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A Survey of Dynamic Bandwidth Assignment Schemes for TDM-Based Passive Optical Network

https://doi.org/10.1515/joc-2017-0186
Received October 23, 2017; accepted December 27, 2017

Abstract: In time division, multiple access (TDMA)-based passive optical network (PONs), a dynamic bandwidth assignment (DBA) is necessary for efficient utilization of the available bandwidth of the upstream link. An efficient DBA scheme can improve the upstream performance of a traffic class of an ONU in two ways. First, it can increase the bandwidth assignment to it by efficiently utilizing the available bandwidth. Secondly, it can reduce the channel and frame idle time by increasing the polling frequency and by assigning extra surplus bandwidth not used by the other ONUs. Many DBA schemes have been reported for both ITU PONs (GPON and XGPON) and IEEE PONs (EPON and 10 G EPON). In this study, we explain the impact of DBA scheme on the upstream performance of PON and then do a thorough survey of both PON standards, categorize the DBA schemes and review them critically. Based on the literature review we also give our opinion on the most suitable DBA scheme for both type PONs on the basis of upstream delays, frame loss and bandwidth utilization efficiency.

Keywords: DBA, dynamic bandwidth assignment, PON, XGPON, EPON

1 Introduction

Information and communication technology (ICT) networks are rapidly expanding. ICT has turned the whole world into a global village. The access to the Internet has become a necessity rather than a comfort. The demand of ICT services has been dramatically increasing at a fast pace. ITU 2015 report mentioned that from 2010 to 2015, the individuals using the internet have risen by 10.8 % with 46 % increase in fixed broadband and 47 % increase in mobile service subscriptions [1]. According to ITU 2016 report, 95 % of the world population lives in an area that is covered by a mobile-cellular network and the coverage of mobile broadband networks (3 G or above) is up to 84 % of the global population. PON is the most attractive access network for the provisioning of these broadband services with very capacity. It is a fiber to the home (FTTH) solution and offer up to 200 Mbps data rates per user [2].

The currently deployed PONs; EPON and GPON and their upgraded versions 10 G-EPON and XGPON use broadcast mechanism for downstream (DS) transmissions [3, 4]. However, for upstream (US) they use time division multiple access (TDMA) mechanism as OLT cannot listen to all ONUs simultaneously on the same US wavelength. Therefore, an arbitration mechanism is required for US bandwidth management.

The most simplistic approach could be a static bandwidth assignment (SBA) to each ONU. However, this leads to bandwidth wastage by the ONUs if their traffic load is low and causes higher queuing delays for the ONUs with higher traffic load [5]. Moreover, with SBA the bandwidth cannot be assigned to a specific traffic class inside ONU. Therefore, for an efficient and as-perneed bandwidth assignment, it is necessary to have a dynamic bandwidth assignment (DBA) mechanism to assign bandwidth to each ONU according to its demand and bounded by the service level agreement (SLA). With a DBA scheme, it is also possible to subscribe more users than the available bandwidth on best effort commitment and thus the service providers can maximize their revenue.

Both ITU and IEEE PON standards [6, 7] have significant MAC layer differences. The ITU PONs are synchronous in which thus both OLT and ONU are required to send US/DS frames every 125us, irrespective of the traffic load. The IEEE PONs are based on Ethernet and thus the OLT and ONU only send US/DS frames if there is some

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traffic or some signaling or control information is to be sent. Therefore, their DBA schemes are also different and generally are not compatible. For bandwidth management purpose ITU PONs use the BW map section of DS frame to send the bandwidth assignments to ONUs and the DBRu section of the US frame to receive the queue reports from them. On the contrary, IEEE PONs use MPCP protocol messages for this purpose. Most of the DBA studies have focused on IEEE PONs, probably due to close resemblance with Ethernet frame structure which is a famous protocol and easier to simulate.

In this study, we critically review and categorize all the reported work on DBA for both IEEE and ITU PONs but focusing more on ITU PONs. We also give our opinion on the best DBA scheme in terms of US delay, frame loss and bandwidth efficiency. Rest of the article is organized as follows: Section 2 describes the impact of DBA on US delays, Section 3 reviews the DBA schemes for IEEE PON, Section 4 reviews the DBA schemes for ITU compliant PONs. In Section 5 we give our opinion about the best DBA scheme. Finally, in Section 6 we conclude this study.

2 Impact of DBA on US delay

The US delay mainly depends on the idle time (T_{Idle}) of frame and its queuing time ($T_{Queuing}$). These can be minimized by an efficient DBA scheme. Figure 1 shows the delays incurred during the DBA process for an ITU compliant PON. The T_{Idle} is the waiting time of a frame until it gets the bandwidth. This time is variable and depends on the instance of the frame arrival. At maximum, it could be $2^*(RTT + T_{OLT} + T_{ONU})$ and at minimum it could be $\left(\frac{RTT}{2} + T_{OLT} + T_{ONU}\right)$. Where the $T_{Queuing}$ is the waiting time of the frame in the queue after being reported to OLT but not getting US time slot due to bandwidth unavailability as a result of high traffic load. Therefore, it exists at higher traffic load and is more significant for the traffic classes with no assured bandwidth like T4. T_{ONU} is the sum of processing delay at the ONU and the equalization delay and its standard value is taken as 35 US plus equalization delay for GPON/XGPON [6]. T_{OLT} mainly depends on the T_{Grant} and T_{DBA} is the DBA processing time that can be neglected due to high processing resources of OLT. T_{Grant} is the time after which DBA algorithm is executed and allocations are sent to ONUs. In ITU PONs, it is defined in number of GPON/XGPON cycles but in the case of IEEE PONs it is a variable and depends on ONU traffic load. The channel idle time (T_{Ch_Idle}) is the time for which the US channel is not being utilized and the ONUs send empty frames. Equations (1)–(3) show the expression for D_{US}, T_{Idle}, T_{OLT} and T_{Ch_Idle}. The T_{Ch_Idle} depends mainly on T_{Grant}. To reduce T_{Ch_Idle}, T_{Idle} and D_{US} the T_{OLT} and RTT should be minimized. RTT mainly depends on the length of optical fiber between OLT and ONU is beyond control while the T_{OLT} can be reduced by reducing T_{Grant} to at minimum one GPON/XGPON cycle. However, the impact of RTT can be further mitigated through efficient and fair distribution of available bandwidth among ONUs and thus the D_{US} can be further reduced.

$$D_{US} = T_{Idle} + T_{Queueing} = 2^*(RTT + T_{OLT} + T_{ONU}) + T_{Queueing} \tag{1}$$

