Bandwidth Distribution Solutions for Performance Enhancement in Long-Reach Passive Optical Networks

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***Abstract*—Long-reach Passive Optical Networks (LR-PONs) aim to combine the capacity of metro and access networks by extending the reach and split ratio of the conventional PONs. LR-PONs appear as efficient solutions having feeder distances around 100km and high split ratios up to 1000-way. On the other hand, transmission of the signals in long distances up to 100km leads to increased propagation delay whereas high split ratio may lead to long cycle times resulting in large queue occupancies and long packet delays. Before LR-PON becomes widely adopted, the trade-off between the advantages and performance degradation problem which is resulting from long reach and high split ratio properties of LR-PONs needs to be solved. Recent studies have focused on enhancing the performance of dynamic bandwidth allocation in LR-PONs. This article presents a comprehensive survey on the dynamic bandwidth allocation schemes for LR-PONs. In the article, a comparative classification of the proposed schemes based on their quality-of-service awareness, base-types, feeder distances and tested performance metrics is provided. At the end of the article, a brief discussion on the open issues and research challenges for the solution of performance degradation in LR-PONs is presented.**

***Index Terms*—Passive optical networks, long-reach PON, dynamic bandwidth assignment, multi-server polling systems, next generation PON, performance enhancement**

I. Introduction

As THE ENTERPRISE, home, and backbone network technologies advance, and the Internet traffic volume increases, access networks form the bottleneck between the backbone and the local area networks [1]. Passive optical networks (PONs) offer low cost and high bandwidth solutions in the *last mile* service of the Internet access [2]. Fiber to the Home/Curb/Building (FTTx) solutions of PONs can meet the requirements of the services such as Internet Protocol (IP) telephony, IP television (IPTV), video on demand and http. A typical PON is a point to multi-point network consisting of passive elements between each source-destination pair. Source-destination pairs are mainly the Optical Network Units (ONUs) that are located in the end users' premises (or close to the premises) and the Optical Line Terminals (OLTs) located at a remote node, namely the central office of the operator [3].

The OLT is connected to the ONUs through a feeder fiber and a passive coupler which splits the optical signal into the number of end users. At an outlet of the splitter, an optical signal is destined to an ONU through a drop fiber of a few kilometers. Taking the advantages of low capital expenditure (CapEx), low maintenance cost and adaptability to higher bit rates, Ethernet PON (EPON) seems a promising PON technology [4], and it has been standardized in IEEE 802.3ah [5]. Gigabit-capable PON (GPON) is another attractive technology which is standardized in ITU-T G.984 [6]. GPON supports high upstream and downstream bit rates of 1.2 Gbps and 2.5 Gbps, respectively and aims to support any level of QoS guarantee while enabling fragmentation of the encapsulated Ethernet frames [7]. Both GPON and EPON employ time division multiplexing (TDM)-based bandwidth distribution in the upstream wavelengths since all ONUs share a single channel. In order to manage the huge bandwidth demanding applications and the increasing traffic intensity, WDM-PON offers virtual point-to-point optical connections at full wavelength capacity by the employment of arrayed waveguide gratings (AWGs) [8]. Furthermore, hybrid WDM-TDM PON incorporates the TDM-PON and WDM-PON technologies to support bandwidth demanding applications such as online gaming and video on-demand while introducing scalability for network management [9]. Theoretically, GPON is capable of accommodating 128 ONUs in 60km reach while EPON can accommodate up to 64 ONUs. In most of the commercial applications, for sake of limiting the loss budget, GPON serves with a split ratio of 1:32 and a maximum reach distance of 20km although it theoretically supports 60km reach with a split ratio of 1:128. Similarly, EPON is practically limited to an OLT-ONU distance of 20km [10]. Network operators and vendors recently included extending the reach in their agenda in order to serve remote subscribers and/or to serve more subscribers in the PON [11].

A. Dynamic Bandwidth Allocation (DBA) in Conventional PONs

PON-based technologies are capable of offering low-cost, high bandwidth and reliable downstream transmission for the services such as IPTV due to the deployment of the passive elements and non-contending nature of point-to-multi-point communication. However, in the upstream direction, a dynamic bandwidth allocation (DBA) protocol has to be employed between the OLT and the ONUs in order to avoid any collision [12]. Below, we shortly summarize the DBA solutions for EPON, GPON and WDM-EPON.

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1) EPON: Multi-Point Control Protocol (MPCP) was standardized in IEEE 802.3ah as a signaling scheme for EPON. MPCP is mainly based on exchanging REPORT and GATE messages between multiple ONUs and the OLT. For each ONU, by the transmission of a GATE message, the OLT grants a certain bandwidth to be utilized in a time window. An ONU receiving the GATE message for the corresponding time window bursts its buffer and sends a REPORT message to the OLT informing on its current buffer status. Interleaved Polling with Adaptive Cycle Time (IPACT) is the first dynamic bandwidth allocation algorithm proposed for EPON employing MPCP as a signaling protocol [13]. According to IPACT, OLT polls the ONUs in a round robin fashion, and upon receiving the REPORT message of an ONU, it determines the appropriate bandwidth to be allocated to the ONU in the next polling cycle. Since IPACT is based on MPCP signaling, the OLT is able to know the start and end times of the transmission of each ONU; hence contention-free upstream transmission is achieved.

Although Quality of Service (QoS) support does not exist in the Ethernet, there have been several proposals to support delay, packet delay variation (PDV) and throughput requirements of multiple Service Level Agreement (SLA) classes. Recently, Choi and Park have proposed an SLA-aware DBA scheme for EPON. The proposed scheme consists of two steps where the first step runs to allocate appropriate bandwidths for each SLA class while the second step grants the ONUs of each SLA class [14].

PDV has also been of interest for the studies in the conventional EPON. For instance, An et al. have proposed to assign a fixed location in the frame to high priority service class frames in order to introduce them less delay variation [15]. Shami et al. take the advantage of deterministic nature of Expedited Forwarding (EF) frames and have proposed to assign bandwidth for the EF frames before receiving the ONU reports so that PDV-sensitive traffic can experience less delay variation in a conventional EPON [16]. Recently, Berisa et al. have proposed delay-variation guaranteed polling where upper bounds for frame delay variations are specified in advance, and they have shown the duality between delay and delay variation guarantee [17].

2) GPON: Similar to the signaling in EPON, ITU-T G.984 standardized the signaling in GPON based on the exchange of report and grant messages. Upon receiving a request message from the OLT, an ONU maintaining k transmission container buffers (T-CONT) sends a report message, namely *Dynamic Bandwidth Request (DBRu)* back to the OLT, informing the OLT on the status of a certain T-CONT buffer. The OLT runs a DBA algorithm to determine the appropriate bandwidth to be allocated for each ONU. Further improvements on dynamic bandwidth allocation in GPON have been proposed. For instance, Jiang and Senior have proposed an enhancement to the ONU reporting in order to inform the OLT on real-time traffic fluctuations. Thus, an ONU reports the increase in the queue length during the last transmission interval as well as the remaining bandwidth in the previous allocations which was too small to be encapsulated in a GPON encapsulation frame. When assigning bandwidth for a T-CONT, the OLT considers the backlog at the T-CONT as well as its reported bandwidth. Backlog of a T-CONT is the difference between the assigned bandwidth and the reported bandwidth of the corresponding T-CONT in the previous period [18].

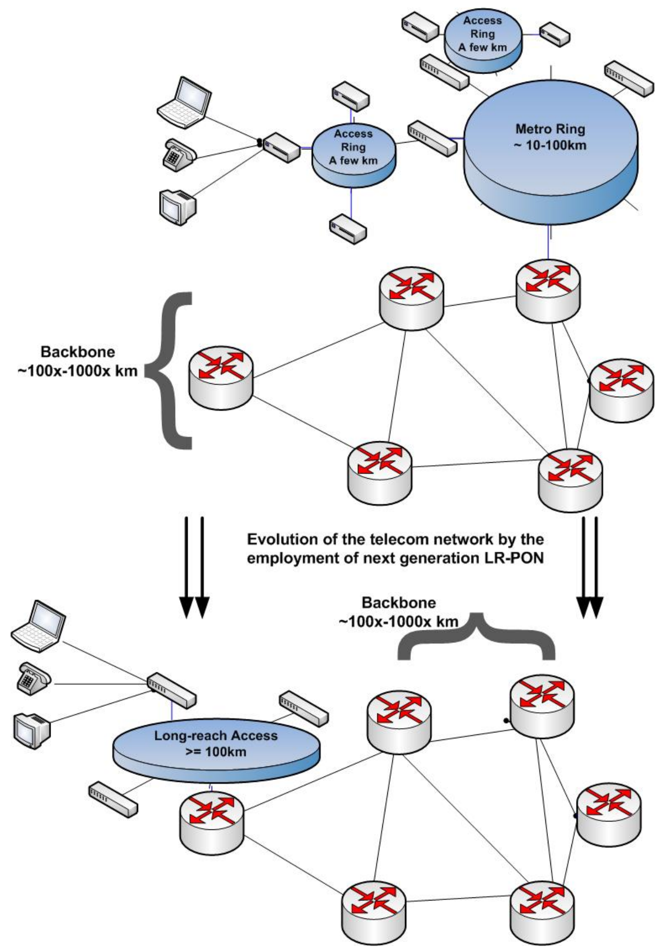


Fig. 1. Evolution of the telecom network by the employment of LR-PON [23]

3) WDM-EPON: Bandwidth distribution in WDM-EPONs is a challenging issue due to inclusion of wavelength assignment sub-problem in the grant scheduling process. McGarry et al. have formulated DBA in WDM-EPON in two sub-problems as follows: 1) grant sizing that denotes the amount of bandwidth to be assigned to each ONU, and 2) grant scheduling that stands for the time and wavelength to transmit data. The main problem of the bandwidth distribution in WDM-EPONs is the grant scheduling sub-problem. Indeed, it seems practical to consider a WDM-EPON as several EPONs and to assign wavelengths based on first-fit or random assignment fashions. However, McGarry et al. have shown that applying joint time and wavelength assignment (i.e., multidimensional scheduling) leads to reduced delay and enhanced utilization. The authors have also proposed to run hybrid online and offline scheduling for WDM-EPONs where a group of ONUs can be scheduled offline while the rest can be scheduled with respect to the online *next available supported channel* fashion so that reduced delay and enhanced utilization can be obtained [19].

B. Challenges in Long-Reach PONs (LR-PONs)

Research towards next generation PON introduces a challenge of consolidation of the capacity of metro and access networks so that the deployment cost is decreased, the reach is extended to 100km and above, and the split ratio is increased tremendously up to 1:1024 [20] [21]. To achieve this goal, an LR-PON runs optical feeder fiber operating either at *C*-band ($\sim$1530-1565nm) or at *L*-band ($\sim$1565-1625nm) wavelength range, deploys Erbium Doped Fiber Amplifiers (EDFA) or transponders at the central office, and incorporates Wavelength Division Multiplexing (WDM) technologies [10], [22], [23]. Fig. 1 illustrates the migration of the access network to the consolidation of metro and access networks by LR-PON. In [23], [24], an extensive survey of LR-PON demonstrations is presented with the hardware details focusing on European and Asian regions while in [25] practical LR-PON deployments in Australia are demonstrated. A detailed comparison of reach extension strategies in LR-GPON is presented in [26].

Despite the advantages of reach extension in PONs, long feeder distance and high split ratio lead to inefficiency in the traditional DBA algorithms that are designed for EPON or GPON to work within 10 $\sim$ 20km span distance and with relatively low split ratio. The reason of inefficiency of the traditional schemes is mainly long round trip time (RTT) and long waiting times to finish a polling cycle [27]. Considering a fundamental DBA service of IPACT running on top of MPCP signalling, the RTT for the REPORT-GATE control messages to propagate is 0.1ms in an EPON with 10-km span coverage, which is tolerable. However, migration to LR-PON by increasing the span coverage to 100km introduces a propagation delay of 1ms. In [28], the authors evaluated the performance of IPACT service disciplines under long-reach EPON and showed that employment of IPACT is not preferable in long-reach access. In [23], the authors have presented a survey on LR-PON implementations and the challenges related to LR-PONs. The fundamental challenge in LR-PONs is the performance degradation due to long feeder distance and high split ratio where a large number of DBA schemes have recently been proposed to address these problems.

