algorithm to adapt to fluctuations in the amount of injected customer traffic is another important feature. This ability is significantly increased by reducing the allocation interval. The shorter interval of the Reduced-Interval DBA allows for greater adaptation to fluctuations; however the large wasted bandwidth produced by this algorithm decreases its ability to issue allocations to handle these fluctuations. The Delta-Buffer DBA algorithm has the shortest possible interval and only allocates the required bytes according to the injected customer traffic. The overall result is that, regardless of traffic category or priority, the average traffic delay for all categories of traffic is fairly uniform until congestion begins to occur. This is evident from Figure 6.11 and Figure 6.14.

While the most widely accepted method of presenting the packet delay results for a PON is to use the average results, much of the literature fails to specify the number of packets or simulation run-time used to generate such results. We have shown in Figure 6.15 that by varying the number of packets used to calculate the average delay, the results of a DBA algorithm can be interpreted as producing a lower average delay. By increasing the number of packets used, the results become more consistent, however averaging over such a large population does not take into account the variability produced by the bursty nature of the injected customer traffic.

In the next chapter we will look at how the DBA algorithms adapt to the bursty nature of the injected customer traffic by analysing the transient response of the packet delay and allocations. This is especially important when characterizing the ability of a DBA algorithm to handle strict jitter, or delay variation, requirements.

We will also use a new method by which to present the delay results in a form that provides the maximum amount of information relating to the packet delay.

7 Transient Response and Histogram Representation

7.1 Introduction

Self-similar models [19, 21, 22, 37, 45] are used widely to model traffic in PONs. Although this model has been widely adopted, the bursty nature of the self-similar traffic model results in some ONUs experiencing high packet delay for some allocation intervals [23]. When the results of the packet delay are analysed in an averaged format these intervals of high delay for some ONUs are not represented. We showed in Chapter 6 that the number of packets used to calculate the average delay can significantly impact the representation of the average delay. While most previous reported work have relied heavily on average delays to validate various proposed DBA algorithms, it is not possible to validate these DBA algorithms in terms of their transient response to bursty injected traffic.

Some traffic categories have not only strict end-to-end delay requirements, but also requirements on the variation in delay on consecutive packets [29-33]. Recall from Chapter 2 that packet delay variance, or jitter, is defined as the magnitude of the difference in delay between consecutive packets of the same traffic flow [24, 31, 34]. This can also be represented as the rate of change of the packet delay. Two common examples of traffic categories that are sensitive to jitter are video and voice because these are real-time traffic categories and the codecs require these packets to be received at regular intervals [102]. Retiming, or jitter, buffers, can be used to handle small delay variations in the received packets [32, 110]; however the effectiveness of these buffers is dependent on the buffer size. A large buffer size increases the ability of the buffer to mitigate against jitter, however the overall end-to-end delay may increase [32]. It therefore is important to ensure that the delay of the received packets exhibits minimal variation to ensure the quality of service (QoS) is maintained.

Throughout this thesis we have shown by both mathematical modelling and simulation that in passive optical networks (PONs), the upstream packet delay is a function of the

DBA algorithm. Most previously published work on DBA in both EPON and GPON focuses on minimizing delay. However some researchers have examined the effect the DBA has on jitter [24, 30, 34, 47, 111]. While GPON has the capability to transport upstream traffic according to priority using T-CONTs, proper network provisioning must be in place to ensure that delay sensitive traffic is awarded a higher priority. Many voice and video services are encapsulated using TCP-IP and UDP protocols [112-115] and consequently are transmitted over GPON as best effort traffic. Due to the strict jitter requirements on voice and video traffic, it is important to determine what effect the DBA algorithms have on the jitter.

In this chapter we use simulations to examine the jitter in LR-GPON using the DBA algorithms defined in Chapter 3, as well as those proposed in Chapter 4, when best effort traffic is present in the network. We also propose a new method for presenting the delay results whereby the delay variation can be observed.

7.2 Transient Response of the DBA Algorithm

In Chapter 3 we modelled the time dependency of buffer occupancy of the ONUs to develop a model for the DBA mechanism. In this model we used the injected customer traffic and the duration of the allocation interval as input parameters and produced an expression for the upstream packet buffering delay given by (3.11). The buffering delay is dependent on the duration of the allocation interval and the number of bytes allocated in each interval. If both of these parameters are constant, then the resulting buffering delay will also be constant; however the DBA mechanism, in conjunction with the service level agreements (SLAs), creates variable allocations which cause varying packet delay.

To assess this variance in LR-GPON, we consider the case where the network is below congestion and inject a single TCP-IP traffic stream at 60.0 Mbps with a target load of 0.5 into each ONU and examine the packet delay produced by one ONU. By examining the delay of each packet received at the OLT we can determine the amount of jitter produced by the DBA algorithm.

7.2.1 RTT-Based DBA Algorithm

Figure 7.1 (a) shows the buffer occupancy and Figure 7.1 (b) shows the corresponding packet delay over time for a 100 km LR-GPON with one active ONU and the RTT-Based DBA algorithm with $t_c = 10t_F$. The result is that the RTT-Based DBA algorithm produces a maximum jitter in the order of 1.0 ms.

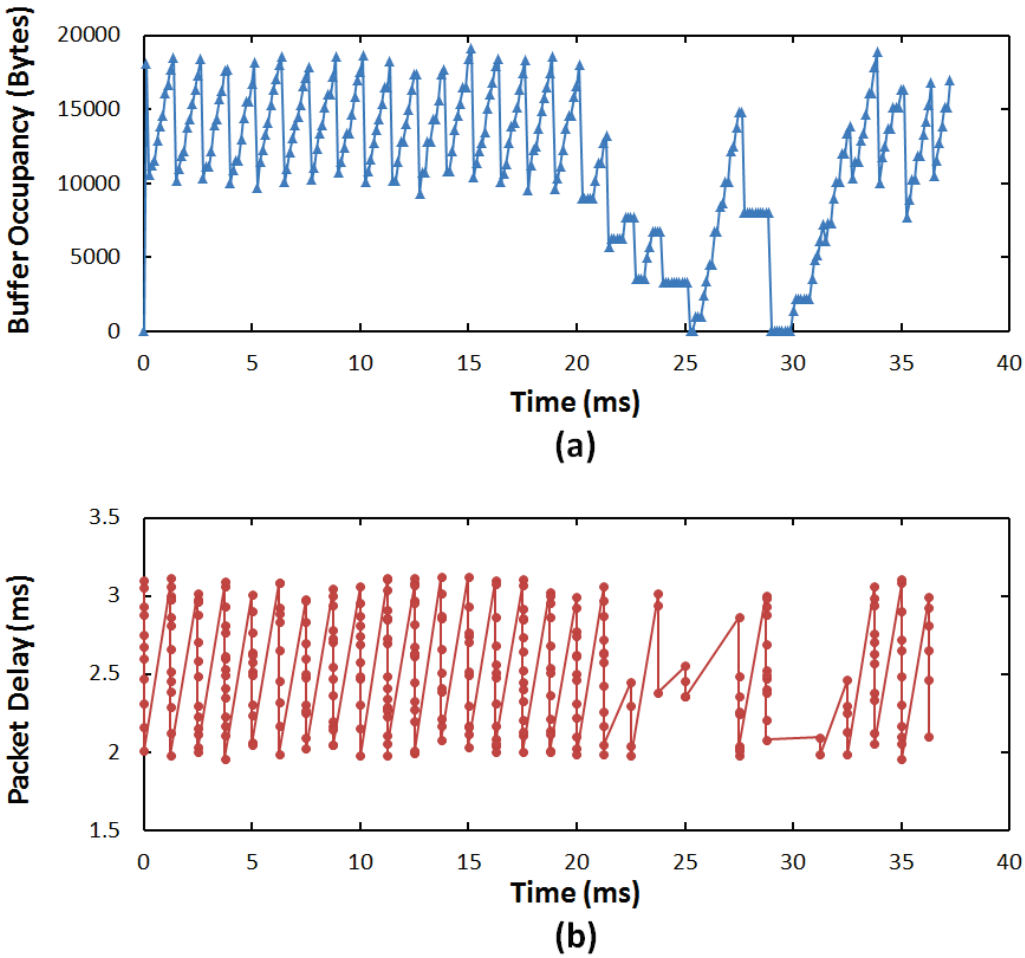

Figure 7.1 – Transient response of (a) buffer occupancy and (b) packet delay for 100 km LR-GPON using the RTT-Based DBA with $t_c = 10t_F$

From Figure 7.1 (a) we can see that up until 20.0 ms the buffer occupancy maintains a fairly repetitive behaviour and at 25.0 ms drops to zero signifying the end of an injected traffic flow and at t= 30.0 ms the commencement of new traffic flow can be seen. When the traffic flows are active, the packet delay in Figure 7.1 (b) displays a periodic behaviour with a burst of packets received each allocation interval.

Using the RTT-Based DBA algorithm, upstream packets are transmitted once per allocation interval and as a result, the maximum jitter is equal to the duration of the allocation interval. The RTT-Based DBA algorithm therefore increases the jitter when the packets are received at the OLT.

7.2.2 Reduced-interval DBA Algorithm

The buffer occupancy using the Reduced-Interval DBA algorithm with $t_c = t_F$ under the same injected traffic scenario is shown in Figure 7.2 (a) and the corresponding packet delay is shown in Figure 7.2 (b).

