Computer Communications 36 (2013) 1570–1580

Contents lists available at SciVerse ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Two-stage report generation in long-reach EPON for enhanced delay performance

Burak Kantarci, Hussein T. Mouftah *

School of Electrical Engineering and Computer Science, University of Ottawa, 800 King Edward Avenue, Ottawa, ON, Canada

ARTICLE INFO

Article history:
Available online 3 August 2012

Keywords:
Dynamic bandwidth allocation
Long-reach EPON
Multi-process polling
Passive optical networks

ABSTRACT

Long-reach passive optical networks (LR-PONs), as a part of the next generation PON technologies, aim at combining the capacity of metro and access networks so that the telecommunication network topology is simplified and the operational cost is reduced. However, in order to eliminate the delay performance degradation introduced by long propagation distance, LR-PONs call for bandwidth distribution schemes that are different than the existing schemes for conventional PONs. In this paper, we propose a new bandwidth distribution approach which employs a two-stage buffering mechanism at the ONUs and adopts the reduced delay advantage of multi-thread polling. REPORT generator at an ONU generates the requests by using an adaptive burst assembly process. According to the proposed scheme, ONUs maintain *time threshold* and *size threshold* values for the upstream input queues. Upon receipt of a GATE message, each ONU runs an adaptive burst assembly procedure to set the appropriate time and size thresholds and determines the bandwidth request of the REPORT message. We evaluate our proposed bandwidth distribution scheme by simulations for the ONU-OLT distances of 20 km and 100 km. The simulation results confirm that consolidation of multi-thread polling and two-stage buffering enhances the delay performance of long-reach EPON (LR-EPON). Furthermore, under heavy loads, the proposed scheme leads to high utilization of the upstream channel.

1. Introduction

As the bandwidth demand over the Internet is growing, optical access networks emerge as a promising solution to satisfy the requirements of the end user applications such as video on demand, Internet Protocol (IP) TV, IP telephony, video conference or http [1]. Passive Optical Networks (PONs) adopt Fiber To The Home/Building/Curb (FTTH/FTTB/FTTC) solutions by offering full wavelength capacity and power efficiency of the passive optical components [2,3].

Ethernet PON (EPON) appears as a promising technology due to low equipment and maintenance cost, large bandwidth capacity and adaptability to higher bit-rates [4]. In EPON, data is encapsulated in Ethernet frames and transmitted between an Optical Line Terminal (OLT) and N Optical Network Units (ONUs). A feeder fiber originating at the OLT is coupled at a distant passive coupler which is connected to the ONUs through N distribution fibers [5]. Signaling between the OLT and the ONUs is handled by the Multi-Point Control Protocol (MPCP). An ONU receives all downstream frames and discards the ones that are not destined to it whereas MPCP manages upstream bandwidth distribution by the exchange of REPORT and GATE messages between the OLT and the ONUs. Thus, the OLT sends the start time and the duration of the transmission to the ONUs in GATE messages while the data of each ONU is followed by a REPORT message specifying the bandwidth request for the next cycle [6]. To the best of our knowledge, one of the first bandwidth distribution solution running on top of MPCP signalling is the Interleaved Polling with Adaptive Cycle Times (IPACT) [7]. In IPACT, the OLT polls the ONUs in a round-robin fashion and grants their bandwidth requests with respect to several service criteria where ONU grants are usually bounded from above with a maximum slot size (i.e., limited service). Several Dynamic Bandwidth Allocation (DBA) schemes have been proposed to enhance the delay and utilization performance in EPON, and several DBA schemes have been proposed to incorporate Quality of Service (QoS) assurance in the bandwidth distribution process. Brief overviews of the dynamic bandwidth allocation approaches have been presented in [8,9], and comprehensive surveys of these algorithms have been presented in [3,10].

As one of the next generation optical access network technologies, Long-Reach Passive Optical Networks (LR-PONs) aim at extending the distance between Optical Line Terminal (OLT) and the Optical Network Unit (ONU). Several hardware demonstrations have been introduced where optical feeder fibers operating either

* Corresponding author. Tel.: +1 (613) 562 5800; fax: +1 (613) 562 5664.
E-mail addresses: kantarci@site.uottawa.ca (B. Kantarci), mouftah@site.uottawa.ca (H.T. Mouftah).

0140-3664/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.comcom.2012.07.008

at C-band (~1530–1565 nm) or at L-band (~1565–1625 nm) wavelength range run between the OLT and the central office which deploys Erbium Doped Fiber Amplifiers (EDFA) or transponders and further utilizes Wavelength Division Multiplexing (WDM) technologies [11,12]. Beyond extending the reach, increasing the split ratio is another target of the LR-PONs. For instance, in [13], an implementation is introduced for a 1000-way split and 100 km reach. The motivation behind the LR-PON concept is the consolidation of the metro and access network capacities, simplifying the telecommunication network infrastructure and reducing the deployment cost per subscriber [14]. However, LR-PONs are prone to long packet delays and reduced utilization due to long propagation delays and long polling cycles which result from the extended OLT-ONU distance. Hence, dynamic bandwidth allocation schemes for the conventional PONs cannot be applied to the LR-PONs [15,16]. In [17,18], the authors propose multi-thread polling which emulates a "multi-process" version of IPACT and reduces delay of the conventional bandwidth distribution up to heavy loads. The idea behind multi-thread polling is allowing the ONUs to send request for an incoming Ethernet frame before receiving the GATE message for the most recent REPORT.