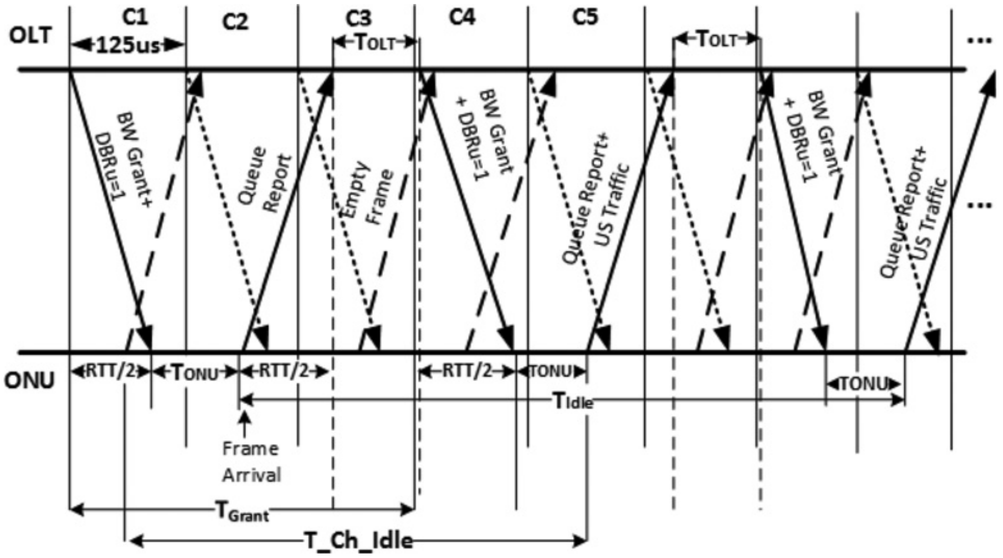


Figure 1: Delays involved in the DBA process.

$$T_{OLT} = T_{DBA} + (remaining)T_{Grant} \propto T_{Grant} \tag{2}$$

$$T_{Ch\_Idle} \approx RTT + T_{OLT} + T_{ONU} \tag{3}$$

The T_{Idle} and T_{Ch_Idle} also exist in IEEE PONs. Many DBA studies have been reported for both IEEE and ITU PONs to address this problem and improve the efficiency of DBA process.

3 Challenges for a DBA scheme

As discussed in Section 2, the main challenge for a DBA scheme is to minimize the T_{Idle} so that the waiting time of the newly arrived frames is minimized and the T_{Ch_Idle} so that the US channel utilization is maximized. This can be achieved by reducing the T_{Grant} and fully utilizing any available surplus bandwidth. However, the reduction of T_{Grant} results in static report inconsistency (SRI) problem.

To understand the SRI problem consider Figure 2 showing a DBA process for an ITU compliant DBA scheme with RTT = 200 us and SI = 10. One DBA cycle comprises of ten XGPON cycles; C0, C1, C2 … .C9. If the OLT sets the DBRu flag in DS frame G0 for an ONU (i) at the start of C0, this DS frame G0 is received at the ONU (*i*) during C1 after a time of $\frac{RTT}{2}$. The ONU (*i*) sends its queue reports $Report_k(i)$ after a time of T_{ONU} and OLT will receive $Report_k(i)$ in C2, where the subscript "k" represents traffic classes T2, T3 or T4. However, OLT will actually be able to use $Report_k(i)$ in C3. It can be seen in Figure 2 that during this time OLT has already sent four grants; G0, G1, G2, G3, G4 for each T1, T2, T3, T4 and T5 traffic classes to ONU (*i*). The T5 carries the excess bandwidth assigned to ONU in the RBW phase and is shared by T2, T3 and T4 traffic classes in a strict class priority. Therefore, it is necessary for OLT to subtract all these sent grants from $Report_k(i)$ before using it in the next GPA or SPA for a $TCONT_k(i)$ of an ONU (*i*). However, if a DBA scheme like IACG and EBU the OLT is not unaware of the actual values of the RBW used by $TCONT_k(i)$, thus grants subtracted from $Report_k(i)$ are not true. Therefore, their polling mechanism suffers with the SRI problem.

To illustrate this further, an example scenario is shown in Figure 3. Initially the ONU queues for T1, T2, T3 and T4 are assumed to be 2000, 3000, 3000 and 4000 bytes respectively. During C0, $Report_k(i)$ has not arrived at OLT and thus the grants G0 (1), G0 (2), G0 (3) and G0 (4) assigned to T2, T3 and T4 are zero. If the RBW value assigned to each ONU is assumed to be 2000 bytes that is sent through T5 traffic class, then G0(5) = 2000 bytes. The ONU uses the G0 (5) as per need and in strict class priority and thus the actual grants used by T2, T3 and T4 TCONTs at the ONU are different and denoted by H0 (1), H0 (2), H0 (3), H0 (4) respectively. Therefore, during C3 when ONU receives $Report_k(i)$ which comprises of ONU queue values at the start of C3, OLT has to subtract the actual grants H0, H1, H2 and H3 from $Report_k(i)$. However, in EBU and IACG schemes, OLT only knows G0, G1, G2 and G3 grants. Therefore, the reports computed by OLT are $Report_2(i)$ = Q2-G0(2)-G1(2)-G2(2)-G3(2) = 3000–0–0–0 = 3000 bytes, $Report_3(i)$ = Q3-G0(3)-G1(3)-G2(3)-G3(3) = 3000–0–0–0 = 3000 bytes, $Report_4(i)$ = Q4-G0(4)-G1(4)-G2(4)-G3(4) = 4000–0-0-0-0 = 4000 bytes. However, in reality it should be $Report_2(i)$ = Q2-H0(2)-H1(2)-H2(2)-H3(2) = 3000–2000-1000–0-0 = 0 bytes, $Report_3(i)$ = Q3-H0(3)-H1(3)-H2(3)-H3(3) = 3000–0-1000–2000-0 = 0 bytes, $Report_4(i)$ = Q4-H0(4)-H1(4)-H2(4)-H3(4) = 4000–0-0-0-2000 = 2000 bytes.

Therefore, in both EBU and IACG, based on the computed values of $Report_k(i)$, the OLT will assign G4(2) = $Report_2(i)$ = 3000 bytes, G4(3) = $Report_3(i)$ = 3000 bytes and G4(4) = $Report_4(i)$ = 4000 bytes. Whereas, as per actual ONU demand these should have been; G4(2) = $Report_2(i)$ = 0 bytes, G4 (3) = $Report_3(i)$ = 0 bytes and G4 (4) = $Report_4(i)$ = 2000 bytes. This shows that both the EBU and IACG schemes over allocate bandwidth due to lack of OLT knowledge of actual grants assigned to ONUs.