To the best of our knowledge, the authors in [29] published the first survey on DBA algorithms for EPON in 2004. In the following years, until early 2009, a large number of DBA solutions have been proposed in order to enhance the quality of service (QoS) performance of the passive optical networks. In [30], [31], the authors have extensively surveyed those DBA solutions for EPON. However, the DBA schemes that have been designed for EPONs are not convenient for LR-PONs due to the difference in the physical deployment properties of EPON/GPON and LR-PON, such as LR-PON having longer feeder distance and higher split ratio than EPON/GPON. These challenging properties of LR-PONs have called for novel DBA schemes, and since late 2007 [32], [33], various DBA schemes have been proposed for addressing the challenges of LR-PONs.

In this article, we present a comprehensive survey of 19 DBA solutions for LR-PONs that have been proposed since late 2007. To the best of our knowledge, except from the MT [33], [34] and TSD [32] schemes, the surveyed DBA schemes have not been included in a survey study before. In our survey, we group the DBA schemes in two categories, namely QoS-aware and QoS-unaware schemes. We present the fundamental properties, advantages and the drawbacks of each scheme. Then, we give a comparative summary of these methods with respect to feeder distance, base PON technology, delay, packet delay variation (PDV) and packet loss performance. At the end of the survey, we discuss the open issues and the possible future directions of research in DBA algorithms for LR-PONs.

The rest of the paper is organized as follows. In Section II, a general information on LR-PON architecture is presented along with the motivation for new DBA solutions. Section III, introduces a detailed survey on DBA solutions for LR-PON. Section IV discusses open issues and research challenges on the performance degradation problem in LR-PON. Finally, Section V summarizes and concludes the paper.

II. Next Generation PON with Extended Reach and High Split Ratio

A. Architecture and Implementation

As shown in the first part of Fig. 1, the end users receive service through the access network in a few kilometers, and the access network traffic is multiplexed on the metro ring network which finally ends up at an ingress router of the backbone network. In the second part of the figure, the employment of LR-PON combines the capacity of the metro ring network and the optical access network which leads to a simpler design of the telecom network as well as the deployment cost reduction [23].

Extending the reach of a Gigabit-capable PON to 60km and the split ratio to 1:128 have been recommended in ITU-T G.984.6 [35]. As a further enhancement, Fig. 2 illustrates a simple implementation of an LR-PON with a single wavelength channel as presented in [10]. The reach of the LR-PON is 100km with a maximum 1000-way of split each of which is operating at 10Gbps and 2.5/10Gbps in downstream and upstream directions, respectively. As seen in the figure, one of the split-ways ends at a wireless gateway which is attached to an ONU while another branch ends at an ONU serving to the business customers with the Fiber-to-the-Premises (FTTP) solution. The last two branches at the bottom of the figure represent the Fiber-to-the-Cabinet/Curb (FTTC) solution. The fiber is operating at 15xx nm and the optical signal is amplified by the EDFAs at the central office where OLT is located. The figure illustrates a TDM-PON where all ONUs have a fixed band-pass blocking filter to enable only one wavelength. Hence, the upstream channel is shared by the ONUs.

An LR-PON can be implemented on either a tree-and-branch topology or a ring-and-spur topology. The tree-and-branch architecture where each branch is similar to Fig. 2 is easy to implement, however it may suffer from deployment cost and resilience. A more resilient and scalable solution which is ring-and-spur topology with hybrid WDM-TDM PON technology is presented in Fig. 3. The topology mainly consists of the OLT and a number of Optical Add/Drop Multiplexer (OADM)-enabled remote nodes on a metro-ring. Each remote node adds or drops one wavelength channel and connects the transmission line to the splitter which is

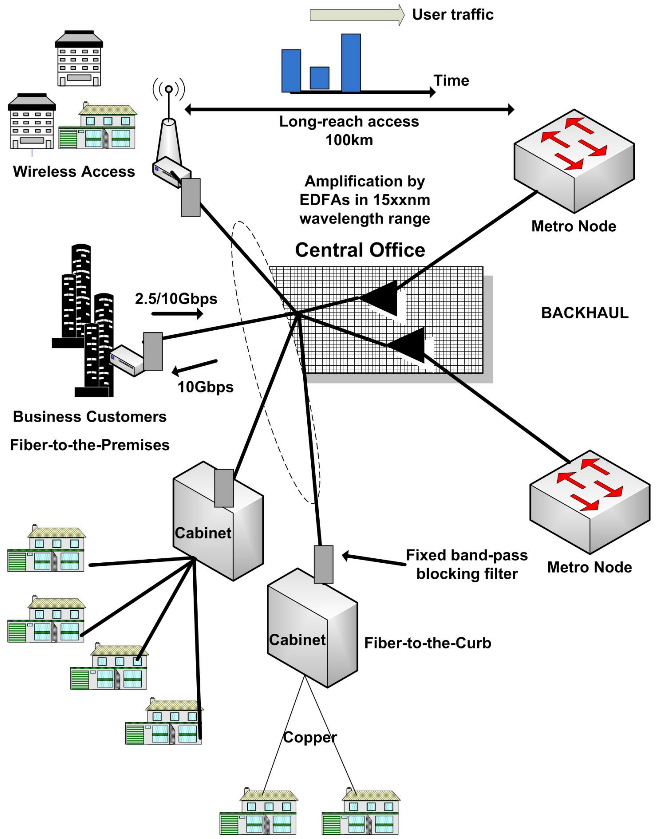


Fig. 2. A single channel LR-PON architecture presented in [10] with a tree topology.

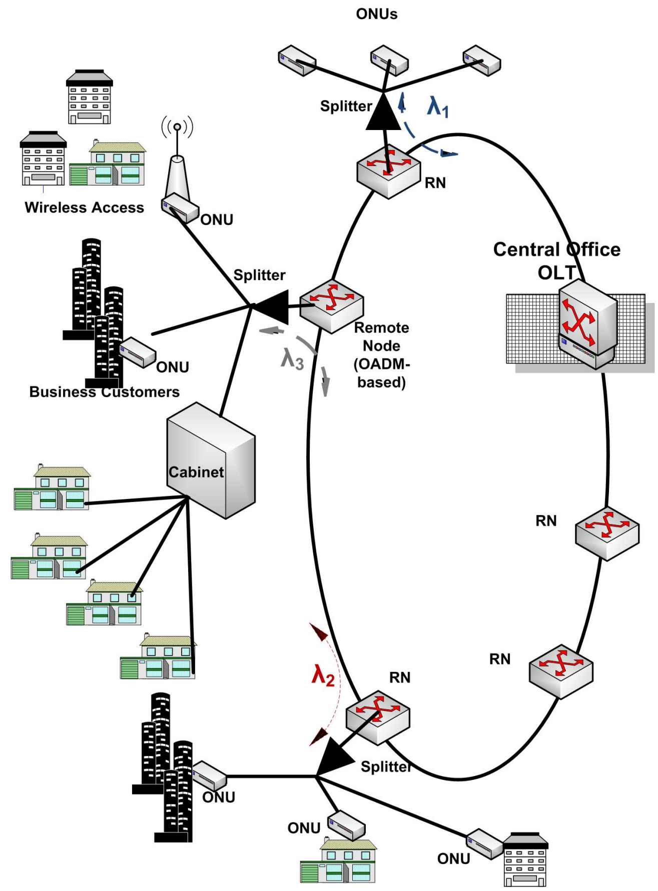


Fig. 3. A WDM-TDM LR-PON architecture with ring-and-spur topology.

then connected to the ONUs through distribution fibers. Thus, TDM-PON is extended to be applied in hybrid WDM-TDM-PON where a wavelength channel is dedicated to each TDM-PON in an LR-PON, and all supported wavelengths are multiplexed on the fiber ring. This architecture is advantageous in terms of resilience and scalability to accommodate large number of users in the extended reach [36]. Furthermore, it is cost-efficient since it can deploy the remote nodes on the existing metro ring [37].

Research in standardization of mid-span reach extension in next generation long-reach GPON (XG-PON) is reviewed in detail in [38]. On the other hand, migration to WDM-PON driven by long-reach and high split access technology does not only require changes in the access network and the backhaul but it is also expected to call for solid changes in core network services and core network architectures [39].

B. Motivation for new bandwidth allocation solutions in LR-PONs

As we mentioned before, the advantage of extended reach and high split ratio requires an efficient DBA protocol since the DBA algorithms based on the traditional MPCP may lead to high ONU buffer occupancy and long packet delays due to high RTT in long distance [34], [40], [41].

Fig. 4.a illustrates an instance of the conventional polling-based DBA solution for an EPON with 2 ONUs and an OLT where both ONUs always have non-empty input buffers. Hence, ONU_1 sends a REPORT message requesting bandwidth for the buffered packets in its input queue. Then, the REPORT message of ONU_2 is received by the OLT. OLT determines the size and start time of the ONU grants, and based on the start times of the ONU grants, it sends GATE messages to the ONUs acknowledging them on their next granted timeslots. In Fig. 4, ONU_1 is granted first, and this is followed by granting of ONU_2. Although a packet arriving at the buffer of ONU_2 reaches before the GATE message, the bandwidth request for the corresponding packet is sent in the REPORT message following the first GATE. The delay between the packet arrival and the request sent for the packet is called the *polling delay (d_{poll})*. By the arrival of the second GATE message from the OLT, ONU_2 is granted to transmit the packet in the specified timeslot. The delay between a REPORT message and its corresponding GATE is called the *granting delay (d_{grant})*. Once the grant is received, the ONU pops the packet from its output buffer and switches it on the related outlet in a certain amount of time which is a function of its buffer occupancy, i.e., *queuing delay (d_{queue})*.

In LR-PONs, the extension of the feeder distance increases the RTT between OLT and ONU. Hence, the delay between two GATE messages will increase accordingly leading to a dramatic increase in the sum of d_{poll} and d_{grant}. Consequently, d_{queue} will also increase due to buffering of more packets as a result of delayed GATE messages. Another observation is that the time gap between two consecutive GATE messages sent by the OLT is not utilized in the downstream

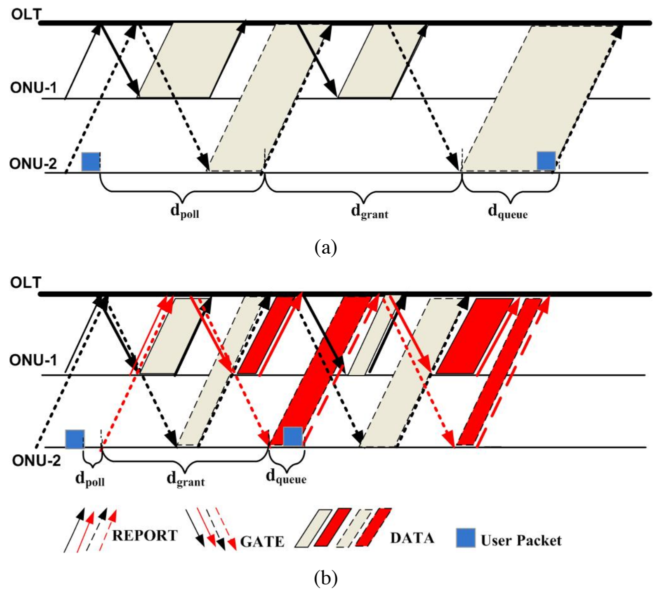


Fig. 4. (a) Conventional polling, (b) Multi-threaded polling DBA proposed in [33], [34]

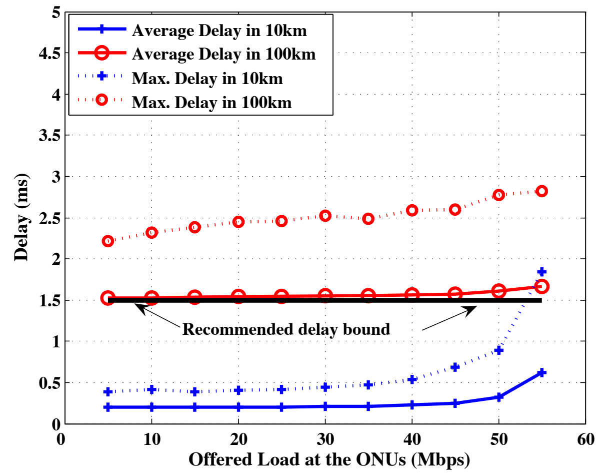


Fig. 5. Average and maximum packet delays for a case study with 10km and 100km OLT-ONU distances in an EPON.

direction. On the other hand, in the upstream direction, there exists a time gap between two consecutive ONU bursts. As the feeder distance increases, these time gaps are expected to increase as well. Based on these phenomena, it is not feasible to employ any traditional MPCP-based dynamic bandwidth allocation (DBA) scheme as is.