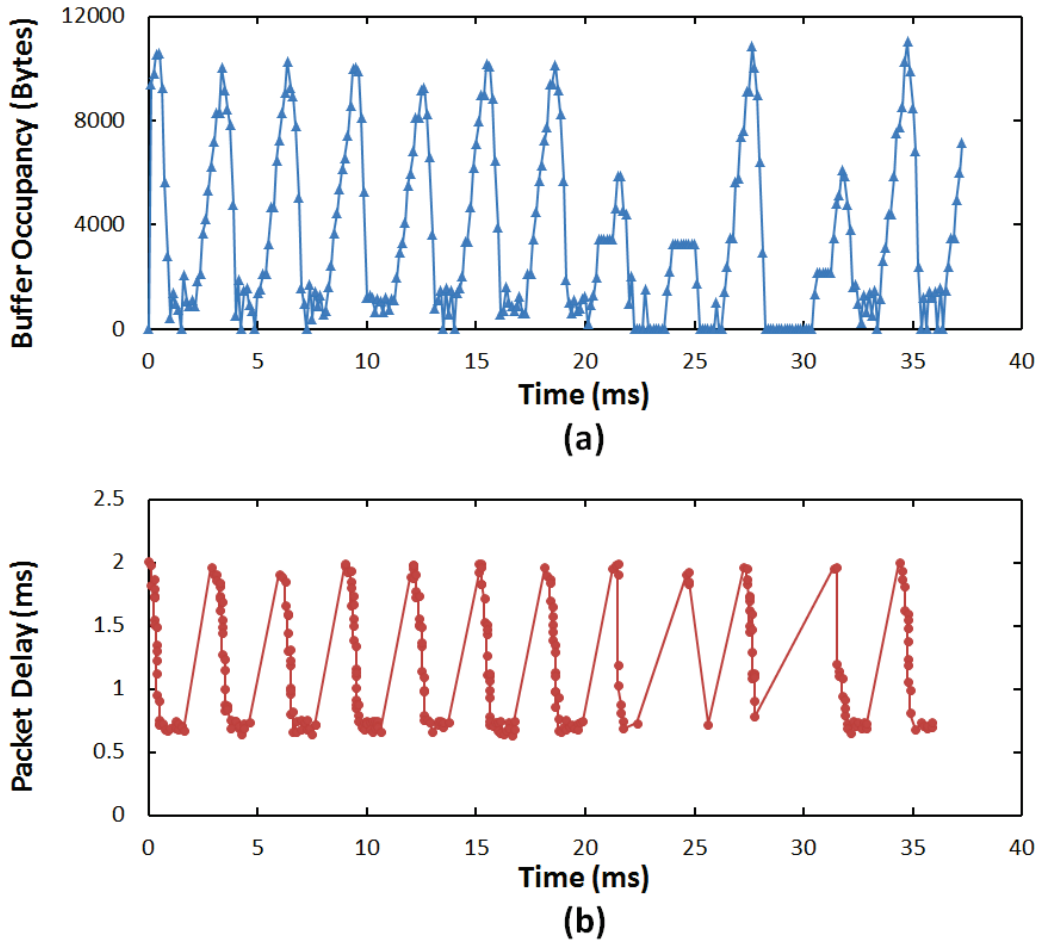

Figure 7.2 – Transient response of (a) buffer occupancy and (b) packet delay for 100 km LR-GPON using the Reduced-Interval DBA with $t_c = t_F$

Although the same injected traffic stream profile was used as in the previous section the buffer occupancy remains lower than that shown in Figure 7.1 (a). This is because the

large wasted bandwidth produced by the Reduced-Interval DBA algorithm allows greater numbers of upstream packets to be transmitted resulting in a lower buffer occupancy than that of the RTT-Based DBA. We can see that while the packet delay produced by the Reduced-Interval DBA displays higher variance that that shown in Figure 7.1, large clusters of packets exhibit a low delay. This is again due to the wasted bandwidth allowing packets to be transmitted prior to being requested. These packets are transmitted with minimal delay and jitter.

In Chapter 3 we defined a t_0 event which occurs when the reported buffer level of an ONU is zero for a time greater than the RTT of the PON. The buffer occupancy shown in Figure 7.2 (a) is the buffer occupancy at the ONU prior to an allocation being processed and we can see that there are periodic instances where the buffer level is in the order of 1,000 bytes for a number of sequential allocation intervals. The large allocations produced by the Reduced-Interval DBA algorithm result in the reported buffer occupancy, after an allocation is processed, being zero for these allocation intervals thereby creating a t_0 event. We can see the repeating t_0 events leading to a clearly visible repeating pattern in both the buffer occupancy and packet delay. Once the reported buffer level drops to zero, the resulting allocations also drop to zero until one RTT later. At this time, transmission of upstream packets resumes and the resulting maximum jitter is therefore RTT + RTT/2. The Reduced-Interval DBA algorithm produces high amounts of jitter when the packets are received at the OLT. The peak jitter is higher than that of the RTT-Based DBA algorithm.

7.2.3 Allocation Reduction DBA Algorithm

In Chapter 4 we proposed the Reduced-Interval DBA algorithm by introducing an allocation reduction factor, $\delta_{e,n}(W)$, to reduce the wasted bandwidth. In Chapter 6, we showed that this proposed algorithm reduced the wasted bandwidth with little impact on the average packet delay. In order to determine the transient response and the jitter produced by this algorithm, we use simulations with the same injected customer traffic parameters used above.

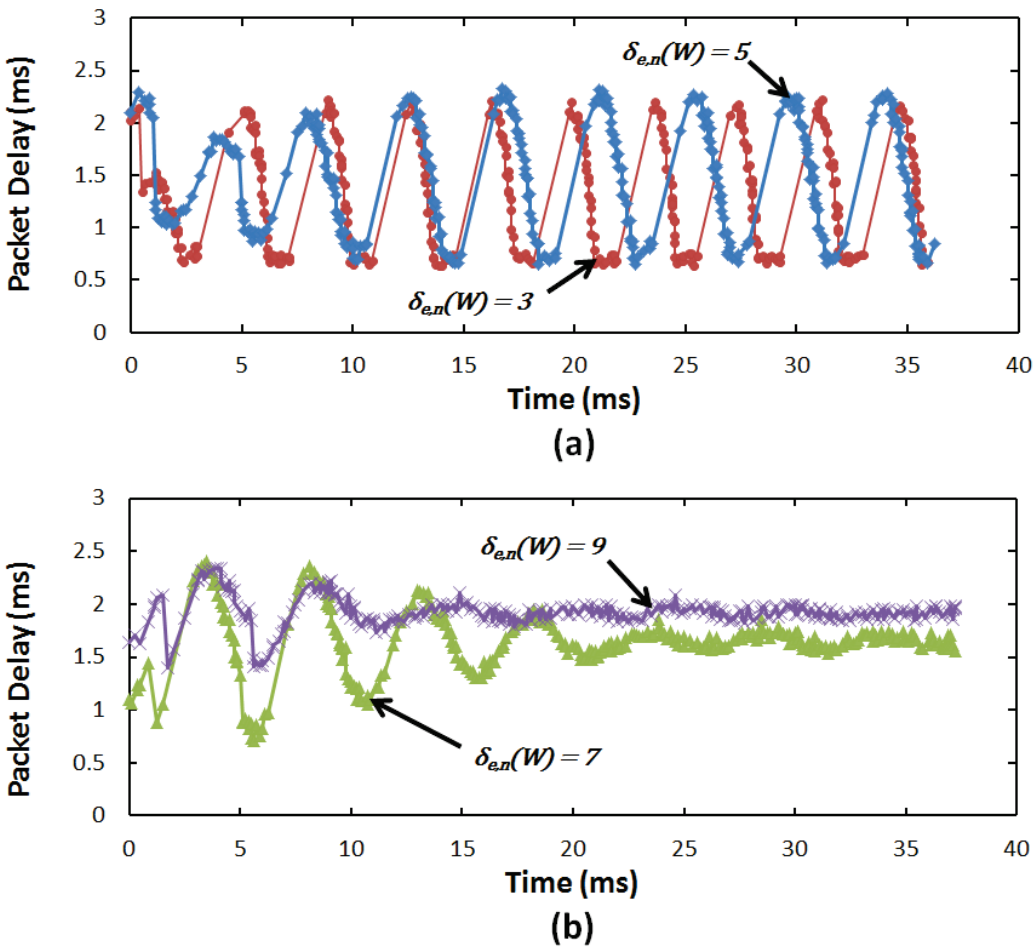

Figure 7.3 – Transient response for 100 km LR-GPON with (a) allocation reduction factors $\delta_{e,n}(W) = 3, 5$ and (b) allocation reduction factors $\delta_{e,n}(W) = 7, 9$

Figure 7.3 (a) shows the transient response for the allocation reduction DBA algorithm in a 100 km LR-GPON below congestion for reduction factors $\delta_{e,n}(W) = 3$, 5 and Figure 7.3 (b) for reduction factors $\delta_{e,n}(W) = 7$, 9 with $t_c = t_F$.

We can see from Figure 7.3 (a) that with a low reduction factor, $\delta_{e,n}(W) = 3$ and 5, the packet delay oscillates as is the case presented in Figure 7.2 when no reduction factor is used. The oscillation of the packet delay is due to the fact that the wasted bandwidth allows the buffer occupancy to drop to zero resulting in the corresponding allocations also being zero. It is interesting to note that there is a decrease in the frequency of oscillation when the allocation reduction factor is changed from 3 to 5. As the allocation reduction factor increases, fewer bytes are allocated per interval resulting in the rate at which the buffer occupancy drops to zero decreasing. Thus a larger reduction factor

results in a longer time between t_0 events thereby lowering the frequency of oscillation as can be seen in in Figure 7.3 (a) and (b).

When $\delta_{e,n}(W) = 7$ and 9, Figure 7.3 (b) shows that while the packet delays display an oscillatory behaviour, the magnitude of the oscillations decreases over time. This is due to the reduction factor decreasing the rate at which the buffer occupancy decreases. As the reduction factor reduces the excessive allocations fewer packets are transmitted each thereby preventing a t_0 event from occurring. As the reduction factor is increased from 7 to 9, we see from Figure 7.3 (b) that the steady-state value of the packet delay increases which was also observed in Chapter 6. When the injected customer traffic rate drops to zero, the buffer will also drop to zero thereby creating a new t_0 event. Once the injected customer traffic rate increases, the oscillatory behaviour repeats. We can therefore conclude that a high reduction factor effectively dampens oscillations in the packet delay while also increasing the steady-state delay value.

7.2.4 Delta-Buffer DBA Algorithm

Figure 7.4 (a) shows the buffer occupancy over time for a 100 km LR-GPON below congestion using the Delta-Buffer DBA algorithm.