In [19], it is shown that by generating large optical bursts, efficient transmission target can be met as well as the user delay requirements in the extended reach PON. The OLT in the corresponding research adopts the idea in [20] where the OLT sets an upper limit for the data burst size and determines the time to generate data bursts based on a time threshold. Here, it is worth to note that this idea is borrowed from Optical Burst Switching (OBS). OBS was initially proposed for the optical Internet backbone as a compromise between optical circuit switching and optical packet switching where the ingress routers collect incoming packets/frames until a size or time threshold is reached [21]. Resource consumption is reduced and utilization is enhanced by generation of large optical bursts. Research on OBS has shown that burst assembly phase has a significant impact on the network performance [22,23]. Hence, for the sake of enhanced network performance, adaptation of the burst assembly thresholds to the dynamic network conditions has been considered in several studies [24–27].

In this paper, we propose to adapt the REPORT sizes with respect to the dynamic network conditions. Hence, we propose to maintain an intermediate buffer, immediately after the user input buffer of an ONU where the OLT polls the ONU requests through multiple threads. The intermediate buffer is referred as the burst assembly queue, and it avoids over-granting the ONUs due to multiple threads running unaware of each other. Whenever a GATE message is received, packets of this queue are transmitted to the OLT in the data frame. It is worth to note that here the term packet is used to refer to a frame. As a parallel process to the data transmission, the packets at the head of the input buffer are enqueued into the burst assembly queue. Here, the key point is selecting the length of the intermediate buffer based on the changing network traffic characteristics. Therefore, the ONU maintains two parameters, namely the size and time thresholds, and the input frames that satisfy the size or time threshold requirements are de-queued from the input buffer and enqueued to the burst assembly buffer. In order to adapt the size and time thresholds with respect to the dynamics of the experienced delay, an ONU adopts the adaptive threshold-based burst assembly in OBS. We call our proposed scheme *Adaptive-Threshold Optical Burst Assembly in Dynamic Bandwidth Allocation (ATH-DBA)*. *ATH-DBA* has two distributed modules namely, the bandwidth distribution module running at the OLT and the adaptive burst assembly module running at each ONU. Bandwidth distribution module emulates multi-thread polling while the REPORT generator emulates the adaptive burst assembly process of OBS. The idea of ATH-DBA is briefly presented in [28]. Here, we evaluate the performance of *ATH-DBA* by simulations, and we show that it enhances the delay performance of multi-thread polling while achieving high utilization on the uplink channel.

The rest of the paper is organized as follows: In Section 2, we briefly summarize the related work on bandwidth distribution in long-reach EPON and explain the motivation of this study. Section 3 explains the proposed scheme, *ATH-DBA* in detail. Numerical results are presented and discussed in Section 4. Finally, Section 5 concludes the paper and gives future directions.

2. Related work

Several bandwidth distribution solutions have been proposed to overcome the performance degradation in LR-PONs. The research in [17,18] and in [29] are the first delay performance enhancement solutions for LR-PONs. The former two propose multi-thread polling for LR-EPON while the latter proposes a two-state DBA for LR-GPON. Multi-thread polling allows an ONU to issue a REPORT message for an incoming packet without waiting for the GATE of its most recent REPORT message. In multi-thread polling, OLT generates multiple threads to poll the ONU requests. Thus, an ONU sends the REPORT message for a recently buffered packet without waiting for the GATE of the previously sent REPORT message. By adopting multi-thread polling, idle timeslots in the upstream channel are reduced while ONUs buffer the packets and wait for the GATE messages from the OLT. In [17,18], the authors show that, in long term, the average packet delay is decreased until the network load gets heavy, when compared to polling the ONUs through a single thread in a LR-EPON.

In multi-thread polling, REPORT and GATE messages of each thread form a sub-cycle whereas the all sub-cycles form one polling cycle of the OLT. However, ONUs are not aware of that the OLT is running multiple threads to poll the bandwidth requests; hence upon the receipt of a GATE message, the ONU transmits the allowed number of packets in its buffer and sends a new requests for the remaining packets in its buffer. Under some circumstances, this situation leads to over-granting the ONUs and consequently waste of bandwidth. Therefore, as proposed in [30], a coordination scheme between multiple threads is required to prevent over-granting the ONUs. In [31], additional polling cycles are inserted into the main polling cycle in order to reduce packet delay.

In [32,33], we have proposed a mechanism where the OLT periodically builds an Integer Linear Programming (ILP) formulation based on the statistical data collected from the network, and it aims to obtain excessive bandwidth credit ratios per thread for each ONU. Service differentiation between the packets is introduced in [33,34]. A pro-active version of this scheme is presented in [35,36] where the ONU assists the DBA process by estimating whether the delay requirement of an incoming packet can be met.

In [37], the authors propose detection and utilization of the wasted bandwidth where each Service Level Agreement (SLA) class has a pre-determined maximum bandwidth grant and an excessive bandwidth credit ratio.

In [19], a time threshold-based burst assembly is proposed to grant the ONU requests while in [38], hybrid (time and length-based) burst assembly modules run at the ONUs. Thus, in [38], an ONU sends a request if either its queue length exceeds a pre-determined threshold or the packet at the head of the queue has been waiting longer than a pre-determined threshold.