Here, we present a case study to illustrate the need for new DBA solutions for LR-PONs. We simulate an EPON for 10km (i.e., conventional) and 100km (i.e., long-reach) distances. We only consider real-time traffic and the delay bound for real-time applications in the access network segment [42]. The OLT is connected to 16 ONUs in a tree topology where the fiber capacity is 1Gbps and the user bandwidth is assumed to be 100Mbps. User frames arriving at each ONU form a Constant Bit Rate (CBR) traffic offering loads between 5Mbps to 55Mbps. ONUs are granted with respect to the limited service scheme in IPACT [13]. Thus, bandwidth granted to an ONU is limited above by the maximum slot size, i.e., 15500 bytes.

Taking the propagation delay in fiber as 5 μs/km, in the conventional scenario (10km), the latency for a REPORT message to propagate to the OLT is 50 μs so as the latency for a GATE message to propagate to an ONU. Thus, the total propagation delay for REPORT-GATE messaging is 100 μs in the conventional EPON with 10km distance. On the other hand, in the long-reach scenario (i.e., 100km), one-way propagation delay for either of the two signaling messages (REPORT/GATE) is 500 μs. Thus, in the long-reach EPON (LR-EPON), the total propagation delay for REPORT-GATE messaging is 1ms. We present the effect of this drawback on a real-time traffic in Fig. 5. In the figure, average packet delay and maximum delay experienced by the packets received by the OLT are presented for conventional and LR-EPON scenarios. According to the ITU-T recommendation [42], the packet delay limit for the real-time traffic in the access network is 1.5ms. As seen in Fig. 5, when the OLT-ONU distance is 10km, average packet delay is always less than 1ms while the maximum packet delay is also less than 1ms until the offered ONU loads reach at 55Mbps. On the other hand, when the OLT-ONU distance is 100km, the average packet delay is at the borderline while the maximum packet delay is between (2ms, 3ms). Based on these phenomena, some packets are expected to be marked as lost at the destination due to the intolerable latency in the access network. Hence, LR-PONs call for novel DBA schemes to avoid performance degradation for delay sensitive applications.

III. Dynamic Bandwidth Allocation Solutions in Long-Reach PONs

In this section we take a closer look at the DBA schemes proposed for LR-PONs. Majority of the DBA algorithms proposed for LR-PONs attempt to utilize the idle timeslots in the upstream or downstream direction. Furthermore, a significant amount of them employ bandwidth prediction to allocate additional bandwidth for the ONU requests so that the utilization is improved. Although QoS-unaware schemes have also been proposed for LR-PON, considering the differentiated requirements and service level agreements of the end-users, DBA schemes have to be improved to meet the SLA requirements of the end-users.

Majority of the DBA schemes focus on reducing the average (and/or per class) packet delay and improving the utilization (or reducing the packet loss). However, applications of CBR and real time-Variable Bit Rate (rt-VBR) service categories specify the peak cell rate traffic parameters, hence PDV is a critical performance metric for these traffic categories. Therefore, DBAs minimizing PDV for CBR traffic and satisfying the cell delay variation tolerance (or PCR) of rt-VBR traffic need to be considered.

Beyond extending the reach to 100km and more, LR-PON also introduces the advantage of high split ratio up to 1000-way [10]. However, most of the DBA schemes are basically tested in LR-GPONs/EPONs with a split ratio of 1:16. The effect of the split ratio on the delay and utilization performance and service level guarantee of the DBAs has not been studied well. A reach independent DBA has been proposed in [43] however, DBAs with advanced delay/PDV performance behavior under varying split ratios need to be explored in order to meet the users' service requirements while taking the advantages introduced by LR-PON.

We categorize the DBA schemes with respect to their service differentiation properties as follows: 1) QoS-unaware DBA schemes, and 2) QoS-aware DBA schemes. Furthermore, at the end of the first subsection, Table I presents a detailed comparison of the QoS-unaware schemes with respect to base PON type (EPON/GPON/WDM-PON), delay/packet delay variation (PDV)/packet loss performance and the challenges of each scheme. Similarly, at the end of the second subsection, Table II presents the same comprehensive summary for the QoS-aware solutions. Furthermore, at the end of this section, a taxonomy of the surveyed DBA schemes is also presented.

A. QoS-Unaware DBA schemes for LR-PONs

1) Multi-thread Polling (MT): Fig. 4.b illustrates the multi-thread polling approach which was proposed in [33], [34]. In the figure, the OLT polls the ONU requests by two threads where the black and red colors of the lines/data refer to polling thread$_1$ and polling thread$_2$, respectively. Data and signalling messages of the two ONUs are distinguished by straight and dashed lines. Multi-thread polling is based on the idea of utilizing the idle timeslots on both downstream and upstream lines by running multiple threads to poll the ONU requests. From the ONU's point of view, an ONU does not wait for the GATE of its last REPORT in order to request bandwidth for an incoming packet. In the illustration, the two ONUs are polled by two threads generated at the OLT, and the idle time between the two GATE messages of *thread*$_1$ is utilized by the GATE messages of *thread*$_2$. Upon receiving a GATE message, each ONU is allowed to transmit a minimum guaranteed bandwidth (B_{Min}). If at *thread*$_k$, an ONU requests less than the minimum guaranteed bandwidth, at the next polling cycle of the corresponding thread, the ONU is granted the requested bandwidth by the GATE message. The difference between B_{Min} and the request is added to the *excessive bandwidth* of the thread. An ONU is considered to be overloaded if its request exceeds B_{Min}. In this case, an overloaded ONU is initially assigned B_{Min}, and at the end of the thread cycle, the excessive bandwidth of the cycle is distributed among the overloaded ONUs proportional to their reported buffer lengths.

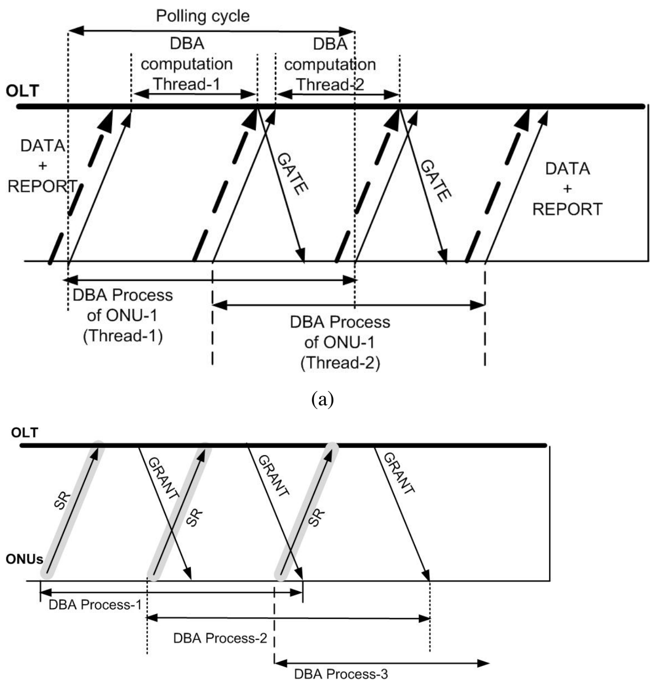
Polling cycle duration is limited by an upper bound which is calculated considering at each sub-cycle (thread), each ONU is granted the minimum guaranteed bandwidth. As mentioned above, at each sub-cycle, the excessive bandwidth is distributed among the overloaded ONUs. Hence, the overloaded ONUs do not have to wait for the next thread. Moreover, since they have been granted by the latest thread, they might have less number of packets in the input queues to be granted by the next thread. Thus, the contribution to the next sub-cycle duration might be reduced. If this scenario continues for a while, multi-thread polling introduces a risk that one of the threads dominates the other threads by monopolizing the whole polling cycle. Therefore, the authors propose an inter-thread scheduling mechanism which runs as follows. At the end of a polling cycle, if the cycle time of *thread*$_i$ is at least K times the cycle time of *thread*$_{i+1}$, then cycle time of the former thread is decreased by a pre-determined unit of Δ timeslots while this amount is used to increase the cycle time of the latter one. Furthermore, selecting the initial thread cycle times after the ONU discovery phase has a significant effect on the performance of *multi thread polling*.

In [34], *multi-thread polling* is tested for an EPON with 1:16 split ratio for the ONU-OLT distances of 20km and 100km. It is shown that *multi-thread polling* is able to keep the average packet delay less than the conventional IPACT services (i.e., single-thread MPCP) and at a level of few milliseconds ($\leq$ 10ms within 100km reach) until the network gets heavily loaded, i.e., beyond 1.0 Erlang. Since the decrease in delay is due to the utilization of the idle timeslots, packet drop at the ONUs is not greater than that of the single-thread (ST) polling.

2) Newly Arrived Frames Plus (NA+): As an extension to the research in [34], the authors in [44] present performance evaluation of multi-thread polling for both EPON and GPON and propose a new scheme called *Newly Arrived Frames plus (NA+)* which acts as a coordinator between the DBA threads. Without loss of generality, NA+ DBA uses the logical queues which correspond to the logical link identifiers (LLIDs) in EPON and the traffic containers (T-CONTs) in GPON. The idea behind this coordination approach is reducing the risk of over-granting the ONUs by multi-thread polling as parallel polling threads are not aware of the bandwidth granted by each other. As shown in Fig. 6, polling ONUs by multiple threads increases the overlapping probability of the polling threads. An ONU reports only the current buffer size in the REPORT message (or the status report (SR) in GPON). Hence, if an ONU is polled by two consecutive threads without being granted, for some packets it may re-request grant within the REPORT message sent through the latter thread. Consequently, duplicated REPORTs are likely to be transmitted due to overlapping DBA threads. Considering R_i to be the REPORT size of the i^{th} DBA thread (process) of a logical queue, the traffic pushed into the logical queue between the threads $i-1$ and i (T_i) is calculated as shown in Eq. 1 where b_i represents the bandwidth allocated to the corresponding virtual queue between the threads $i-1$ and i. Here, b_i can be obtained through the resulting grants of a previous thread j where $j < i$.

$$T_i = R_i - R_{i-1} + b_i \quad (1)$$

Since a thread cannot always grant the requested bandwidth, the backlogged traffic remains unallocated since the next thread is unaware of the traffic backlog. Hence, NA+ aims to come up with a compensation for the backlogged traffic when the OLT receives the REPORT of a thread, and it computes the bandwidth demand of the corresponding logical queue (D_i) as follows: $D_i = T_i + C_i$ where C_i is referred as the compensation for the backlogged traffic. The authors address the importance of setting the compensation term to an appropriate value since if the compensation term is too small, then the backlogged traffic will monopolize the grant and newly arriving traffic will be backlogged for the next thread.



(a)

(b)

Fig. 6. Increasing the number of polling threads increases the overlapping probability of the DBA threads in a. EPON and b. GPON [44].

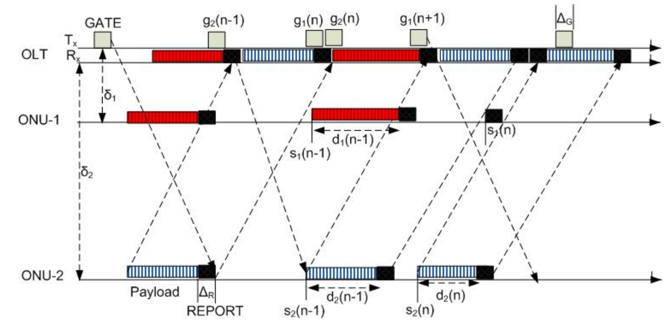


Fig. 7. Gate-Driven bandwidth allocation for two ONUs on a single wavelength [47].