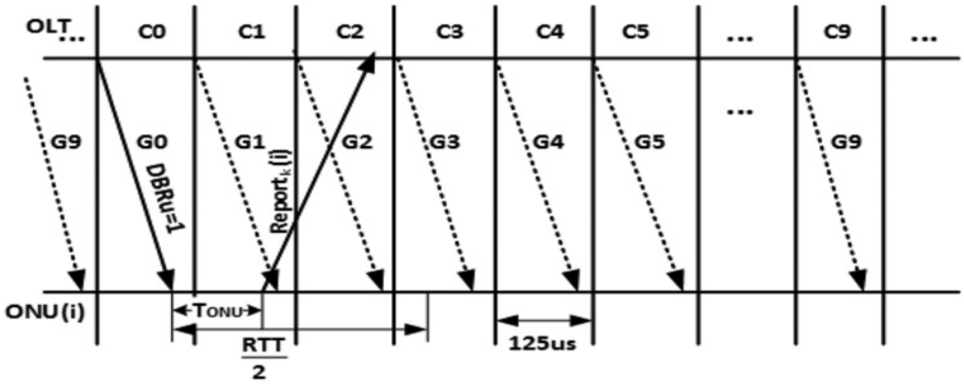
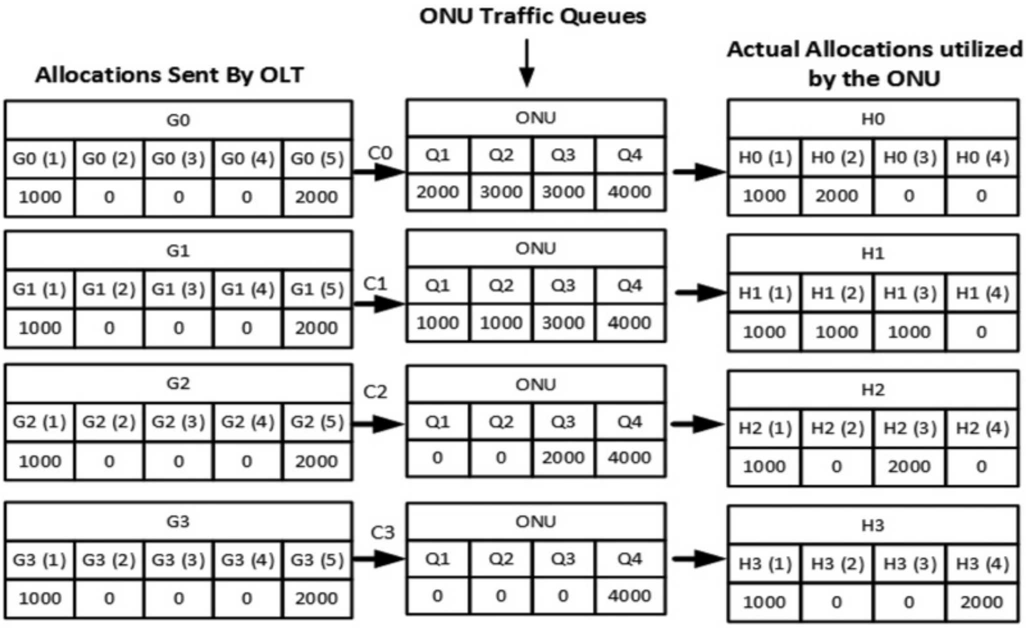


Figure 2: ONU reporting and DBA process.



G0 (1)	G0 (2)	G0 (3)	G0 (4)	G0 (5)
1000	0	0	0	2000

ONU Q1	Q2	Q3	Q4
2000	3000	3000	4000

H0 (1)	H0 (2)	H0 (3)	H0 (4)
1000	2000	0	0

G1 (1)	G1 (2)	G1 (3)	G1 (4)	G1 (5)
1000	0	0	0	2000

ONU Q1	Q2	Q3	Q4
1000	1000	3000	4000

H1 (1)	H1 (2)	H1 (3)	H1 (4)
1000	1000	1000	0

G2 (1)	G2 (2)	G2 (3)	G2 (4)	G2 (5)
1000	0	0	0	2000

ONU Q1	Q2	Q3	Q4
0	0	2000	4000

H2 (1)	H2 (2)	H2 (3)	H2 (4)
1000	0	2000	0

G3 (1)	G3 (2)	G3 (3)	G3 (4)	G3 (5)
1000	0	0	0	2000

ONU Q1	Q2	Q3	Q4
0	0	0	4000

H3 (1)	H3 (2)	H3 (3)	H3 (4)
1000	0	0	2000

Figure 3: Example scenario for the illustration of SRI problem.

4 Review of DBA schemes for IEEE PONs

Broadly, DBA schemes for IEEE PONs can be divided into single-thread and multi-thread schemes as shown in Figure 4. In single thread, a new GATE message is sent to an ONU after it has responded to the previous GATE message. Multi-thread schemes on the other hand send multiple GATE messages to ONU without waiting for the previous response. Multi-thread polling (MTP) approach is suitable for LR-PONs as in normal PONs it will lead to

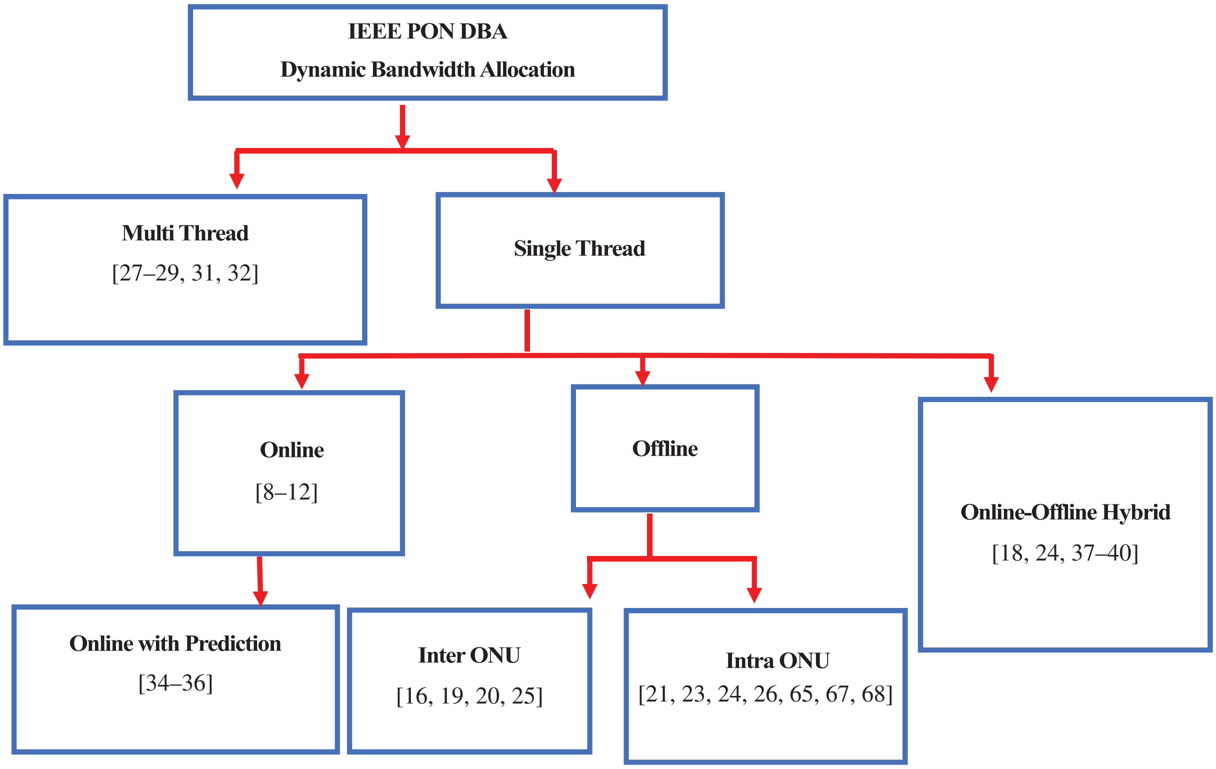


Figure 4: DBA schemes for IEEE PONs.

reduced throughput due to more bandwidth wastage because of extra gate and report messages. The single thread schemes [8–13] can be classified as: online, offline and online-offline hybrid schemes.