Scheduling the grants seems as another factor which affects the performance of LR-PON. An offline grant scheduling scheme is proposed in [39] where the ONUs with the Shortest Propagation Delay (SPD) are granted first [39], and it is shown that SPD leads to more efficient delay performance when ONU-OLT distances are heterogeneously distributed.

Downstream bandwidth distribution solutions have also been proposed for long-reach EPON. In [40], the authors have proposed a flow-scheduling scheme in order to efficiently utilize the tunable laser and fulfill differentiated SLA requirements of the users. The authors take the advantage of the Reconfigurable Optical Add Drop Multiplexer (ROADM) nodes in the metro ring network and allow a wavelength channel to be shared among various user ONU groups.

As a hardware-oriented solution, in [41], the authors propose placing active repeater remote nodes between the OLT and a subnet of ONUs. The remote nodes run in compatible with MPCP in the upstream direction while maintaining multiple buffers to schedule the downstream traffic.

We have recently presented a comprehensive survey of the DBA solutions in LR-PON [42]. In Table 1, an overview of the current DBA schemes for LR-EPON and motivation of ATH-DBA is summarized. Majority of the research agrees on multi-process polling emulation for better utilization and delay performance in LR-EPON [18,30,31,43,44]. On the other hand, OBS-oriented solutions neither adapt the thresholds to the changing traffic characteristics nor adopt a multi-process polling solution in their polling processes. Hence, LR-EPON requires further enhancement in the delay and utilization performance of multi-thread (multi-process) polling-based solutions and efficient reporting mechanism which has adaptability to the varying traffic characteristics, and our proposed solution, *ATH-DBA* aims to fulfill these requirements.

3. Adaptive Threshold Based Optical Burst Assembly in Dynamic Bandwidth Allocation for LR-EPON (*ATH-DBA*)

Adaptive threshold-based optical burst assembly in dynamic bandwidth allocation for LR-EPON (*ATH-DBA*) was initially presented in [28] which recently have been adopted by a fiber-wireless (FiWi) access network deployed in the extended reach [47]. As mentioned above, *ATH-DBA* aims at combining the multi-thread polling in LR-EPON and adaptive optical burst assembly. In order to achieve this goal, a burst assembly queue is maintained at the ONUs as seen in Fig. 1. Upon receiving a GATE message, an ONU determines the appropriate total size of the packets that can be dequeued from the input buffer and enqueued to the intermediate buffer by using two parameters, a time threshold and a size threshold. Thus, if the input buffer length exceeds the size threshold, the packets in the input queue are dequeued and enqueued into the intermediate (burst assembly) buffer. Otherwise, ATH-DBA keeps de-queueing a packet from the head of the input queue as long as there exists a packet which has been waiting for longer than the time threshold. Formation of the burst at the intermediate buffer is adopted from the hybrid burst assembly in OBS, and as stated in [19], allowing the ONUs to generate larger bursts lead to enhanced utilization of the upstream channel.

Once an ONU receives a GATE message through one of the polling processes, it runs the burst assembly procedure which is illustrated by the flowchart in Fig. 2. According to the burst assembly procedure, an ONU keeps track of the average packet delay behavior by using the following three parameters:

Θ': Previous upstream idle interval value.

G^k: Arrival of the GATE message at the kth sub-cycle.

T_s^{k-1}: Departure time of the REPORT message at the $(k-1)$th cycle.

For an ONU, Θ stands for the idle interval in the upstream transmission, and it is updated as soon as the ONU receives a GATE message of a sub-cycle. The difference between the arrival of the GATE message and the departure time of the REPORT message at the last sub-cycle is assigned to Θ as seen in Eq. (1) while the previous value is saved in Θ'.

$$\Theta = G^k - T_s^{k-1} \tag{1}$$

Upon updating the Θ, an ONU determines whether average packet delay tends to increase or decrease. Time threshold for the bandwidth request at the kth sub-cycle (TTh_k) is determined based on the idle time behavior. To this end, ATH-DBA defines an hypothesis as shown below:

Hypothesis 1. An increase in the idle time on the uplink of an ONU denotes a tendency of average packet delay increase and vice versa.

Hypothesis 2. Given that the packet delay has a tendency to increase, de-queueing frequency of the packets in the input buffer requires to be increased. Otherwise, packets can be de-queued less frequently.

Based on the two hypotheses above, if the idle time (Θ) seems to increase, an ONU decrements the time threshold for the k^{th} period by Δ_{TTh}. If the idle time is less than the previous idle time, the ONU does not immediately increase the threshold but lets the packet delay keep decreasing. It first checks the *idle time shrinking ratio* (β) which is formulated in Eq. (2).

$$\beta = \frac{G^k - T_s^{k-1}}{G^{k-1} - T_s^{k-2}} = \frac{\Theta}{\Theta'} \tag{2}$$

As seen in the equation, if the upstream idle time is decreasing for an ONU, β is expected to be less than one. Hence, if the idle time shrinking ratio is less than a previously set *threshold increase trigger ratio* (δ), in order to avoid under-utilization of the upstream chan-

Table 1
Overview of the current DBA schemes for LR-EPON and ATH-DBA.

