Analytical Approach to Dynamic Bandwidth Allocation Algorithms used in LRPON

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved June 2012 by the
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August 2012

ABSTRACT

With internet traffic being bursty in nature, Dynamic Bandwidth Allocation*(DBA)* Algorithms have always been very important for any broadband access network to utilize the available bandwidth efficiently. It is no different for Passive Optical Networks(PON), which are networks based on fiber optics in the physical layer of TCP/IP stack or OSI model, which in turn increases the bandwidth in the upper layers. The work in this thesis covers general description of basic DBA Schemes and mathematical derivations that have been established in research. We introduce a Novel Survey Topology that classifies DBA schemes based on their functionality. The novel perspective of classification will be useful in determining which scheme will best suit consumer's needs. We classify DBA as Direct, Intelligent and Predictive back on its computation method and we are able to qualitatively describe their delay and throughput bounds. Also we describe a recently developed DBA Scheme, Multi-thread polling(MTP) using for LRPON and describes the different viewpoints and issues and consequently introduce a novel technique Parallel Polling that overcomes most of issues faced in MTP and that promises better delay performance for LRPON.

DEDICATION

To my Parents, Mercian Sheela and Sister, Anju

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my Advisor Dr. Martin Reisslein, for giving me this opportunity to research and for the continuous guidance to maintain the right path towards research. I would like to express my sincere gratitude to Dr. Michael McGarry, for his constant help throughout my research. I would like to thank Dr. Cihan Tepedelenlioglu and Dr. Yanchao Zhang, whose classes were my fundamental building block for research. I thank my lab mates, Revak Raj Tyagi, Yousef Dashti, Du Zhao, Kishanram Kaje, Xing Wie and all of the others, who provided me with immediate help and support that helped me complete my thesis. I would like to also thank my family and friends, whose constant support and encouragement kept me going till the end. Last but not the least, I thank The Almighty for making this thesis possible.

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Chapter 1

INTRODUCTION

Passive Optical Networks have gained high precedence in the entire Broadband Network as the last mile solution as it gained popularity because of the immense amount of bandwidth(BW) it can offer and can satisfy higher QoS standards. The digital subscriber line(DSL) which provided a copper physical layer, was previously provider and used widespread. Although it provided a stable and reliable access network, it was not able to support the newer technologies such IP Telephony, Video conferencing etc and copper cables soon degraded which led to high maintenance cost. Thus, PON access network was sought-out for, along with high bandwidth capacity, it was easy to deploy and maintain because of its physical elements consist of only combiners, couplers and splitters in its network [19] and was also cost effective in terms of capital and operation.

Passive Optical Network has three major components, namely Optical Line Terminal (OLT) which forms the base station which connects the core network to the access network, Optical Network Unit (ONU) which is the terminating unit of the network and the optical spitter which is the point that splits the network into multiple ONUs. The ONU was the base station and receiver which handled most of the operations such as bandwidth allocation, amount of bytes that can be allocated for an ONU or which is termed transmission window [10], the count of number of ONUs etc. ONU is the interface between the end user and access network. It consists of a queue buffer that collects data/packets from the user and transmits. PON was easily adoptable to the present structure and so it can be overlaid on the existing topologies as can be seen in Fig 1.1.

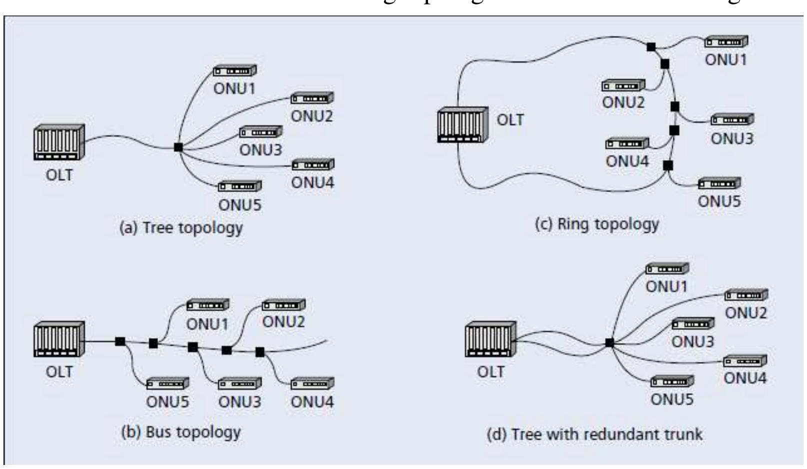


Figure 1.1: PON topologies [20].

Evolution of PON started with the ATM PON (APON) which was based asynchronous transfer mode(ATM) wherein packets were transfered as fixed sized packets [20] that proved to be

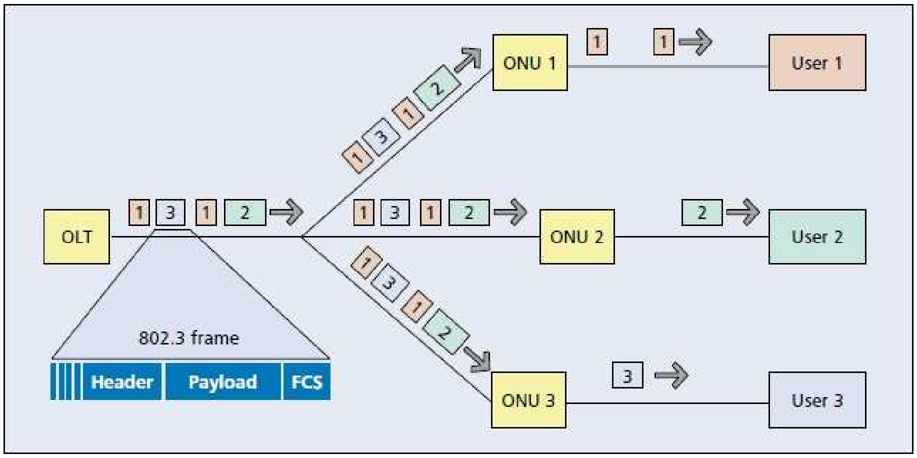


Figure 1.2: Downstream Traffic in EPON [20].

an inefficient use of bandwidth. Later packets were transfered in variable packet sizes and in bursts which gave more bandwidth efficiency. This was later called Broadband PON (BPON)[18]. Gradually by improvemnt of bandwidth allocation schemes and standards, it was possible to obtain gigabit (GB) bandwidth and this gave rise to Gigabit PON (GPON). All the mentioned access networks were designed by ITU-T standardization. The IEEE standard, on the other hand, which was more popular at that time designed the Ethernet PON (EPON) with standard *IEEE 802.3ah*. Since the GPON and EPON were two attractive standards, they were combined to give the GE-PON. Most present day researches revolve around these two standards. All the above standards initially covered a physical distance between OLT and ONU of about 20Km. This later turned out to be a disadvantage and it was overcome by Long-reach PON (LRPON) that covers a distance of 100Km .

The traffic from the OLT to the ONU is the downstream traffic and it is a single-point to multipoint transfer and can be compared to a broadband networks. As shown in Fig 1.2, all packets from OLT are sent to all ONU and a unique ID number will determine the respective ONU [20]. And the transfer from each ONU to the OLT is the upstream traffic which follows the multi-point to single-point traffic and can be compared to peer-to-peer(P2P) network. As shown in Fig 1.3, all packets come towards a center point, there could be collision, if the packets are not sent on a sharing basis. Thus multiplexing techniques were introduced such as time-division multiplexing(TDMA) and wavelength-division multiplexing(WDMA) are introduced. The techniques will be described in Section 1.1.

Bandwidth allocation is done by communication between ONU and OLT about the requirements of ONU and the resources of the OLT. This communication is possible by a protocol

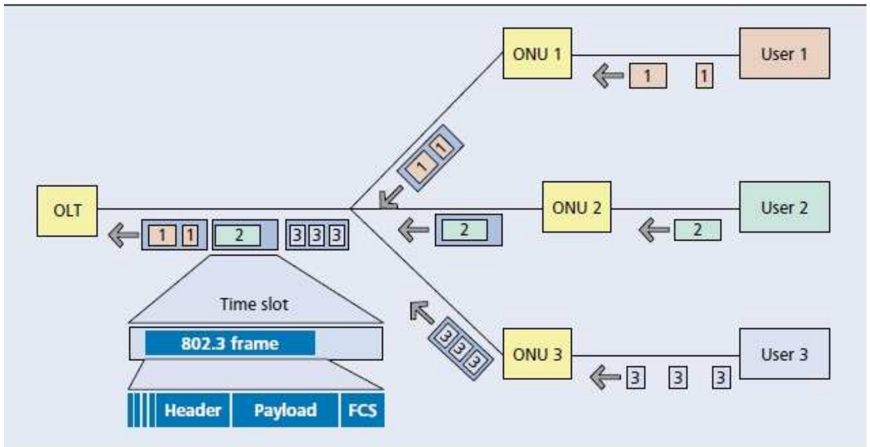


Figure 1.3: Upstream Traffic in EPON [20].

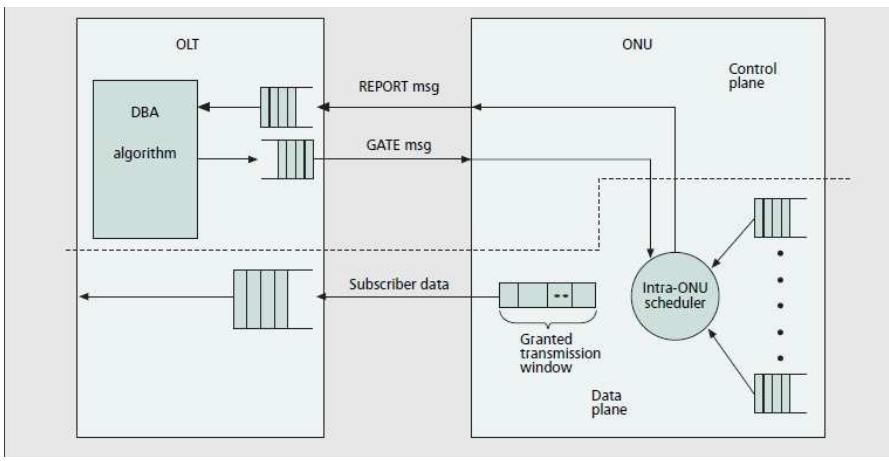


Figure 1.4: MCPC operation [10].

called the Multi-point Control Protocol [10]. The protocol consists as explained in Fig 1.4:

1. REPORT that is used by the ONU to inform the OLT the remaining packets in the queue that have to be transfered
2. GATE which provides the ONU with the transmission window size, the amount of data that can be transfered in one cycle time.
3. REGISTER_REQ, used to request the ONU if a new ONU can be installed to the existing system
4. REGISTER, used to register the new ONU
5. REGISTER_ACK, used by OLT to acknowledge the new ONU request

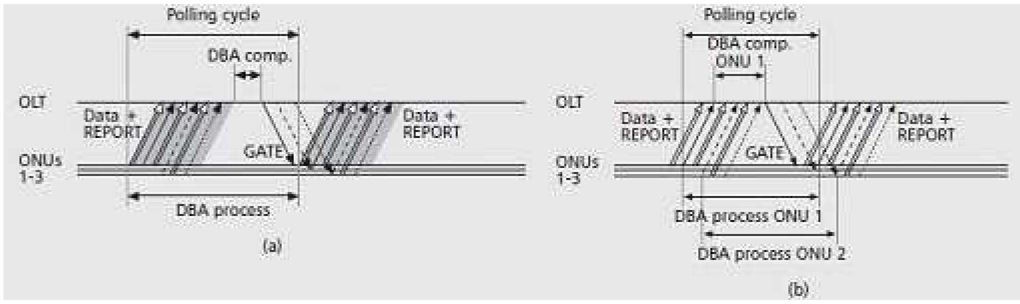


Figure 1.5: Packet transfer in EPON (a) Offline (b) Online[13].

We will be including a survey study as a part of the thesis work where we will be discussing how Bandwidth allocation evolved for the different PON types and classify them according to taxonomy that has been entirely contributed by us in Chapter 3. The rest of the paper is organized as follows. Section II gives an overview of related surveys in this field to highlight the contributions of this paper.In Chapter 3, we will discuss the major PON classification that will be used in the taxonomy. In Section 3.1, we will be discussing in detail the DBA classification and in Section 3.2, we will consider couple of papers that analyze how certain parameters such as delay, jitter and bandwidth utilization is affected by load and reach.

1.1 Passive Optical Networks

In this section, we want to give certain basic classifications of PON types. Passive Optical Networks evolved because to cater the need of broadband access networks bandwidth requirements. When APON was deployed initially, its bandwidth was a lot lesser than expected with 155-622Mbits/sec [18]. Later by improving DBA schemes and other standardizations, bandwidth was gradually improved to present day where almost 1Gbits/s is obtained. As mentioned before, EPON and GPON is the main attraction for present day commercial deployment and research requirements. Thus they are explained in detail in this section.

EPON vs GPON

As we know from Section I, EPON is an IEEE standard that follows the MPCP protocol for data transfer, the REPORT and GATE messages are used for the ONU-OLT communication [20]. The advantage of EPON is that it can support Differentiated Services(DiffServ) and various levels of QoS [1]. Thus Differentiate Services covers a large amount of traffic types and thus gives way for future technologies such as IP Telephony, video conference etc. Fig 1.5 gives an illustration of the different DBA approachs(Online and Offline explained later in this section) in EPON with labels to illustrate the use of MPCP protocol (REPORT and GATE messages).