4.1 Online schemes

In the online schemes, an OLT polls each ONU for its queue report and allocates bandwidth to it, as soon as its report message is received. Interleaved Polling with Adaptive Cycle Time (IPACT) is the first online DBA scheme presented in Ref. [8, 11] for EPON. In this scheme, each ONU is assigned a US time slot and polled for its bandwidth demand one after the other. The ONU ($i + 1$) is polled before the US transmission from the ONU (i) finishes. The bandwidth allocation by the OLT follows any of the five disciplines; Fixed, Gated, Limited, Credit and Elastic. The fixed discipline is essentially the same as FBA. The Gated discipline grants bandwidth to ONUs without any limitation and thus may lead to monopolization of the channel by the heavily loaded ONUs. The Limited service discipline, therefore, limits the maximum allocation to an ONU to W_i^{min} so that an ONU (i) is assured to get its minimum share of bandwidth allocation. The W_i^{min} could be simply $\frac{W^{max}}{N}$, where W^{max} is the maximum available bandwidth on the US channel and N is the total number of active ONUs connected to OLT. The W_i^{min} may also be assigned to each ONU as per its SLA as in [8]. However, in all of these approaches the unassigned remainder bandwidth (UBW) is wasted and the traffic frames arriving after the ONU has sent its Report suffer from idle time as they have to wait for next allocation cycle. To mitigate the impact of idle time, an additional excess bandwidth W_i^{Excess} may also be assigned to all ONUs in addition to W_i^{min} in the Credit disciplines. If W_i^{Excess} is assigned in strict priority order of the traffic classes then this scheme works the best according to the results of [8]. However, it was discovered in [14] that the combination of limited scheme with strict priority leads to Light Load Punishment (LLP). To overcome LLP, this study proposed a two stage buffer scheme at the ONU which eliminates LLP but leads to increase in US delay of higher priority classes. The study in Ref. [9] presents a detailed mathematical modeling of the Gate and Fixed disciplines with IPACT. A similar study in [10] finds that if an ONU sends its queue report first before sending data frames to OLT, it results in lower US delays. The problem of LLP is basically concerned with fair allocation of bandwidth to ONUs which cannot be completely assured in Online schemes. Due to variable cycle period in IPACT, one more problem is increase of delay variance for the higher priority traffic classes like EF and AF. This is addressed by the delay aware grant sizing (DAGS) [15] and modified delay aware grant sizing (MDAGS) schemes [13] which use differential polling and adapt the DBA cycle time according to the maximum delay allowed for a traffic class. The differential polling means, the ONUs are grouped according to their delay requirements and the ONUs with lesser delay requirement are polled more frequently. Another Online scheme Bandwidth Guaranteed Polling (BGP) [16] improves the IPACT by dividing the available US bandwidth into equal number of bandwidth units. The OLT maintains two tables for the Guaranteed (GR) and Non-guaranteed (NGR) ONUs. In the GR table all the entries are assigned to ONUs as per the SLAs while in the NGR list ONUs are listed for polling purpose. The GR ONUs are assigned a bandwidth unit through a Gate message and OLT waits for the ONU reply for the needed bandwidth. If the ONU bandwidth need is less than the assigned, then the NGR ONU from the list is polled for the unused bandwidth units. The simulation results show that for GR ONUs with four or more bandwidth entries, delays are lower compared to IPACT. However, the delays for the NGR ONUs are comparatively higher. Compared to IPACT the throughput in BGP decreases as the traffic load increases due to higher messaging overhead and bandwidth waste in guard bands for each bandwidth fragment [17]. Moreover, BGP does not support the DiffServ framework as it cannot assign bandwidth to a non-assured traffic class of an ONU. In order to ensure intra-ONU allocation with fairness it is necessary that OLT waits for the queue Reports of all the ONUs that is only possible in an Offline scheme.

4.2 Offline schemes

In an Offline scheme OLT waits for all ONU reports and then allocates bandwidth to all ONUs. These schemes can also assign the excess bandwidth to ONUs which it can divide to its specific traffic classes at its own discretion. This approach is termed as Inter-ONU allocation [16, 19, 20, 25]. It is also possible for the OLT to allocate bandwidth directly to each traffic class of an ONU termed as Intra ONU approach [65, 21, 23, 26, 67, 68, 24]. Many Offline DBA schemes have been presented. The study in quality of service DBA (QoS-DBA) in [18] presents an Offline DBA version of IPACT and shows that LLP is eliminated by allowing ONUs to allocate the bandwidth to lower priority class frames instead of the newly arriving frames after the Report message has been sent by the

ONU. Another improvement of IPACT is double phase polling (DP) DBA [19] which divides the ONUs into two groups and executes the bandwidth assignment process for one group and simultaneously executes the polling process for the other group. The results show better performance compared to Offline IPACT scheme. The Sort-DBA scheme in [20] claims to completely eliminate idle time by sorting the ONU reports in descending order and executing the DBA process in parallel when the data from an ONU with largest granted bandwidth in previous cycle is being received. However, during this time due to bursty nature of traffic, the lightly loaded ONUs might have sudden traffic arrival after sending the Report message to OLT and thus the idle time problem will still be there. Moreover, this work does not describe the excess bandwidth allocation procedure. To fix this deficiency, the study in [21] combines the Sort-DBA with an intra-ONU scheme which assigns the unused bandwidth of lightly loaded ONUs to the heavily loaded ONUs. Another solution to handle the self-similar traffic for the EF traffic class with strict delay guarantee requirements is to use a PID controller [22] to compute the bandwidth assignments according to the delay requirements. However, this is a very complicated approach and requires accurate values of the controller.

Overall, all of the above discussed Offline schemes do not utilize the W_i^{Excess}. If the W_i^{Excess} is also assigned from UBW to ONUs then delays can be further reduced. The study in [23] addresses this problem and divides the W_i^{Excess} equally among all active ONUs. To do so, it classifies ONU DBA cycles as busy and absent. In case of absent cycles, which means total bandwidth request is less than the available then a credit is assigned as requested. During the busy cycles, which means the total bandwidth report of ONUs is greater than the available bandwidth, a credit is assigned to an ONU if its queue report is higher than a threshold. However, fairness among the traffic classes at the ONU is not considered. To improve this work, the study in [21] combines an Intra-ONU allocation scheme with Sort-DBA. The W_i^{Excess} is distributed between the ONUs in an ascending order of their demands. However, no upper limit for the excess bandwidth assignment is defined. If an ONU demand is high it may get all of the W_i^{Excess}. Further, allocation mechanism between the EF, AF and BE traffic classes at the ONU is not described in this work. A similar study in [24] proposes a novel W_i^{Excess} sharing mechanism, which allows all ONUs to share excess bandwidth over the time period of one polling cycle in the DPA framework and keep the cycle length bounded by limiting the number of forwarding credits. Another comprehensive DBA mechanism to eliminate LLP and fairly distribute the W_i^{Excess} is presented in Ref. [25]. It reduces the frame and channel idle time by changing the interleaved polling style to broadcast, hence also termed as Broadcast polling (BP), by sending Gate messages to all ONUs simultaneously. It combines the Inter-ONU and Intra-ONU allocation into one DBA process at the OLT and thus also reduces ONU computational load. However, ONUs are required to send queue reports of all three traffic classes explicitly. First it allocates the W_i^{min} keeping in view the SLA of ONUs and then there are two possible cases. In first case if the sum of the queue reports of "N" ONUs is greater than the NW_{min} then it allocates the W_i^{Excess} to ONUs one by one by setting a certain windows size until all the excess bandwidth is exhausted. The window sizes should be greater than 64 bytes which is the minimum Ethernet frame size to avoid bandwidth waste. In the second case if the sum of the queue reports is less than NW_{min} then the procedure is as follows; EF class is assigned as per demand, AF class is assigned as per demand but upper bounded by a maximum allowed bandwidth limit. The remaining W_i^{Excess} is distributed equally among all the ONUs. However, BP scheme does not bound EF class which may lead to unfair bandwidth allocation among AF and BE classes. To address this problem the study in [26] improves BP algorithm by employing a fuzzy Logic based bandwidth allocation mechanism. Overall the Offline schemes suffer from higher channel and frame idle time due to an increase in OLT waiting time for ONU queue reports and thus do not efficiently utilize US channel.