Scheme	Upstream/ downstream	Base schemes for delay performance enhancement	Requirements
Song et al. [18,17]	US	DBA for conventional EPON	On-line inter-thread scheduling
Skubic et al. [30]	US	[17,18] through thread coordination	On-line inter-thread scheduling and compensation term setting
Lin et al. [38,45]	US	DBA for conventional EPON	Selecting the appropriate thresholds is an open issue
Kantarci and Mouftah [32,35,36]	US	Multi-thread polling	CPU power at the OLT for ILP solution
Segarra et al. [19]	US	DBA for conventional EPON	Appropriate threshold selection needs to be addressed
Merayo et al. [31]	US	DBA for conventional EPON	Storage of two recent REPORTs of each ONU to determine the next grant
Ferguson et al. [46]	US	DBA for conventional EPON	Needs integration to multi-thread polling
McGarry et al. [39]	US	Limited grant sizing in conventional EPON	Off-line scheduling of grants
Song et al. [40]	DS	SLA-aware flow scheduling	Determining the thresholds to add or release wavelengths
Chan et al. [41]	US/DS	Conventional solutions in EPON	Active remote node deployment
ATH-DBA	US	Multi-thread polling	Intermediate burst assembly buffer

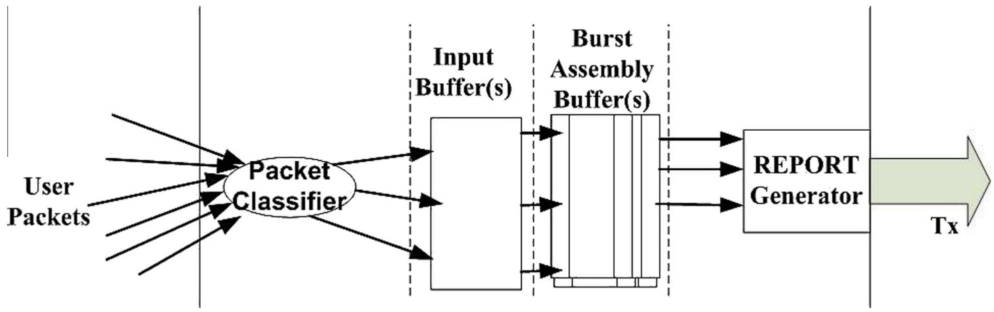

Fig. 1. Framework for REPORT generation utilizing ATH-DBA.

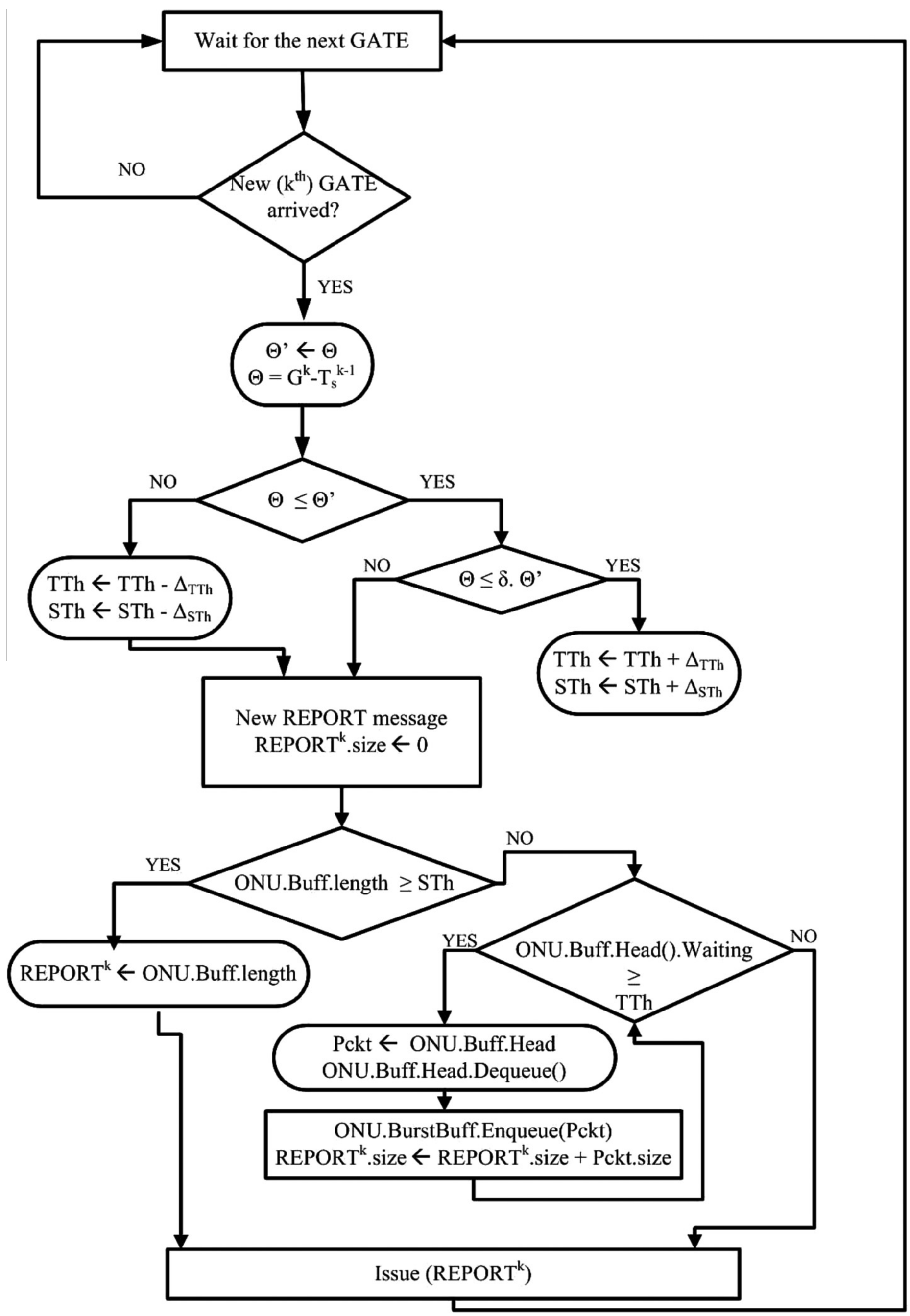

Fig. 2. Adaptive threshold-based REPORT generation procedure.