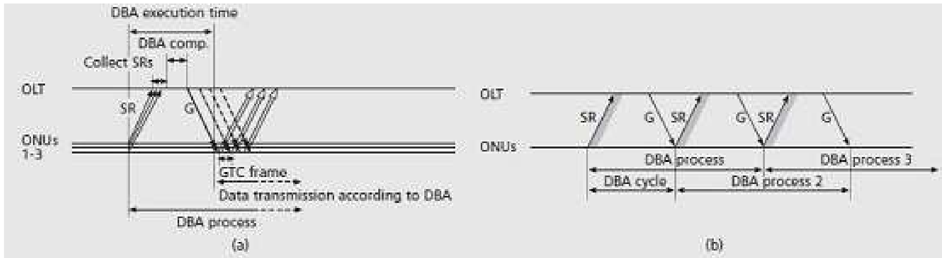


Figure 1.6: Packet Tranfer in GPON (a) The SRs sent to OLT to inform OLT of the queue size and Grants being sent to ONU (b) more compact form of the packet transfer figure [10].

The GPON on the other hand is a ITU-T G.984 standard and uses T-CONTs(Transmission Container) buffer as a part of Status REPORT(SRs) and BW-maps(Bandwidth) as a part of GRANT within GPON Transmission Convergence (GTC) header. T-CONTs sent to the OLT to inform, of the remaining queue size that has to be transfered. And BW-maps contain the Transmission window size that can be alloted to the ONU. In the case of GPON, ONU reports any increase in remaining bandwidth in previous allocations included in the GPON encapsulation frame [12]. More differences can be observed when describing the bandwidth allocation in each in the next section. In Fig 1.6, we present a figure that illustrates the packet transfer between OLT and ONU in GPON.

Standard-Range(SR) PON vs Long-Range(LR) PON

This comparison will be very important in the analysis we do, as they form large part of today's research. The major difference between SR and LR is the difference in distance. The distance between the ONU and the OLT is only 20km in case of standard-range and for LRPON is 100km. The latter is advantageous because it covers a large distance and the splitting ratio can be increased to accommodate more ONUs for a single OLT. Hence lesser requirement of equipments, thus rendering reduction in Capital Expenditures (CapEx) and Operational Expenditures (OpEx) [7]. But the disadvantage in LR-PON is that because of the larger distance coverage, packet strength may diminish and the packet can be lost while propagating and it could also account for high propagation delay. Optical amplifiers are used to amplify the signal strength and new DBA schemes are introduced to utilize the propagation delay to accommodate more packet transfer. The comparison between SRPON and LRPON are shown in Fig 1.7.

TDM vs WDM

These multiplexing techniques were mentioned earlier as methods to avoid collision at the optical splitter during upstream transmission of data from the ONUs to OLTs. Time-division multiplexing (TDM) [4] is a technique wherein each ONU is allocated certain time slot to access the channel.

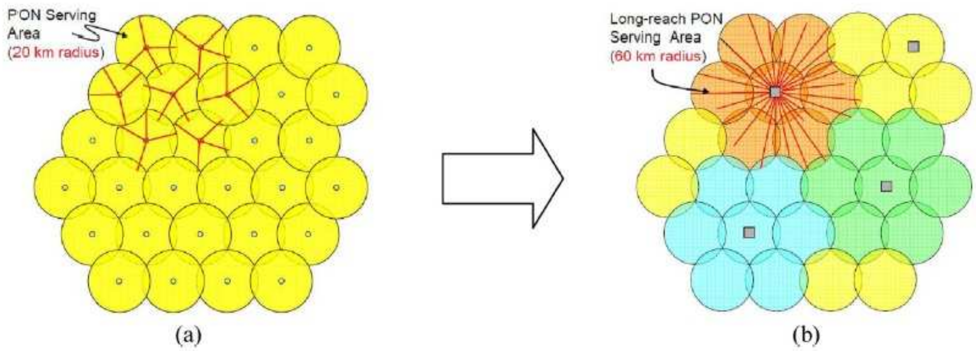


Figure 1.7: Comparison of SRPON and LRPON Coverage [17].

This is useful such that all ONUs are given fair share of the channel[6]. But the disadvantage in this case is the time each ONU has is limited, thus only smaller transmission window can be granted for each ONU and correspondingly lesser throughput.

Wavelength-division multiplexing (WDM)[8] is another technique where a set of wavelengths are shared between all ONUs. For example, 4 wavelengths can be shared between 16 or 32 ONUs. Therefore the entire bandwidth of the channel will be available to an ONU at any point of time. And a channel will be shared by comparatively lesser number of ONUs using a same wavelength[9]. This technique proves to be better than TDM because the ONU has the entire channel at any point of time.

Chapter 2

DYNAMIC BANDWIDTH ALLOCATION(DBA) DESIGN SPACE

Internet traffic which mostly is data, voice and video are sent in the network and they come in the form of packet bursts. Therefore, in case of TDM where the network is shared between multiple ONUs, sending bursts of traffic can leave certain timeslots empty and overflow the other when there is heavy traffic. In order to avoid PON bandwidth being either under-utilized or over-utilized, it is always better to have a bandwidth allocation algorithm in the OLT that decides how efficiently the available bandwidth can be utilized. . Therefore this area attracts huge attention for research. The initial methods of bandwidth allocation was Static Bandwidth Allocation (SBA). SBA, as the name implies allocates static or fixed bandwidth to each ONU irrespective of the packet load or traffic[1]. This definitely had its downside for the following reasons:

1. Network traffic was bursty in nature and thus SBA could not utilize the bandwidth efficiently. For example, in case of a heavy load, the bandwidth was insufficient and for a light load, the bandwidth was overwhelming.
2. Network traffic was increasing in dimension with services like IP telephony, video conferencing etc. SBA was not able to cater these needs.

Static bandwidth allocation (SBA) was using a standard technique of fixed timeslots to each ONU in case of TDM. This does not help the situation of bursty internet traffic, where it is unaware when the traffic is going to be light and heavy. In such situations, allocations that make decisions dynamically will be a more feasible solution.

DBA, as the name implies dynamically changes bandwidth allocated based on the requirement or in other words, it provides statistical multiplexing amoung ONUs. The oldest type of DBA is the Standard polling. From Chapter 1, we are aware of the Multi-point Control Protocol, where in case of EPON, GATE messages are sent to ONU from OLT and REPORT messages from ONU to OLT. As shown in Fig 2.1, standard polling is sending the grant (GATE in case of EPON) to the ONU, which specifies the amount of data that can be transfered and ONU sending the report and date (REPORT) to the OLT indicating the amount of data remaining to be transfered[10]. In standard polling, high idle time is introduced because of which there will be high delay incurred. In order to avoid this, another method Interleaved Polling with Adaptive Cycle Time(IPACT) was introduced [14].

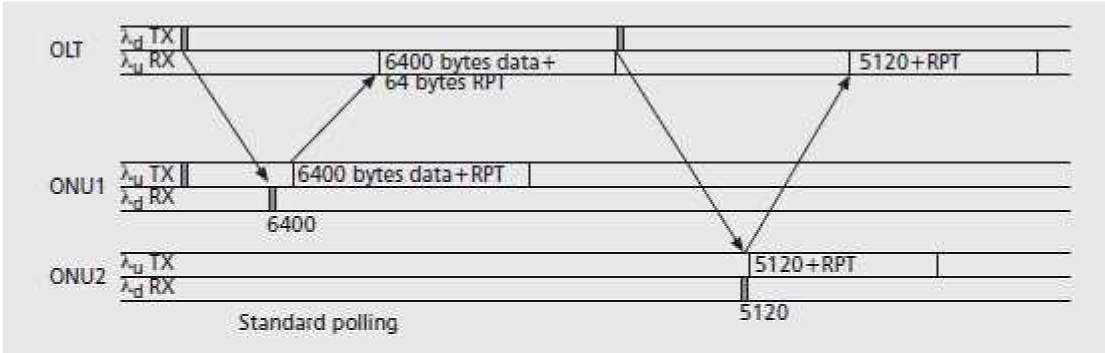


Figure 2.1: DBA technique: Standard polling [10].

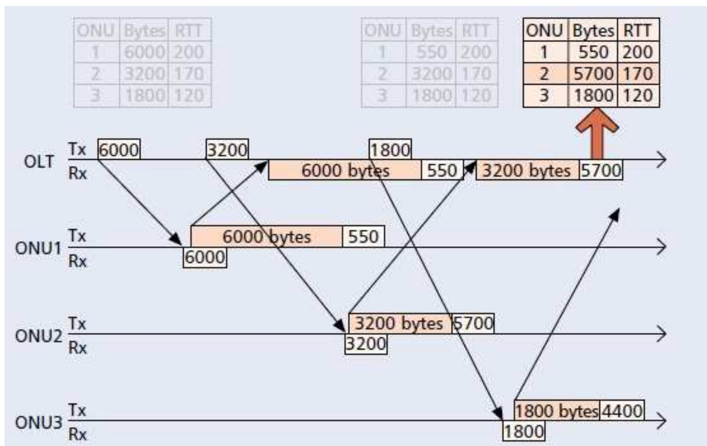


Figure 2.2: DBA technique: IPACT [14].

The used of Interleaved polling (IPACT) resulted in reduced idle time, which is equivalent to increased channel utilization as more packets can be sent and this subsequently reduces queuing delay for the packets in each ONU queue buffer. In IPACT, we assume that the OLT knows the round-trip time(RTT) of the each ONU-OLT connection[14]. RTT is the time it takes for a bit to propagate from ONU-OLT-ONU, it depends on the distance between the OLT and the ONU. The OLT also has information of the byte requirement of the ONU (from the REPORT message). As shown in Fig 2.2, the Grant is sent to the second ONU even before the data from the first ONU is received. As we compare Fig 2.1 to Fig 2.2, we can see the difference in wait time and that IPACT is better. IPACT has five different types: Fixed, Limited, constant-credit, linear-credit and elastic service. Each will be descibed in the next section.

Design Space The OLT(Optical Line Terminal) processes the bandwidth allocation algoritms. When Dynamic Bandwidth Allocation (DBA) is analyzed on an overall basis, most schemes follow an flowchart to implement that mechanism. Most of the time, it is referred by different names and hence, the flowchart gets hidden. From the effects of McGarry .et. al. [22], it has been made possible to categorize the different levels when designing dynamic bandwidth allocation algorithms. All the schemes are predefined. The attempt of categorizes it is to enable different experimentation, thus possibility to obtain the optimized combination. In this paper, they take an attempt to categorize DBA mechanisms as follows:

grant scheduling framework — which is for the types of events that initiates grant scheduling

grant sizing — which determines after DBA processing, what is the optimized size of the grant that is will make the DBA efficient

grant scheduling policy — which decides the manner in which the grants are scheduled to the ONU

In order to mathematically represent the different elements of the design space, we need to introduce certain parameters that will help us in understanding the different schemes. We consider a DBA Model that describes upstream traffic. While introducing the different schemes, we state corresponding start time and end time equations, when traffic arrives at the OLT at a cycle time. These equations will later be useful in deriving the idle time equations for established Grant scheduling frameworks and the new grant scheduling framework we will later introduce in our work. α describes the start time of upstream traffic and when it is added with the transmission window size G, granted to ONU by the OLT, it gives us the end time β for that upstream traffic from ONU, which is explained in Equation 2.1. Equation 2.2 gives the start time in terms of scheduling time γ and polling time T or time at which upstream channel is free, which is denoted as η. Similarly Equation 2.3 describes upstream free time in terms of end time β. These equations form the basics of our design space model.

$$\beta(j,n) = \alpha(j,n) + G(j,n) \tag{2.1}$$

$$\alpha(j,n) = max((\gamma(j,n) + T(j,n)), \eta(j,n)) \tag{2.2}$$

$$\eta(j,n) = \begin{cases} \beta(M,n-1) + t_g & \text{if } j = 1 \\ \beta(j-1,n) + t_g & \text{if } j \neq 1 \end{cases} \tag{2.3}$$

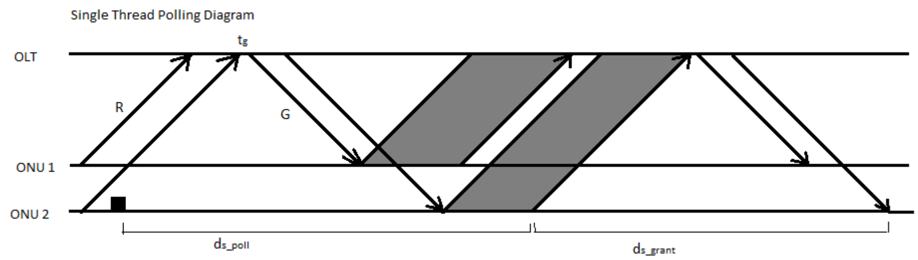


Figure 2.3: Example of offline scheduling framework

2.1 Grant Scheduling Framework

The scheduling framework determines how the OLT and ONU respond on the receipt of REPORT or GATE. Basically, make access decisions for OLT and corresponding send GATEs to ONUs. The different grant scheduling frameworks vary based on the ONUs response in a grant cycle, that triggers the transmission window. We will discuss each of the grant scheduling framework that we are going to analyze later in this work, theoretically and mathematically. Thus we will be able to provide qualitative and quantitative analysis.