4.3 Multi-thread schemes

For long reach PONs, due to long RTT, the frame and channel idle time increases and thus the US delay increases even with the Online schemes. To mitigate this effect, the MTP has been presented in Ref. [27]. This study shows that, compared to single thread, in multi-thread approach the US delays are reduced and throughput increases. In these schemes, each thread refers to one active control loop between the ONU and OLT and thus by parallelizing the DBA process, idle time is reduced and average packet delay is also reduced. The basic idea is to allow an ONU to send its queue Report before the previous Gate message is received, thereby creating a new thread of signaling between ONUs and the OLT. For classic PON structure, MTP approach may bring unnecessary messaging and shorter slot sizes for ONUs in a cycle that may degrade the overall performance. Moreover, executing multiple threads in an Online style restricts the utilization of excess bandwidth. To address this problem, the study in [28] executes the MTP in an offline style. The study compares the performance of IPACT with single, two and three threads. The results showed that the MTP achieves lower reporting and queueing delays but the IPACT showed higher throughput. The study in [29] presents a scheme to utilize excess bandwidth in an Online MTP scheme. It records the unused bandwidth of lightly loaded ONUs and assigns it to heavily loaded ONUs. The study in [30] showed that the Online MTP reduces the idle time of channel compared to offline MTP. It also shows lower US delay than the offline MTP if the polling cycle is longer. A detailed review and analysis of MTP scheme is given in [31]. Overall, all the MTP schemes are computationally expensive and require careful handling of the multiple threads to the same ONU to avoid over granting especially at higher loads, as increased overheads leads to the degraded MTP performance compared to Single Thread schemes. Another reason of overgranting in MTP schemes is lack of fragmentation in EPON which results in bandwidth waste because of it being reported in multiple threads as studied in [32]. The solution proposed by the authors to overcome overgranting is to inform ONU of the maximum allowed timeslot threshold at OLT and have a counter at ONU to measure the un-reported frames. The ONU limits the queue report to the maximum allowed limit by comparing with the counter value. However, the maximum timeslot threshold at OLT is not clearly explained in this study. Another solution to overgranting is studied in [31, 33] which suggests that ONUs should only report the newly arrived frames (NA+) between the last queue report and the current report. However, if the Report message is lost due to transmission error then the frames reported will never be again reported.

4.4 Traffic prediction-based schemes

Another approach to reduce US delays and mitigate the impact of frame idle time is queue size prediction [34–36]. In this scheme an ONU predicts the expected future arrivals and adds to the current report being sent to OLT. Initially, this idea for EPON was presented in [34] but no details of the prediction mechanism were presented. In [35] the authors presented the use of a linear predictor to estimate the traffic arrival during the idle time based on the traffic arrivals during previous DBA cycle. The results show reduced delays compared to QOS-DBA and basic IPACT with strict priority. A similar prediction mechanism is also studied in [36]. However, unfortunately, due to the bursty nature of local network traffic, if early prediction method fails, the extra allocated bandwidth may be wasted and lead to increase in the overall US delay of the network.

4.5 Online-offline hybrid schemes

To combine the advantages of Online and Offline schemes, the Online-Offline hybrid schemes have also been presented. The study in [37] presents an offline scheme per slot DBA (PS-DBA) and combines it with IPACT with strict priority. In this scheme, OLT assigns the bandwidth to an ONU (i) if the Report (i) is less than W_i^{min} in an Online manner, otherwise an Offline approach is followed and PS-DBA scheme is executed. The results show lower mean US delays for all of the EF, AF and BE classes compared to IPACT and QOS-DBA. Another similar approach is presented in [38] in which lightly loaded ONUs are assigned allocation in an Online manner while for the heavily loaded ONUs, OLT waits for all the reports. However, in this approach excess bandwidth could only be assigned to heavily loaded ONUs. A tracker is used to keep record of the last assigned time to ONU. A newer study in [20] suggests to sort the ONU reports in a descending order to eliminate the idle time. Another method used to reduce the idle time in high traffic load cases is proposed in [39] termed by authors as Enhanced DBA (eDBA) algorithm. This method calculates a vector of complimentary bandwidth amounts to be assigned to the ONUs for the channel idle time. These extra bandwidth assignments are based on the traffic arrival rate prediction by the ONU between the previous and current Gate message sent by the OLT. The half cycle DBA (hcDBA) in [40] improves this scheme by assigning bandwidth to ONUs in an offline manner until the queue reports from half of the ONUs are received, after this OLT switches to an Offline mode. To allocate the excess bandwidth, W_i^{Excess} is computed for half of the ONUs by estimating the total excess bandwidth from the received queue reports of the previous cycle for the ONUs whose report has not yet been received. This scheme also uses a prediction mechanism for its Online mode as reported earlier in [36] with limited IPACT scheme. The results show better performance than the both Online and Offline IPACT and eDBA

5 Review of DBA schemes for ITU PONs

Since, in ITU PONs, all ONUs may be polled simultaneously using BWmap field and all queue reports are received at OLT via DBRu field in a single US frame. Therefore, there is no Online and Offline differentiation in ITU PONs and they may be categorized as shown in Figure 5.

Broadly, ITU PONs may be classified based on ONU polling mechanism as static reporting (SR) and non-status reporting (NSR). Almost all of the schemes proposed in literature for ITU PONs follow the SR approach except the studies in [41, 42] which presents a fuzzy logic based NSR DBA scheme. However, an OPNET-based comparative study of SR and NSR DBA schemes in Ref. [43] shows that SR-DBA is better than NSR DBA schemes in terms of delay performance, scalability and bandwidth utilization efficiency.

In the SR-based DBA schemes, almost all the reported schemes keep the service interval (SI) fixed except the offset based scheduling with flexible intervals (OFSI) in [44]. This scheme uses an adaptive SI instead of a fixed one for all the traffic classes except the T4 as it is the BE. If the traffic load is low, then a longer SI is used, otherwise shorter SI periods are used. The shortest possible SI termed as SI_b in this study is selected according to the criteria; $SI_b \geq RTT + OLT_p + ONU_p$ for a traffic class, where OLT_p and ONU_p are the processing delays at the OLT and ONU respectively. An offset is added to SI_b based on the maximum allowed delay for a traffic class. However, the rationale behind this offset computation is not clearly explained in this study. This study also presents a prediction based version of OFSI to reduce idle time in LR-PONs. ONUs add the predicted bandwidth to their queue reports. The prediction is based on the arrivals during previous idle time. Overall this scheme is computationally very expensive and complex as an OLT is required to have additional counters to keep track of the remaining time of an SI for each traffic class and update the maximum allocation bytes (AB_{min}) per SI for each traffic class according to the selected SI.