nel, the ONU increments the time threshold by Δ_{TTh}. Otherwise, time threshold for the most recent sub-cycle is used as is for the current sub-cycle. This time threshold adaptation procedure is given in Eq. (3) in its closed form.

$$TTh_k = \left\{ \begin{array}{ll} max(TTh_{k-1} - \Delta_{TTh}, TTh_{min}) & \Theta' < \Theta \\ min(TTh_{k-1} + \Delta_{TTh}, TTh_{max}) & \beta < \delta \\ TTh_{k-1} & else \end{array} \right\} \tag{3}$$

Longer size thresholds lead to longer bursts and longer packet delays so as the longer time thresholds do. Hence, adaptation of the size threshold of the kth sub-cycle (STh_k) is the same as that of the time threshold. Eq. (4) presents the closed form of this procedure. Here, although size and time thresholds are adjusted by exactly the same function, this is not to imply a correlation between the two thresholds. The motivation behind having two thresholds is as follows. Packet delay experienced by an ONU is a function of the input traffic at the corresponding ONU and the buffer occupancies of the other ONUs in the network. Therefore, *STh* helps controlling the report size based on the input traffic (i.e., buffer occupancy) while *TTh* helps determining the report size based on the buffer occupancies of the other ONUs. Indeed, ONUs are unaware of the buffer occupancies of others in the network however, waiting time of a packet in the input buffer is a function of the buffer occupancies of all ONUs in the network.

$$STh_k = \left\{ \begin{array}{ll} max(STh_{k-1} - \Delta_{STh}, STh_{min}) & \Theta' < \Theta \\ min(STh_{k-1} + \Delta_{STh}, STh_{max}) & \beta < \delta \\ STh_{k-1} & else \end{array} \right\} \tag{4}$$

It is worth to note that the tuple (TTh_k, STh_k) is adjusted together in one function based on the idle time behavior in uplink as seen in Fig. 2. However, for the sake of simplicity, we present threshold adjustment function by Eq. (3) and (4).

Hypothesis-1 and/or *Hypothesis-2* may fail under certain circumstances. Failure of *Hypothesis-1* will lead to a wrong assumption for *Hypothesis-2* which will result in invalid adjustment of the thresholds and consequently in degraded service quality in terms of average and maximum packet delay, as well as the average packet drop probability. In order to explain the circumstances where hypotheses may fail and how ATH-DBA can rectify these failures, we denote an increase in packet delay by a "positive event" while decrease in packet delay is denoted as a "negative event". Thus, failure of hypothesis for packet increase is denoted by False Positive (FP) while failure of the hypothesis for packet decrease is denoted by False Negative (FN).

Both FP and FN can occur due to bursty nature of the traffic arriving at any ONU in LR-EPON. In case of FP, the thresholds are decreased, and consequently the ONU receives reduced grant although there is available bandwidth in the upstream direction. As a result, the ONU reduces its utilization which will further increase the chance of additional packet delay. However, uplink delay will definitely increase under these circumstances. Then, thresholds will immediately require to be decreased to reduce packet delay (i.e., True Positive (TP) case). Thus, ATH-DBA will converge shortly.

In case of FN, packet delay is not really decreasing but thresholds are increased. This may cause more severe problems since increasing thresholds will introduce further delay although the uplink conditions are not convenient to reduce delay as in FP case. Therefore, employment of the idle time shrinking ratio plays a key role against experiencing long delays due to hypothesis failure, and it avoids immediate threshold increase in case of tendency of increased delay.

Indeed, adjusting the thresholds may lead to large *STh*/*TTh* values under light loads while zero threshold may be experienced under very heavy loads. Hence, *TTh* and *STh* are allowed to be varied between their minimum and maximum bounds as seen in Eq. (3) and Eq. (4) above.

Upon updating the thresholds, the ONU proceeds with the REPORT generation. REPORT generation is triggered by the burst assembly queue. In Eq. (5), report generation function is given in its closed form where α_i and t_i denote the size and arrival time of packet-i in the input queue, respectively. If the length of the input buffer exceeds the size threshold (STh_k), the packets in the input queue are dequeued and enqueued into the burst assembly queue. Otherwise, the burst assembly module of the ONU checks the *time threshold-based eligibility* of the packet at the head of the input queue. As seen in Eq. (6), time threshold-based eligibility of packet-i is denoted by π_i^k where π_i^k is a binary variable, and it is one if the corresponding packet has been waiting longer than the time threshold (TTh_k), and zero, otherwise. If a packet is eligible with respect to the time threshold constraint, it is dequeued and enqueued into the burst assembly queue. The burst assembler dequeues a packet from the input buffer and enqueues it into the burst assembly queue until the packet at the head of the input buffer has been waiting less than the time threshold. Once the burst assembly process ends, the change in the length of the burst assembly queue is sent to the OLT in the REPORT message of the kth sub-cycle.