We can see that in Figure 7.4 (b) the jitter produced by the Delta-Buffer DBA algorithm is minimal compared to the other DBA algorithms. The allocated bandwidth in terms of injected customer traffic for the Delta-Buffer DBA algorithm is given by (4.14) and the corresponding allocated bandwidth from the OLT is sufficient such to consist of only the GEM frames required to transmit the traffic bytes. So long as the network remains below congestion, the overall result is that the variation in the delay of each upstream packet is only dependent on the arrival time, $\Delta t_{a,i}(t)$.

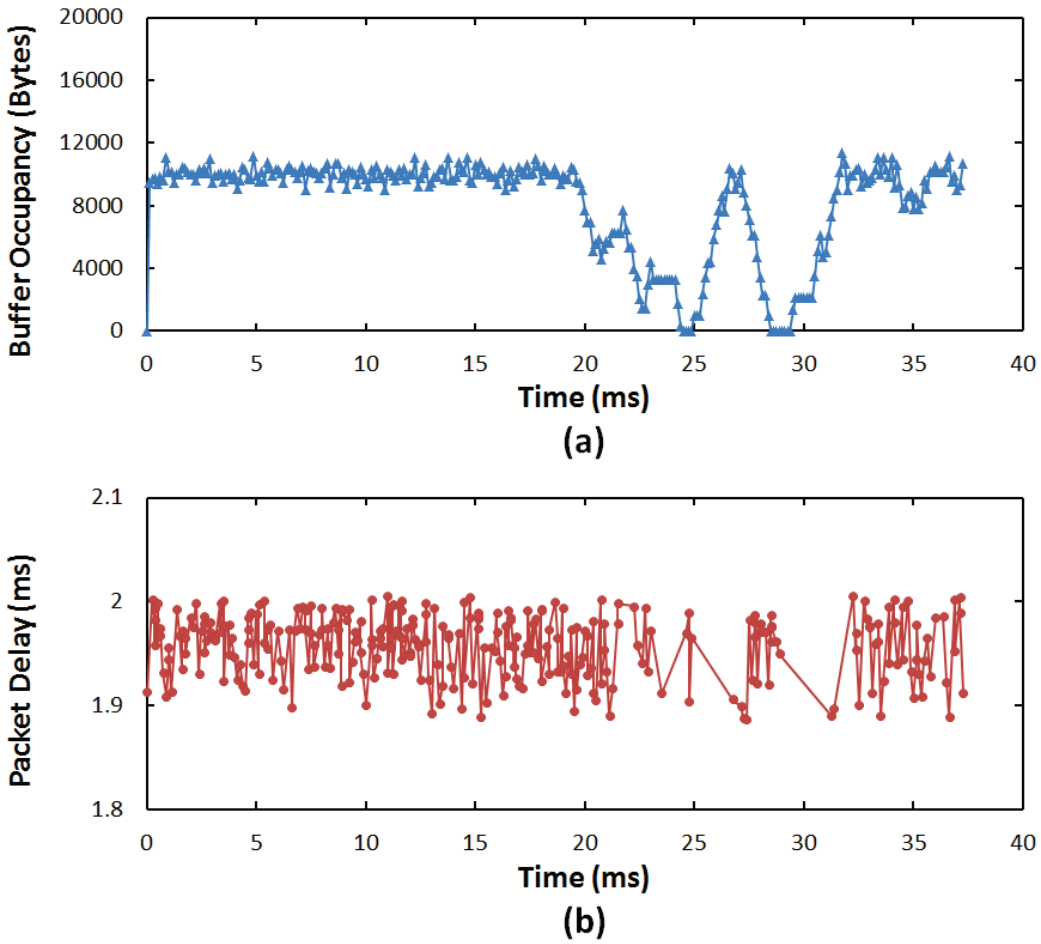

Figure 7.4 – Transient response of (a) buffer occupancy and (b) packet delay for 100 km LR-GPON using the Delta-Buffer DBA with $t_c = t_F$

We have so far examined the transient response of the packet delay and the injected customer traffic is below congestion. When the injected traffic exceeds the available bandwidth in an allocation interval, congestion begins to occur as described in Chapter 6. Once this situation occurs, the allocated bandwidth to each ONU becomes a function of the injected traffic of all ONUs on the network. As a result, the upstream packet delay no longer exhibits a delay dependent on the injected traffic profile for that specific ONU; rather the delay also becomes dependent on the injected traffic of all ONUs on the network. For this reason we do not examine the transient response above congestion, instead we must consider another method by which to examine the variance in upstream packet delay. In the following section we use the delay distribution to examine the delay variance of an LR-GPON.

7.3 Histogram Representation of the Delay

In Chapter 2 we saw that the majority of papers on DBA algorithms have presented upstream packet delay results in terms of average delay as a function of the network load [19, 20, 22, 23, 27, 42, 44, 63]. In recent years, this has become the traditionally accepted method for analysing the DBA algorithms as it provides an understanding of the expected delay as the amount of injected customer traffic increases or varies. Averaging the delay does not provide a measure of the variance of the packet delay. In the previous section of this chapter we showed that the packet delay can exhibit variations over time due to the bursty nature of the injected customer traffic and the behaviour of the DBA algorithm. A probability density function (PDF) of the delay has been presented in some papers [25, 29, 39, 41, 44, 116]. While this provides an indication of the performance of the DBA in terms of delay variation, the PDFs presented in the papers listed above only provide the PDF at a specific network load. This representation does not show the delay variance as the network load varies.

In the simulations described in Chapter 6, we recorded the delay of each received packet in order to generate the average delay. We can use this data to analyse the distribution of the delay as the network load increases. To do so, we use the results from Chapter 6 and analyse each packet received over each simulation run to create a delay histogram. The frequency axis used in the histogram is normalized to the total number of packets received over each simulation run. Such normalization is necessary as the number of packets received in each simulation run varies. The delay interval, t_{di}, is used for the bin size and is chosen such that a representative histogram output is achieved in terms of packet delay.

7.3.1 RTT-Based DBA Algorithm

Figure 7.5 shows the complete histogram for 32 ONUs when the RTT-Based DBA is used in a 100 km LR-GPON with only TCP-IP traffic present in the network. A bin size, t_{di}, of 0.05 ms is used and the range of delay values is from 0.5 ms to 211 ms. We can see that the majority of the packet delay at low network load occurs at a delay of less than 10 ms. At network loads greater than 0.8, or after congestion, the majority of the packet delay occurs around 210 ms which is the maximum delay as determined by the ONU buffer size, $B_{B,n}^{\max}$. Over the range of network loads, the majority of the packet delay in

Figure 7.5 falls into two main regions: pre-congestion and saturation, which were described in Chapter 6. As the network load increases, Figure 7.5 shows that the frequency of the packet delay trends towards higher delay values. Although the average delay as shown in Figure 6.4 displays an increase with load, the histogram also shows that there is a very wide delay distribution with a very small frequency in the transition region.

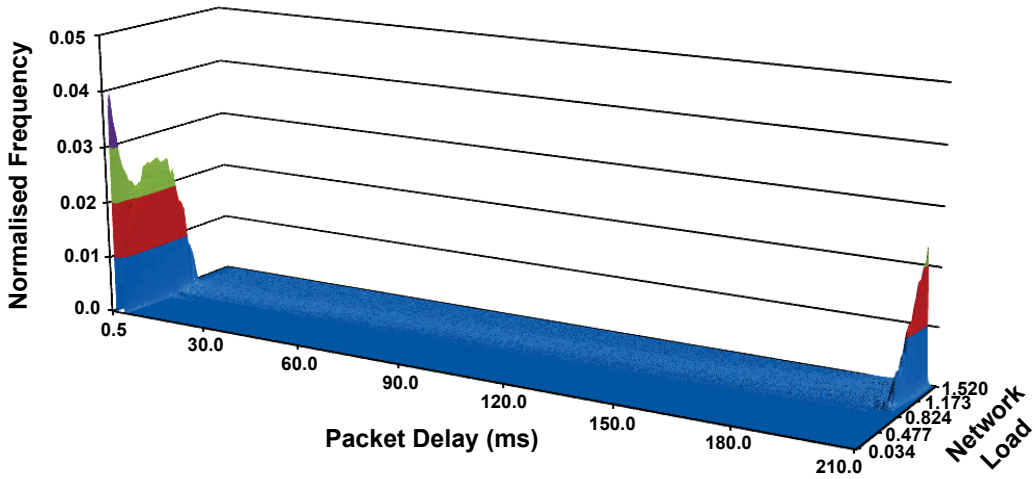

Figure 7.5 – Normalised frequency of the packet delay for the RTT-Based DBA algorithm, 0.5 ms ≤ t_p ≤ 211 ms and delay interval, t_{dl} = 0.05 ms.

Figure 7.6 and Figure 7.7 show the histograms of the packet delay produced by the RTT-Based DBA algorithm for packet delays between 0.5 ms and 6.0 ms with a bin of 0.005 ms with a different rotational angle of the histograms. We can see that at low network loads the majority of the packets produce a delay between 1.8 ms and 3.0 ms, which corresponds to an allocation interval duration of $10t_F$. We can also see that there are 10 peaks created within this region which correspond to the 10 GPON frames constituting the allocation interval. At very low network loads the number of injected packets is small thereby allowing the majority of the packets within the buffer of each ONU to be transmitted at the first allocation interval after the packets are reported to the OLT.

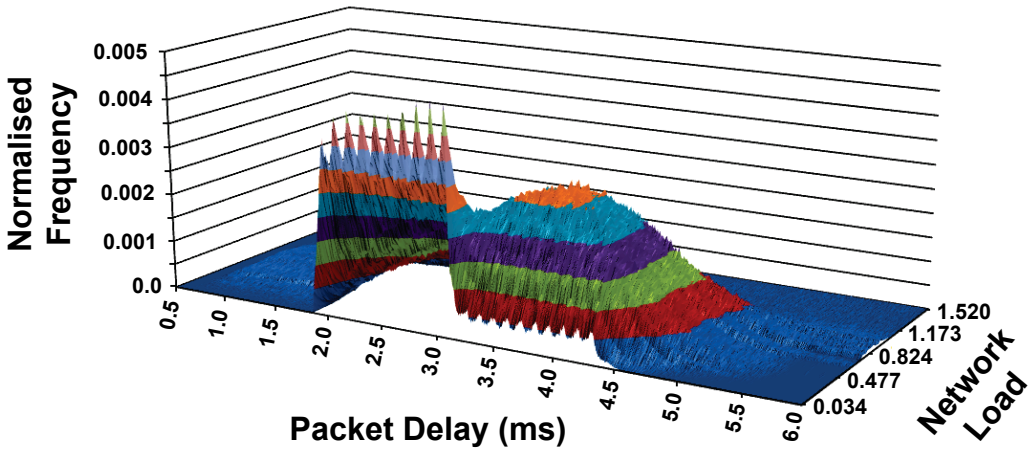

Figure 7.6 – Normalised frequency of the packet delay for the RTT-Based DBA algorithm, 0.5 ms ≤ t_p ≤ 6.0 ms and histogram frequency = 0.005 ms, rotation = 30°.