Offline

DBA initially was introduced with the offline scheme. In an offline DBA scheme as shown in Fig 2.3, all the ONUs are polled together with their granted transmission window but they are triggered only after the receipt of REPORTs from all the ONUs. Therefore, the OLT will have to wait to receive the REPORTs from all ONUs. This helps the OLT make or compute intelligent allocation schemes, which will be described later in this section.

Mathematically, all M ONUs are scheduled at granting j when the REPORT messages of all ONUs are received in granting cycle, j-1. Thus, scheduling time and polling time for all ONU scheduled together can be given as below:

$$\gamma(j,n) = \beta(M,n-1) \quad \text{if } \forall_j \tag{2.4}$$

$$T(j,n) = jt_G + 2\tau([j,n]) \tag{2.5}$$

Online

The online DBA was the first renowned DBA scheme in PONs that was introduced by the term IPACT [14], as shown in Fig 2.4. This technique refers to scheduling an ONU as soon as the OLT

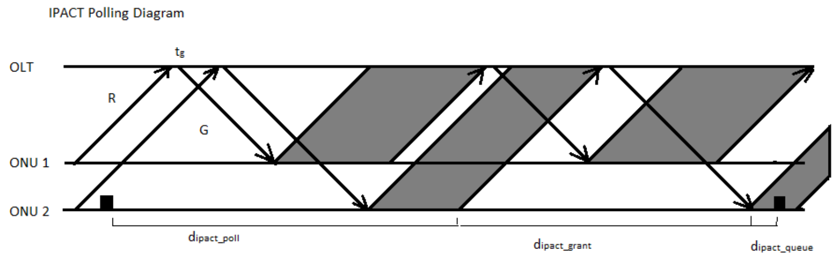


Figure 2.4: Example of online scheduling framework

receives the REPORT from that ONU. In this case, the requested window size is granted, no more or no less, because of which, different allocation algorithms cannot be implemented in the OLT. Also, this is considered the most simple technique.

Mathematically, the granted transmission window for kth ONU in granting cycle j is sent on the receipt of the REPORT from ONU k in granting cycle j-1. Therefore, the scheduling and polling time for kth ONU is given as:

$$\gamma(j,n) = \beta(j,n-1) \tag{2.6}$$

$$t_{poll}(j,n) = t_G + 2\tau([j,n]) \tag{2.7}$$

Double Phase Polling

Double phase polling [2] was introduced as an advanced technique in DBA algorithms. This algorithm has proven to be efficient especially in case of long-reach PONs [22]. Although research is quite prominent in this technique, it is included in our work for qualitative and quantitative comparative study. In this technique, all ONUs are divided into two independent groups. Offline DBA is performed in each group independently, that is, within each group, all ONUs in that group are scheduled when the REPORTs of that ONUs are received at the OLT. From the statement, we can note that wait time for OLT will be reduced by half for each group. Moreover, when one group is sending REPORTs, the other group schedules the ONUs. Therefore, this techique makes use of the idle time. The first half is termed subgroup 1, and the second as subgroup 2.

Mathematically, all ONUs in subgroup 1 are scheduled in the granting cycle j, when the REPORT message of M/2 ONUs of subgroup 1 in granting cycle j-1 are received at the OLT.

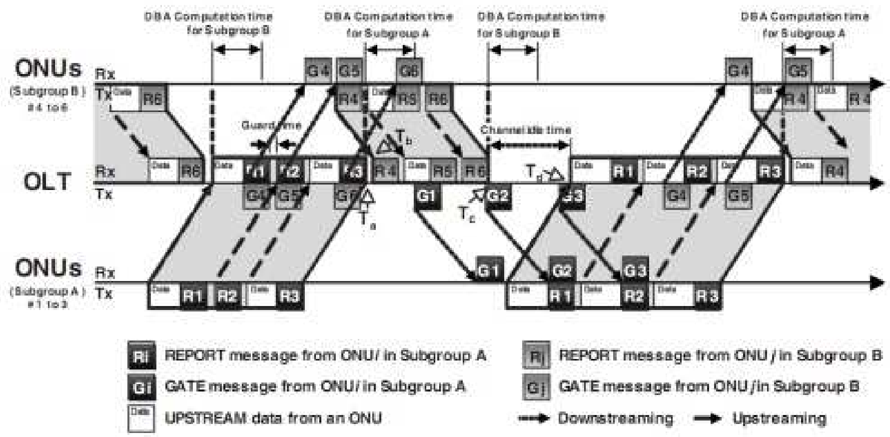


Figure 2.5: Example of Double Phase Polling scheduling framework[2]

Therefore, the scheduling time and polling time for all M/2 ONUs in a subgroup together can be designed accordingly as:

$$\gamma(j,n) = \begin{cases} \beta(M/2, n-1) & \text{if } j <= M/2 \\ \beta(M, n-1) & \text{if } j > M/2 \end{cases} \tag{2.8}$$

$$T(k,j) = \begin{cases} jt_G + 2\tau([j,n]) & \text{if } j <= M/2 \\ (j - M/2)t_G + 2\tau([j,n]) & \text{if } j > M/2 \end{cases} \tag{2.9}$$

[j, n] depends on scheduling policies for all schemes. In case of online, scheduling policies do not play an important role, thus it will k only. More on scheduling policies later in this section.

2.2 Grant Sizing Schemes

This scheme or policy determines the size of window size or GATE that can be provided for each ONU. This scheme is the most important as we will see later that the comparisons of the schemes will vary tremendously. The important terms in grant sizing to be noted from Table 1 are: G(i,j) which is the transmission window size granted to ONU i in granting cycle j; $G_{max}(i)$ is the maximum grant size that any ONU can be assigned, this will determine the bandwidth provided in the fiber network; R(i,j) is the requested window size by the ONU i in the granting cycle j via REPORT. The different grant sizing schemes are:

Fixed

In this technique, the granted transmission window for any ONU j, is fixed by the OLT. This saves the OLT from any further processing and simplifies the DBA computation process. But the disadvantage will be, even if the ONU requests a very small Window size, it will receive the maximum window size and the remaining bandwidth is wasted. The fixed grant sizing can be represented as:

$$G(j,n) = G_{max}(j) \tag{2.10}$$

Gated

In this technique, the transmission window size granted will be equal to the requested window size in the REPORT. The advantage of this scheme in comparison to Fixed will be, in case of small Report size, the OLT will save the remaining bandwidth. But the disadvantage is if the ONU requests a large window size, even larger than the maximum allowed window size G_{max}, then that ONU will occupy the entire bandwidth and monopolize it, thus preventing the other ONUs from their fair share of bandwidth, this is a very unrecommended technique especially if Fairness is a concern. The gated grant sizing for ONU j, in granting cycle n can be given as:

$$G(j,n) = R(j,n) \tag{2.11}$$

Limited

Considering the flaws of Fixed and Gated techniques, Limited was designed. This scheme grants the requested window size in all cases except if the requested window size exceeds that of the maximum allowed Grant size G_{max}, in the latter case, that ONU is allocated the maximum granted window size. Thus this prevents any ONU from monopolizing the bandwidth and also saves the bandwidth being wasted in the case of Fixed. The limited grant sizing for ONU j and in the granting cycle n can be given as:

$$G(j,n) = min(R(j,n), G_{max}(j)) \tag{2.12}$$

Excess Bandwidth distribution

The concept of excess bandwidth was developed as advanced DBA schemes to utlize the available bandwidth even further. This type of DBA has been extensively dealt with in [25]. Some of the concepts are briefed here for using it in our future analysis. Excess bandwidth allocation accounts for the fairness for each ONU in the network. The concept of excess bandwidth distribution is to share the excess bandwidth that is obtained from each lightly-loaded ONU in each cycle and distribute them among heavily-loaded ONUs. This required to categorize ONUs as either lightly-loaded or heavily-loaded based on the ONU traffic. The threshold for classification is set as the maximum grant transmission window size G_{max}.

Lightly-loaded ONUs are defined as all ONUs whose requested window size R(j, n) of ONU j and granting cycle n to be less than the maximum allowable window size and this group will be denoted by the term U(n) for a granting cycle (see Table 1 for reference).

$R(j,n,\delta) <= G_{max}(j,\delta) \quad 1 <= j <= M \quad 1 <= \delta <= N$

The δ denotes the thread number, a concept that will be explained in the later sections under Multi-thread polling. For now, assume it as a quantity that has to be considered for each REPORT and GATE.

$$G(j,n,\delta) = R(j,n,\delta) \tag{2.13}$$

Heavily-loaded ONUs are defined as all ONUs whose requested window size R(j, n) of ONU j and granting cycle n is larger than the maximum allowed window size. This set will belong to the set O(n) for any granting cycle n. (Table 1 reference)

$R(j,n,\delta) > G_{max}(j,n,\delta) \quad 1 <= j <= M \quad 1 <= \delta <= N$

In order to service extra bandwidth for these heavily-loaded ONUs in O(n), excess bandwidth is calculated from the extra bandwidth obtained from lightly loaded ONUs in any granting cycle n.

$$E_{total}(n,\delta) = \sum_{i \in U(n)} G_{max}(n,\delta) - R(i,n,\delta) \quad \forall 1 <= \delta <= N \tag{2.14}$$

From the pool of excess bandwidth in E_{total}, heavily loaded ONUs can be serviced differently. Here we consider three important excess bandwidth distributions.

1. Equi-driven Controlled Excess Allocation

$$E(j,n,\delta) = E_{total}(j,\delta)/O(n) \quad \forall j \in O(n) \tag{2.15}$$

$$G(j,n,\delta) = min((G_{max}(j,\delta) + E(j,n,\delta)), R(j,n,\delta)) \quad \forall j \in O(n) \tag{2.16}$$

2. Demand-driven Excess Bandwidth Allocation

$$G(j,n,\delta) = G_{max}(j,\delta) + E_{total}(n,\delta) * R(j,n,\delta) / \sum_{j \in O(n)} R(j,n,\delta) \tag{2.17}$$

3. Overload-driven Excess Bandwidth Allocation

$$G(j,n,\delta) = G_{max}(j,\delta) + (R(j,n,\delta) - G_{max}(j,\delta)) * E_{total}(n,\delta)) / \sum_{j \in O(n)} (R(j,n,\delta) - G_{max}(j,\delta)) \tag{2.18}$$

2.3 Scheduling Policies

When the ONUs are scheduled mostly in an offline scheduling framework, the ONUs can be scheduled in an orderly manner in a granting cycle based on different logical flows. The ordering of ONUs helps obtain operator [k,j] that was mentioned earlier. In case of offline framework, all the REPORTs are received at the OLT before scheduling them. If the ONUs are arranged, we can observe some change in throughput. This scheme is possible for cases when the REPORTs are collected, therefore, this scheme is not necessary for online/IPACT schemes where only one ONU is scheduled at any time. There are many scheduling policies that have been discussed in literature earlier. In our analysis, we do not compare different scheduling policies, but from previous literature results, we utilize the most optimized scheme. The different scheduling policies are:

1. Shortest Propagation Delay – the ONUs are arranged in the ascending order of their propagation delays or RTTs (Round Trip Times).
   $\tau([1,n]) <= \tau([2,n]) <= ...... <= \tau([N,n])$

2. Shortest Grant or Shortest Processing Time First (SPT) – The ONUs are arranged in the ascending order of grant sizes

3. Largest Number of Frames first (LNF) – The ONUs are ordered by the number of frames queued every granting cycle

4. Earliest Arrived Frames (EAAF) – ONUs are ordered based on which frames reach earlied in a granting cycle.

Table 2.1: DBA Model Parameters [22]

Parameter	Meaning
M	Total Number of ONUs
N	Total Number of Threads
n	granting cycle index
j	ONU index
δ	thread index
t_g	Guard time
t_G	Transmission time for GATE message
α	start time of granted transmission window of kth ONU in granting cycle j
T	polling time for the kth ONU and granting cycle j
γ	time when OLT schedules granted transmission window of the kth ONU for cycle j
β	time that grant to the kth ONU for granting cycle j ends.
η	time the upstream channel is free when the OLT schedules the granted transmission window for the kth ONU granting cycle j
Δ	representation for idle time
$[k, j]$	operator that returns the ONU index if scheduling policy is involved.
$\tau(i)$	symmetric propagation delay
R(k,j)	Requested REPORT size for kth ONU in jth granting cycle
G(k,j)	Length of the granted transmission window for kth ONU in jth granting cycle
$G_{max}(i)$	Maximum possible Granted size for limited scheme for jth granting cycle
U(j)	lightly-loaded ONUs
O(j)	heavily-loaded ONUs

2.4 Delay Analysis

In this section, we discuss more in detail about delay by analyzing idle time equations for the techniques introduced in the previous sections. In order to analyse packet delay, we need a mathematical model that supports the dynamic bandwidth allocation schemes. We adopt the DBA model explained in [22] and the measurable quantities expressed in Table I. This quantity t_{idle} will help in understanding the effect of delay on the model.

When computing the expression for δ, we observe from previous expression eq 2.2, $\alpha = \eta$ and generally for any ONU in any cycle n, $\alpha = \gamma + T$. Therefore, idle time can be computed as follows for each scheduling framework.