$$R_m^k = \left\{ \begin{array}{ll} \sum_i \alpha_i & \sum_i \alpha_i \geqslant STh_k \\ \sum_i \alpha_i \cdot \pi_i^k & \text{else} \end{array} \right\} \tag{5}$$

$$\pi_i^k = \left\{ \begin{array}{ll} 1 & G^k - t_i - TTh_k \geqslant 0 \\ 0 & \text{else} \end{array} \right\} \tag{6}$$

Since *ATH-DBA* employs multi-thread polling (i.e., multi-process polling) as the basis of the bandwidth distribution, the GATE of the (i)th thread may arrive before granting a packet which has already requested bandwidth through the $(i-1)$th thread. However, since the corresponding packet has not been granted yet, the ONU will include its bandwidth request in the REPORT message which is sent as a response to the GATE of the ith thread. This situation may lead to over-granting the ONUs since the threads are not aware of each other. Another risk may occur when a thread cannot fulfill the bandwidth request of an ONU, leaving backlogged traffic for the next polling thread. These two situations are stated in [30] and their effects are eliminated by the employment of a compensation term in the bandwidth demand of a logical queue. Here, *ATH-DBA* eliminates these effects by the employment of the intermediate burst assembly buffer. The burst transferred from the input buffer to the burst assembly buffer is guaranteed to be granted in the next cycle of the corresponding thread.

4. Performance evaluation

4.1. Simulation settings

We have implemented the LR-EPON simulation environment in Visual C++ by adopting the discrete event simulation library in [48]. We evaluate the performance of *ATH-DBA* through simulations in a tree topology consisting of 16 ONUs. User packet arrival is self-similar [49] with $H = 0.8$, and offered line load is varied. We evaluate the performance of *ATH-DBA* under short (20 km) and long distance (100 km) scenarios. Table 2 summarizes the simulation settings in detail.

STh_{max} is selected based on the experienced maximum queue occupancy values. In order to set a minimum value for the size threshold (STh_{min}), we assume that an ONU is always granted bandwidth, and the minimum grant in the worst case is more than the minimum packet size which is 64B in the simulations. Hence,

Table 2
Simulation parameters.

Number of ONUs	16
OLT-ONU distance	100 km and 20 km
Initial thread cycle	0.3 ms (100 km), 0.1 ms (20 km)
STh_{min}	$10^{-4} \cdot C$
TTh_{min}	1 µs
STh_{max}	$0.7 \cdot C$
TTh_{max}	500 µs (in 100 km), 300 µs (in 20 km)
Δ_{STh}	$(STh_{max} - STh_{min})/N$
Δ_{TTh}	$(TTh_{max} - TTh_{min})/N$
Th. increase trigger ratio (δ)	0.3
ONU buffer size (C)	1 MB
Number of polling threads	3
R_U	1 Gbps
R_D	100 Mbps
Input traffic	Self similar (H = 0.8)
Guard time between threads	1 µs
Packet size interval	[64, 1518] Bytes
Standard Max-slot	15,500 Bytes

assuming the buffer capacity of an ONU, a minimum size threshold greater than minimum packet size is acceptable. In the simulations we set this value to 10^{-4} times of the selected buffer capacity. Minimum time threshold is set to 1 µs which is small enough to switch to gated service during very lightly loaded intervals. On the other hand, maximum time threshold value is selected based on the average cycle time analysis and the simulation results of the conventional DBA under the heavy loads. Thus, maximum polling delay (d_{poll}) is considered to determine the maximum time threshold. Given the average cycle time (ψ) under conventional polling, the average cycle time under multi-thread polling is calculated as $\psi/(2K)$ where K stands for the number of threads. Therefore, based on the average cycle time measured for conventional (single thread) DBA under heavy loads, we set the maximum time threshold to $\psi/6$ which is 500 µs for 100 km reach and 300 µs for 20 km reach in the simulation settings. Selection of the ΔSTh and ΔTTh partitions the intervals of $(STh_{max} - STh_{min})$ and $(TTh_{max} - TTh_{min})$, respectively, affecting the number of increment/decrement steps. We have first partitioned the intervals into three regions so that the REPORT generator switches between three threshold values (for both time and size thresholds). However, we have seen that setting this value to such a large value cannot adapt the changes in the traffic quickly. Moreover, since it leads to dramatic changes in delay variation, it leads to an increased number of increment/decrement operations at the REPORT generator. We have partitioned these intervals to 100 regions, and we have seen that setting ΔSTh and ΔTTh to small values leads to similar performance with multi-thread polling. Having determined the selection of $TTh_{max}, STh_{max}, TTh_{min}, STh_{min}$ parameters, in the worst case assumption where all ONUs are to increase their thresholds, we want the total change in the STh not to be more than $(STh_{max} - STh_{min})$. The motivation behind this idea is that STh_{max} has been selected as a function of input buffer capacity, and it is significantly larger than the maximum transmission timeslot in the traditional multi-thread polling. If the total change in STh values exceeds $(STh_{max} - STh_{min})$, then, increased average packet delay is expected due to high increase in the sub-cycle time (e.g., under these settings, sub-cycle time increases up to fifty times the traditional maximum slot). Therefore, we have partitioned the total STh increase allowance equally among the ONUs (N), and we have set ΔSTh to $(STh_{max} - STh_{min})/N$. In accordance with the number of steps in STh adjustment, we have set ΔTTh to $(TTh_{max} - TTh_{min})/N$.