Conversely, if the compensation term is too large, then the virtual queue may be over-granted in the corresponding cycle. Therefore, the backlogged traffic is calculated for a previously completed thread $i-n$ where all report and grant information is available. Thus, compensation term is calculated as follows:

$$C_i = D_{i-n} - b_{i-n} \tag{2}$$

The authors evaluate the performance of the proposal by adapting NA+ into an EPON-DBA [45] and a GPON-DBA [46]. In both PON technologies, it is shown that NA+ leads to a significant delay reduction as the reach increases towards 100km. Besides, NA+ does not introduce any performance degradation to the single-thread DBA in terms of PDV. Furthermore, the research in [44] addresses the trade-off between the number of threads and the PON performance. Increasing the number of threads aims introducing higher bandwidth utilization however, additional message exchange is generated by each DBA thread. Hence, depending on the system settings, the number of the DBA threads has to be limited to an appropriate value. NA+ was not initially proposed considering QoS metrics. However, as discussed in [44], it is worth to note that this scheme leads to reduced delay for high priority packets in a multi-class GPON system due to the overlapping threads.

3) GATE-Driven DBA for long-reach WDM-PON: In [47], a GATE-driven dynamic bandwidth allocation (GD-DBA) method is proposed for a WDM EPON where all ONUs are assumed to be capable of utilizing all available wavelengths. GD-DBA has two objectives as follows: i) Determining the right time to issue the GATE messages before receiving the corresponding messages from the ONUs, and ii) based on the GATE messages, determining the right transmission start time for the corresponding ONUs.

Let, $g_i(n)$ and $s_i(n)$ denote the time to issue the n^{th} GATE message to ONU$_i$ and the transmission start time of ONU$_i$, respectively. Based on the GATE message that has already been issued to ONU$_{i-1}$, the OLT already knows the duration for the data transmission of ONU$_{i-1}$ ($d_{i-1}(n)$). Then, OLT calculates the GATE message issuing time for ONU$_i$ as shown in Eq. 3 where $\triangle_R$ stands for the duration of a REPORT message.

$$g_i(n) = g_{i-1}(n) + d_{i-1}(n) + \triangle_R \tag{3}$$

Transmission start time for ONU$_i$ is calculated from $g_i(n)$. Hence, $\triangle_O$ and δ_i representing an offset value greater than the total of the RTT and the maximum size of an Ethernet frame, and one-way propagation delay between the OLT and ONU$_i$, respectively, $s_i(n)$ is calculated as shown in Eq. 4.

$$s_i(n) = g_i(n) + \triangle_G + \triangle_O - \delta_i \tag{4}$$

The equation set formed by these two equations forms a recursion enabling to compute the GATE issuing time and the transmission start time of the next ONU, i.e., ONU$_{i+1}$.

GD-DBA employs limited-service polling where the maximum transmission size (W_{max}) is previously set. Thus, an ONU receiving the n^{th} GATE message will utilize the bandwidth it had requested by the $(n-1)^{th}$ REPORT message if the requested bandwidth was less than or equal to W_{max}. Otherwise, the ONU will transmit W_{max} units of data. Hence, the OLT does not wait for the arrival of the REPORT message of the $(n-1)^{th}$ polling cycle to grant the ONU for the n^{th} cycle. Fig. 7 illustrates a simple scheduling scenario consisting of two ONUs utilizing a single upstream wavelength channel. ONU$_1$ and ONU$_2$ have different distances to the OLT leading to the one-way propagation delays of δ_1 and δ_2 where $\delta_1 < \delta_2$. Since ONU$_2$ is located at a further distance, it is more likely to experience a performance degradation in terms of packet delay. However, as seen in the figure, GD-DBA aims to fully utilize the upstream channel by calculating the GATE times before the REPORT messages arrive from the ONUs. Although GD-DBA is not specifically proposed for LR-PON, since the ONUs are assumed to be located from 2km to 100km away from the OLT, the proposed algorithm can be accepted as a protocol enhancement solution for the LR-PON. Furthermore, as seen in Fig. 7, and as the authors analyze in [47] [48], GD-DBA runs like a multi-server polling system which appears as a mandatory concept for better utilization in the long-reach access.

4) Online Excess Bandwidth Distribution (OEBD): In [49], [50], the authors present a comparison of online and offline excess bandwidth distribution approaches. The term *online bandwidth distribution* refers to granting mechanisms where the OLT prepares the GATE message for an ONU as soon as it receives its REPORT message whereas an OLT running an *offline bandwidth distribution* prepares the grants by running a scheduling algorithm upon receiving all requests from the ONUs [51]. According to the research in [49], [50], in LR-EPONs, offline excess bandwidth distribution demonstrates a stability problem above a certain load level by introducing higher delays when compared to the conventional limited-service polling in IPACT. An *online excessive bandwidth distribution (OEBD)* scheme is proposed to overcome this drawback. OEBD maintains a list of the ONU bandwidth fairness weights (w_i) and an excessive bandwidth credit pool (E_t) which is dynamically decayed by a factor (γ) and enlarged by the unutilized bandwidth. Thus, if ONU_i requests to transmit R_i units which is less than the minimum guaranteed bandwidth, B_{min} (i.e., maximum allowed bandwidth), then the size of the excessive bandwidth credit pool is increased by $(B_{min} - R_i)$. If the requested bandwidth of the ONU (R_i) is greater than the minimum guaranteed bandwidth (B_{min}), then the ONU is assigned a bandwidth with respect to the following function: $min(R_i, B_{min} + w_i \cdot E_t)$. After every N grants, OEBD decays the excessive bandwidth credit pool (E_t) by the decay function, $\gamma \cdot E_t$ where $\gamma \epsilon [0, 1]$.

OEBD is based on single thread polling but it demonstrates promising results for the delay performance of the LR-EPON if the N and γ parameters are selected properly. However, further enhancements to fulfill the delay objectives of the extended reach PONs can be obtained by a multi-thread polling implementation of OEBD as it is mentioned as a future insight of the proposal in [50].

5) Minimum Packet Delay Variance (minPDV): Real-time applications such as video conferencing or on-demand audio services require QoS guarantee referring to low-latency and minimal packet delay variance (PDV). In the LR-PON literature, most schemes deal with decreasing the average packet delay in the extended reach EPON or GPON. The research in [52] shows that the conventional report/allocate mechanism in GPON DBA algorithms increases the PDV. Moreover, those approaches have also shown to lead to tremendous increase as the GPON reach is extended from 20km to 100km. Hence, *delta buffer reporting* is proposed to guarantee *minimum packet delay variance (minPDV)* for *Constant Bit Rate (CBR)* class packets. Since minPDV focuses on minimizing the delay variation for CBR packets, it is included among the first group of DBA schemes.

According to the proposed scheme, the OLT stores the most recent two reports (DBRu) from each ONU. Each time the OLT receives a DBRu from the ONU, it calculates the incremental buffer occupancy at the ONU to allocate appropriate bandwidth. Incremental buffer occupancy stands for the difference between the last two requests, which is allocated for the received report. Since sufficient bandwidth is assigned to each arriving packet, packet delay variance is eliminated. As it is specified in [52], this scheme also helps simplifying the receiver architecture due to eliminating the need for re-timing the traffic at the receiver.

6) Periodic GATE Optimization (PGO): An enhancement to multi-thread polling is presented in [40], [53], and it is called *Periodic GATE Optimization (PGO)*. PGO is mainly based on multi-thread polling in EPON where the OLT periodically builds an ILP formulation by using the recent ONU REPORTs at each thread. OLT calculates appropriate credit ratios for the overloaded ONUs per thread according to the results of the optimization. Thus, until the next ILP formulation, whenever an ONU sends a REPORT of overload through a thread, the OLT allocates an additional bandwidth for the corresponding ONU by a certain portion of the excessive bandwidth of the corresponding thread.

The ILP formulation is built periodically at the OLT by taking the snapshot of the most recent REPORTs. The objective is to minimize the total granting delay introduced at each thread. Furthermore, the formulation also forces to set a direct proportion between the assigned and granted bandwidths of the heavily loaded ONUs. The outputs of the model gives optimized bandwidth allocation values per thread for the ONUs. For each thread, the difference between bandwidth allocation value obtained for an ONU and the minimum guaranteed bandwidth is normalized by the sum of these values for all ONUs, and this normalized value stands for the credit ratio of the ONU for the corresponding thread until the next optimization.

In [40], [53], PGO is tested under 20km and 100km reach distances, and it is shown that it can decrease the average packet delay of multi-thread polling without increasing the packet loss probability. However, for high split ratios, for the sake of scalability, ONU clusters may be considered, and a representative ONU of each cluster can contribute to the optimization as suggested in [40]. On the other hand, it is worth to note that the OLT requires sufficient CPU power to be able to formulate and solve such an optimization model.

7) Adaptive Threshold-Based Dynamic Bandwidth Allocation (A-Th DBA): In [54], a bandwidth distribution mechanism is proposed by adopting multi-thread polling in LR-EPON [34] and adaptive threshold-based burst assembly in OBS networks [55]. The proposed bandwidth distribution scheme is called *Adaptive Threshold-based Dynamic Bandwidth Allocation (A-Th DBA)*. According to A-Th DBA, each ONU maintains a report buffer (other than the input buffer) and a threshold pair consisting of size and waiting time thresholds. The report buffer stores the frames for whom the ONU has requested bandwidth. Hence, if bandwidth request is sent for a frame in the input queue within the current REPORT, the corresponding frame is dequeued from the input buffer and enqueued into the report buffer.

The OLT polls the ONU requests based on the multi-thread polling fashion. Whenever an ONU receives a GATE message through a thread, it checks the length of the input buffer. If the current length of the input buffer is larger than the size threshold, all frames in the input buffer are dequeued and enqueued into the report buffer. Otherwise, the frame at the head of the input buffer is checked, and if the frame has been waiting for longer than (or as long as) the waiting time threshold, it is de-queued and enqueued into the report buffer. Then, the report generator proceeds with the new frame at the head of the input queue and performs the same waiting time threshold check operation. Transmission of the frames in the report buffer within the current granted timeslot is followed by the ONU's bandwidth request to transmit the remaining frames in the report buffer.

Upon the receipt of each GATE message, the ONU re-adjusts the threshold pair as follows: If the total of idle upstream timeslots is increasing, the thresholds are decreased. Otherwise, the thresholds are increased only if the total upstream timeslots are decreasing more than a certain amount, i.e., *a low-watermark* [54].

In [54], A-Th DBA has been evaluated in an LR-EPON with an ONU-OLT distance of 100km, and it has been shown to reduce the packet delay of multi-thread polling. A-Th DBA is easy to implement and does not require a complex OLT architecture however, it requires selection of an appropriate low-watermark value to trigger the threshold increase operation.

8) DBA for STARGATE (SG) EPONs: STARGATE (SG) EPON stands for an architecture to integrate the access and metro networks all-optically [56]. A WDM single-hop star subnetwork consisting of passive star couplers (PSCs) and Arrayed Waveguide Gratings (AWGs) connects the central offices serving WDM-TDM PONs as illustrated in Fig. 8. Although it cannot be considered as a typical LR-PON, SG-EPON offers long-reach communication between the ONUs located in different WDM-TDM PONs across the WDM star subnetwork. As stated in [57], this architecture offers a promising solution for online gaming and peer-to-peer file sharing applications.

The research in [58] presents three types of ONUs deployed in SG-EPON as follows: 1) *TDM-ONU* is a typical ONU deployed in TDM EPONs, 2) *WDM-ONU* inherits the transmission capabilities of a TDM-ONU and enhances them by incorporating the multi-wavelength operating transceivers, 3) *LR-ONU* is an enhanced WDM-ONU with additional capability of communicating with the other LR-ONUs in the same or another WDM-TDM EPON across the WDM star subnetwork on a single-hop basis.