1. Online scheduling framework:

   Case 1: j =1

$$\Delta(1,n) = [\alpha(j,n) - \beta(M,n-1)] \tag{2.19}$$

Case 2: otherwise

$$\Delta(j,n) = [\beta(j,n-1) - \beta(j-1,n)] + t_G + 2\tau([j,n]) \tag{2.20}$$

2. Offline scheduling framework:

   Case 1: j = 1

$$\Delta(j,n) = t_G + 2\tau([j,n]) \tag{2.21}$$

   Case 2: otherwise

$$\Delta(j,n) = t_G + (2\tau([j,n]) - 2\tau([j-1,n])) - G(j-1,n) \tag{2.22}$$

3. Double Phase Polling scheduling framework: Offline analysis can be extended to express delay analysis for DPP scheduling framework. For DPP, j varies as follows $1 < j <= M/2$, $M/2+1 < j <= M$

   Therefore, idle time can be expressed as follows:

   Case 1: $j <= M/2$

$$\Delta(1,n) = [\beta(M/2,n-1) - \beta(N,j-1)] + t_G + 2\tau([1,n]) \tag{2.23}$$

   Case 2: $j > (M/2+1)$

$$\Delta(M/2+1,n) = [\beta(M,n-1) - \beta(M/2,n)] + t_G + 2\tau([M/2+1,n]) \text{if } otherwise \tag{2.24}$$

Chapter 3

Novel EPON-LRPON Classification

We go onto explaining the DBA taxonomy which forms the main content of the rest of the paper. After we analyzed many DBA techniques, it was possible to classify DBA as Direct, Predictive and Intelligent as in Fig 3.1. The use of such a classification is important because as we know network traffic could vary depending on the user's requirement. Users can be categorized as Home users and Business users. A Home user will mostly be using internet for video streaming, online games. An Industry user will have large data traffic, video conferencing etc, bandwidth plays a crucial role here, it should offer large speeds, delay is intolerable and throughput performance should be maximum. While for a home user, bandwidth should be fairly large, delay is slightly tolerable and throughput can be moderate. This problem statement can be more efficiently managed with this taxonomy.

Motivation Research introduces many dynamic bandwidth allocation and provides impressive results of the algorithms under certain configurations. How useful can these algorithms be considering it will be useful for commercialization. There has be number of classifications based on QoS-aware and unaware effects. But there has been no classification so far to the best of our knowledge, that classifies algorithms based on their grant sizing mechanisms which would be useful for various user traffic types. For example, a residential area would have traffic type like video traffic that can allow buffering/playback time for intelligent bandwidth allocation algorithms and on the other hand, a business area will mostly have Voice-over-IP, data traffic, that would not allow any idle time and requires bandwidth as per its requests leading to a direct bandwidth allocation algorithm. Thus, we came up with a classification Direct, Predictive and Intelligent which is based on the grant sizing schemes of various DBA Algorithms.

3.1 Classification Description

Direct

Direct Approach of DBA techniques refers to approachs where grant size is allocated immediately when the report is received from the ONU. Thus, there is no requirement of granting transmission window anything more than what is requested by the REPORT. And also, not much time is utilized for DBA computation. The different techniques under this category are as follows:

1. Online — This techniques is mostly used in time-division multiplexing. When the Report of the ONU is received, based on the byte size it provides, the trasnmission window is granted.

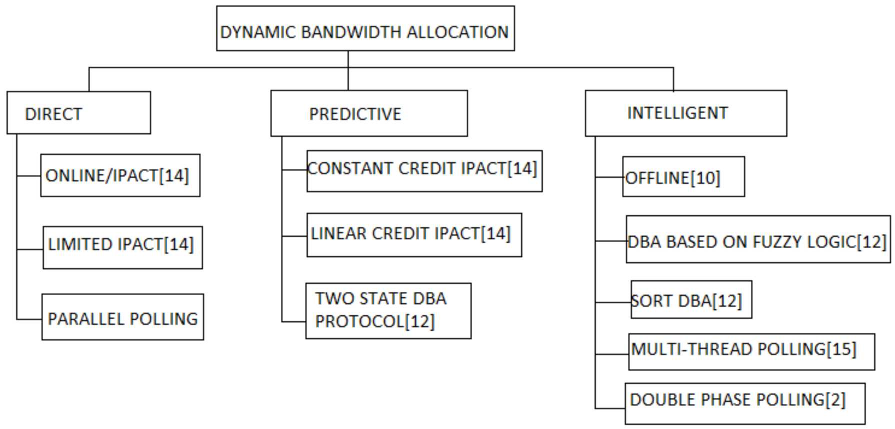


Figure 3.1: DBA Taxonomy

This is similar to Fig 2.1 and Fig 2.2, the former being standard and the latter interleaved, but both of them behave as online. Features of this type of DBA is, very less wait time, hence less average delay. Performace can be understood better when compared to the other categories[24].

2. Limited IPACT — In IPACT the transmission window can be sized differently. Different sizing of the transmission window gives different techniques. Limited IPACT is similar to limited grant sizing explained earlier[14]. Each ONU is granted the requested byte size, but no more than the maximum Grant size or transmission window. Since this is done without any computation, it is categorized under Direct DBA. Again, in this technique delay is minimum. Analysis of this technique will be seen in the next section.

3. Multi-threading DBA — This DBA technique is used for long-range PON (LRPON). This technique will be described more in detail in a later section, in this section it is introduced so that it can be used in the topology. In LRPON, as we saw earlier due to the large distance between the ONU and OLT, there is large propagation delay. The delay or wait time can be utilized to initiate a new thread of data transfer, in this way delay can be utilized for more packet transfer as mentioned earlier [7]. As can be seen in Fig 3.2, the first thread, sends data based on a REPORT that was received earlier. Meanwhile, in the same cycle time, a new grant is sent to the ONU. In this way, the wait time is utilized efficiently and the delay is reduced immensely. This is categorized as Direct as it does not evaluate or compute the Grant/Transmission window that is sent, but sends the Grant simply based on the Report.

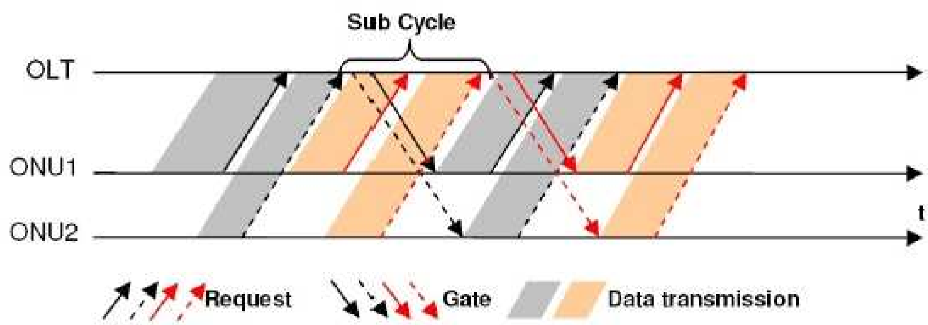


Figure 3.2: Multi-threading in LRPON [7]

Predictive

In this section, we will see certain techniques that send transmission window not only based on the requested REPORT but also on a predictive basis. This will help increase the throughput and will be useful to heavily loaded ONUs. This type of DBA scheme reduces delay only moderately because some lightly loaded ONUs will be granted excess transmission window size because of the predictive nature of bandwidth allocation. Some of the DBA schemes that fall under this category:

1. Constant-credit IPACT — As discussed earlier, different IPACT schemes are evolved by changing the size of the transmission window size. If the maximum window size/Grant that can be granted by the ONU is G_{max} then the grant at of ONU i, will be given by $G_i = R_i + x$, where G_i and R_i are similar to the terms defined in Grant sizing techniques, x is a byte that is randomly predicted by the OLT and sent to ONU[14], thus for a heavy loaded ONU, this is help in reducing the traffic load on the ONU faster. The value of x is constant. Since x is predictive, this DBA scheme falls in this category. As mentioned earlier, this category gives moderate delay.

2. Linear-credit IPACT — This technique is similar to the previous technique, constant-credit IPACT, with the only difference that the value x will change linearly with respect to resquested window or REPORT [14]. Thus x is variable in this case. Although this schemes is better in terms of control than the previous one, the delay performance is almost the same as will be seen in the next section.

3. Two-state DBA protocol — Two-state protocol is a technique that is exclusively used for LRPON. When this is used for Short range PON (SRPON), the performance is either similar

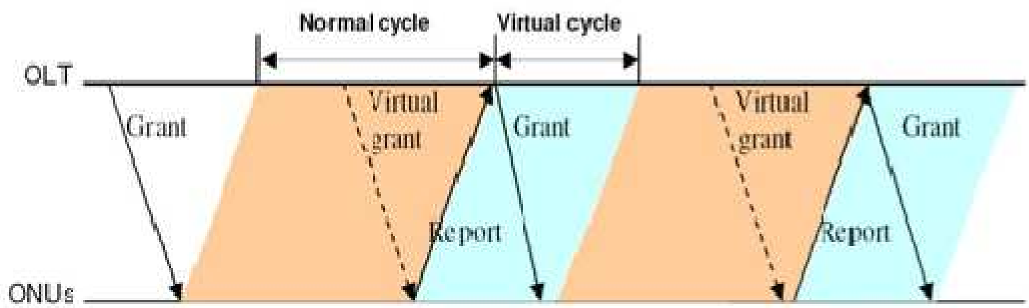


Figure 3.3: Two-state DBA protocol in LRPON [7]

or worse than the general SRPON DBA schemes. This technique is again used to minimize the large propagation error that is faced in the LRPONs. In this technique, two states are defined: one the normal state and another virtual state. In the normal state, the OLT grants the ONU the requested window size or grant. And in the virtual state, when the ONU is receiving the next Grant from the OLT, some predicted amount of packets are transfered[7]. As shown in Fig 2.3. Again this technique falls in this category because the in virtual state, packets are sent on a predictive basis. The analysis and comparison of this technique will be presented in the next section.

Intelligent

1. Offline — Offline DBA is the contradictory technique to the Online DBA discussed previously. In Online, OLT grants transmission windows size/ grant size to each ONU as soon as it receives the REPORT. On the other hand, in Offline DBA, the OLT waits for REPORTs from all the ONUs before granting transmission window [10]. The illustration can be seen in Fig 3.4. This technique gives the OLT maximum control even though it suffers from large delay time, because of the wait time involved. The OLT will be able to grant large grant size for heavy loaded ONUs and less grant size for lightly loaded ONUs.Therefore, intelligent bandwidth allocation is possible which is why this technique falls in this category.

2. Online Just-in-time — This is a technique similar to Online, introduced in [24] mainly for wavelength-division multiplexing. In WDM, a couple of ONUs can access the different wavelengths of the channel simultaneously, thus the number of ONUs in the scheduling pool will be more than one when compared to online, where only 1 ONU will be in the scheduling pool at any point of time. For example, if N denotes the number of ONUs avaiable, M is the number of upstream channels, then (N-M) ONUs will be available in the scheduling pool at

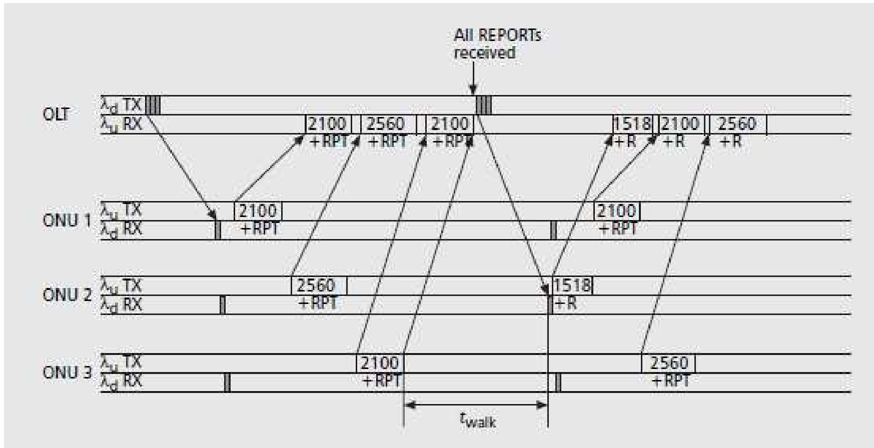


Figure 3.4: Offline DBA [10]

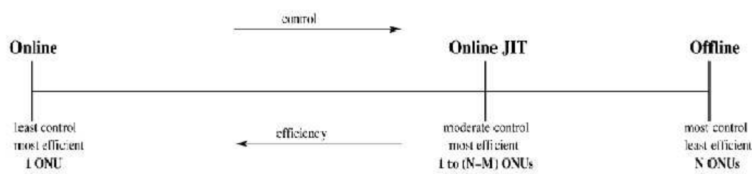


Figure 3.5: Comparison Graph of Online, Online Just-In-Time and Offline [24]

any point of time that is wait-listed to be transfered in the next available channel, this illustrates the meaning of scheduling pool. Thus this technique gives control over some ONUs (typically the ONUs in the scheduling pool) and is considered mostly as an Offline technique. Hence, although certain amount of delay is incurred, control over the bandwidth is possible. Fig 3.5 gives an overview of the online JIT when compared to online and offline.

3. DBA based on fuzzy logic — In case of heavily loaded ONUs, the excess bandwidth from lightly loaded ONUs can be given to the heavily loaded ONUs in order to reduce the delay in that network. This weighted priority for heavily loaded ONUs can affect delay sensitive traffic classes and can increase delay extensively [23]. In order to solve this problem, fuzzy-logic based scheduling was introduced. This algorithm uses information such as traffic class and delay to make its decision. This is to divide bandwidth fairly between different ONUs and within each ONU by using fuzzy logic. [23] comes up with an efficient DBA based on fuzzy logic that proves to improve bandwidth utilization by 20% and reduce delay by nearly 50%, the analysis of which will se seen in the next session. This is considered an Intelligent approach as it makes bandwidth allocation decisions based on parameters such as traffic delay and class.