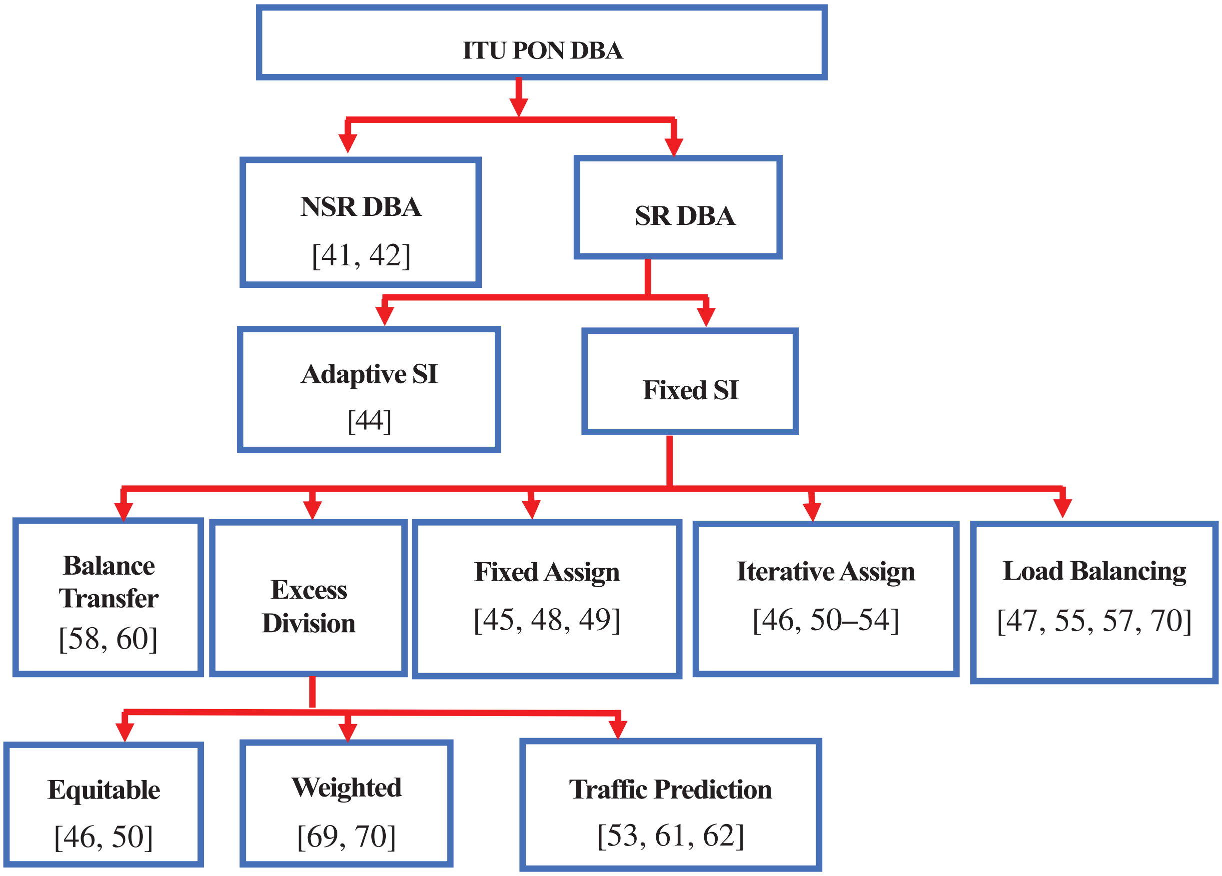


Figure 5: DBA schemes for ITU PONs.

5.1 Fixed assign schemes

These schemes execute DBA process only once during an SI. Typical chosen values are 5 and 10 GPON/XGPON cycles [45–47]. Giga-PON Access Network (GIANT) [48] is the first scheme in this category that was developed under the European Commission project in 2004. It uses an SI value of 10 for all traffic classes and divides the bandwidth assignment process into two phases; Guaranteed Phase Allocation (GPA) and Surplus Phase Allocation (SPA), both executed only once in an SI. During the GPA, it assigns a bandwidth according to the queue report but upper bounded by AB_{min} to T2 and T3 traffic classes. During the SPA, the bandwidth is assigned to T3 and T4 upper bounded by maximum surplus allocation bytes (AB_{sur}). However, in this work no detailed algorithm is presented and only an overall picture of the proposed scheme is described. The detailed GIANT algorithm is presented in [45] with a demonstration on an FPGA based hardware. To keep count of SI for GPA and SPA termed as SI_{max} and SI_{min}, two separate timers are maintained by an ONU. For fairness of grants to ONUs, they are picked in a round robin manner. Bandwidth allocation is sent only once during an SI and simultaneously all ONUs are polled for their queue reports. The results show that T2 traffic class has the lowest mean delay followed by T3 and T4. The study in [49] verifies these results. The study in [69] also presents a similar DBA scheme with an a surplus bandwidth assignment mechanism. Overall, these schemes suffer from idle channel problem due to a higher value of T_{Grant}.

5.2 Iterative assign schemes

An Iterative Assign scheme outperforms both Adaptive SI and Fixed Assign schemes as demonstrated in Immediate Allocation with Colorless Grant (IACG) [46, 50] studies. This scheme reduces the US delays by decreasing the T_{Grant} and thus the T_{OLT}. This is achieved by allowing GPA and SPA execution in every DS frame and sending bandwidth grants to ONUs. However, the bandwidth grant is only assigned until the $VB_k(i)$ or $VS_k(i)$ for a $TCONT_k$ (i) are greater than zero. Where the “k” indicates traffic class T2, T3 and T4 and “i” is total number of active ONUs. Although these schemes increase GPA and SPA frequency and send allocation to ONUs in every DS frame, however, the $VB_k(i)$ or $VS_k(i)$ counters are recharged only once during an SI to maintain the agreed data rate for each traffic class as per SLA. Therefore, compared to GIANT, the mean US delays improve for all traffic classes due to lower T_{OLT}. The IACG scheme also utilizes the remaining unassigned bandwidth (RBW) at the end of DBA cycle termed as Colorless Grant (CG). It divides the RBW equally among all the ONUs using T5 traffic class. ONUs utilize this RBW in a strict class priority and need basis which helps to reduce US delays further due to reduction in frame idle time. Another Iterative Assign scheme for GPON is proposed in [51]. However, the details of the proposed scheme are not presented.

Overall, all the Iterative Assign schemes reduce the US delays by minimizing the idle time by sending bandwidth grants every DS frame. However, this also leads to over granting due to duplicate bandwidth reporting termed as SR-Inconsistency problem (SRI), explained in detail in Section 3. This SRI problem results in reduced US delays at low traffic loads due to over granting but it results in bandwidth waste and causes increase of US delay at higher traffic loads as studied in [52]. The solution suggested in this study is to subtract all the previous grants sent by OLT from the received queue reports during the time period the DBRu slot is sent to ONU and the queue reports are actually received. The IACG scheme follows the same notion but only subtracts the last four grants from the received queue $Report_k(i)$ of traffic class T_k of ONU (i) before using it in next GPA or SPA. However, due to CG phase, the OLT is unaware of complete bandwidth $Grant_k(i)$ and thus still suffers from the SRI problem. Moreover, subtracting a fixed number of previous grants will only work if the RTT value never changes from the assumed value. However, in practical PON deployments the RTT may vary due to fiber degradation or environmental temperature which will lead to wrong computation of the ONU $Report_k(i)$ by the OLT. SRI problem becomes more serious in LR-PONs due to larger RTT values. This is addressed in [53, 54] and an improved DBA scheme termed as GPON Redundancy Eraser Algorithm for Long-Reach (GREAL) is presented. Instead of subtracting a fixed number of grants from the received ONU queue reports, GREAL records all the sent $Grant_k(i)$ during the RTT after sending DBRu slot and subtracts them from the respective $Report_k(i)$ which is a more reasonable approach. This scheme does not suffer from SRI problem as it does not utilize RBW. Instead, this scheme adds a constant demand to the queue reports of higher priority traffic classes to reduce channel idle time. However, this is inefficient as it will waste bandwidth as the added demand is not proportional to traffic load. The results of this study are yet to be compared with other earlier reported works.