In [58], one of the first DBA algorithms that aims to deal with the heterogeneous structure of SG-EPON and to support long-reach communication between the LR-ONUs has been proposed. At each WDM-TDM EPON segment of the SG-EPON, at the end of each polling cycle, the OLT runs a DBA algorithm to assign appropriate time windows to the ONUs. At the end of the DBA algorithm, each TDM-ONU (say ONU_i) is assigned a TDM time window ($t^{TDM,i}_{start}$,$t^{TDM,i}_{length}$) whereas each WDM-ONU (say ONU_z) is assigned a TDM time window and a WDM channel window ($t^{\lambda_j,z}_{start}$,$t^{\lambda_j,z}_{length}$). Finally, an LR-ONU (say ONU_x) is also assigned a TDM time window, a WDM channel window, and in order to ensure long-reach communication, an AWG channel window ($t^{\lambda_l,x}_{start}$,$t^{\lambda_l,x}_{length}$) is assigned to an LR-ONU by the DBA algorithm. According to the DBA scheme, an ONU is served based on limited service scheme where three types of minimum guaranteed bandwidths are considered, such as B^t_{min} for a TDM wavelength, B^a_{min} for an AWG wavelength, and $B^{w,up}_{min}$ and $B^{w,down}_{min}$ for upstream and downstream WDM wavelengths, respectively. Upon receiving the REPORT message from an ONU, the OLT first checks the type of the ONU. If it is a TDM-ONU, the OLT assigns the minimum of B^t_{min} and B^i_{req} where B^i_{req} stands for the bandwidth requested by ONU_i. For a WDM-ONU (ONU_z), the OLT first attempts to provision the request by the WDM channels since WDM channels are shared by less number of ONUs compared to the TDM channels. If B^z_{req} is less than the minimum guaranteed upstream WDM channel bandwidth ($B^{w,up}_{min}$), then requested bandwidth is allocated to ONU_z. Otherwise, if requested bandwidth is greater than $B^{w,up}_{min}$ but it is still less than the sum of $B^{w,up}_{min}$ and minimum guaranteed TDM bandwidth (B^t_{min}), then a WDM channel window is assigned to grant $B^{w,up}_{min}$, and the remaining bandwidth is granted by the TDM channels ($B^z_{req}-B^{w,up}_{min}$). If none of these conditions holds, then a WDM channel window of $B^{w,up}_{min}$ and a TDM channel window of B^t_{min} are allocated for the WDM-ONU z. Bandwidth allocation for an LR-ONU (ONU_x) is done by using the same approach for a WDM-ONU. However, since an LR-ONU is capable of utilizing the AWG wavelengths, instead of using $B^{w,up}_{min}$ in the bandwidth allocation process, minimum of $B^{w,up}_{min}$ and B^a_{min} is used. Apart from TDM-ONUs and WDM-ONUs, LR-ONU is capable of communicating with other LR-ONUs in the SG-EPON across the AWG. Therefore, it also reports its bandwidth request for the upstream AWG wavelengths ($B^{x,l}_{req}$). Then, OLT obtains upstream bandwidth assignment for ONU_i by using the minimum of $B^{x,l}_{req}$, $B^{w,up}_{min}$ and B^{min}_a. Similarly, for downstream bandwidth assignment for an LR-ONU, the OLT uses the minimum of the buffer length allocated for the downstream traffic to be sent to ONU_i ($Q^x_{w,ds}$) and minimum guaranteed downstream WDM bandwidth ($B^{x,l}_{min}$). Here, after bandwidth assignment, scheduling of the WDM-ONUs and LR-ONUs on the wavelengths is a challenging subproblem of the DBA since in the proposed SG-EPON, each LR-ONU (also each WDM-ONU) has one Reflective Semiconductor Optical Amplifier (RSOA), i.e., each ONU can utilize at most one wavelength in a time window. For WDM-PON, first-fit assignment is employed by checking the horizon (start of the first available timeslot) of the WDM channel. Scheduling of LR-ONUs is done following the scheduling of the WDM-ONUs. First, the ONUs are scheduled on the available time windows of upstream and downstream WDM channels without any overlapping. Finally, for each AWG wavelength, the ONUs are scheduled without overlapping any of their AWG or WDM time windows. Although this contention-free scheduling approach may lead to void time windows on the wavelength channels, in each cycle, bandwidth assignment on one or more channels for a WDM-ONU or a LR-ONU can be segmented and re-scheduled as proposed in [58].

9) Slotted Media Access (SMAC): In [59], the authors propose an architecture called *Slotted Passive Optical Network (SPON)* which enables both ONU-OLT communication and direct ONU-ONU communication in the long-reach through wavelength spatial reuse offered by the AWGs. The proposed architecture has four main components as the OLT, the AWG, the distribution section and the local PONs. The local ex-

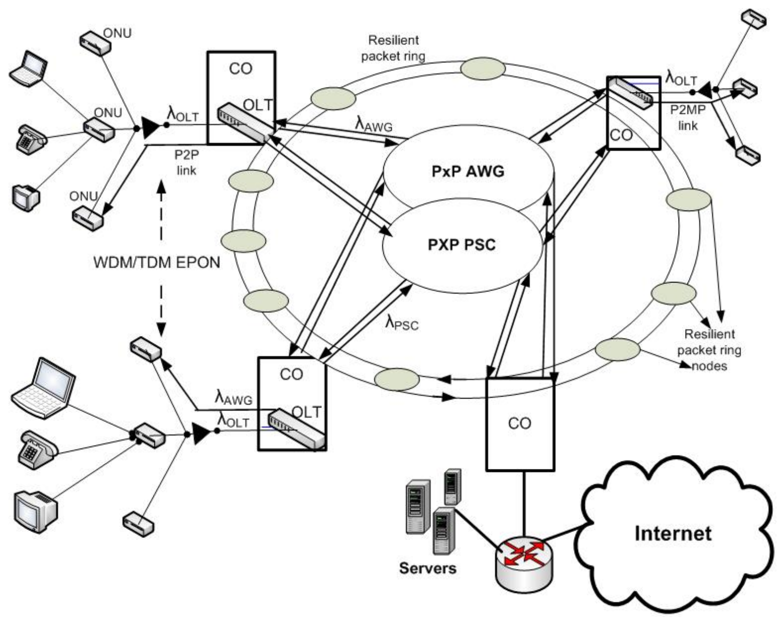


Fig. 8. STARGATE EPON infrastructure [58].

change module, namely the AWG enables the OLT to transmit its traffic in the downstream direction to the ONUs and the ONUs in the same PON to communicate with each other without using the OLT as a proxy device. Fig. 9 illustrates a simple transmission and receiving architecture in SPON where λ_0 and λ_1 are used by the ONUs for upstream transmission, and λ_{2-3} for broadcasting by the OLT while λ_4 is used for control message transmission by the OLT.

In [59], the upstream traffic destined to the OLT is referred as *public traffic* while the upstream traffic destined to another ONU in the SPON is referred as the *inner traffic*. In the distribution section, cascaded placement of two 1:16 couplers enables 1:256 split ratio for each local PON. Since the SPON architecture comprises 4 local PONs, 1:1024 split ratio is achieved in the long-reach. The ONUs are equipped with a Fabry-Perot Laser Diode which is used as a tunable transmitter, and fixed-tuned receiver array in order to receive data on multiple wavelength channels. 32 wavelength channels $\{\lambda_0 - \lambda_{31}\}$ are partitioned into two groups as follows: $\{\lambda_0 - \lambda_{15}\}$ in the upstream direction are used by the ONUs to transmit data to the OLT and to communicate with the other ONUs in the SPON while $\{\lambda_{16} - \lambda_{31}\}$ in the downstream direction are used by the OLT to transmit messages to the ONUs.

In [59], the *Slotted Media Access (SMAC)* is proposed to run on top of the SPON architecture. SMAC has two main assumptions: 1) OLT-ONU distance is the same for all ONUs, and 2) the OLT is capable of estimating the RTT between itself and each ONU. Each wavelength is partitioned into fixed-length frames, and each frame starts with the *bandwidth reservation (BR)* slot. The timeslots in a scheduling frame are divided into two sub-frames, namely the inner sub-frame and the public sub-frame. The BR slots are utilized by the ONUs to send REPORT messages to the OLT in order to reserve timeslots for their inner and public traffic frames. Before the end of the scheduling frame (F), the OLT informs the ONUs on the termination of the scheduling frame F by sending an advertisement message (ADV). Here, termination of the scheduling frame F stands for the notification of the BR slot of the next scheduling frame, *F+1*. In this timeslot, the OLT partitions the upstream wavelength channels into $\frac{N}{W}$ sub-slots where N is the number of the ONUs, and W is the number of the upstream wavelength channels. A sub-slot is equal to the size of a REPORT message, and in order to avoid any collision, ONU-sub-slot assignment is done based on a fixed one-to-one matching fashion. The OLT computes the upstream wavelength (λ) to be assigned to ONU$_i$ by considering Eq. 5.

$$\lambda = \lfloor \frac{i \cdot W}{N} \rfloor \tag{5}$$

To avoid any collision, the sub-slot (s) on the corresponding wavelength is determined based on a simple modular operation as follows: $s = i \ mod \ (N/W)$.

The OLT avoids any upstream collision between the public frames. The inner frames may collide at the OLT receiver however, taking the advantage of the spatial wavelength reuse offered by the AWG, the inner traffic can be carried between the ONUs in SPON without any collision. According to the proposed architecture, each ONU maintains a public queue for the public traffic and one inner queue per destination local PON (i.e., IG: internetworking group). Furthermore, the authors use a two-step inner queue scheduling mechanism based on a two-phase round-robin [60] in order to increase bandwidth utilization by the inner traffic and to guarantee fairness among the inner queues at each ONU.

10) Online Upstream Scheduling and Wavelength Assignment with Void Filling (USWA-VF): Kanonakis and Tomkos have proposed two online upstream scheduling wavelength assignment (USWA) algorithms, namely *Earliest Finish Time (EFT)* and *Latest Finish Time (LFT)* for WDM-EPON [61]. Both schemes run based on the gated service fashion, i.e., grant sizing is not considered, and an ONU is granted the bandwidth it has requested. EFT assigns a wavelength to an

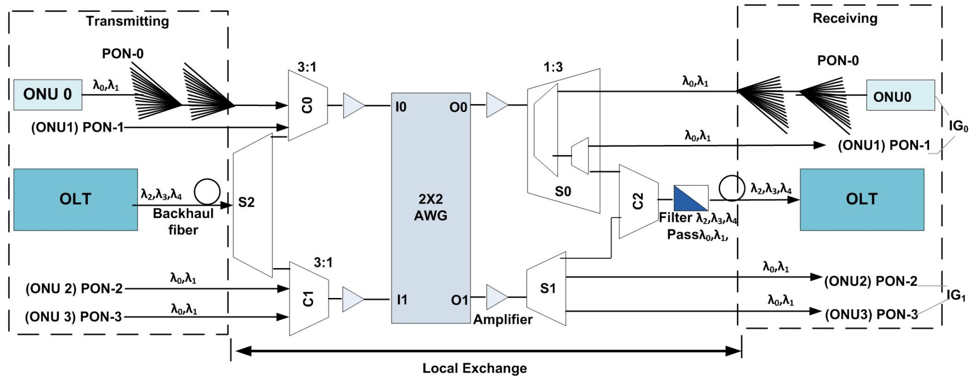


Fig. 9. SPON transmission and receiving architecture [59].

ONU by guaranteeing the following two conditions: $i)$ There is no reservation on any later timeslot in the corresponding wavelength channel, $ii)$ The corresponding wavelength has the earliest finish time in the wavelength set that is available to the ONU. LFT is a modified version of EFT, and it satisfies the first constraint (i) of EFT however, it assigns the wavelength channel with the latest reserved timeslot out of the wavelength set available to the ONU.

In [61], EFT and LFT have been modified to utilize the void timeslots on the wavelength channels. Thus, OLT keeps track of the void timeslots on each wavelength channel and selects an eligible timeslot which has the earliest or latest finish time. The former scheme is named as *Earliest Finish Time with Void Filling (EFT-VF)* while the latter is called *Latest Finish Time with Void Filling (LFT-VF)*. The motivation behind these proposals is the large unutilized timeslots due to long/differential propagation delays. It is stated that EFT-VF and LFT-VF are expected to leave very short unutilized timeslots hence, they are expected to introduce almost the same delay performance. Therefore, in this paper, we refer to these schemes as *Upstream Wavelength Assignment with Void Filling (USWA-VF)*. EFT-VF is tested under a ring-and-spur topology for a maximum ONU-OLT distance of 100km, and it has been shown to reduce the delay of non-void filling scheduling up to 30% for 128 ONUs connected to four remote nodes. EFT-VF can further be enhanced in terms of queue length management and packet delay variation by considering grant sizing.