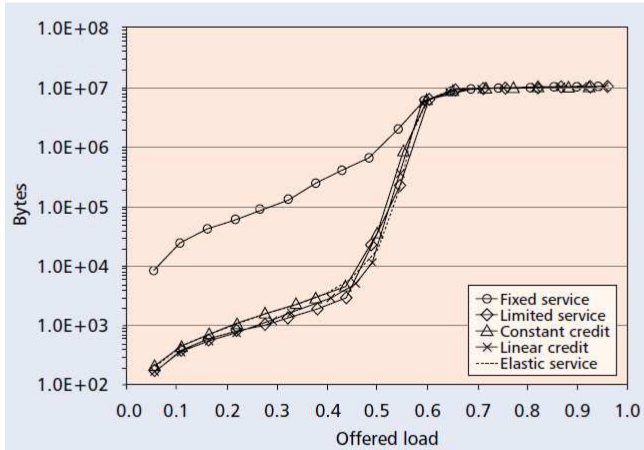


Figure 3.6: Comparison of delay for different IPACT schemes [14]

4. Sort-DBA — This technique works by sorting all the received REPORT messages by request length at the next transmission cycle by utilizing the idle time between cycles[27]. This techniques works parallelly with Offline and Online JIT techniques. Thus the walk time/idle time is utilized fairly for sorting the REPORTs and makes intelligent bandwidth allocations. The only constraint in this technique is that it requires atleast one long data transmission time for an ONU. Thus delay is a parameter that might have to be compromised. But for the compromise, good throughput performance is obtained.

3.2 Graphical Analysis and Theoretical Conclusions

This section is majorly used to compare the existing analysis of the techniques that were introduced in the previous sections. The graphical analysis of the different IPACT schemes, multi-threading and DBA based on fuzzy logic and qualitative analysis of two-state DBA protocol effects and Sort-DBA will be concentrated.

The different IPACT schemes for EPON described so far, Limited, constand-credit, linear-credit are compared along two other schemes such as fixed IPACT, which is similar to fixed grant sizing technique, and elastic IPACT, in which the maximum transmission window size linearly changes according to the requested window size in REPORT. As seen in Fig 3.6, apart from fixed IPACT, all the other IPACT schemes are almost similar when delay is plotted. Thus this validates the statement mentioned earlier, that limited IPACT as a 'Direct' approach has low delay. And constant-credit and linear-credit as 'Predictive' also give low delay, but gives better throughput when compared to limited IPACT.

We shall cover EPON and GPON graphical analysis for Multithreading analysis. In Fig

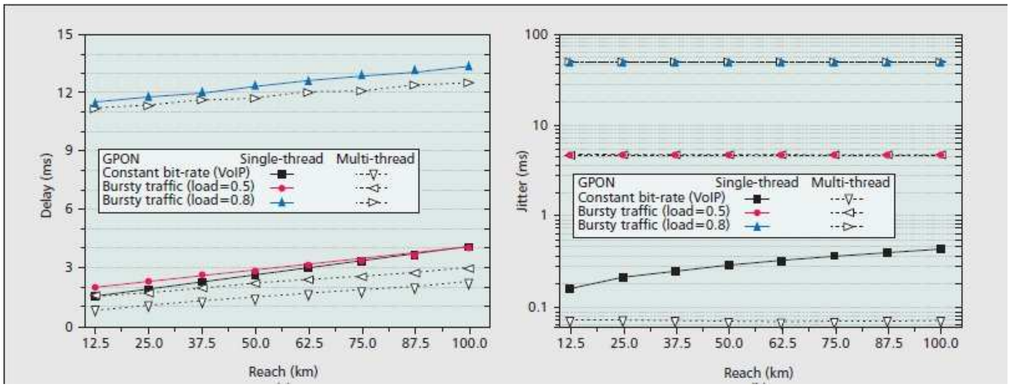


Figure 3.7: (a)Delay and (b)Jitter Analysis of GPON for multi-threading technique [13]

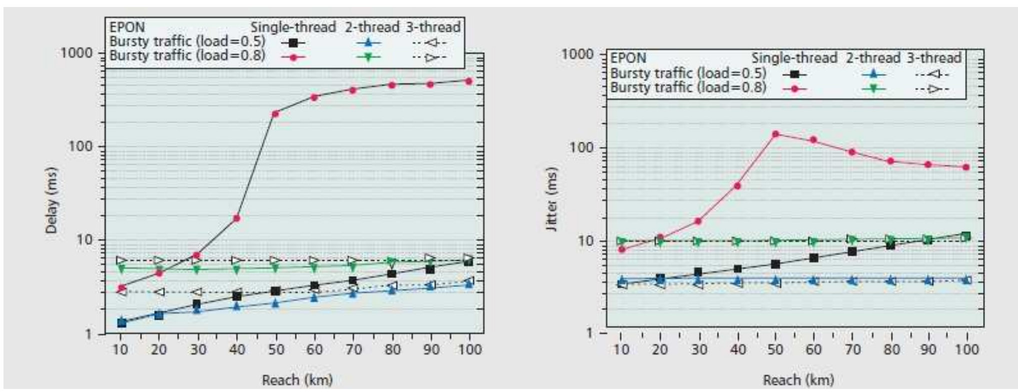


Figure 3.8: (a)Delay and (b)Jitter Analysis of EPON for multi-threading technique [13]

3.5, we provide the graphical analysis of GPON for delay and jitter comparisons for 50% and 80% load. The x-axis represents the Reach which is the distance between the ONU and OLT and we can compare the trends for Standard-reach and Long-reach PON. The y-axis is delay for Fig 3.7(a) and jitter which is the noise in the network in Fig 3.7(b). Larger load suffers more delay but by using multi-threading, delay can be reduced to an extent. Multi-threading being a 'Direct' Approach immediately responds to requested window size from the OLT and thus is responsible for reducing delay.

In Fig 3.8, similar analysis is presented for EPON. In EPON significant differences can be seen. In case of high load, the delay reduces significantly only after a reach of 20-30Km. Thus we could analyse that multi-threading is more effective for long-range PON (LRPON) than for standard range PON. Another important analysis that can be derived from this graph is the importance of 2 or 3 threads. For low load (50%), 3 threads become effective only after 50Km when compared to 2 threads which are effective from a reach of 20Km. Thus, 2 threads are an optimum count for Multi-threading DBA approach as per [13].

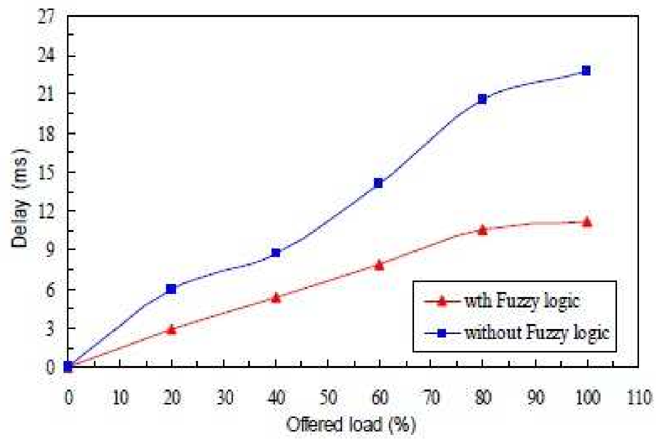


Figure 3.9: Delay comparison of DBA schemes with and without fuzzy logic [23]

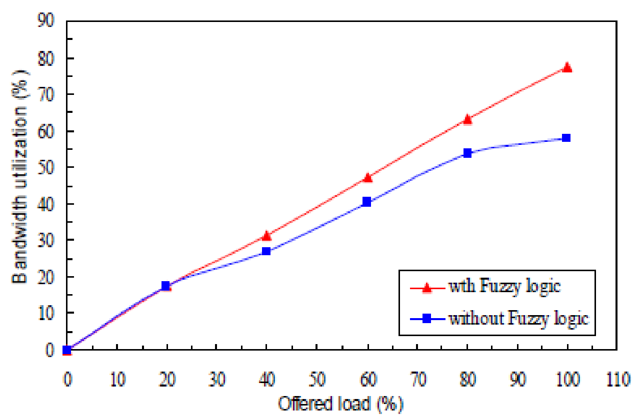


Figure 3.10: Comparison of Bandwidth Utilization of DBA-based on fuzzy logic and without fuzzy logic [23]

Next, we will compare the 'Intelligent' scheme–DBA-based on fuzzy logic, where REPORTs are arranged based on the traffic class and delay so that tranmission window can be granted fairly and efficiently [23]. In Fig 3.9 and 3.10, we present delay and bandwidth utilization comparison respectively for DBA-based on fuzzy logic and without fuzzy logic, which is based on IPACT scheme. In Fig 3.9, delay comparison with Load; as load increases, delay increases but in case of DBA-based on fuzzy logic, the delay increases comparatively lesser. In Fig 3.10, the bandwidth utilization is more in case of DBA-base on fuzzy logic. This technique is still in research stages and have not been deployed yet due to the complexity involved in accommodating fuzzy logic algorithm in the OLT for DBA computation.

Finally, we qualitatively analyze two-state DBA protocol and Sort-DBA. Two-state DBA protocol accounts for more packet transfer in the virtual mode. Although it is predictive, it accounts for the transfer of new incoming traffic. Thus, it helps in reducing delay to a great extent, and because the new incoming traffic can also be sent immediately(in most cases the same cycle time), throughput is also better than the Direct case, where incoming traffic will have to wait in the buffer for the next cycle time.

In the case of Sort-DBA, it can be compared to Offline. Sort-DBA waits for all REPORTs from all ONUs and then utilizes one long transmission time for intelligent DBA computation, and the remaining DBA computation on-the-fly without accounting for long transmission time in those cases. While Offline waits for all REPORTs and DBA computation is done in each cycle time and accounts for long transmission times in each cycle. Thus, the delay component is better in Sort-DBA and throughput is almost similar in both.

Chapter 4

Analysis of Multithread Scheduling Framework

Multi-thread Polling (MTP) is a technique that was introduced in [15] as a solution to the excess delay concurred when deploying LRPON. As we know, LRPON is a promising deployment that could reduce CAPEX and OPEX for PON to a great extent. But the most important criterion of maintaining performance measures should be considered for any deployment, in that way LRPON was known to provide large delays. Among many solutions was MTP that had promising results.

Dynamic Bandwidth Analysis in LRPON is about utilizing the given bandwidth in a dynamic fashion, so that the idle time can be reduced. But inspite of dynamically allocating the memory, we have to adhere to some idle time which increases in case of LRPON, where distance between ONU and OLT is almost 100Km. Even though the advantage of reducing the number of OLTs in the back-haul network, the compensation by increase in delay brings down its fame or practicality. Thus different types to reduce the delay in LRPON spefically became an interesting area of research. Some of techniques introduced for LRPON are highlighted in [12] covering all techniques, some of them are covered here in detail:

1. Multi-thread polling
2. Newly Arrived Frames(NA+)
3. GATE-Driven DBA for long-reach WDM-PON
4. Online Excess Bandwidth Distribution (OEBD)
5. Minimum Packet Delay Variance (minPDV)
6. Periodic GATE Optimization (PGO)
7. Adaptive Threshold-based DBA
8. DBA for STARGATE (SG) EPONs
9. Slotted Media Access (SMAC)
10. Online Upstream Scheduling and Wavelength Assignment with Void-filling (USWA-VF)

The techniques considered here is only Multi-thread polling (MTP) which will evaluated in depth with necessary comparisons.

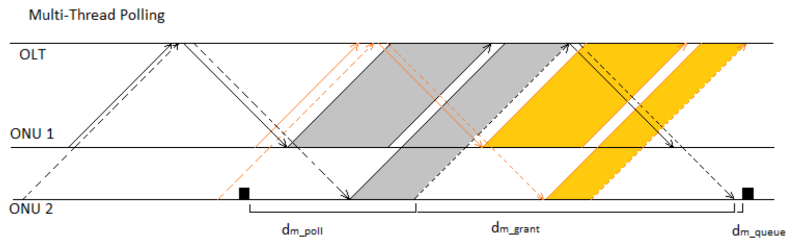


Figure 4.1: A illustrative figure of MTP

Multi-thread polling is a technique where ONUs polling the OLT more than once in one cycle time. Because of the large delay incurred in one cycle time, time can be shared such that ONUs can be given multiple opportunities to send data to OLT, thus increasing the throughput and reduces the delay. In dynamic bandwidth allocation, the number of bytes an ONU wants to send is already known from the previous GATE message, the estimated time for the DATA and its RTT time can be calculated and possibility of having multiple such threads by proper calculations can be done.

Huan Song et. Al [16] explained the technique based on combining multiple offline scheduling in sequential, such that each cycle time has multiple polling. It proved to perform that delay performance was better than conventional offline technique based on single polling for SRPON and LRPON. Later Ahmed Helmy et. Al [11] came up with an analysis that proved IPACT to be better than MTP for SRPON and LRPON, which brought in sufficient doubt regarding the requirement of MTP in research.

In this section, we discuss MTP in detail based on the analysis in the published work and extended as per our DBA design space.

4.1 Design Space Equation

Design Space Equation for MTP is newly introduced in this thesis proposal based on the work [22], in order to provide a different perspective to the already established concept. The advantage of this derivation is the better understanding of delay performance which will be later discussed in this section. The DBA model adopted is maintained standard as per in Section 2 and the parameters are as seen in Table 1.