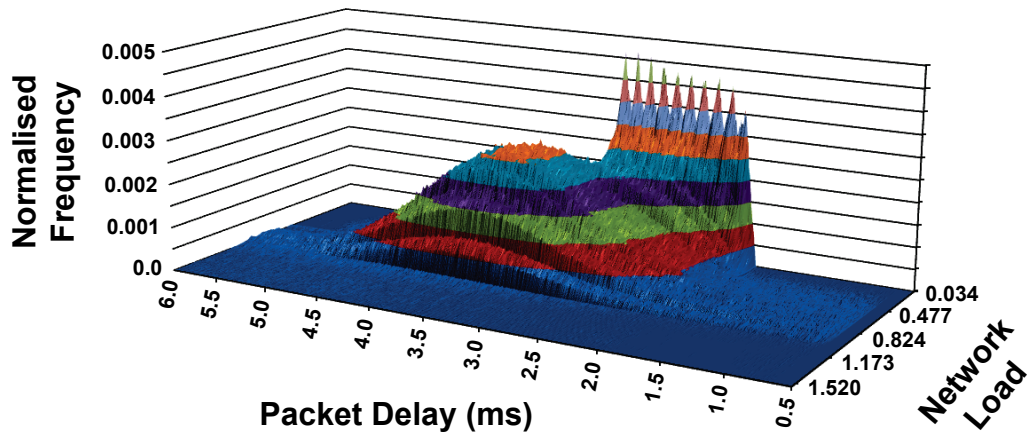

Figure 7.7 – Normalised frequency of the packet delay for the RTT-Based DBA algorithm, 0.5 ms ≤ t_p ≤ 6.0 ms and histogram frequency = 0.005 ms, rotation = 210°.

A secondary set of peaks in the histogram is also apparent at low network load. These correspond to the next allocation interval because some packets may have arrived after the request for bandwidth has been sent and consequently must wait until the next allocation interval. This secondary set also displays the 10 peaks corresponding to an allocation interval of $10t_F$. These two distinct sets correlate with the analysis in Chapter 3, equation (3.11), whereby the majority of packets can be transmitted within two allocation intervals. Equation (3.11) was formulated assuming that the injected traffic

rate was below the GPON frame capacity thereby satisfying the service level agreements (SLAs). At low network loads, this assumption holds true.

In Figure 7.6 and Figure 7.7 we can also see that as the network load increases towards 0.8, the ratio of packets displaying a delay in these two sets shifts. At a network load of 0.6 the majority of the packet delay occurs in the second allocation interval. As the network load increases towards 1.0 the distribution of the packet delay below 6.0 ms reduces as congestion begins to occur. At this network load packets begin to be buffered for longer thereby increasing the packet delay. Above a network load of 1.0, or in the saturation region, very few packets produce a delay below 6.0 ms.

As the network load increases towards 0.5, the peaks corresponding to the GPON frames that constitute an allocation interval become less pronounced. This is because as the amount of injected traffic increases, each ONU requires a greater proportion of the allocation intervals to transmit the packets. Furthermore some packets require buffering and are transmitted in the next allocation interval. The result is that the distribution of the packet delay shifts from the first allocation interval to the second interval. As the network load further increases above 0.6, the packet delay increases as the transition region occurs.

The distribution of the delay in the saturation region for the RTT-Based DBA algorithm is shown in Figure 7.8. We can see that as the network load increases towards 1.5, the peak of the distribution of the packet delay is at the maximum delay, in the order of 208 ms.

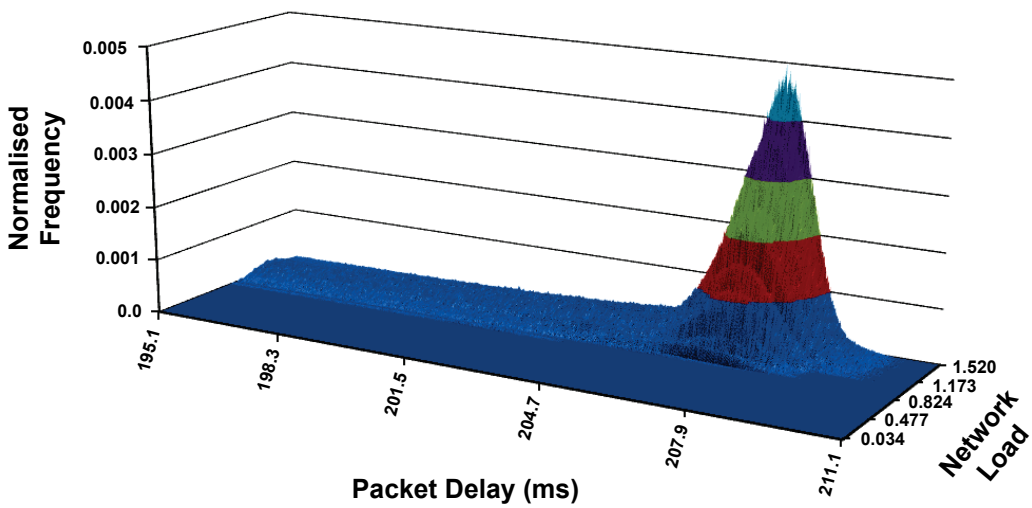

Figure 7.8 – Normalised frequency of the packet delay for the RTT-Based DBA algorithm, 195.1 ms ≤ t_p ≤ 211 ms and histogram frequency = 0.005 ms.

Figure 7.8 shows that above saturation, the majority of the packets experience the maximum delay as set by the ONU buffer size. The variance in this peak delay distribution is caused by the variation in packet length thereby producing a variance in the delay. Recall from Chapter 3 that it is not until the last bit of a packet is received that the delay can then be recorded. Therefore, variations in the packet length result in variations in the packet delay distribution. As the network load further increases, we can see that the frequency of packet delay distribution around the maximum delay value also increases.

From examination of Figure 7.5 through to Figure 7.8 we can see that the upstream packet delay variance using the RTT-Based DBA is only predictable during the pre-congestion and post-saturation regions. During the transition region the delay exhibits a large variance and therefore traffic may suffer large jitter during this region.

7.3.2 Reduced-Interval DBA Algorithm

In Chapter 3 we showed that as the duration of the allocation interval, t_c, decreased below the RTT, the resulting allocations issued by the OLT increased due to the reduced-interval waste effect. In Chapter 6 we showed that with this DBA algorithm the average packet delay in the pre-congestion region was lower than when $t_c = 10t_F$, however the network load at which the transition region occurred was also lower. Figure 7.9 shows the histogram distribution of the Reduced-Interval DBA when only TCP-IP traffic is present in the network with a bin size of 0.05 ms.

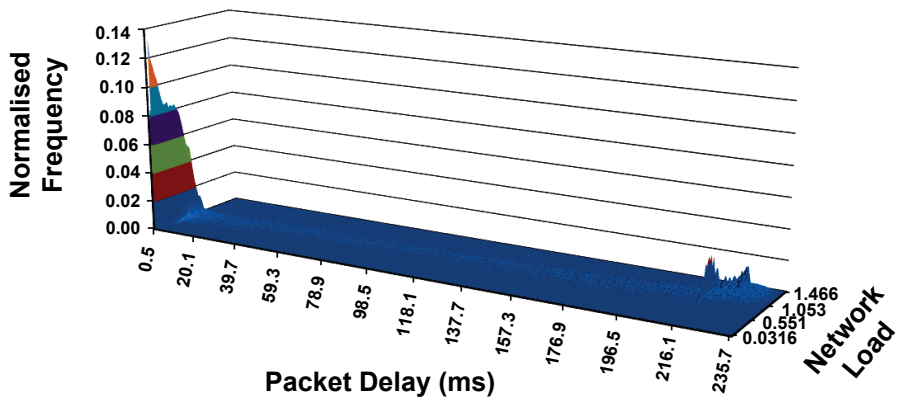

Figure 7.9 – Normalised frequency of the packet delay for the Reduced-Interval DBA algorithm, 0.5 ms ≤ t_p ≤ 237 ms and delay interval, t_{di} = 0.05 ms.

From Figure 7.9 we can see that, as with the RTT-Based DBA, the majority of packets experience a delay below 5 ms or above 200 ms, however with the Reduced-Interval DBA there is a greater distribution of packets exhibiting a delay below 5 ms as a result of the excessive bandwidth allocated to each ONU.

The distribution of the packet delay from 0.5 ms to 2.5 ms is shown in Figure 7.10 and Figure 7.11 at a chart rotation of 30° and 210° respectively. We can see that when the Reduced-Interval DBA is used, there are two distinct distribution peaks occurring at 1.8 ms and at 0.75 ms. The peak at 1.8 ms corresponds to the packets whose presence in the ONU buffers has been reported and transmitted in the next allocation interval. The peak at 0.75 ms corresponds to those packets that are transmitted in subsequent intervals due to the excessive bandwidth allocations. We can also see that between the two major peaks, there are small, but noticeable, peaks in the delay distribution corresponding to the GPON frames that constitute the RTT of the PON.