5.3 Load balancing schemes

For idle time elimination in addition to reducing T_{Grant}, efficient and fair bandwidth utilization is also very important. It efficient bandwidth assignment leads to improved performance of all T2 to T4 traffic classes while fairness ensures correct utilization of RBW. The Load Balancing schemes look at the overloaded and under loaded queues of the same traffic class. They utilize the unused bandwidth (UBW) of under loaded queues for overloaded queues and improve the US delays. The borrow refund (BR) DBA scheme in [55] achieves this task by allowing an overloaded queue to borrow bandwidth from the other traffic class during a cycle and refund that borrowed amount in the next cycle. However, this is not a wise approach as an overloaded queue will need more bandwidth continuously and refunding in just the next immediate cycle may not be helpful. Moreover, it is not necessary that the other queue need the same bandwidth in the next cycle and hence the refunded bandwidth may again be wasted. Another such scheme was proposed in [70] for GPON. However, it did not consider the ITU compliant traffic classes. A more comprehensive and efficient bandwidth utilization (EBU) scheme is presented in Refs [47, 56, 57] which improves the IACG by utilizing the UBW of other queues belonging to the same traffic class. To achieve this task, it allows the $VB_k\ (i)$ of a $TCONT_k\ (i)$ belonging to ONU (i) to become negative if the $Report_k(i)$ is greater than its $VB_k\ (i)$ to indicate that its demand is higher than its $AB_{min}\ (i)$. To do so it assigns the $Grant_k\ (i)$ as $\min(\mathrm{AB}_{\mathrm{mink}}\ (i), \mathrm{Report}_{\mathrm{k}}(i), \mathrm{FB})$ and then sets $VB_k(i) - = Grant_k(i)$. This allows the $VB_k\ (i)$ of a $TCONT_k\ (i)$ to become negative if the $Report_k\ (i)$ for the $TCONT_k\ (i)$ is greater than its $VB_k\ (i)$. The update operation of EBU computes $\boldsymbol{Sum_{VB_k}} = \sum \boldsymbol{VB_k(i)}$ and then if $\boldsymbol{Sum_{VB_k}}$ is positive, the overallocation is adjusted from the UBW of other $TCONT_k\ (i)$ with positive $VB_k\ (i)$. However, if $\boldsymbol{Sum_{VB_k}}$ is negative then it means all other ONUs are also overloaded and this over allocation is adjusted by reducing the respective $\mathrm{AB}_{\mathrm{mink}}(\boldsymbol{i})$ to keep overall allocation compliant to SLA. However, this BR operation leads to reduced bandwidth availability during the current SI for T4 traffic class. The performance of T3 class may also be affected at higher traffic loads. Moreover, EBU uses the same polling mechanism of IACG and thus also suffers from the SRI problem.

5.4 Balance transfer schemes

All the SR-DBA schemes discussed above require ONU to maintain queues for all the traffic classes and send the queue length to OLT. Another alternative proposed in [58, 59], termed as Balance Transfer (BLT) scheme. In this scheme, an ONU only reports the newly arrived frames between the period the last queue report was sent till the time new report is being sent to OLT. This results in drastic decrease of queue sizes at ONU and reduces buffer size requirements. Moreover, OLT records the balance ONU demand not fulfilled in previous cycle and adds it to the newly received ONU report. Although the results in this work show reduced frame loss and lower queuing delays compared to previous schemes but this scheme has not been compared to previously reported work. Moreover, there is a very serious flaw in this approach that if a transmission error occurs in the US frame containing the queue report, then the newly arrived frames being reported may permanently be trapped in the ONU. They will never be reported to OLT again and this reporting error will never be corrected, unlike the other methods that report the total queue length. Moreover, RTT is not considered in this study and OLT waits for the new queue report which, although, resolves the SRI problem but the channel idle time will increase due to increased OLT waiting time. Another study in [60] adapts the methodology of BLT to efficiently utilize UBW during a DBA cycle and assign it in a rate proportional manner. Although the results of this study show better delay and frame loss performance compared to EBU but the method for computation of ONU traffic arrival rate has not been explained which is a challenging task for a bursty traffic. Moreover, the BLT mechanism is flawed as discussed earlier above.

5.5 Traffic prediction-based schemes

Another approach to mitigate the impact of idle time is to predict the future traffic arrivals during the idle time. This prediction is sent to OLT in addition to the queue report [54]. However, this study does not explain the prediction mechanism used. Another study in [61] uses a prediction mechanism in which the predicted arrivals are computed in proportion to the ONU waiting time, historical traffic arrivals in last 10 cycles and current traffic status information. Another study in [62] employs a fourth order moving average model with different weights assigned to previous cycle arrivals to predict the traffic arrival in the current DBA cycle. Although in this study, self-similar traffic is used for analysis in OPNET environment but the details of the traffic generation method are missing. Another recent prediction based DBA scheme is reported in [63]. This scheme follows the polling and scheduling mechanism of IACG but for RBW it uses a prediction-based mechanism instead of CG. The results show lesser delays compared to both IACG and EBU. Generally, the traffic prediction for bursty traffic is challenging. Therefore, the success of prediction schemes solely depends on the accuracy of the prediction method, otherwise they may severely degrade the performance with wrong estimates.

6 Pros and Cons of DBA schemes

From the literature review in Sections 4 and 5, a summary of the features and shortcomings of the different DBA categories is summarized in Table 1. From this comparison of DBA schemes, it may be concluded that for normal IEEE PONs, an Online-Offline hybrid scheme with excess bandwidth assignment will be very effective in reducing the US delays for all the schemes as it will not only optimize the frame and channel idle times but will also minimize the bandwidth waste by utilizing the excess bandwidth. However, for LR-PONs multiple thread approach is more useful in mitigating the impact of longer RTT by executing multiple DBA processes in parallel.

For ITU PONs, a combination of Iterative Assign, Load

Balancing and Excess Division schemes should show the best possible performance for both normal and LR-PONs.

7 Most efficient DBA scheme for ITU PONs

To the best of our knowledge, only the schemes shown in Table 2 are compliant to ITU PONs. The BLT schemes have a severe bug that newly arrived frames may be trapped forever if there is a transmission error in US frame as also studied by [47]. The IACG study in [46] is an improvement of GIANT DBA scheme and the results of IACG show that it outperforms it in delay and frame loss performance for all the traffic classes. The EBU scheme is an improvement of IACG and the results of EBU show that it performs much better than both IACG and PCG-OFSI schemes in [47]. The GREAL scheme has not been compared with any other schemes; however, it cannot outperform EBU and IACG schemes as it does not utilize the surplus bandwidth as it does not any RBW assignment phase. Therefore, it can be concluded that compared to IACG, GIANT, BLT, and GREAL, the EBU shows the best performance in terms of US delays and frame loss for T2 and T3 traffic classes as it is a combination of Iterative Assign, Load Balancing and Excess division schemes. However, EBU leads to degraded performance of T4 traffic class. Thus, in terms of fairness IACG is better than EBU. However, both schemes also suffer from SRI problem. The IBU scheme improved the performance of T2 and T3 compared to both these schemes but it also suffers from higher delays of T4. Moreover, its polling mechanism is not compliant to XGPON standard as it requires OLT to send bandwidth allocations for 10 cycles at once.