In this case, the scheduling and polling times will vary for each thread, therefore they are designed based on the thread number δ as well. Considering the number of threads are two:

$1 <= \delta <= 2$

$$\gamma(j,n,\delta=1) = \begin{cases} \beta(M,n-1,\delta=2) & \text{if } \delta=1 \\ \beta(M,n,\delta=2) & \text{if } \delta=2 \end{cases} \tag{4.1}$$

$$T(j,n,\delta) = (jt_G + 2\tau([j,n,\delta])) \tag{4.2}$$

4.2 Delay Analysis

In Networks, delay is an important factor as it accounts for the efficiency of the transmission in that network. Generally, in a Protocol stack, each layer is independent of the errors of the other layers. For example, if there was a packet loss in the Physical layer due to errors in the medium, the packet loss will request for a retransmission. This loss/error is not considered loss in any of the higher layers of protocol stack, but account for the delay in that layer. In our analysis we concentrate on the algorithms performed in the MAC (Medium Access Layer), therefore the delay help account for the losses in the lower layers and proagation delays, thus it forms a very important parameter for the Quality-of-Service analysis of any network. In PON, we consider the following standard delays that are agreed upon most researchers: Pretransmission delays[11], which will consist of all the delays that occur before the actual transmission of the packet and Post-transmission Delays, which will be the delays encountered once the transmission has started. The former consists of Reporting/polling delay, Granting delay and Queueing delay that illustrated in Fig 4.1and the latter consists of Transmission delays and propagation delays.

1. Reporting/Polling Delay – Packets are sent to the ONU from the end users, depending on the time these packets reach the ONUs, they may be reported to the OLT right away or in the next cycle. This is because data trasmission or reporting to the OLT happens only when the ONU is polled. Therefore, the time taken by the packet to get reported to the OLT is the reporting/polling delay. The lower bound on this delay is zero, as if the packet arrives at the ONU just before the REPORT being sent, then this packet will also get reported. And the upper bound will be an entire cycle length, if the packet just misses a report.

   $0 <= d_{poll} <= C_{eff}$

   $$d_{poll,avg} = C_{eff}/2 \tag{4.3}$$

   where C_{eff} for granting cycle n can be given as:

$$C_{eff}(n) = \sum_{j=1}^{M} G(j,n) + Mt_g \tag{4.4}$$

2. Granting Delay – Once the packet has been reported to the OLT, it will have to wait for the OLT to send the transmission window through the GATE. This delay is generally bounded by a maximum of RTT, therefore, it depends on the distance between ONU-OLT, so for LRPON, this delay will play an important role. Granting delay is most important because, the delay due to transmission and propagation will be included in this as well. Thus analysis of the granting delay will be helpful in LRPON.

$$d_{grant,max} = RTT \tag{4.5}$$

3. Queueing Delay – Once the GATE/transmission window is received at the ONU, the packets collected in the queue buffer in the ONU is transmitted as per the window size to the OLT in order. Any packet will experience delay to be transmitted when sent in order. This delay is lower bounded by zero, for a packet that is placed first in the buffer and upper bounded by the window size.

   $0 <= d_{queue} <= G_{max}$

   where G_{max} is obtained as the maximum Grant transmission window.

4. Transmission Delay – Transmission delay is part of the post-transmission delay and accounts for packet length and upstream transmission rate [11].

5. Propagation Delay – The propagation delay will be half of RTT (Round Trip Time), and this is computed from the distance between OLT-ONU.

6. Overall Delay – The delay that accounts for delay starting from the acceptance of the packet onto the ONU until just before the transmission of the packet. Therefore, this delay will account for the entire pretransmission delays.

$$d = d_{poll} + d_{grant} + d_{queue} \tag{4.6}$$

Since post-transmission delays cannot be modified by better algorithms, they are generally not dealt with mathematically and analytically. The pretransmission delay are considered important for analysis as it can be reduced by effective bandwidth algorithms. Therefore, in our analysis we will consider pretranmission delays.

In order to utilize the long idle time in LRPON caused due to the large RTT delay (0.1ms for 10Km which increases to 1ms for 100Km), one possible technique is polling the OLT more than once in one cycle time. This type of DBA gave rise to a new class algorithms, called the multi-thread polling, which also means initiating more than one thread in one polling cycle. The technique was first introduced in [15]. The idea of MTP is to target the overall delay incured in a polling cycle. The delay components mentioned above are reduced in MTP as shown in Fig 4.1 and the mathematical analysis of that is as illustrated below:

1. Polling Delay: Polling delay reduces as per the number of threads as the ONU gets the opportunity to poll that many times as the number of threads

$$d_{m,poll} = d_{poll}/N = C_{eff}/N \tag{4.7}$$

where N is the total number of threads.

2. Granting delay: Granting delay will be reduced as during the granting time, the data of another thread is being utilized. Therefore, the granting delay is reduced to the time required to send data of that ONU in that thread.

$$d_{m,grant} = C_{eff}(n) - C(n,\delta) - RTT/2 - T_w \tag{4.8}$$

whereC_{eff} is total effective cycle time in cycle n, C(n, δ) is the cycle time for the specific thread, and T_w is the wait time incurred for MTP as in each thread, the OLT waits for all the ONU REPORTs in that thread δ.

3. Queuing delay: Queuing delay again reduces as the number of threads as the data sent in one thread is now reduced.

$$d_{m,queue} = d_{queue}/N \tag{4.9}$$

As we know, in LRPON, the delay reason is RTT, which increases the d_{grant}, which increases the grant window size and more packets are sent, that the OLT has to wait that longer to receive the REPORTs and this in turn will increase d_{poll} and d_{queue} further.

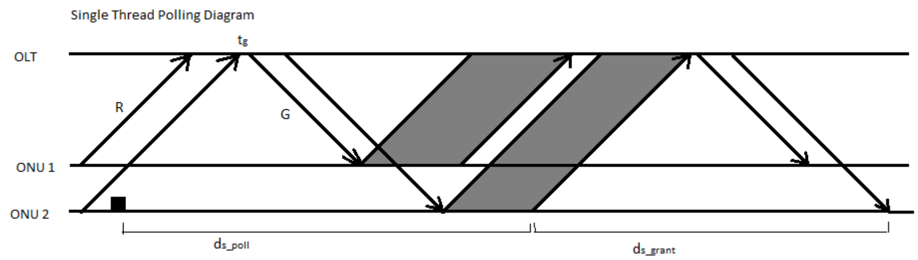


Figure 4.2: The figurative explanation of delay components in STP

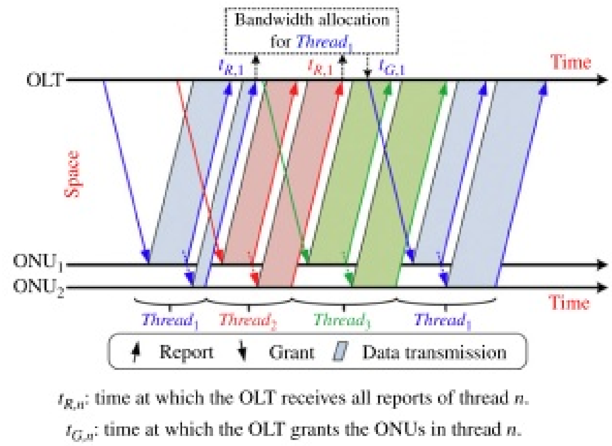


Figure 4.3: The figurative explanation of MTP in steady state[11]

In single-thread polling, when the OLT awaits the data packets from the ONU, the second thread is started. So the idle time after send a grant window is mainly targeted. If the total cycle time is large, even more than two polling is possible in the set-up. The increase in number of polling, provided an analysis of the optimum number of threads required in one cycle time.

The concept of MTP. In the above figure, initially only one thread is initiated by sending a grant to the ONUs. While the OLT waits to receive the REPORTs from the ONU, and when the downstream channel is free, the second thread is initiated.

Analyzing more on MTP, from the steady-state diagram, again considering two ONUs and two threads for convenience, it can be seen, how the idle time in single thread polling is utilized for another thread. Another issue that is considered in single-thread polling, that has to continue in MTP is that of fairness. All ONUs, either lightly-loaded or heavily loaded, should have equal fairness to the bandwidth. In order to assure that, after all the REPORTs are obtained to the OLT. The OLT allocates bandwidth in the next cycle by the sharing of the excess bandwidth of the lightly-loaded ONUs to the heavily-loaded ONUs. The algorithm for which will be discussed later in this section.

Delay analysis based on Design space As mentioned in Section 2.4 the delay analysis based on design space will consider idle time as a deciding factor. This section is again introduced only in this thesis work to the best of our knowledge, which describes idle time in terms of start time and end time. In this way, it is possible for us to compare the idle time with that of the online (IPACT) and offline(single thread) schemes.

Case 1: j = 1, δ = 1

$$\Delta(j,n,\delta=1) = t_G + 2 * \tau([j,n,\delta=1]) \tag{4.10}$$

Case 2: $1 < j < M$, δ = 1

$$\Delta(j,n,\delta=1) = \beta(M,n-1,\delta=2) + j * t_G + (2\tau([j,n,\delta=1]) - \beta([j,n,\delta=1])) \tag{4.11}$$

4.3 Issues in MTP

1. As mentioned in [11] IPACT performs better than MTP for both SRPON and LRPON as MTP is a technique based on offline scheduling framework, which in turn introduces idle time larger than IPACT. Also in case of MTP, the consecutive thread will have to wait until all the ONUs are serviced unlike IPACT, which is based on online scheduling framework, and schedules immediately after the previous ONU is scheduled.

2. Many issues of threads in scheduling have been highlighted in [3]. An important issue mentioned is that of thread spread or convergence as described. The threads are ordered as per completion of the previous thread sequentially. Therefore, when one thread becomes larger than the other threads in one data cycle, this could monopolize the data cycle by one thread and thus Multi-thread polling will degrade to single-thread polling. Thread tuning is a technique already introduced in [16] as a solution to this problem, but this technique introduces complexity and lengthiness of the algorithms

3. Fairness is an important factor in DBA schemes. It is necessary to make sure that all ONUs are serviced fairly. This brings in introduction of excess-bandwidth distribution which is a technique for obtaining fairness in offline scheduling framework. The excess-bandwidth technique used in [16] and [11] are demand-driven and overload-driven respectively which

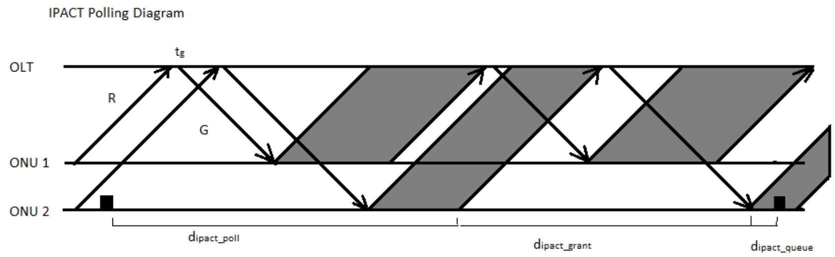


Figure 4.4: Explanation of IPACT or online

were explained previously in Section 2.2.4. Introduction of fairness, although justified, introduces more complexity to the MTP algorithms.

4. A possibility of void formation is possible in MTP, as highlighted in [3] but the reasoning explained in it can be misleading as the paper assumes MTP as a technique based on IPACT which in reality is not the case, as MTP is based on multiple offline techniques with excess-bandwidth distribution in one cycle. The possibility of void formation is when any thread cycle requires more time than the data cycle and because of which the start time of the data cycle is postponed.

4.4 Comparison of IPACT and MTP

This comparison is introduced in this section in order to form the basis for the next Section, where we will be introducing a novel multi-polling technique. The requirements for which are highlighting the issues faced in MTP and the explicit description of the MTP techniques as it has been widely misled as a technique based on IPACT or online, when in reality is a technique based on offline technique which incorporation of excess-bandwidth grant sizing policy. To describe in terms of design space equation , MTP is (mutliple-offline, excess-bandwidth, SPD). This combination is responsible for providing better performance than single-thread polling techniques which is generally (offline, gated, SPD).

IPACT is an online centralized algorithm for bandwidth allocation in EPON [12]. Mechanism of IPACT involves granting the requested window size on receipt of REPORT for an ONU, without waiting for other ONUs. The advantage of this scheme is the delay/idle time caused due to RTT/2 is used to interleave the OLT by another ONU. Thus the delay is reduced a lot less when compared to offline technique, although techniques such as excess bandwidth share between highly-loaded and lightly-loaded ONUs cannot be implemented. Online Excess Bandwidth Distribution (OEBD) introduced in [21] is an opportunity for consideration in this case.