The study in [17,18] is taken as a basis to the multi-process polling and uses the function in Eq. (7) to grant the ONU requests received through each thread where $G_m^{(k)}$ denotes the bandwidth granted to ONU-m by thread-k. Thus, under a certain maximum allowed timeslot (W_{max}) value, ONU-m is granted its requested bandwidth (R_m^k) by thread-k if its request does not exceed the maximum timeslot value, which means that it is in the set of lightly loaded ONUs (L). Otherwise, the ONU is in the set of heavily loaded ONUs (Q), and it is granted by the maximum timeslot value plus a fair fraction of the total unused bandwidth by the lightly loaded ONUs.

$$G_m^{(k)} = \left\{ \begin{array}{ll} W_{max}, & R_m^k < W_{max} \\ W_{max} + \frac{R_m^k}{\sum_{q \in Q} R_q^k} \cdot \sum_{l \in L} (W_{max} - R_l^k), & else \end{array} \right\} \quad (7)$$

Indeed, multi-thread polling and multi-thread polling-based approaches enhance the delay performance of the limited bandwidth distribution for the conventional EPON. However, in order to give an idea on the enhancement of *ATH-DBA* over both conventional and long-reach EPON solutions, for the long distance scenarios, we also present the performance evaluation of the limited DBA which was initially proposed for the conventional EPON [7].

The number of threads introduces a trade-off between average packet delay and bandwidth utilization in the performance of multi-thread polling-based solutions. Since ATH-DBA is based on multi-thread polling, it inherits the properties of multi-thread polling. As analyzed in [18], larger number of threads results in shorter cycle times and consequently reduced packet delay. However, increasing the number of threads introduces a drawback in terms of increased bandwidth utilization for exchanging the control messages as well as increased guard band times between the granted timeslots. Hence, when determining the number of threads, we rely on the analysis derived in [18], where the optimal number of threads is presented to be three.

4.2. Simulation results

First performance metric is average packet delay of *ATH-DBA*. Fig. 3(a) illustrates the delay performance of limited service polling for the conventional EPON, multi-thread polling and *ATH-DBA*. It is worth to note that the results present the average of ten runs with 90% confidence intervals. Since *ATH-DBA* is able to generate large bursts, multi-thread polling is evaluated for two different maximum timeslot sizes, i.e., standard maximum slot size (W_{max}) and larger maximum slot size ($2 \cdot W_{max}$). As seen in the figure, under low traffic intensity, *ATH-DBA* introduces the same packet delay with multi-thread polling with larger maximum slot size. Furthermore, using larger maximum slot value allows multi-thread polling to utilize the upstream channel better until the moderate loads. However, when the line load moves towards moderate loads, starting from 0.4 Erlang, multi-thread polling starts increasing packet delay although this increase still leads to a significantly lower delay when compared to the limited DBA for conventional EPON. On the other hand, starting from the moderate loads, performance of multi-thread polling for two maximum slot sizes starts to coincide with each other. Here, taking the advantage of the bursty requests limited by the adaptive size and time thresholds, *ATH-DBA* achieves keeping the average packet delay around one tenth of the delay introduced by the multi-thread polling during the moderate load levels. Since ONU requests increase starting from 0.8 Erlang, transmission of large bursts does not introduce an enhancement in terms of delay which can also be observed at the performance of multi-thread polling for the two maximum slot sizes. Hence, average packet delay introduced by *ATH-DBA* increases as well. However, by decreasing the thresholds and generating shorter bursts as the delay increases, packets can still experience shorter delays than the other two schemes under *ATH-DBA* at the heavy loads.

Fig. 3(b) illustrates the average packet delay of multi-thread polling and *ATH-DBA* for a shorter distance, i.e., 20 km. Due to

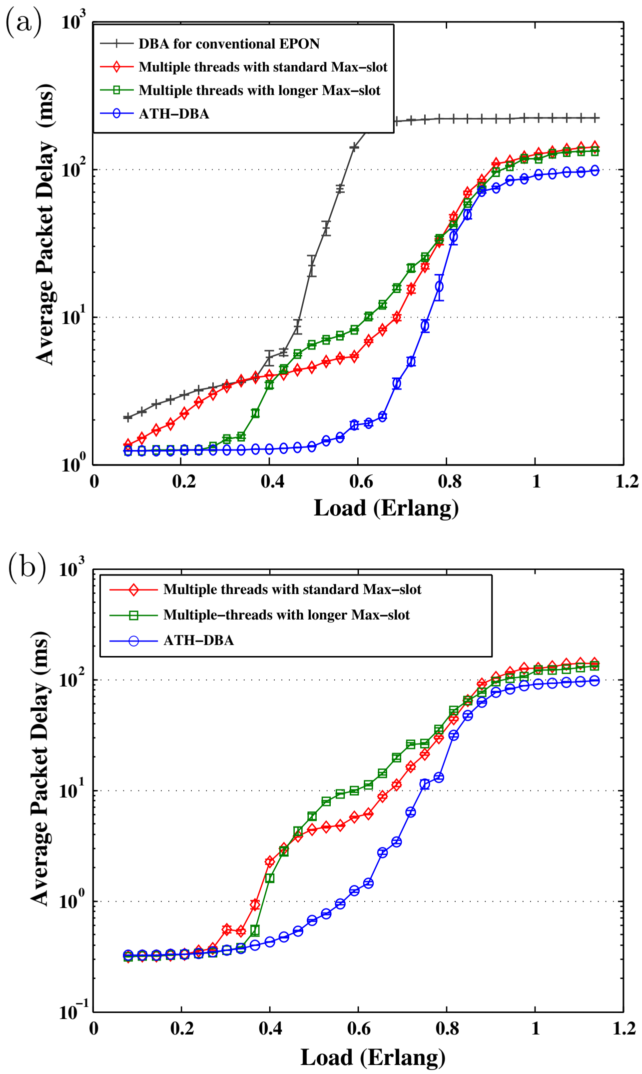

Fig. 3. Average packet delay under multi-thread polling and ATH-DBA when OLT-ONU distance is (a)100 km, (b) 20 km.