B. Quality-of-Service (QoS)-Aware DBA Schemes

1) Predictive Colorless Grants-Offset-based Scheduling with Flexible Intervals (PCG-OSFI): The research in [62], [63] proposes *Offset-based Scheduling with Flexible Intervals (OSFI)* for GPON in order to decrease packet delay and packet delay variation. OSFI supports three Allocation Identifier (Alloc-ID) types at the ONUs, namely the *Fixed Type*, *Flexible Type* and *Best Effort Type*. *Fixed Type* Alloc-IDs are allocated guaranteed rate bandwidth periodically by the OLT without waiting for a DBRu. *Flexible Type* Alloc-IDs specify QoS requirements such as delay, delay variation and packet loss. Packets in these type of queues have a guaranteed rate bandwidth and a maximum additional bandwidth, namely *maximum surplus rate (SR)*. OSFI, aims to decrease the

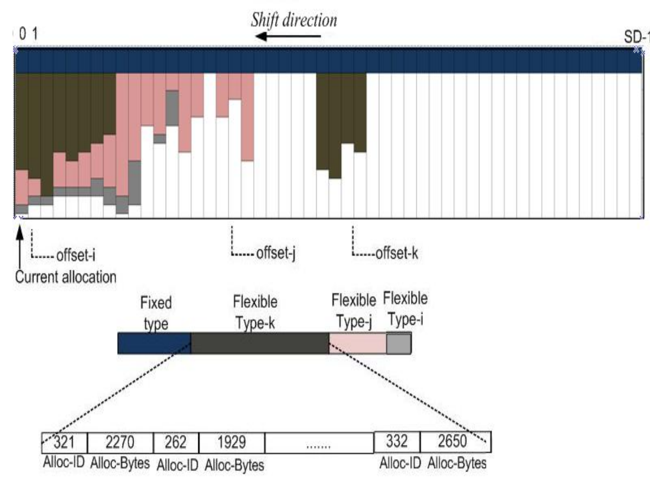


Fig. 10. Scheduling log instance for fixed type, flexible type-i, flexible type-j and flexible type-k Alloc-IDs in PCG-OSFI [62].

queuing delay of the *Flexible Type* Alloc-IDs by dynamically modifying the scheduling interval (SI_i) of each Alloc-ID of this type. Here, scheduling interval stands for the time between two consecutive DBRu frames of the same Alloc-ID. Thus, OSFI consists of the following two modules: 1) Bandwidth allocation for the Alloc-IDs, 2) On-line determination of the scheduling interval of the corresponding Alloc-ID. A lower bound for the scheduling interval (SI_b) is determined based on the RTT and ONU/OLT processing delays, and the SI_i of an ONU is set to a maximum value of SI_b+ $offset_i$. Here, the offset value sets a lower bound for the queuing delay of the corresponding Alloc-ID. A scheduling log is maintained at the OLT, each column of which represents the allocations by the future downstream frames. OSFI selects the eligible columns of the scheduling log, and then the one leading to the largest unallocated bandwidth out of the eligible ones. Finally, the maximum possible service rate is calculated by considering the guaranteed bandwidth and the upstream frame size.

Fig. 10 illustrates an instant of the scheduling log at the OLT employing OSFI where three types of flexible services (Type-i, Type-j, Type-k) exists. In the figure, allocated bytes for each Alloc-ID type are represented by a unique color, and the white spaces denote the unallocated bytes. As seen in the figure, Flexible-Type-i Alloc-ID queues have the lowest

TABLE I
SUMMARY AND COMPARISON OF THE QOS-UNAWARE DBA SCHEMES FOR LR-PON

Scheme	Base PON Type	Maximum Reach Tested	Delay	PDV	Packet Loss	Runtime overheads
MT [33], [34]	EPON	100km	Lower than ST (<10ms until 1.0 Erlang, ≤100ms beyond 1.0 Erlang)	N/A	Low	On-line inter-thread scheduling
NA+ [44]	EPON / GPON	100km	Enhances MT.	Same as ST	Low	On-line inter-thread scheduling and compensation term setting
GD-DBA [47], [48]	WDM EPON	2∼100km	Enhances REPORT-Driven scheduling with small W_{max}	N/A	N/A	Needs integration to multi-wavelength environment
OEBD [49], [50]	EPON	100km	Between limited service and gated service polling [13]	N/A	N/A	δ, N factor selection
minPDV [52]	GPON	100km	Not main focus; possibly higher delay	Zero PDV for CBR traffic	N/A	Memory allocation for the last two REPORTs
PGO [40], [53]	EPON	100km	Lower than ST and enhances MT	N/A	Lower than ST	CPU power at the OLT for ILP solution
A-Th DBA [54]	EPON	100km	Lower than ST and enhances MT	N/A	Lower than ST	Needs to select an appropriate low-watermark to increase the thresholds
*SG-EPON DBA** [58]	SG-EPON	20∼100km (Average 40km)	Delay of the LR-ONUs similar to that of the WDM-ONUs.	N/A	N/A	Scheduling LR-ONUs on WDM and AWG wavelengths
SMAC [59], [60]	WDM EPON	100km	Lower than ST (<100ms until heavy loads)	N/A	Low	Needs adaptation to differentiated ONU-OLT distances
USWA-VF [61]	WDM-EPON	max 100km	<1ms until 0.8 Erlang per wavelength.	N/A	N/A	Calls for efficient grant sizing module

*SG-EPON architecture enables LR-ONUs to communicate between each other in long distance although it is not specifically an LR-PON technology.

offset value while Flexible-Type-k Alloc-ID queues lead to the highest offset value which leads to the highest queuing delay among all Alloc-ID types. The authors in [62] name the number of columns of this matrix as the *scheduling depth*. The scheduling depth of the log in Fig. 10 is 20 which seems to provide a good differentiation among the Flexible Type Alloc-IDs in terms of the scheduling interval. As it is stated in [62], service depth demonstrates a trade-off between the service differentiation performance and memory allocation. Increasing the scheduling depth leads to a more significant scheduling interval differentiation among the Alloc-IDs however, OLT requires larger memory to store the scheduling log and consequently more time to process it.

In order to avoid huge delays due to long feeder distance in LR-GPON, a predictive mechanism, namely *Predictive Colorless Grants (PCG)* is further proposed in [62]. According to the PCG, the OLT predicts the accumulated bytes at the corresponding Alloc-ID by using the current DBRu, previous DBRu, previous GRANT and the previous idle timeslots transmitted by the ONU. For further improvement, the additional bytes to the report are granted as *colorless grants* to enable the other Alloc-IDs of the same ONU to utilize them if the accumulated length of the corresponding Alloc-ID is overestimated.

In [62], performance of PCG-OSFI is evaluated for two Flexible Type classes in a 100-km reach GPON with a split ratio of 1:16. It is shown that the employment of PCG in OSFI decreases the average packet delay for the high priority QoS classes. Furthermore, inclusion of PCG leads to less PDV for the high priority classes in the long-reach GPON.

2) OBS-DBA (A Hardware-Driven Solution): Optical Burst Switching (OBS) was initially proposed for the optical back-

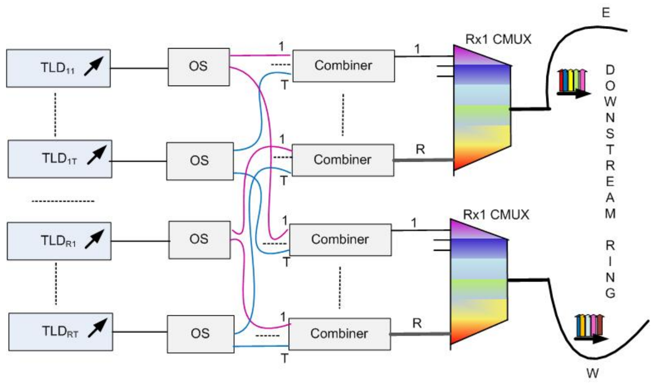


Fig. 11. OLT architecture proposed for SARDANA employing tunable laser diodes. Tunable laser diodes of the OLT operate at R optical sub-bands and are shared among the tree PONs [67].

bone networks for efficient utilization of the wavelength channels [64]. According to OBS, the ingress routers of the backbone collect IP packets until a time or size threshold is reached. Upon hitting the threshold, the ingress router assembles the packets in the virtual queue(s) in an optical burst and transmits the burst to the destination following a burst header packet which reserves the appropriate timeslots on the wavelength channels along the path. OBS-based PON was initially considered in [65] employing a special type of OBS, namely *Wavelength Routed OBS (WROBS)*. WROBS offers a guaranteed lightpath transmission from source to destination by employing a central control node. Hence, packet drop is only due to buffer overflow at the ingress nodes [66].

The authors in [67] propose an OBS-based DBA for the Scalable Advanced Ring-based Dense Access Network Architecture (SARDANA) which is a project for the next generation PONs. SARDANA simply consists of remote tree PONs which are connected through a resilient WDM ring. Furthermore, at the remote nodes, Erbium Doped Fiber amplification is done through the OLT lasers in order to handle the fiber losses leading to a reach of 100km [68]. The related work offers performance enhancement solutions for both DBA and resilience.

In [67], the authors propose two OLT architectures where the first one dedicates fixed laser diodes (FLDs) to each tree PON whereas the second OLT architecture which is illustrated in Fig. 11 shares the tunable laser diodes (TLDs) among several PONs in order to assure enhanced traffic efficiency and network resilience. According to the OLT architecture in the figure, an optical switch (OS) selects the part of the WDM ring where the traffic from the TLD will be forwarded. Traffic of the TLDs are coupled at the combiners that are multiplexed by a coarse multiplexer (CMUX). The multiplexed signal is then directed to one of the two halves of the WDM ring.

The proposed OLT architectures manage the traffic by using an existing DBA scheme for a WDM-PON [69] based on the OBS paradigm. Thus, the Ethernet and/or the IP packets are collected until the total queue size or waiting time exceeds a pre-specified threshold. Here, enabling OBS transfer mode leads to forming large optical bursts so that enhanced utilization is achieved in the extended reach. Moreover, QoS-awareness is adapted in the DBA by considering three classes of service. At the ONUs, strict priority (SP) queuing is employed, i.e., the first data burst is selected from the highest priority non-empty queue. For the OLT architecture where tunable laser diodes are shared among several PONs (Fig. 11), it is shown that TLD sharing mechanism does not introduce a significant increase in delay while it leads to a significant enhancement in the bandwidth utilization. Moreover, the authors further show that the first two CoS group users experience a very low delay when compared to the overall delay and the delay of the best-effort class.

3) Long-reach Interleaved Polling Service Level Agreement algorithm (LIPSA): Long-reach Interleaved Polling Service Level Agreement (LIPSA) algorithm is proposed to achieve user and service differentiation in LR-EPON [41]. LIPSA mainly focuses on bandwidth prediction for the ONUs of k service level agreement (SLA) classes in each polling cycle. At each cycle, the algorithm calculates the maximum allowable bandwidth for each SLA class ($B_{max}^{SLA_k}$) based on the available cycle bandwidth and the SLA class weights. At cycle $N+1$, limited service scheme is employed as follows: If the difference between the demands of the ONU at the N^{th} and $(N-1)^{th}$ cycles is less than $B_{max}^{SLA_k}$, the ONU is granted by the bandwidth demanded, otherwise it is granted by $B_{max}^{SLA_k}$.

As shown in [41], LIPSA enhances the delay performance of IPACT for high priority class packets however, it requires further enhancement in terms of utilization and overall delay as it is achieved by the inclusion of inserted cycles by the next scheme, LIPSA-IC.

4) Long-reach Interleaved Polling Service Level Agreement algorithm with Inserted Cycles (LIPSA-IC): In [43], *Long-Reach Interleaved Polling algorithm with Inserted Cycles (LIPSA-IC)* is proposed for long-reach EPON as an enhancement to the initially proposed LIPSA algorithm. LIPSA-IC uses the same bandwidth allocation method with LIPSA but it enhances its predecessor algorithm by attempting to utilize the large idle timeslots in downstream and upstream directions which are the consequences of the typical DBAs in long-reach EPON. LIPSA-IC inherits SLA class differentiation in LIPSA by applying a specific maximum allowable bandwidth ($B_{max}^{SLA_k}$) for each SLA class. In LIPSA-IC, a normal polling cycle is followed by an inserted cycle which uses a similar principle with [34]. However, LIPSA-IC does not deal with scheduling the sub-cycles as MT does. Furthermore, MT behaves as if the OLT is polling the ONUs by multiple parallel threads while LIPSA-IC restricts a polling cycle by a normal cycle followed by an inserted cycle.