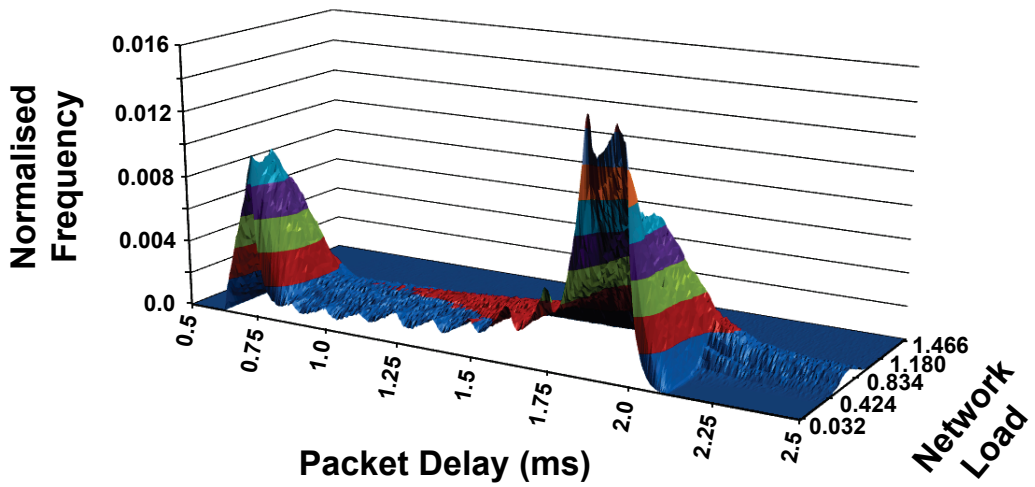

Figure 7.10 – Normalised frequency of the packet delay for the Reduced-Interval DBA algorithm, 0.5 ms ≤ t_p ≤ 2.5 ms and histogram frequency = 0.005 ms, rotation = 30°.

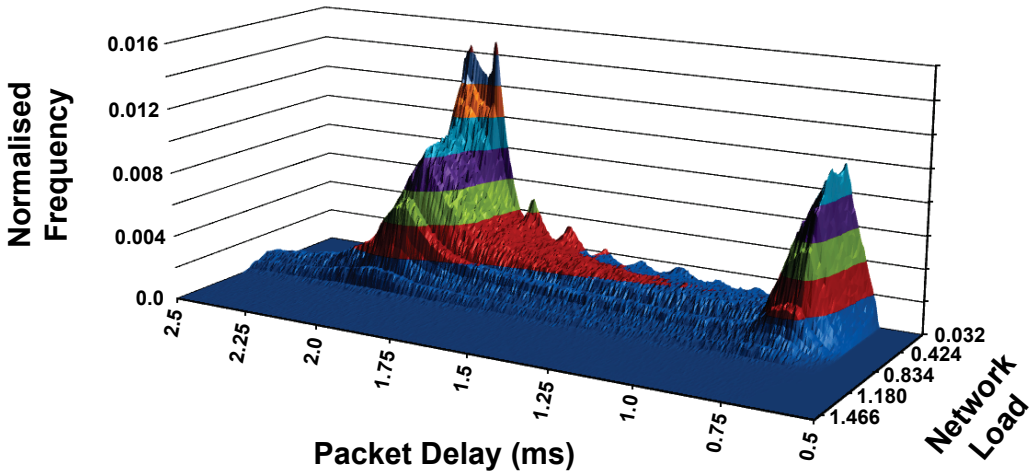

Figure 7.11 – Normalised frequency of the packet delay for the Reduced-Interval DBA algorithm, 0.5 ms ≤ t_p ≤ 2.5 ms and histogram frequency = 0.005 ms, rotation = 210°.

Comparing the distribution of the delay produced at low network loads when the Reduced-Interval DBA algorithm is used to that of the RTT-Based DBA, shown in Figure 7.6 and Figure 7.7, we can see that the variation in packet delay for the Reduced-Interval DBA is less than that of the RTT-Based DBA algorithm. This is because the duration of the allocation interval is shorter when the Reduced-Interval DBA is used thereby resulting in a smaller delay distribution.

In Figure 7.11 we can see that as the network load increases, the distribution of packets in the two major peaks decreases as more packets are buffered thereby displaying a higher delay. At network loads above 1.0, very few packets exhibit a delay below 2.5 ms as the amount of injected customer traffic exceeds the available bandwidth thereby resulting in the majority of the packets being buffered for longer.

Figure 7.12 shows the distribution of the delay for the Reduced-Interval DBA algorithm in the saturation region. We can see that, unlike the distribution for the RTT-Based DBA as shown in Figure 7.8, the packet delay distribution produced by the Reduced-Interval DBA algorithm above saturation does not exhibit a uniform distribution.

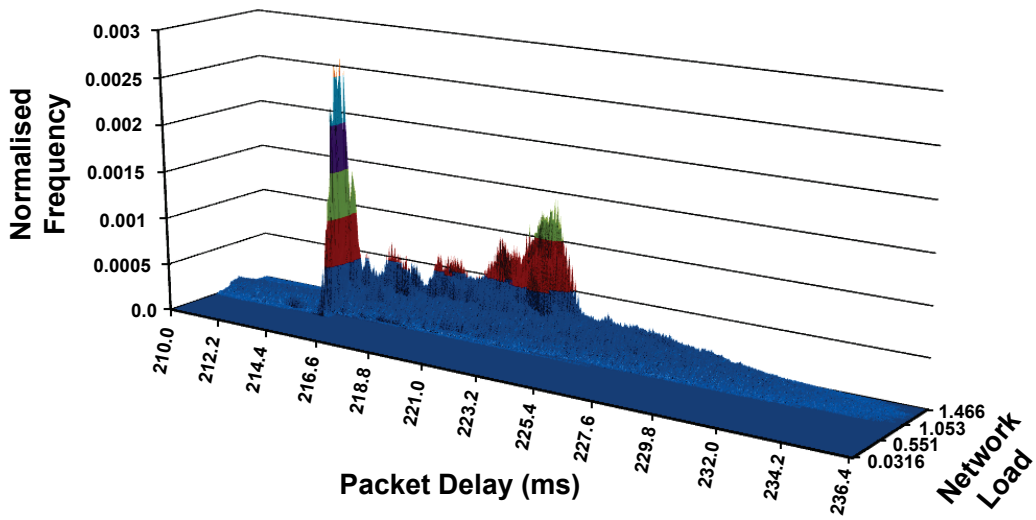

Figure 7.12 – Normalised frequency of the packet delay for the Reduced-Interval DBA algorithm, 210 ms ≤ t_p ≤ 236.5 ms and histogram frequency = 0.005 ms.

As the network load increases towards saturation, the distribution of the packet delay displays a peak at a delay of 215 ms and as the network load further increases, the distribution of the delay further increases. This variation in the delay distribution is due to the variation in injected packet sizes as only full packets are retained in the buffer. The duration of the allocation interval when the Reduced-Interval DBA algorithm is used is set to a single GPON frame, t_F, resulting in fewer packets per allocation interval transmitted than when the RTT-Based DBA algorithm is used. This translates to only packets of smaller size being buffered each interval. As a result, we can see that the distribution of the delay above saturation increases towards a maximum peak delay of 223 ms.

7.3.3 Delta-Buffer DBA Algorithm

To generate a histogram distribution for the packet delay produced when the delta buffer DBA algorithm is used, the results obtained in Chapter 6 when only TCP-IP traffic is present in the network was used. Figure 7.13 shows the full histogram of the delay distribution with a bin size of 0.05 ms. As with both the RTT-Based DBA and Reduced-Interval DBA algorithms, the packet delay in Figure 7.13 exhibits a main peak occurring at a delay below 3.0 ms and a small distribution of delay occurring above 210 ms.

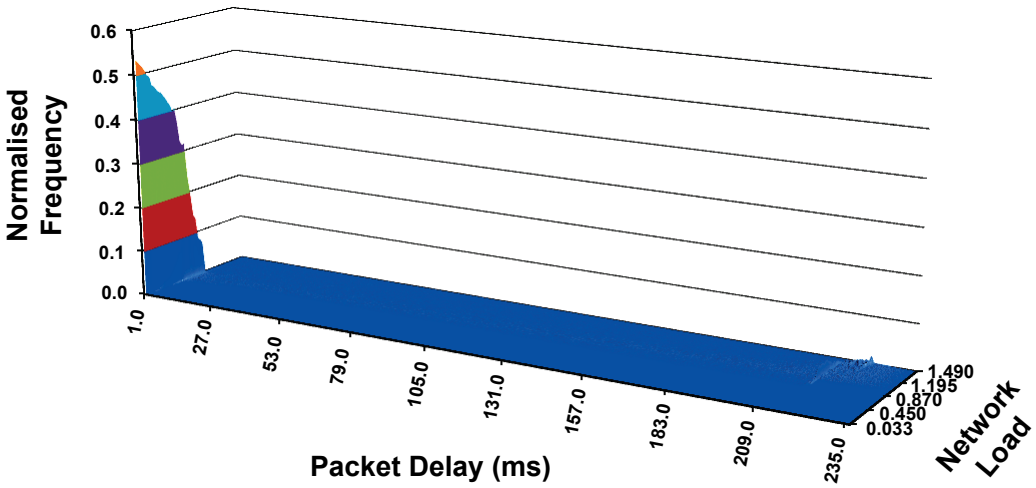

Figure 7.13 – Normalised frequency of the packet delay for the Delta-Buffer DBA algorithm, 1.0 ms ≤ t_p ≤ 236.5 ms and delay interval, t_{di} = 0.05 ms.

The distribution of packet delay for the Delta-Buffer DBA algorithm below congestion is shown in Figure 7.14 and Figure 7.15 with a chart rotation of 30° and 210° respectively. We can see from these distributions that the majority of the packet delay is distributed between a value of 1.8 ms and 2.0 ms which corresponds to a single GPON frame. As the duration of the allocation interval is set to the lowest possible value, $t_c = t_F$, and minimal wasted bandwidth is produced, the resultant packet delay is distributed over a single GPON frame offset by the RTT of the network. This frame corresponds to the first allocation interval after which each packet is requested. The variance in this region is only due to the arrival time and the packet size.