Table 1: Pros and Cons of PON DBA Schemes.

Scheme	Main feature	Shortcomings/Advantage	Compatibility
Multi-Thread	– Executes multiple parallel DBA threads between same ONUs	– Computationally expensive. – Coordination between multiple threads required. – Performance degradation at higher loads due to more over heads. – Bandwidth waste due to lack of fragmentation in IEEE PONs and over granting.	IEEE PON
Online	– Assign and send bandwidth allocation to ONU as soon as its queue report is received.	– OLT does not have queue reports of all ONUs and thus cannot assign bandwidth with fairness. – May suffer from Light Load Punishment.	IEEE PON
Offline	– OLT waits for all the ONU queue Reports and then allocates bandwidth fairly.	– Due to OLT waiting time, such schemes suffer from idle channel and idle frame time problems.	IEEE PON
Prediction based	– In an Offline scheme an ONU predicts the expected arrivals during the idle time and adds to queue report to reduce idle time problem.	– Difficult to predict the bursty traffic with accuracy. – An inaccurate prediction will lead to bandwidth – waste and increase of US delays	IEEE/ITU PON

(*continued*)

Table 1: (*continued*)

Scheme	Main feature	Shortcomings/Advantage	Compatibility
Online-Offline Integrated	– Combination of both Online and Offline schemes. – OLT waits only up to a certain limit.	– Combines advantages of Online and Offline schemes. – Improves fairness of allocation as well as reduce idle time.	IEEE PON
Inter ONU DBA	– OLT only allocates bandwidth among ONUs and not to its specific traffic classes.	– Increase ONU processing load as ONU has to manage bandwidth itself. – Unused bandwidth of a traffic class of an ONU cannot be utilized by same traffic class of another ONU.	IEEE/ITU PON
Intra ONU (Offline)	– OLT allocates bandwidth to each traffic class of an ONU	– Can allocate bandwidth more efficiently and fairly as OLT has information of the bandwidth need of each traffic class of an ONU.	IEEE PON
NSR DBA	– ONU does not send queue Reports to OLT and OLT estimates the bandwidth need from the ONU traffic arrivals.	– Not efficient as OLT is not aware of actual ONU bandwidth demand. – Intra-ONU allocation not possible at OLT.	IEEE/ITU PON
Adaptive SI	– OLT adapts the SI for each traffic class according to its traffic load	– Computationally very expensive and complex as an OLT is required to have additional counters to keep track of the remaining time of an SI for each traffic class and update the respective AB_{Min} values accordingly.	ITU PON
Fixed SI	– The SI value for a specific traffic class remains constant throughout the DBA process.	– Simpler, computationally inexpensive and efficient.	ITU PON
Fixed Assign (Fixed SI)	– OLT executes DBA process once during an SI.	– Simple scheduling mechanism but not efficient. – Higher US delays and bandwidth waste per cycle.	ITU PON
Iterative Assign (Fixed SI)	– OLT executes DBA process and assigns bandwidth to ONUs every DS cycle during an SI.	– Reduced US delays due to lower T_{Grant} time. – Low delays for all traffic classes due to reduction of idle time.	ITU PON
Load Balancing	– OLT allocates the unused bandwidth of lightly loaded TCONTs to heavily loaded TCONTs belonging to same traffic class of an ONU	– Improves delay of higher priority traffic classes. – If BR mechanism not carefully used, may lead to severe performance degradation of lower priority traffic classes.	ITU PON
Excess Division	– Any RBW is divided equally or in a weighted manner to ONUs.	– Helps to further reduce US delays of all ONUs and improve overall network performance.	ITU PON

Table 2: Comparison of ITU compliant DBA schemes.

Scheme	Main Weaknesses/Advantage	Impact of Weaknesses/Advantage
GIANT [45, 64]	– Very Low Polling and Scheduling frequency. – Surplus Bandwidth not used.	– Higher US delays and Frame Loss for all traffic classes.
IACG [46, 56]	– Suffers from SRI problem	– Shows improved delay and frame loss performance compared to GIANT. – Shows increased US delays at higher Traffic Loads due to SRI.
GREAL [53]	– Do not utilize Surplus bandwidth	– Higher US delays compared to IACG and EBU at low Traffic Loads.
BLT [58, 59]	– Only reports newly arrived traffic frames	– Newly arrived frames may be trapped forever at the ONU if there is an error in US frame containing the queue report.
OFSI/PCG-OFSI [44]	– Adaptive SI for T2 and T3. – AB_{min}/AB_{sur} values to be updated every DS frame. – Also, suffers with SRI problem.	– Complex and computationally expensive for OLT. – Poor T4 performance. – Higher delays compared to the EBU scheme.

(*continued*)

Table 2: (*continued*)

Scheme	Main Weaknesses/Advantage	Impact of Weaknesses/Advantage
EBU [47, 56, 57]	– SRI Problem. – BR mechanism in UBW assignment.	– Very high delays and frame loss for T4 traffic class. – Shows lower Delays for T2 and T3 compared to IACG and OFSI;
IBU [65]	– Not compliant to XGPON standard – Gives too much preference to T2 and T3 traffic classes	– Shows improved delay performance of T2 and T3 compared to EBU and IACG but with higher delays of T4 traffic class.
CBU [66]	– Resolves SRI and BR problems	– Improves performance of T3 and T4 compared to IACG, EBU, GIANT and GREAL Schemes. – Shows slightly higher delays for T2 compared to EBU.

Which means for four traffic classes with 16 ONUs, it will require BWmap to carry 640 entries while it is only restricted to 512 entries as per G.987.3 standard. The CBU scheme also improves EBU and IACG schemes by resolving the SRI problem and BR problems and shows better delay and frame loss performance for all traffic classes compared to GIANT, GREAL, IACG and EBU schemes. However, it shows slightly higher delay for T2 compared to EBU which shows that EBU gives too much preference to T2 which also results in unnecessary bandwidth waste per XGPON cycle by the EBU scheme as evident from CBU results. The CBU minimizes the bandwidth waste per cycle. Therefore, it may be concluded that if the ratio of user of all the traffic classes is equal then the CBU scheme is the most suitable DBA scheme compared to all other schemes discussed in Table 2. However, if the ratio of T2 traffic class users is higher compared to T3 and T4 then EBU will be more suitable choice. Moreover, a comparative study of IACG, EBU and CBU schemes in terms of fairness is also needed as the as the present studies have not compared the performance from the fairness perspective.

8 Conclusion

The performance of a TDMA PONs is critically dependent on a DBA scheme as the US bandwidth has to be shared by all the ONUs. An efficient DBA scheme is the one that reduces the channel and frame idle time. A detailed review of DBA schemes for ITU and IEEE PONs is presented in Sections 3 and 4 respectively. From the review study, it is concluded that for IEEE PONs, an Offline-Online hybrid scheme is most suitable as it reduces the frame idle time as well as maintains the fairness in bandwidth assignment process. However, for LR-PONs, Multi-Thread approach is more suitable but in normal PONs it reduces the throughput due to higher messaging overheads.

For the ITU PONs a combination of Iterative Assign, Load Balancing and Excess Division schemes should give the best performance result. Therefore, CBU is currently the best DBA scheme in terms of US delay and bandwidth efficiency for ITU PONs. However, it has not been studied from the fairness point of view.

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