Fig. 12 illustrates the operation of LIPSA-IC and compares it to the operation mode of conventional polling algorithm. The first part of the figure corresponds to a conventional polling behavior consisting of two polling cycles with timeslot gaps in the upstream direction. In the second part of the figure, under the same arrival scenario, the OLT issues the $(N-1)^{th}$ GATE message of ONU$_i$ at $(t_1 - RTT/2)$ which propagates to ONU$_i$ at time t_1. The grant size for the corresponding cycle is $B_{alloc}^{ONU_i,N-1}$. ONU$_i$ appends its REPORT message to the end of its transmission, informing the OLT on the demand for the next *normal* polling cycle, i.e., $B_{demand}^{ONU_i,N-1}$ for the $(N+1)^{th}$ cycle. It is worth to note that in the conventional polling, the ONU does not send the next frame until t_4 as seen

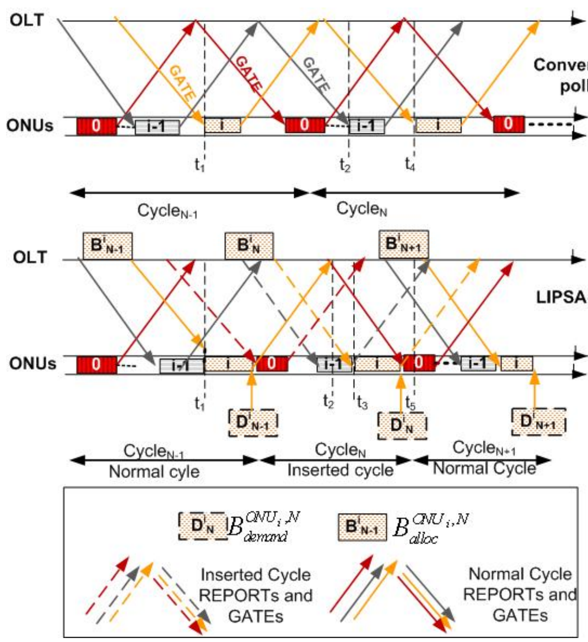


Fig. 12. Illustration of LIPSA-IC and its comparison to conventional polling [43].

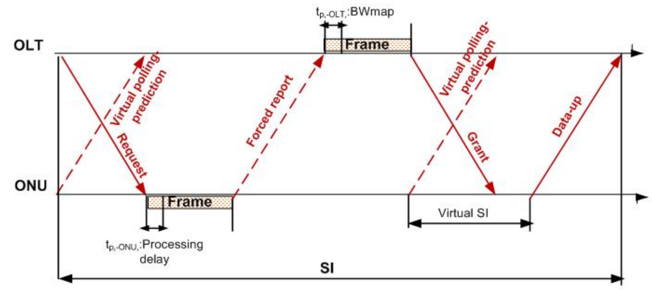


Fig. 13. Building BWmap based on status reporting in a scheduling interval [71].

in the first part of the figure. However, LIPSA-IC takes the advantage of utilizing the voids in the upstream direction by inserting additional cycles, i.e., here, N^{th} cycle. When issuing the GATE message of ONU$_i$ for the $(N+1)^{th}$ cycle, the OLT uses three parameters, the last two bandwidth allocations for ONU$_i$ ($B_{alloc}^{ONU_i,N-1}$, $B_{alloc}^{ONU_i,N}$) and the last bandwidth demand reported by ONU$_i$ ($B_{demand}^{ONU_i,N-1}$). As it is clearly seen in the figure, in long-term, LIPSA-IC is expected to behave like a multi-server polling system as most of the solutions in the literature do.

In [43], it is shown that LIPSA-IC leads to less average packet delay compared to single cycle polling for the reaches beyond 150km. On the other hand, LIPSA-IC is shown to achieve the same throughput and delay levels independent of the distance when tested for reaches varying from 125km to 225km.

5) Two-state Dynamic Minimum Bandwidth Assignment (TSD): The research in [32], [70] proposes a *two-state dynamic minimum bandwidth allocation (TSD)* scheme to improve channel utilization in LR-GPON. Similar to [34], [43], an extra polling cycle, namely the *virtual cycle* is employed to utilize the idle timeslots between two normal polling cycles. The algorithm is based on the typical limited service-based dynamic minimum bandwidth (DMB) allocation considering the service requirements [13]. In TSD, bandwidth request of an ONU in a virtual cycle is determined by bandwidth estimation relying on the fact that self-similar traffic demonstrates similar packet arrival rates in short time, such as the total polling cycle. Therefore, by using the ONU report, a linear estimation runs for the normal cycle, normal cycle length and the virtual cycle length. Thus, at the end of the polling cycle, the ONU is assigned a normal-cycle bandwidth which is based on the ONU request and a virtual-cycle bandwidth based on the bandwidth estimation.

Since TSD is proposed for LR-GPON, each ONU maintains k transmission containers (T-CONTs) where each T-CONT is associated with a service class. In order to assure CoS differentiation, strict priority queuing is adopted by the TSD on the T-CONTs so that T-CONT2, T-CONT3 and T-CONT4 flows are delivered sequentially. Here, T-CONT1 is allocated a fixed guaranteed rate, T-CONT4 refers to the best effort service, and T-CONT2-3 correspond to the Flexible CoS which has pre-specified QoS requirements. Minimum bandwidth of the T-CONT2 and T-CONT3 traffic types is assigned dynamically to guarantee their delay requirements. In each polling cycle, the unutilized portion of minimum guaranteed bandwidth of T-CONT2 and T-CONT3 classes is used to provide extra bandwidth for the best effort traffic type, i.e., T-CONT4.

In [32], [70], performance of TSD is evaluated for a 100km-reach GPON with 1:16 split ratio, and it is compared to the performance of the standard DMB algorithm. According to the results, by adapting the virtual polling cycle and bandwidth estimation mechanism together with strict priority queuing policy on T-CONTs, TSD can reduce average overall packet delay as well as the packet delay for delay sensitive traffic classes.

6) Multi-service GPON scheduling (MSGS): The study in [71] proposes a multi-service GPON scheduling scheme for bursty traffic, which we shortly call MSGS here, where four classes of service (CoS) traffic containers (T-CONTs) are considered similar to [32], [62]. The proposed scheme is based on status reporting where the OLT builds a bandwidth map (BWmap) for each frame in scheduling intervals as shown in Fig. 13. Grants of the Alloc-IDs are calculated based on the sum of the current status report and the backlogged bandwidth in the previous scheduling interval. However, based on the bandwidth availability and the CoS / SLA requirements, the actual bandwidth assignment is determined. Thus, the difference between the calculated grant and the assigned bandwidth is stored as the backlogged bandwidth to be used in the next scheduling interval.

In order to avoid long delays and improve utilization in long-reach GPON, the proposed scheme employs a bandwidth prediction method in the DBA for T-CONT2 and T-CONT3 traffic. Since the DBA is proposed to run under bursty traffic, data bursts of the ONUs may not be predicted directly by employing linear prediction at the OLT as in [62], [63]. Hence, virtual polling cycles are introduced within a scheduling interval. As in [32], a virtual polling cycle stands for the

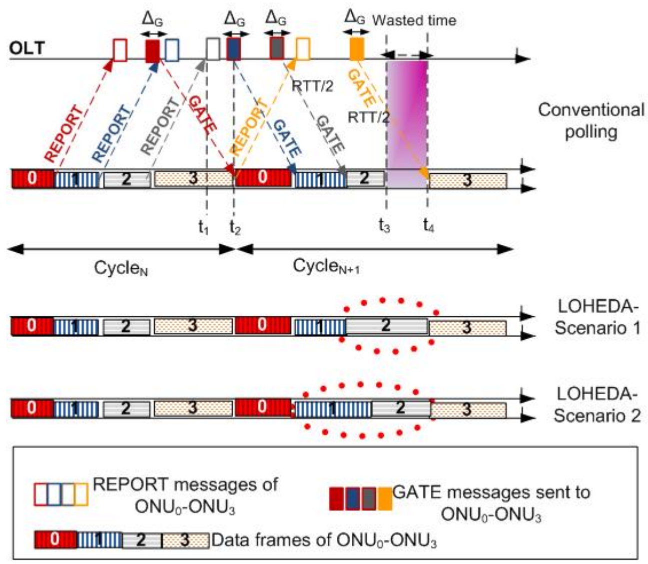


Fig. 14. Bandwidth assignment in LOHEDA. Wasted bandwidth in the regular polling mode is utilized based on the bandwidth request of ONU_2. ONU_2 is assigned the whole wasted bandwidth (Scenario-1) or ONU_1 and ONU_2 share the wasted bandwidth (Scenario-2) [72].

transmission of a predicted bandwidth frame. For each of these frames, BWmap is re-built at the OLT. In [71], it is shown that MSGS achieves to introduce low delay for the high priority queues by the employment of virtual polling cycles for the predicted bandwidth frames.

7) Long-Reach Highly Efficient Dynamic Bandwidth Assigment (LOHEDA): LOHEDA is proposed as an enhancement to the conventional polling in order to utilize the gaps (i.e., *wasted bandwidth*) in the upstream direction of the LR-EPON [72]. Bandwidth allocation for an ONU (ONU_i) in LOHEDA is as follows: Let ONU_i be with the k^{th} service level agreement (SLA) class (SLA_k) and $B_{max}^{SLA_k}$ be the maximum bandwidth allocation amount for the corresponding SLA class. If the demand of ONU_i is less than $B_{max}^{SLA_k}$, then ONU_i is granted by its demand ($B_{demand}^{ONU_i}$) and an additional bandwidth $B_{wasted}^{ONU_i}$. Otherwise, the ONU is granted by the maximum allowed bandwidth for its corresponding class $B_{max}^{SLA_k}$ and the additional bandwidth, $B_{wasted}^{ONU_i}$. Here, $B_{wasted}^{ONU_i}$ denotes the idle time in the upstream direction between two consecutive ONUs, i.e., ONU_i and ONU_{i+1}. At each cycle, maximum allowable bandwidth for each SLA class is calculated by the same way of LIPSA-IC [43], i.e., weighted fair distribution of the total available bandwidth among the classes.

The key issue in LOHEDA is the detection and the utilization of the wasted bandwidth. When a wasted bandwidth is detected in the upstream direction between ONU_i and ONU_{i+1}, the wasted bandwidth calculation for ONU_i ($B_{wasted}^{ONU_i}$) is as follows: If ONU_i has requested more than zero, it is granted the whole wasted bandwidth. Otherwise, the wasted bandwidth is distributed among the ONUs whose REPORTs have been received but the GATE messages have not been issued yet. In this case, the distribution of the wasted bandwidth is done with respect to the SLA class weights of the corresponding ONUs. Fig. 14 can help understanding these issues. In the figure, four ONUs are considered. In the first part of the figure, a snapshot of the conventional polling in EPON is illustrated. At t_1, the OLT receives a REPORT message from ONU_2 corresponding to the bandwidth request for the $(n+1)^{th}$ cycle. At this point, the OLT knows if there will be a wasted bandwidth in the upstream direction between ONU_2 and ONU_3 if it grants ONU_1 and ONU_2 by limited service scheme. Once it calculates the wasted bandwidth between ONU_2 and ONU_3, it checks whether the bandwidth demand of ONU_2 is non-zero. If ONU_2 has a non-zero demand, the whole wasted bandwidth is assigned to ONU_2 (Scenario-1 in the figure). Otherwise, if ONU_2 has a zero bandwidth demand, then the wasted bandwidth is distributed between ONU_1 and ONU_2 with respect to the weight of their corresponding SLA classes (Scenario-2 in the figure).

In [72], performance of LOHEDA is evaluated for various OLT-ONU distances up to 150km and compared with the performance of LIPSA [41]. It is shown that LOHEDA is capable of reducing the delay of all SLA classes. Furthermore, it leads to reduced buffer occupancy due to efficiently distributing the wasted bandwidth among the ONUs.