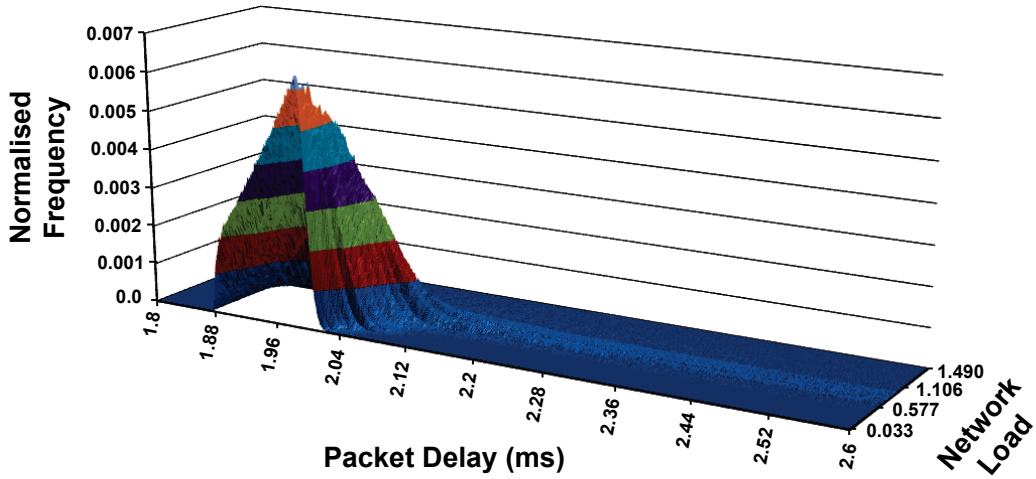

Figure 7.14 – Normalised frequency of the packet delay for the Delta-Buffer DBA algorithm, 1.8 ms ≤ t_p ≤ 2.6 ms and histogram frequency = 0.0005 ms, rotation = 30°.

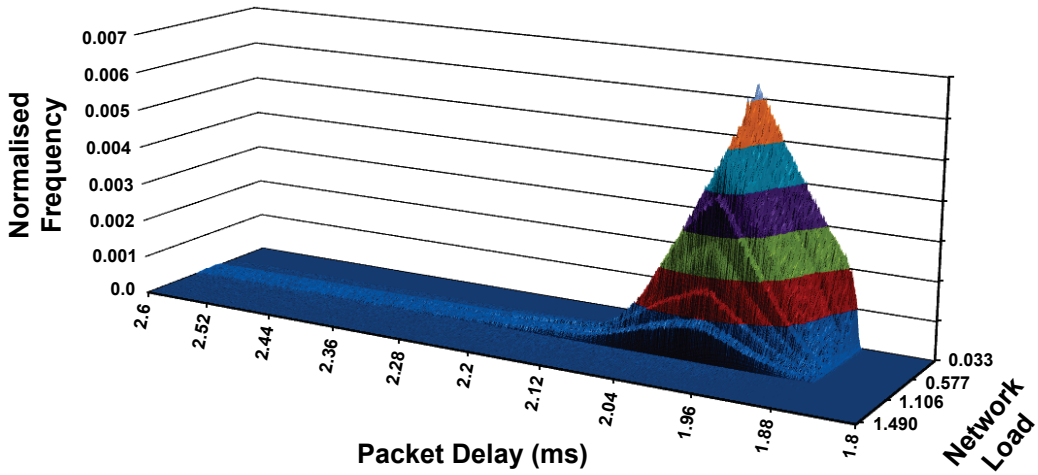

Figure 7.15 – Normalised frequency of the packet delay for the Delta-Buffer DBA algorithm, 1.8 ms ≤ t_p ≤ 2.6 ms and histogram frequency = 0.0005 ms, rotation = 210°.

As the network load increases towards the transition region, Figure 7.15 shows the histogram for the packet delay within the first allocation interval for the Delta-Buffer DBA algorithm decreases as the histogram begins to exhibit a greater spread. This is because as more customer traffic is injected to each ONU, more packets require buffering before being transmitted.

Figure 7.16 shows the distribution of the packet delay above congestion for the Delta-Buffer DBA. We can see a similar distribution to that of the Reduced-Interval DBA algorithm, as shown in Figure 7.12. The duration of the allocation interval when the Delta-Buffer DBA algorithm is used is set to a single GPON frame, the same interval as used with the Reduced-Interval DBA algorithm. The Delta-Buffer algorithm histogram displays similar distribution behaviour above saturation due to the variation in the size of the buffered packets.

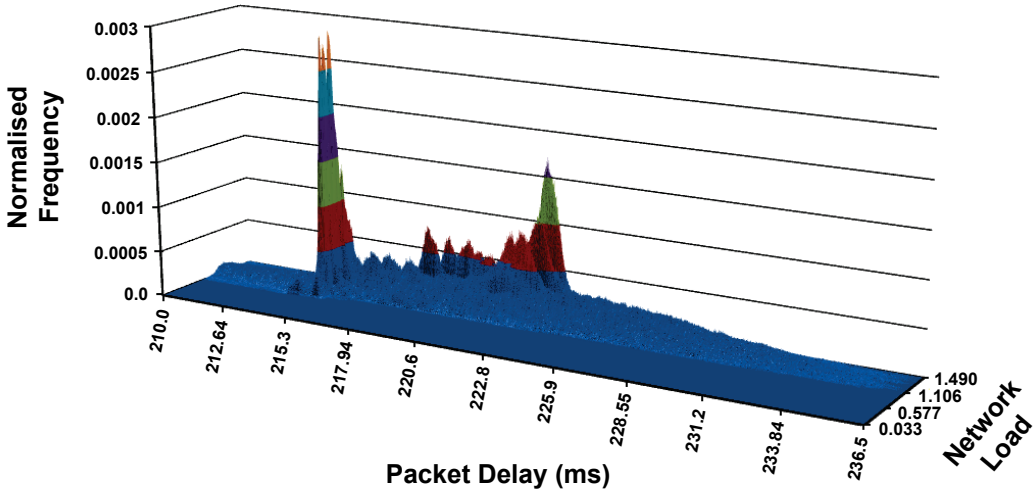

Figure 7.16 – Normalised frequency of the packet delay for the Delta-Buffer DBA algorithm, 210.0 ms ≤ t_p ≤ 236.5 ms and histogram frequency = 0.005 ms.

7.4 Conclusion

In this chapter we have examined the transient response of several DBA algorithms to understand the variance in packet delay produced by these algorithms. As some traffic services are not only delay sensitive, but also sensitive to the variance in delay, it is important to understand how each DBA algorithm behaves over time. With the injected customer traffic exhibiting bursty characteristics with long range dependence [51, 53], the injection rate of packets varies considerably from one allocation interval to the next. Any increase in delay variation can impact the availability of the network to provide real time traffic services. Examining the average delay does not provide any insight to the delay variance, or jitter, however by examining the transient delay response of an ONU we can determine how the upstream packet delay produced by a DBA algorithm occurs during sequential packet flows.

Section 7.2 demonstrates that the RTT-Based DBA algorithm produced a degree of delay variance over time and that the highest variance occurred between allocation interval boundaries. By reducing the duration of the allocation interval using the Reduced-Interval DBA algorithm, the delay variance actually increased due to the wasted bandwidth produced by the Reduced-Interval DBA algorithm allowing unrequested packets to be transmitted. While this can reduce the average delay, the delay variation increases.

The allocation reduction DBA algorithm, described in Chapter 4, included a reduction factor, $\delta_{e,n}(W)$, designed to reduce the amount of wasted bandwidth produced by the Reduced-Interval DBA algorithm. As the reduction factor increases, the delay variance settles over time so long as a continuous traffic flow is injected into the ONU. This decreasing delay variation occurs from a t_0 event and behaves similar to a damped control loop. As the nature of the injected traffic is bursty, this dampening effect repeats at each t_0 event. Therefore, the allocation reduction allocation DBA algorithm is effective in reducing the variations in the upstream packet delay, but only for continuous traffic injection.

The transient response of the Delta-Buffer DBA algorithm shows that regardless of the injected traffic, for a single ONU there is minimal upstream delay variation over time. This is because the algorithm is operating at the minimal allocation interval and only the required bandwidth is allocated to the ONU.

In section 7.3 we examined the distribution of the upstream packet delay produced by the RTT-Based DBA, Reduced-Interval DBA and Delta-Buffer DBA algorithms. We showed that the Delta-Buffer DBA algorithm produces a tighter delay distribution below congestion than the RTT-Based DBA. The longer allocation interval used in the RTT-Based DBA means that packets are buffered for a time equal to the allocation interval. The result is that for the RTT-Based DBA algorithm, the delay distribution below congestion is spread over two allocation intervals. Although the Reduced-Interval DBA algorithm displays a smaller delay distribution below congestion than the RTT-Based DBA, the transient response of the Reduced-Interval DBA showed that the delay variation of sequential packets was higher than the RTT-Based DBA.

Once congestion begins to occur, the delay distribution for all DBA algorithms is spread over the full range of the upstream delay and once saturation occurs, the majority of the

delay is distributed around the maximum delay value for each algorithm. Once congestion begins to occur, the upstream packet delay produced by the DBA algorithm no longer exhibits predictable behaviour as the delay of one ONU is severely affected by the injected traffic of all ONUs on the network. Above saturation, however, the delay exhibits some form of predictable behaviour as the allocated bandwidth to each ONU becomes constant. We can therefore conclude that in order to fully characterise the upstream packet delay for all network load, the transition region must be eliminated. This cannot be realistically achieved as the transition region is a product of the injected customer traffic which is beyond the control of the network operator.

Conventional representation of the average upstream packet delay produced by DBA algorithms in PON does not provide any information regarding the delay variation or distribution. For traffic services that are sensitive to variation in the delay, or jitter, such as video and voice traffic, there are often strict requirements on the variation in the delay. For LR-GPON, the upstream delay is determined by the DBA mechanism and specific algorithm used. This chapter has shown that by presenting the transient response of the delay as well as the delay distribution, full insight as to the delay behaviour can be obtained. By allocating the injected upstream traffic using the Delta-Buffer DBA algorithm in an LR-GPON, we have shown that minimal delay variation and distribution can be achieved below congestion and saturation.