IPACT is generally deployed as (online,limited) as grant scheduling policy does not play a role in IPACT, hence, it is not mentioned in this case. Mathematically, IPACT is represented as (check Table I for reference):

$$G(j,n) = min(R(j,n), G_{max}(n)) \tag{4.12}$$

where $R(j,n)$ is the requested transmission window for ONU_j and in cycle n

As we discussed earlier, the DBA schemes before LRPON generally worked with a single polling per ONU in one cycle time, and a window size is allocated based on its request. Therefore, complete cycle time n for all M ONUs is[11]

$$C_{max}(n) = \sum_{j=1}^{M} G_{max}(n) + Mt_g \tag{4.13}$$

Although this cycle time, does not remain constant, and varies based on load traffic. And therefore, the effective cycle duration can be given as:

$$C_{eff}(n) = \sum_{j=1}^{M} G(j,n) + Mt_g \tag{4.14}$$

$C_{eff} <= C_{max}$

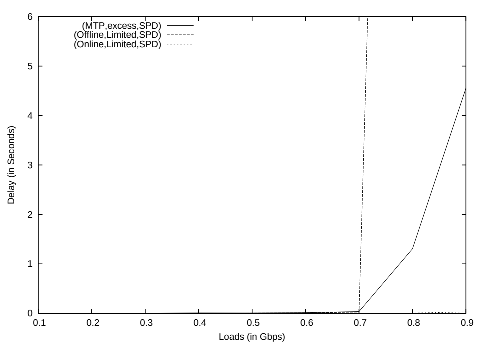
For lightly-loaded traffic C_{eff} will be a lot smaller than C_{max}, thus making a way to include fairness algorithm. Fairness algorithm is mostly based on excess bandwidth algorithm as discussed in Section 2.3.

We designed an experiment to run simulations to prove the point of difference stated in [15] and [11] and re-implemented Dr. Mukerjee's and Dr. Mouftah's MTP method. This is to prove that what has been stated in [12] has been proved from algorithms implements and simualtion results. Comparison of MTP with online and offline for SRPON and LRPON based on the implementation in [17] and [12]. As per our design space, MTP can be described as (Multi-thread offline, excess, SPD).

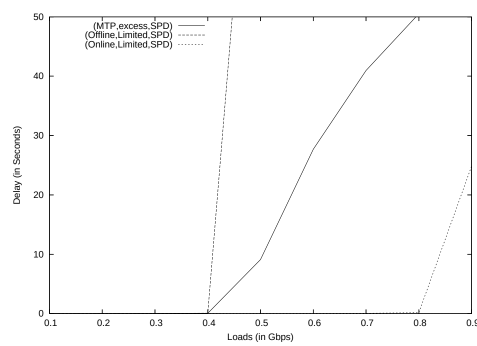
1. Traffic generator is self-similar

2. Distance between ONU and OLT is a. 20Km and b. 100Km

3. Distance between all ONU and OLT are same.



a) Compare[17] MTP with IPACT, offline, 20km



b) Compare[17] MTP with IPACT,offline, 100km

Figure 4.5: Delay Analysis for same dist ONU-OLT with self-similar traffic for two different propagation delay ranges, where MTP here is that in [17]

Chapter 5

Parallel Polling

Parallel Polling (PP) is a novel technique that is introduced as a part of the thesis work which promises to provide the better delay performance for LRPON even when compared to IPACT. The analysis and derivations of PP are first introduced here to the best of our knowledge.

5.1 Motivation

The motivation of this technique came from the widespread analysis of MTP. From the issues faced in MTP, it motivated us to develop a technique that would overcome most of the issues and reduce the complexity of the algorithm.

1. It was necessary to introduce a technique that would surpass the delay performance of IPACT, as it proved to be the technique that gave the least delay for LRPON, so far.

2. Usage of multiple threads, gives rise to issues of thread spread or convergence. The main reason for this is sharing one cycle time with multiple threads, therefore, a need of a technique to overcome this problem was required.

3. Fairness issues arises when the technique involves offline scheduling framework, whereas if an online scheduling framework is used, the ONU is serviced with a window size it requests. Therefore, there is no requirement of managing fairness issue.

4. Certain amount of void formation is inevitable, because certain REQUESTs may consume large part of cycle time. But void formations can be reduced in online scheduling framework when compared to offline scheduling framework, therefore it was necessary to define the new technique based on online scheduling framework.

5.2 Definition

Parallel polling is the technique of introducing multiple online/IPACT polling in parallel. Although the concept of PP is similar to MTP, the implementation and delay performance analysis are novel and unique. When multiple IPACT processes are in parallel, the advantages of multiple polling in one cycle time and online scheduling framework are utilized.

This technique can be visualized similar to the parallel architecture/mechanism on Network Processor that proves to provide much better performance when compared to multi-thread mechanism as in [26]. As mentioned in [26], in multi-thread mechanism, one packet is sent through

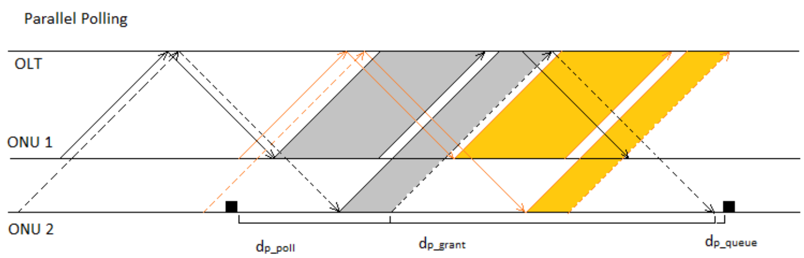


Figure 5.1: An example of Parallel polling

one thread, and in the case of parallel mechanism, it is possible to send uncorrelated packets to different threads, in this way, it is possible to send more packets in case of parallel mechanism.

As shown in the figure above, PP is implemented such that two threads, each providing a transmission window (2 processes are initially chosen for convenience) are initiated simultaneously in an online fashion. Therefore, the ONU is given two opportunities to send the data to OLT. The advantage of this kind of a mechanism is that more data is sent in one cycle time when compared to IPACT. Since IPACT gave the best delay performance as yet, this technique surpasses it.

PP proves to provide better delay performance for LRPON as the delay incurred due to distance between ONU-OLT is made use to initiate more threads. On the other hand, PP gives bad delay performance for SRPON. The reason for this is, PP works by initiating two threads in parallel to a single ONU in one cycle time. Therefore, the RTT for thread 1 and thread 2 should be less than the entire cycle time for that ONU, which is not possible for SRPON where distance of ONU-OLT is 20km. And for LRPON, it is possible to incorporate RTT for thread 1 and thread 2, quite sufficiently and provides very good performance. Therefore, this technique targets LRPONs.

5.3 Design Space Equation

The PP technique is explained using the design space equations as defined before, in order to provide mathematical quantification.

As in the case of MTP, thread number will be an important factor. Although the limit of the thread number in case of Parallel polling is not the same as MTP. The number of times the OLT can be polled by the ONU in one cycle time will be the thread number n, and is kept varied in this case.

$$\gamma(j,n,\delta) = \begin{cases} \beta(j,n-1,\delta=2) & \text{if } \delta=1 \\ \beta(j,n-1,\delta=1) & \text{if } \delta=2 \end{cases} \tag{5.1}$$

$$T(j,n,\delta) = (t_G + 2\tau([j,n,\delta])) \quad (5.2)$$

5.4 Delay Analysis

The delay analysis for parallel polling can be explained in two perspectives, one as per in MTP where the three delay components $d_{poll}, d_{grant}, d_{queue}$ are explained for PP and one as per delay analysis based on design space where the idle time is analyzed in detail.

Considering the definitions of $d_{poll}, d_{grant}, d_{queue}$ as in Section 4.2. Analysis of delay for MTP [16] where the defined delay components show significant reduction to corresponding delay components such as $d_{m_poll}, d_{m_grant}, d_{m_queue}$, which sums up to overall MTP delay:

$d_m = d_{m,poll} + d_{m,grant} + d_{m,queue}$

In PP, reduced corresponding delay components are defined as follows $d_{p,poll}, d_{p,grant}, d_{p,queue}$.

1. Polling delay - the effect of PP will be the same as that of MTP on polling delay, as the more number of polls gives the ONUs that many opportunities to transmit packets to OLT. Thus it reduce according to the thread number.

$$d_{p,poll} = d_{poll}/N = C_{eff}/2N \quad (5.3)$$

   where N is the number of threads, C_{eff} is the cycle time.
   The difference between MTP and PP for polling delay will be the cycle time. The cycle time considered in the case of MTP is that of offline scheduling framework, so it will be larger as all the ONUs are serviced in one cycle time, whereas cycle time for PP is that of online scheduling framework and includes the time to service only 1 ONU.

2. Granting delay - the effect of PP will also be the same as MTP for granting delay, with the cycle time difference as mentioned earlier, also for MTP granting delay calculations, a quantity T_w, the waiting time is considered as the time interval when the ONU has to wait for its time window in the cycle is considered, which need not be included in our calculations. Also the second case of heavily-loaded situations is not a problem. Thus providing a much simpler algorithms for LRPON.

$$d_{p,grant} = C_{eff}(n) - C(n,\delta) - RTT/2 \quad (5.4)$$

For cycle time n and any thread number δ

3. Queuing delay - Queuing delay also reduces by the number of threads, as it is clear that if the number of threads are more, then each thread has less data to transmit and the data cycle is reduced.

$$d_{p,queue} = d_{queue}/N \tag{5.5}$$

$$d_p = d_{p,poll} + d_{p,grant} + d_{p,queue} \tag{5.6}$$

From Fig 5.1 when compared with Fig 4.1, we can easily compare the $d_{p,poll}$ and $d_{m,poll}$ and from illustration, it can be shown that $d_{p,poll} < d_{m,poll}$. And also since PP is implemented based on Online scheduling framework, the technique saves on the waiting time, which in the case of MTP is very high. Therefore, $d_{m,grant} > d_{p,grant}$. From these two inequalities, it can be derived that:

$$d_p < d_m \tag{5.7}$$

Delay Analysis based on Design Space: Delay analysis for design space will be the effect of PP on delay when analyzing the idle time in the DBA model. The parameters used here are similar to that defined in Table I. As can be seen from equations, the idle time considered is a smaller time interval than idle time considered for Online, Offline and DPP as in Chapter 2. When compared, we can say that idle time is much less. Delay analysis of PP when compared to MTP, already illustrates that it is lesser in the previous section. Thus overall, we can say that delay of PP can be lower when compared to Online, Offline, DPP and MTP. Consider just two threads and their idle times are as follows:

Case 1: j=1, δ=1

$$\Delta(j,n,\delta=1) = [\beta(1,n-1,\delta=2) - \beta(M,n-1,\delta=1) + t_G + 2\tau([j,n,\delta=1])] \tag{5.8}$$

Case 2: j ¿ 1, δ = 1

$$\Delta(j,n,\delta=1)=[\beta(1,n,\delta=2)-\beta(j-1,n,\delta=1)+t_G+2\tau([j,n,\delta=1])] \tag{5.9}$$

From the equations, we can illustrate that the idle time difference is very small, and in most cases will be negative, and hence the idle time will be equated to the small guard time. Therefore, the delay of PP will be guard time divided N times, where N is the total number of threads.

Chapter 6

SIMULATION MODEL

The simulation model used in this work is called Eponsim, which stands for EPON simulator. This simulator was initially designed and developed by Dr. Michael G McGarry. The simulator source code has been modified to provide the platform for the work in this thesis.

The Eponsim is a software developed using C programming language and also has Graphical User Interface(GUI) built over it using Python programming language, therefore making it possible to be used by anyone with basic networking knowledge.

Description of Poisson and Self-similar Traffic model Possison process has a memory-less waiting time distribution, mostly used for telephony networks, because of the similarity in the packets it can be used to represent internet traffic as well [5]. Poisson traffic are based on certain assumptions that make more of a theoretical model. The assumptions for Poisson traffic model are:

1. There are infinite number of sources
2. Packets are served in random order
3. If there are packets that block then they have to be held
4. holding times are exponentially distributed or constant.

Internet traffic generally depicts self-similar or fractal characteristics, therefore conventional models do not generally apply to internet traffic. Internet traffic generally involves data, voice and now even video. The combination of data and voice traffic can be depicted using self similar traffic based on packetised traffic.

Considering the performance of network for self-similar traffic, it degrades with increasing self-similarity [5]. More self-similar the traffic, longer the queue size and the queue length will decay more slowly. Clustering of packets generally has a negative effect on network performance. In Poisson traffic, clustering occurs in the short term but smooths out in the long term. Therefore, for long simulations, poisson traffic results generally is ideal case. Whereas in self-similar traffic, where the traffic is bursty, it exhibits more of the clustering effect and degrades the networks performance. So in general, if a practical model is considered results will be in between the poisson traffic model results and self-similar traffic model results.

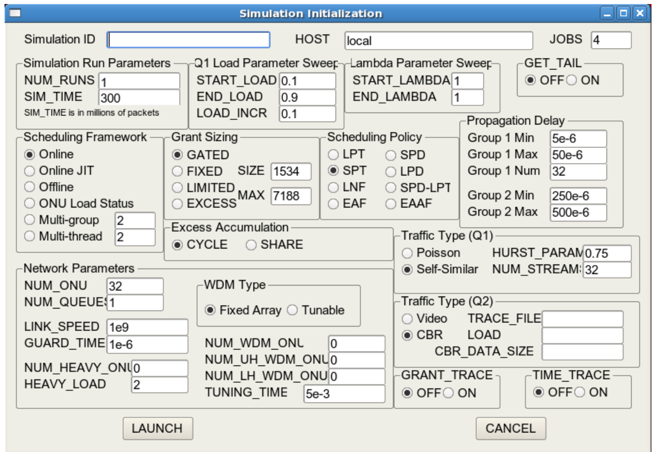


Figure 6.1: A simple model of Eponsim

In our work, we have therefore considered both traffic models in order to obtain a clearer view of the picture.