8) PGO with QoS-Awareness (PGO-QoS): In [40], [73], a modified version of PGO, PGO-QoS is presented to provide differentiation between QoS classes. PGO-QoS consists of two modules, namely the *burstification* module running at each ONU and the DBA module running at the OLT. Burstification module deals with the problem of de-queuing of the QoS sub-queues at the ONUs upon receiving a GATE message where each ONU maintains K QoS sub-queues. The objective of the burstification module is obtaining a de-queuing proportion for the queues such as d_1:d_2:d_3 for a system with three QoS classes. By setting the sum of the proportion components to a constant value, borrowing and lending of de-queuing proportion components is possible between the sub-queues.

According to PGO-QoS, each ONU periodically updates the de-queuing proportion components starting from sub-queue of the highest priority class. If the sub-queue length of this class has increased since the previous update, then starting from the sub-queue of the least priority class, it attempts to borrow one de-queuing component from the corresponding sub-queue. If decrementing the de-queuing component of the least priority class by one leads to starvation of the lending sub-queue, the same attempt goes with the next QoS sub-queue which has less priority than the class of the current sub-queue. If de-queueing proportion of the highest priority class sub-queue has not been changed, the algorithm proceeds with the next less-priority sub-queue to update its de-queueing proportion component. The de-queuing proportion is used to burst the incoming packets from various QoS classes. Moreover, each ONU calculates a polynomial value by using the de-queuing proportion such that the de-queuing proportion component of the highest priority class (say d_3 in the 3-class case) contributes the most while the least priority class (say d_1 in the 3-class case) contributes the least to the value of the polynomial. The polynomial value is appended to the REPORT message.

DBA module of PGO-QoS is mainly PGO [40], [53]. Thus, the OLT periodically builds an ILP formulation to determine how to credit the overloaded ONUs at each thread cycle until the next formulation period. Due to the transmission of the polynomial values in the REPORT messages, at the end of a thread cycle, the OLT is informed about the QoS sub-queue occupancy status at the ONUs. Hence, QoS differentiation is provisioned by having an additional constraint in the ILP formulation which forces the model to provide greater bandwidth credits for those ONUs requesting more bandwidth and having larger buffer occupancy at the high priority sub-queues.

In [40], [73], PGO-QoS is shown to enhance the average packet delay of multi-thread polling and the conventional single-thread polling as well. On the other hand, incorporation of QoS differentiation leads to further enhancement in average packet delay of the high priority classes, i.e., class-3 and class-2. Furthermore, decrease in average packet delay does not cause an increase in the overall packet loss. Moreover, QoS differentiation of the scheme also leads to a significant decrease in the packet loss probability of the high priority classes.

9) Delay-Constrained PGO (DC-PGO): A proactive version of PGO-QoS is proposed in [74] where packets are assumed to arrive with pre-specified delay tolerance values. Hence, an admission control module is added into the *burstification* module, and the scheme is called *Delay-Constrained Periodic GATE Optimization (DC-PGO)*. According to the admission control scheme of the DC-PGO, for each arriving packet, sum of the sub-queue lengths, minimum guaranteed bandwidth and the time difference between the last REPORT messages of two successive threads are used to get an estimated delay for the arriving packet. If the estimated delay is greater than the delay tolerance of the packet, the packet is dropped, otherwise it is admitted and pushed into the appropriate sub-queue.

In [74], performance evaluation of DC-PGO is presented in terms of average packet delay and average packet drop probability for different delay tolerance set values in a 100km-reach EPON. Since the proactive admission control is employed together with PGO-QoS, average packet delay of high priority classes of multi-server polling is decreased. Furthermore, average packet drop probability of multi-server polling is decreased under DC-PGO due to the inclusion of the PGO-QoS.

IV. Open issues and Future Directions

In Table I and Table II, we have outlined the fundamental properties of the surveyed techniques. Fig. 15 provides a taxonomy of the surveyed DBA schemes in order to demonstrate the main differences between them. As seen in the figure, majority of the schemes use LR-EPON or LR-GPON while only five out of the 19 schemes use the hybrid WDM-TDM EPON. Currently, SG-EPON DBA calls for an enhancement in terms of multiple CoS and service levels support. Moreover, as stated in [75], appropriate deployment of WDM-TDM PON leads to a significant decrease in the outside plant and active equipment costs of the next generation long-reach access network. Therefore, another open issue for the researchers in this field is the design of efficient bandwidth allocation algorithms to guarantee low delay, high utilization and QoS guarantee in long-reach WDM-TDM PONs.

Although performance degradation mainly refers to long cycle times and long delays due to long feeder distance and high split ratio, LR-PONs are more prone to fiber and component failures than any other short-reach access technology [76]. In case of a failure, the amount of data loss and the duration of service outage would be considerably huge for the subscribers. Therefore alternate protection mechanisms [76]–[78] have to be considered for resilience of LR-PONs as well as resilient planning of LR-PONs [79], [80]. Despite the fact that protection and resilient planning mechanisms have been explored by a few studies, considering a user restoration requirement below 50ms [76], development of fast restoration schemes and adaptation of those schemes into the bandwidth assignment protocols seem to be the open issues in this area.

Scheduling the grants seems as another factor which affects the performance of LR-PON. McGarry et al. have shown that granting the ONUs with the shortest propagation delay (SPD) first [81] leads to more efficient delay performance when ONU-OLT distances are heterogeneously distributed. Hence, this information can provide useful insights for the future offline DBA schemes which can offer enhanced grant sizing solutions in LR-PONs.

Combining the high capacity and reliability of optical networks and the ubiquity and mobility support of the wireless access technologies has appeared as an attractive solution for the emerging broadband applications. Hence, Fiber-Wireless (Fi-Wi) networks propose the convergence of PONs and wireless access technologies such as WiFi (IEEE 802.11a/b/g) or WIMAX (IEEE 802.16) [82]. Although there have been proposals for converged DBA schemes in Fi-Wi networks consisting of EPON at the optical back end and WiFi at the wireless front-end [83] or EPON at the optical back end and WiMAX at the wireless front-end [84], converged DBA for long-reach Fi-Wi networks still calls for novel solutions.

Energy savings in the telecommunication networks started in the first half of 2000s [85] and has become a hot topic today. Access networks contribute to a significant portion of the energy consumption of the Internet [86]. Energy-efficient design has recently been explored to minimize the number of active wavelengths in a hybrid long-reach WDM-TDM PON [37] which is based on daily user behavior-based planning [87]. However, as stated in [88]–[90], ONUs are always kept in the operating mode although they do not send or receive any frames, and significant energy savings can be achieved if ONUs can be put in the sleep mode when they are neither transmitting nor receiving signals. Furthermore, power consumption of an OLT is almost twenty times of an ONU [91]. Hence, putting the OLTs in the sleep mode while satisfying the delay constraints in the extended reach seems a promising and at the same time, a challenging issue. On the other hand, as we have presented in this survey, majority of the solutions aim to reduce the cycle time in LR-PONs by inserting additional cycles or emulating multi-server polling approach which keeps the OLT and the ONUs busy. Hence, an open issue for future research is building energy-efficient protocols without violating the bandwidth allocation solutions that aim to mitigate the performance degradation in LR-PON.

V. Conclusion

This article focuses on the recently proposed DBA solutions for long-reach (LR) PONs. LR-PONs call for novel DBA

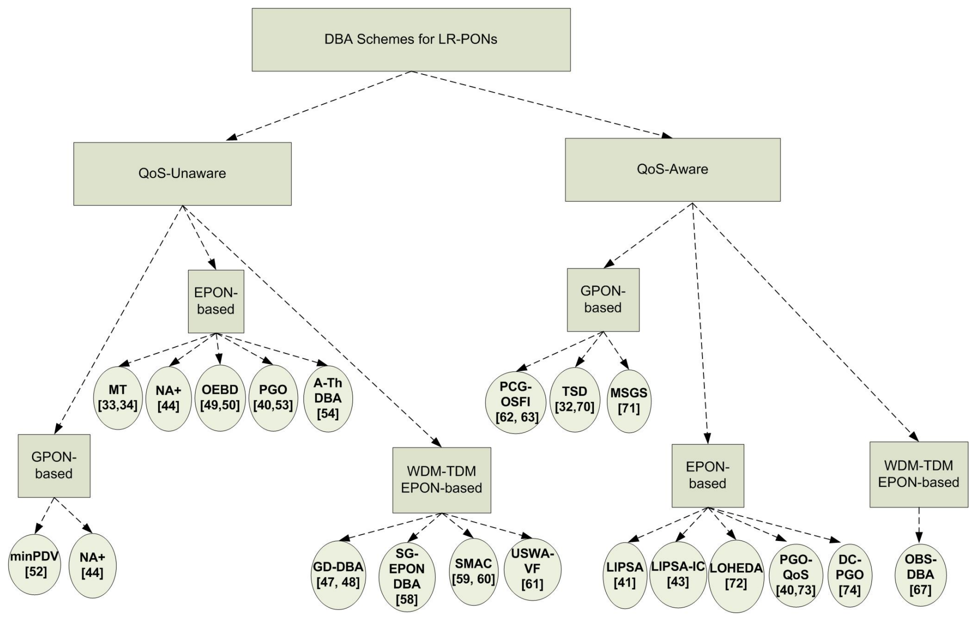


Fig. 15. A taxonomy of the surveyed DBA schemes for LR-PONs

schemes other than those proposed for conventional EPON or GPON since long feeder distance (up to 100km) and high split ratio (up to 1000-way) lead to longer service delays. In this survey, we have grouped the dynamic bandwidth allocation solutions that have been proposed for LR-PON under two main categories as QoS-unaware and QoS-aware DBA schemes. Each scheme is described by highlighting the main steps of its workflow. A detailed comparison and summary of the schemes are also presented with respect to the base PON type, maximum distance, delay/PDV/packet loss performance and the runtime overheads.

Although a large number of DBA schemes have been proposed, there are still open issues. DBA schemes meeting a wide range of QoS metrics need to be explored. The existing schemes need to be evaluated for high split ratios. Furthermore, novel DBA schemes for the emerging hybrid WDM-TDM LR-PONs are still open issues. Finally, energy efficient DBA design needs to be explored in LR-PONs.

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TABLE II
SUMMARY AND COMPARISON OF QoS-AWARE DBA SCHEMES FOR LR-PON

Scheme	Base PON Type	Maximum Reach Tested	Delay	PDV	Packet Loss	Runtime overheads
PCG-OSFI [62], [63]	GPON	100km	Lower delay for FT-1 and FT-2 classes compared to non-predictive OSFI	Low PDV for FT classes	Zero for FT classes, decreased packet loss for BE class	Storing previous REPORTs and prediction of backlog. Selecting an appropriate scheduling depth
OBS-DBA [67]	SARDANA (WDM/TDM PON)	100km	A few milliseconds of delay for high priority classes	N/A	N/A	Appropriate burst assembly threshold selection
LIPSA [41]	EPON	100km	Enhances delay performance of IPACT for the high priority classes.	N/A	Reduced packet loss ratio for high priority classes.	Idle timeslots in the upstream line
LIPSA-IC [43]	EPON	225km	Same delay behavior for $125 \sim 225km$. Less delay for SLA_0 and SLA_1 (reach $\geq 150km$).	N/A	Same utilization for $125 \sim 225km$. Better than that of single cycle polling.	Storage of two recent REPORTs of each ONU to determine the next grant
TSD [32], [70]	GPON	100 km	Low delay for the high priority service levels and delay-sensitive classes	N/A	Loss free communication for T-CONT2 traffic, reduced packet loss for T-CONT3 traffic	Virtual cycle bandwidth request estimation based on a self-similar arrival pattern
MSGS [71]	GPON	100 km	Low delay for high priority classes by virtual polling cycles (<10ms)	N/A	N/A	On-line bandwidth prediction for the high priority classes
LOHEDA [72]	EPON	150 km	Reduces the delay of LIPSA for all SLA classes	N/A	Reduced queue length of LIPSA. Expected to reduce packet loss	On-line wasted bandwidth detection
PGO-QoS [40], [73]	EPON	100 km	Low delay for the high priority SLA classes (<10ms)	N/A	Low packet loss for high priority classes	CPU power at the OLT for ILP solution
DC-PGO [74]	EPON	100 km	Delay guarantee for the SLA classes	N/A	Low packet loss for high priority classes	CPU power at the OLT for ILP solution and prediction-based admission.

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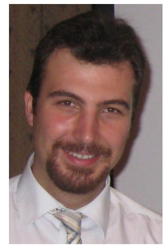

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