8 Conclusion

8.1 Summary of Contributions

In this thesis we have addressed the issue of how to maintain low upstream packet delay produced by dynamic bandwidth allocation (DBA) in gigabit-capable passive optical networks (GPONs) and long-reach GPONs (LR-GPONs). Much of the literature surrounding PONs uncovers a direct, inverse relationship between the allocated bandwidth and the resulting average upstream packet delay. This relationship leads to a common approach in developing DBA algorithms whereby the principal focus is on minimising the upstream packet delay by increasing the amount of upstream bandwidth that is allocated to a particular subscriber or sets thereof [23, 25, 27, 41, 42, 45, 76]. While this approach is not without merit, the fixed amount of available upstream bandwidth in any GPON means that if allocations are increased to one set of subscribers, they must be reduced to other set thereby increasing their upstream packet delay. As the reach of the network increases the resulting upstream packet delay also increases. This thesis has addressed these issues by (a) modelling the delay of GPON, (b) developing DBA algorithms to minimise delay and maximise bandwidth efficiency and (c) analysing the average, variation and distribution of the delay.

8.1.1 Modelling the Delay of GPON

From the literature analysed in Chapter 2, we noticed that the majority of models for DBA in PONs are concerned with bandwidth allocation among subscribers and/or traffic categories of varying priorities. While such modelling can provide guidance to improve GPON quality of service (QoS), it does not specifically address the root-cause of the packet delay in PONs. In Chapter 3 we developed a mathematical model that describes the relationship between the various parameters of the DBA mechanism, the subscriber buffer levels and the resulting upstream packet delay. This model allowed us to develop an expression for the time difference, or delay, between an injected subscriber packet

and the corresponding reception of the packet at the optical line terminal (OLT). We then showed that the packet delay is not only affected by the allocated bandwidth, but is proportional to the duration of the allocation interval, t_c.

By reducing t_c in an effort to reduce the packet delay, we showed that when using the conventional request-allocate (report-grant) DBA mechanism, the round trip time (RTT) of the network is a limiting factor. Although t_c can be reduced below that of the RTT, the upstream bandwidth efficiency decreases as large amounts of bandwidth is allocated but not required.

8.1.2 Developing DBA Algorithms to Minimise Delay and Maximise Bandwidth Efficiency

In Chapter 4 we continued the modelling to reduce the wasted bandwidth produced when t_c is reduced below the RTT. We showed that an allocation reduction factor, $\delta_{e,n}(W)$, can be used to reduce the wasted bandwidth. In Chapter 6 we demonstrated through simulation that by reducing the allocated bandwidth using the allocation reduction DBA algorithm, the amount of wasted bandwidth is proportionally reduced, however a minimal increase in the packet delay is also observed.

We then proceeded to investigate the root-cause of the wasted bandwidth when t_c was set below the RTT to an absolute minimal value of one GPON frame. We developed the Delta-Buffer DBA algorithm that eliminates the wasted bandwidth using only the conveyed information in the DBA mechanism. We showed in Chapter 6 by simulation that the proposed Delta-Buffer algorithm allocates only the required bandwidth thereby eliminating the wasted bandwidth. We also showed that the Delta-Buffer DBA algorithm can provide excellent bandwidth efficiency and produce lower average upstream packet delay than conventional request-allocate DBA algorithms. While other proposed DBA algorithms in the literature have attempted to achieve a similar result, often the algorithms are not specific in their operation [22], rely on significant modification to the DBA mechanism [43], or utilise traffic prediction schemes [25, 50, 75].

8.1.3 Analysing the Variation and Distribution of the Delay

Throughout our analysis of the literature concerning DBA algorithms in both PONs and LR-PONs, we observed that the majority of the published results presented the steady-state average delay against the amount of injected subscriber traffic. We have shown in this thesis that the packet delay and jitter are parameters that are determined by the allocation interval as well as the dynamics of the injected subscriber traffic. The most common model for subscriber traffic used in the literature is a self-similar model that exhibits bursty characteristics [36, 51-53]. The bursty nature of this traffic model results in the ONU buffer levels fluctuating over time. These fluctuations translate to variations in the packet delay, or jitter. We have shown that analysing the effectiveness of a DBA algorithm purely by the steady-state response does not provide full insight as to how the DBA algorithms behave. This is especially of concern when analysing the jitter produced by the algorithms.

In this thesis we have tackled this issue by also analysing the packet delay by means of two approaches; the transient response of the delay and the distribution of the delay against the density of the injected subscriber traffic. We have shown that by using DBA algorithms based on the conventional request-allocate mechanism, the resulting packet delay displays large variations which directly translate to large jitter. We have shown that by reducing the duration of the allocation interval below that of the RTT, these variations increase. By using our proposed Delta-Buffer DBA algorithm, we have shown that below network congestion, this algorithm virtually eliminates variations in the upstream packet delay [117, 118].

In Chapter 7 we analysed the distribution of the packet delay and showed that the duration of the delay has a wide distribution in the regions below congestion and above saturation. Using conventional request-allocate DBA algorithms, the delay below network congestion is widely distributed over the allocation intervals leading to large variations in the packet delay. We showed that by using the proposed Delta-Buffer DBA algorithm, the delay below congestion has a much slimmer distribution thereby reducing the variations in delay, or jitter.

8.2 Possible Future Research Directions

This thesis is principally concerned with the dynamic bandwidth allocation mechanism for the ITU standardised GPON and LR-GPON. The key results of this thesis revolve around the modelling of the packet delay and bandwidth efficiency as well as the development of efficient DBA algorithms. These principals can assist in potentially new areas of research.

8.2.1 Higher Capacity Access Networks

The ITU has recently standardised the next generation of PONs, or XG-PON, that can operate at synchronous line rates of up to 10 Gbps [119] and the IEEE has released the standards for 10GEPON that also operates at line rates of 10 Gbps [120]. While the framing structures of these higher capacity PONs differ to that of GPON, the underlying concepts of the DBA can still be applied to other point to multi point (PTMP) access networks. In any PON, each ONU resides at a fixed location with respect to the OLT and therefore the PTMP architecture is still used. The models developed in this thesis can still be applied; however further investigation into the specifics of the timing and bandwidth allocation would be required. The development of a universal DBA mechanism based on the Delta-Buffer DBA could help maintain efficient bandwidth utilisation, low latency and low jitter in future passive optical networks as their capacity continues to grow.

8.2.2 Modelling Complete Buffer Behaviour

Further investigation can be applied when multiple priorities and/or ONUs are included into the modelling of the buffer levels. In Chapter 2 we saw that the majority of the DBA modelling is concerned with bandwidth redistribution [48, 66] and inter-ONU/intra-ONU scheduling [20, 50]. By incorporating these models into the model we have developed in Chapter 3 and Chapter 4, further insight in to how the buffer levels of one subscriber are affected by other subscribers can be realised. The development of such a model is not without challenges as the buffer behaviour of one subscriber is dependent on the total available bandwidth which is in turn affected by the dynamics of the injected traffic of all the other subscribers.

8.2.3 Interaction of QoS Amongst Subscribers

Some of the literature examined in Chapter 2 was concerned with network behaviour when varying priorities were allotted to different subscribers. By varying the allocated bandwidth due to differing levels of subscriber priority, variations into the resulting packet delay could be introduced thereby potentially affecting the quality of service (QoS). Further research could investigate the interactions between QoS of different users due to the properties of a given user's traffic.

8.2.4 Occurrence of Chaotic Behaviour

Our DBA modelling developed in this thesis uncovered that the buffers display periodic behaviour due to the occurrence of t_0 events, or initial conditions for a given subscriber. The subsequent buffer behaviour for that subscriber depends on the available bandwidth which is in turn dependant on the buffer levels of all other subscribers. As the density of the network traffic increases, it is unlikely that all buffers experience t_0 events simultaneously. Being a highly non-linear, high dimensionality system [121], it is possible that chaotic behaviour may occur due to the random nature of the injected traffic and complexity of the DBA model. An opportunity therefore exists to expand on the DBA model presented in this thesis to investigate potential chaotic behaviour of the system and its impact on PON quality of service.

8.2.5 Integrating the Delta-Buffer DBA into future PON standards

In Chapter 4 we developed the Delta-Buffer DBA algorithm and showed that this DBA algorithm produced low upstream packet delay while maintaining excellent bandwidth efficiency. As future PON standards are developed further investigation is required to integrate the Delta-Buffer DBA into these standards.

8.2.6 Dynamics of t_0 Events

In Chapter 3 we showed that when the requested buffer level at an ONU was zero and stayed zero for a time equal to, or longer than, an RTT a t_0 event was created that affected the dynamics of the buffer behaviour model. When the conventional RTT-Based request-allocate DBA algorithms are used and the duration of the allocation interval is less than the RTT we showed that these t_0 events are responsible for a severe degradation in bandwidth efficiency. Using the Delta-Buffer DBA algorithm, no decrease in bandwidth efficiency was observed at a t_0 event; however as further DBA algorithms for LR-PONs are developed these t_0 events cannot be ignored. Therefore further investigation of the dynamics of t_0 events and their impact on QoS would be of value.

A Appendix – Simulation Environment

A.1 Adapting the DBA Models to the Simulation Environment

In Chapter 3 we developed a mathematical model for the ONU buffer behaviour based on the duration of the allocation interval t_c. From there, we went on to develop general expressions for the total upstream delay for a given packet arriving at time t. These expressions, (3.11) and (3.19), rely on knowledge of the buffer level at the time the packet arrived and the upcoming allocations from the OLT. As the allocations exist in future time, it is not possible to pre-determine the exact delay a given packet will suffer. It is only possible to estimate the delay based on the knowledge of past allocations. We also showed that the allocations made in the BWmap are derived from the buffer occupancies whilst also factoring in the service level agreements (SLAs). The buffer occupancies are determined by both the newly arriving BWmaps and the injected traffic.

For the DBA mechanisms described in Chapter 3, the only parameters that a network operator has the ability to adjust or control are t_c and the maximum window sizes defined by the SLAs. t_c can be adjusted with relative simplicity as the parameter is defined by a simple number of GPON frames. The SLAs are not quite so straight forward. In GPON, multiple types of T-CONTs exist to handle the varying levels of traffic priority [11]. At the OLT, these T-CONTs can consist of multiple arrangements of maximum window sizes, or allowable bandwidth, based on the T-CONT type.