The EPON simulator configuration that was adopted for running the simulations for experiments are:

1. channel capacity, C of 1Gbps
2. Number of ONUs, M = 32

Propagation delay was modified to decide the distance between ONU and OLT. In most practical cases, the distances between ONU and OLT are kept constant or only modifying the distance only in the last 5km distances, therefore, some of our results consider same distance between ONU and OLT. We have also provided results for varying distances between OLT and ONU from 1 to the maximum distance possible. The different set of results is to provide a lower bound and upper bound for the results obtained.

Different EPON reaches:

1. 1Km to 10Km (6.67 μsec to 50 μsec)
2. 1Km to 50Km (6.67 μsec to 250 μsec)
3. 1Km to 100Km (6.67 μsec to 500 μsec)

The self-similar traffic model used will be a quad modal packet size distribution which includes the following sizes:

1. 60% 64 bytes
2. 4% 300 bytes
3. 11% 580 bytes
4. 25% 1518 bytes

The guard time t_g is set to be 1μsec and the maximum grant size set especially for the limited grant sizing will be G_i^{max} = 7688bytes.

Chapter 7

RESULTS & OBSERVATIONS

In this chapter, we cover the experiments we conducted to validate Multi-thread polling as per our definitions, Parallel polling and comparisons of these schemes with Online, Offline and Double Phase Polling, which is also called Multi-Group polling. The experiment set-up is as mentioned in the previous chapter. We set a configuration file to design our simulator based on certain assumptions. The annotations used in the graphs are:

1. IPACT – is the graph for Online scheduling framework
2. Offline/STP – is the offline scheduling framework which is also referred to as Single Thread Polling
3. Multi-Group – is the generalization of Double Phase Polling technique which is also known as Multi-Goup polling
4. MTP – Multi-thread polling
5. PP – Parallel Polling

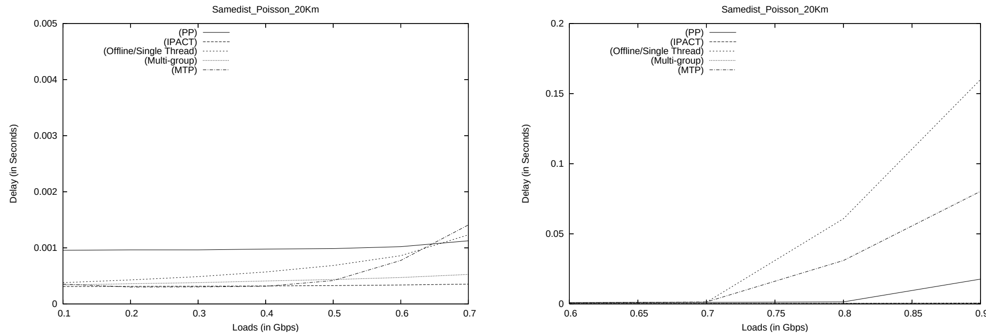
7.1 Overall Delay and Channel Utilization Analysis

In any broadband network, importance is given for parameters that affect the Quality of Service (QoS) of the network. The case is the same for PON as well. The parameters that determine QoS are generally, overall delay performance, fairness, throughput and bandwidth utilization. Here we have considered the overall delay as primary analysis parameter and also from our delay curves we obtain values for maximum achievable channel utilization for different experiments that help us make important observations. Channel utilization is obtained at the point when delay in the channel becomes asymptotically unstable [22], that is when the channel reaches it maximum point of utilization.

Poisson Traffic Analysis

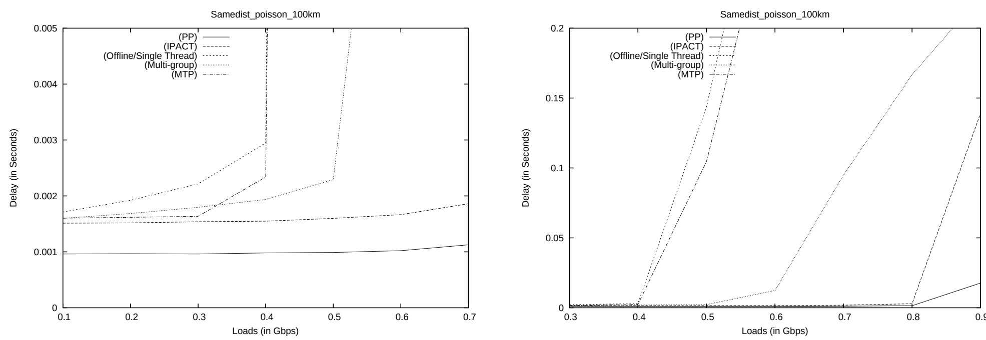
The traffic generator uses poisson traffic to compare the different mechanisms. Although poisson traffic cannot be used to explain real-traffic, it is very useful in understanding the basic performance of the DBA techniques and will be helpful is comparison.

SRPON



a) Poisson, 20km, Delay Analysis b) Poisson, 20km, Channel Utilization

Figure 7.1: Comparison Delay Analysis for same dist ONU-OLT with poisson traffic for 20km.



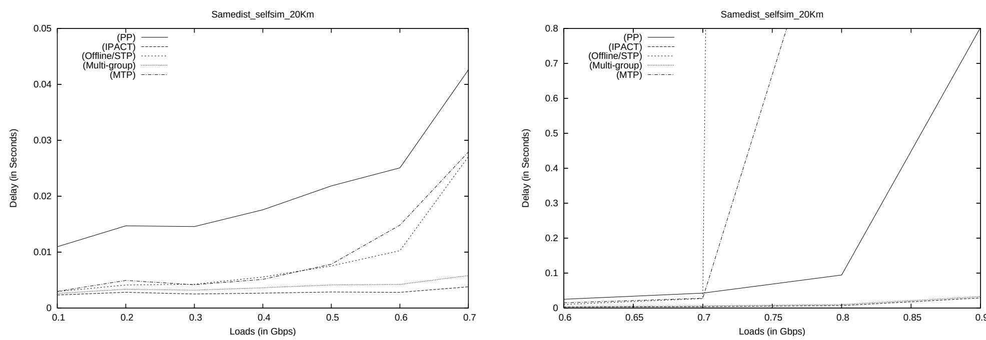
a) Poisson, 100km, Delay Analysis b) Poisson, 100km, Channel Utilization

Figure 7.2: Comparison Delay Analysis for same dist ONU-OLT with poisson traffic for 100km

1. Traffic generator is poisson in nature.
2. Distance between the ONU and OLT are same
3. Distance of 20km(SRPON)
4. (a) Delay Analysis (b) Channel Utilization

LRPON

1. Traffic generator is poisson in nature.
2. Distance between the ONU and OLT are Same
3. Distance of 100km(LRPON)
4. (a) Delay Analysis (b) Channel Utilization



a) Self-Sim, 20km, Delay Analysis b) Self-Sim, 20km, Channel Utilization

Figure 7.3: Delay Analysis for same dist ONU-OLT with self-similar traffic for two different propagation delay ranges

Self-similar Traffic Analysis

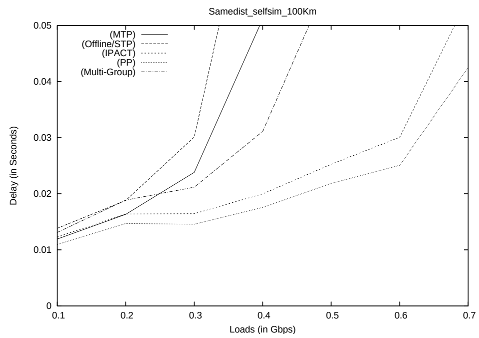
Self-similar traffic as described in the earlier section, depicts internet traffic and is mostly used to validate the results of any DBA technique. Experiment analysis and observations are done on the following experiment set-up.

SRPON

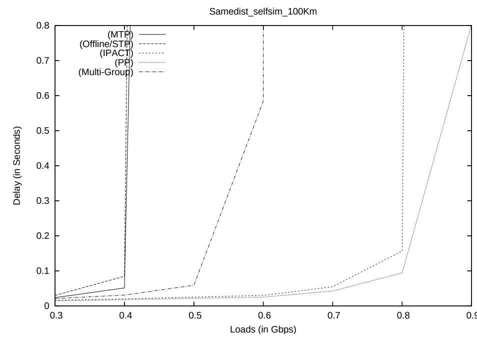
1. Traffic generator is Self similar in nature.
2. Distance between the ONU and OLT are same.
3. Distance of 20km(SRPON)
4. (a) Delay Analysis (b) Channel Utilization

LRPON

1. Traffic generator is self similar in nature.
2. Distance between the ONU and OLT are same.
3. Distance of 100km(LRPON)
4. (a) Delay Analysis (b) Channel Utilization



a) Self-Sim, 100km, Delay Analysis



b) Self-Sim, 100km, Channel Utilization

Figure 7.4: Delay Analysis for Same dist between ONU-OLT as 100Km with self-similar traffic

7.2 OBSERVATIONS

1. Observation 1 – We initially prove with our re-implementation of MTP that our results match the results of [11] and that IPACT performs better than MTP but MTP performs better than Single Thread polling which is the offline scheduling framework. Thus we were able to remove the discrepancies that we existent in research. From our design space description, it was possible to define MTP as based on offline scheduling framework, with excess bandwidth distribution grant sizing technique, and with specific grant scheduling policy explicitly mentioned. By addressing MTP as per the design space, the performance of the technique is easier to analyze and explain.

2. Observation 2 – From our implementation of Parallel polling, we see very good delay performance for Long reach PONs. PP basically uses the availability of high propagation time which leads to large idle time in any cycle time, this time is utilized to serve the second thread in parallel polling as illustrated and which can be generalized. As shown in PP polling diagram, the waiting time when compared to MTP is the reason for reduction in delay which is reflected on parameters d_{poll} and d_{grant}.

3. Observation 3 – PP has the highest channel utilization for LRPON, losing its stability only beyond 0.8Gbps, when compared to IPACT which has channel utilization capacity of 0.79Gbps and MTP with very low channel utlization of 0.4Gbps.

4. Observation 4 – Multiple polling of OLT in one cycle time, proves to be a promising area of research for LRPON. The availability of large idle time because of the high propagation delay gives room for multiple polling in one cycle time. This opens room for research

towards a study for multi-polling techniques. We observe the performance of Double-phase polling, which is also multi-polling of OLT in different groups. The performance of DPP is quite promising especially for SRPON as it gives delay performance close to IPACT.

5. Observation 5 – PP does not provide its best performance for SRPON. The reason for this being, PP technique utilizes the idle time for initiating a new thread. In case of SRPON, the idle time is much lesser and introducing a new thread performs negatively for delay. This is the cost that has to be paid to obtaining the best performance for LRPON case.

Chapter 8

FUTURE WORK

In this section, we will briefly discuss the issues that were faced in our results and the future work. The main topics presented here are MAC layer analysis of a Network module. Mostly considering Passive Optical Network(PON) as the physical(PHY) layer. Bandwidth and Resource allocation is by far the most important area of research for any network, as improvements in DBA algorithms helps improvise the standards of already established standard. Although LRPON is promising with supporting results, the concept has not been vastly deployed thus giving the DBA techniques only theoretical research value. But sooner, most of the back haul network is going to be replaced by LRPON.

1. When LRPON is our main focus, we have provided results to prove that when self-similar traffic is considered as our input, Parallel polling gives the best delay performance. Therefore providing a new area of research. Improvements to this technique can be provided by utilizing excess online bandwidth distribution(OEBD) technique. This will help in reducing delay further and now PP gives promising results when number of threads is two, by incorporating excess bandwidth distribution or fairness, more threads will prove to be useful.

2. PP and other techniques have now been implemented on EPON based simulator. Considering the working of PP that utilizes large propagation delay, it provides room for implementing this technique to GPON where grant is transmitted every 125 μs irrespective of the queue depth. The intermediate time can be utilized for a second thread and performance can be analyzed.

3. In our present experiments, we assume same distance between ONU and OLT, as it is the most general case, in case the distance between ONU and OLT are different, then how will the performance vary? Can the scheduling policies like SPD, LNF etc be implemented and give promising results. For example, no scheduling policy is experimented on MTP, how useful can be render MTP with scheduling policies?

4. Also, throughput analysis will have to be performed for MTP, PP and DPP and compared. With these schemes, it is possible to bring in a new topology that varies techniques based on their number of threads (polling the OLT) is possible in one cycle time.

Chapter 9

CONCLUSION

Therefore, in this paper, we have taken a new survey perspective to categorize the different DBA schemes. The advantage of such a classification is to target each category for a specific need so that the customer can be served efficiently.

In the Direct category, we see no delay but less throughput. Such a category suits best for Business needs. In Business, the major form of network traffic is video conferencing, data transfer. Also the network is close-knit with respect to distance and a large bandwidth can be provided. In Business, the speed provided should be high and delay in intolerable.

In the case of Intelligent category, it is best suited for Home users. Where the traffic could be video streaming(eg. Netflix that requires large bandwidth), video chat (for eg Skype and Hangout) etc. For Home users, delay can be compensated a little bit, but throughput or performance provided should be satisfactory. Predictive, on the other hand can be used for both types of users.

Thus, this type of categorizing can help understand user's behaviour and by considering the network traffic nature, different schemes can be utilized efficiently.

The second highlight for this work is detailed analysis of multi-thread polling and description of the major issues and correspondingly introducing a new technique Parallel polling that surpasses the issues of MTP and gives good delay performance with delay lesser than IPACT as well for LRPON. The observations based on our results that illustrate PP can be an efficient technique for LRPON with least delay when compared to IPACT, DPP and offline and highest channel utilization capacity.

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