Recall that the relationship between a T-CONTs DBRu, $B_{B,n}(Mt_c)$, the corresponding allocation in the BWmap, $B_{A,n}(Mt_c)$, and the SLAs, $B_{A,n}^{SLA}\left(Mt_c\right)$, using the DBA mechanisms described in Chapter 3 is given by (3.9) where the allocations to all N T-CONTs are bound by

$$\sum_{n=1}^{N} B_{A,n}\left(Mt_c\right) = B_{PON}^{\max}\left(Mt_c\right) \tag{A.1}$$

where $B_{PON}^{\max}(Mc)$ is the maximum number of bytes available in the current interval as per the GPON capacity. Equation (3.9) is applicable for all T-CONT types except for type 1. Type 1 T-CONTs do not fall within the jurisdiction of the DBA

The simulation environment allows for multiple T-CONT types to transport the upstream packets. Each of these types consists of varying SLA components. To implement (3.9) into the simulation we must specify the maximum window sizes for each T-CONT type according to the SLA.

A.1.1 SLAs for Type 2 T-CONTs

Type 2 T-CONTs comprise of only a single maximum window limit. The assured bandwidth component is always allocated should it be required by the T-CONT. The maximum number of bytes according to $B_{A,n}^{SLA}(Mt_c)$ is set by the maximum assured bandwidth. However, we also incorporated a leaky bucket policer to increase the allocation to account for the bursty nature of the traffic. This leaky bucket may allow for a larger maximum window depending on the number of tokens within the bucket. Incorporating the effect of the leaky bucket, the SLA for type 2 T-CONTs, $B_{A,n}^{SLA_2}(Mt_c)$, is therefore given by

$$B_{A,n}^{SLA_2}(Mt_c) = \max\begin{bmatrix} B_n^{\max} \\ Btk_n(t_c) \end{bmatrix} \tag{A.2}$$

where $B_n^{\max}$ is the maximum window size and $Btk_n(t_c)$ is the number of bytes in the leaky bucket due to tokens being added. The default token rate for type 2 T-CONTs is one GPON frame and the token size is equal to the maximum window size, $B_n^{\max}$. This dictates that at any given allocation interval, $Btk_n(t_c) \geq B_n^{\max}$ therefore, assuming that the leaky bucket is active and the token rate is one GPON frame, the SLA for type 2 T-CONTs is

$$B_{A,n}^{SLA_2}(Mt_c) = Btk_n(t_c) \tag{A.3}$$

A.1.2 SLAs for Type 3 T-CONTs

Type 3 T-CONTs consist of two bandwidth components; assured and non-assured. The simulation environment does not utilize any leaky buckets for type 3 T-CONTs and therefore the SLA for these T-CONTs, $B_{A,n}^{SLA_3}\left(Mt_c\right)$, can be broken into two parts.

$$B_{A,n}^{SLA_3}\left(Mt_c\right) = B_{assured,n}^{\max} + B_{non-assured,n}^{\max} \tag{A.4}$$

where $B_{assured,n}^{\max}$ is the maximum window of the assured component and $B_{non-assured,n}^{\max}$ is the maximum window of the non-assured component. The assured component is fixed and does not depend on the amount requested in a DBRu and cannot be over-subscribed. The non-assured component is assumed to be oversubscribed and the total number of bytes allocated to all T-CONTs is still bound by (3.8) giving the total number of bytes allocated in the non-assured component, $\sum_{n=1}^{N} B_{non-assured,n}$, as

$$\sum_{n=1}^{N} B_{non-assured,n} \leq B_{PON}^{\max}\left(Mt_c\right) - B_{A,n}^{\psi} \tag{A.5}$$

where $B_{A,n}^{\psi}$ is the total bytes allocated prior to allocating the non-assured component. As the non-assured bandwidth can be oversubscribed, provision must be enforced on the allocation of the non-assured bandwidth such that (A.5) holds true. To do this, the simulation uses min-max scheduling that re-distributes the available bandwidth, $\sum_{n=1}^{N} B_{non-assured,n}$, among the required T-CONTs with a degree of fairness.

Min-max scheduling is used to provide fairness to subscribers or network elements [108, 109]. When compiling the non-assured bandwidth components for the BWmap, the simulation environment polls each T-CONT in numerical order as this simplifies the code. If a fairness scheme is not utilized, polling in a preset order may result in the first T-CONT being allocated larger amounts of bandwidth than the last T-CONT. Min-max scheduling ensures that each T-CONT is only allocated up to a proportion, P_n, of the remaining bandwidth. After each T-CONT has been allocated the proportion is recalculated and the process continues. This ensures that all T-CONTs are allocated fairly and that (A.5) is satisfied.

The SLA component for the non-assured bandwidth component is therefore given by

$$B_{non-assured,n}^{\max} = \min\left[\begin{array}{l} B_n^{\max} \\ P_n \end{array}\right. \tag{A.6}$$

where P_n is given by

$$P_n = \left(B_{PON}^{\max}\left(Mt_c\right) - B_{A,n}^{\psi}\right)\left(\frac{B_n^{\max}}{\sum_{j=1}^{N} B_j^{\max}}\right) \tag{A.7}$$

Using (A.4), (A.6) and (A.7) to construct the SLA for type 3 T-CONTs, both assured and non-assured bandwidth can be allocated whilst guaranteeing fairness amongst the T-CONTs and only allocating available bandwidth.

A.1.3 SLAs for Type 4 T-CONTs

Type 4 T-CONTs are considered best-effort (BE) and are only allocated is sufficient bandwidth remains after all other T-CONT types have been allocated. The method by which the SLA for these T-CONT types is determined is similar to that of the non-assured component of type 3 T-CONTs. For BE T-CONTs, the SLA is given by

$$B_{BE,n}^{\max} = \min\left[\begin{array}{l} B_n^{\max} \\ P_n \end{array}\right. \tag{A.8}$$

where P_n is given by

$$P_n = \left(B_{PON}^{\max}\left(Mt_c\right) - B_{A,n}^{\zeta}\right)\left(\frac{B_n^{\max}}{\sum_{j=1}^{N} B_j^{\max}}\right) \tag{A.9}$$

where $B_{A,n}^{\zeta}$ is the total bytes allocated by the OLT prior to allocating the BE T-CONTs.

Constructing the SLA for type 4 T-CONTs according to (A.8) and (A.9) allows for these T-CONTs to be allocated only if any remaining bandwidth is available and ensuring that no unavailable bandwidth is allocated.

A.1.4 Allocation Reduction

In Chapter 4 we devised a DBA algorithm to minimize the wasted bandwidth when the duration of the allocation interval is less than the RTT of the GPON. This algorithm, defined by (4.5), modifies the relationship between the DBRu and the BWmap such that the number of bytes allocated in the BWmap is a lower proportion than that requested in the DBRu. In the simulations, the OLT module holds a variable that represents the buffer level at each T-CONT according to the relationship between the DBRu and the BWmap. In the standardized DBA mechanism this relationship is 1:1, as defined by (3.9). When the allocation reduction algorithm is used this relationship is defined by (4.5). The result is that the OLTs variable is not an exact representation of the T-CONTs buffer occupancy, rather a representation of the occupancy from the OLTs *perspective*.

A.1.5 Delta-Buffer DBA

Recall that the Delta-Buffer DBA algorithm is defined by (4.13). The OLT calculates the differential incremental buffer occupancy over each allocation interval and compiles the BWmap accordingly. In order for the OLT to accurately calculate the buffer occupancy, knowledge of the BWmap issued in the last RTT must be used. In the simulation environment the OLT retains the BWmaps issued for a duration of up to one RTT as they are required to ensure that the current upstream frame contains the correct bursts from the specified ONUs. These retained BWmaps are also used for the Delta-Buffer algorithm.

To implement the Delta-Buffer DBA algorithm in the simulations, (4.13) is used to create a relationship between the DBRu and the BWmap for the given T-CONT. The OLT uses this relationship to create a variable to store the T-CONTs buffer occupancy. This variable is used to then construct the BWmap.

A.2 Simulation Parameters

The SLAs provide limitations as to the maximum number of bytes allocated to any given T-CONT. Although the SLAs and the duration of the allocation interval are the principle parameters of the DBA mechanism that the network operator can manipulate, many of the other parameters in the simulation environments can be varied to suit a particular

configuration. Some parameters are common across all the simulations and are listed in Table A.1 and Table A.2.

Table A.1: Common simulation environment parameters.

Parameter	Value
Number ONUs	32
Upstream frame size	19,440 Bytes
No. of guard bytes	12 Bytes each ONU
No. of PLOAMu bytes	13 Bytes each ONU
DBRu size	3 Bytes each associated T-CONT
T-CONT buffer size	1.0 Mbyte
T-CONTs per ONU	6
GEM frame payload	48 Bytes

Table A.2: Common simulation traffic parameters.

Parameter	Value
Self-similar frame sizes	64 to 1500 Bytes
Self-similar α parameter	1.4
Self-similar inter-packet gap	20 Bytes
TCP-IP streams	1 per ONU
TCP-IP injection rate	60.0 Mbps
TCP-IP target load	0.0125 to 1.0
VoIP packet size	192 Bytes
VoIP injection rate	78.6 Kbps
HD Video packet size	296 Bytes
HD Video injection rate	2.0 Mbps ±1.0 Mbps
HD Gaming injection rate	2.0 Mbps
HD Gaming target load	0.75
P2P injection rate	2.0 Mbps
P2P target load	0.5
UDP injection rate	0.5 Mbps
UDP target load	0.5

While the parameters in Table A.1 and Table A.2 do not change throughout the simulations, other parameters are varied depending on the associated simulation. These parameters are listed in Table A.3 along with the minimum and maximum values.

Table A.3: Variable simulation parameters.

Parameter	Range
Allocation interval (t_c)	Min: 1 GPON frame Max: 10 GPON frames
Allocation method	Total requested Delta-Buffer
Traffic estimation (δ)	Min: 1.0 Max: 10.0
BWmap allocation order	Random Ascending Descending Fixed-numerical
Equalization delay buffer	Buffer on receive Buffer on transmit Buffer on both

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