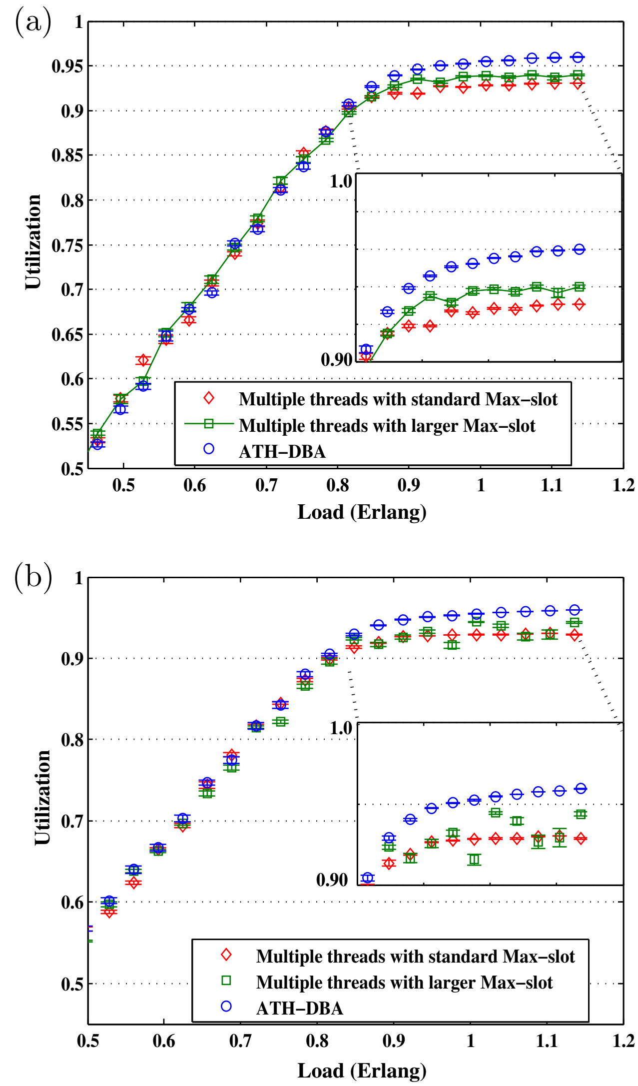

Fig. 4. Average utilization under multi-thread polling and ATH-DBA when OLT-ONU distance is (a) 100 km, (b) 20 km.

the lower propagation delay, packets experience lower delays until the heavy loads when compared to the long distance scenario. Under the heavy loads, due to the larger bandwidth requests and longer queue lengths, average packet delay values approach to that under the long distance scenario. However, relative behaviors of the schemes remain almost the same with those under the long distance scenario in Fig. 3(a). Thus, *ATH-DBA* significantly enhances the delay performance of multi-thread polling under moderate loads (until the load level exceeds 0.8 Erlang) while it still introduces a slight enhancement under the heavy loads. Besides, as mentioned before, multi-thread polling requires coordination between the threads. Since, threads are uncoordinated, over-granting becomes more likely as propagation delay approaches to the conventional distance (i.e., 20 km and shorter) and maximum slot increases. Therefore, below the moderate loads, multi-thread polling does not demonstrate a smooth behavior, especially when the maximum slot is longer. Thus, by adopting *ATH-DBA*, delay performance shows a smoother behavior due to enhanced utilization of the bandwidth as illustrated below in Figs. 4(a)–(b).

Next performance evaluation metric is utilization of the proposed scheme. Fig. 4(a) and (b) compare the upstream link utilization of *ATH-DBA* and multi-thread polling for different maximum slot sizes. As seen in the figures under both long distance (100 km) and short distance (20 km) scenarios, *ATH-DBA* improves the utilization of multi-thread polling up to a level above 95% beyond the load level of 0.8 Erlang. The reason behind this behavior is that *ATH-DBA* allows the ONUs to adapt their burst sizes based on the delay prediction obtained from the arrival and departure times of the GATE and REPORT messages at each polling thread. It is worth to note that under some load levels, errors-bars cannot be seen clearly although they lie inside the markers. This is due to the significantly low standard deviation at the corresponding points.

Long queues lead to long packet delays as well as higher packet drop probabilities [50,51]. Hence, as the next step, we evaluate the behavior of the queue length. In Fig. 5(a), average queue length under the limited DBA for conventional EPON, multi-thread polling with standard and longer maximum timeslots and *ATH-DBA* is illustrated by setting the OLT-ONU distance to 100 km. As seen in the figure, the success of multi-thread polling is due to running multiple processes to collect requests and to grant the ONUs so that shorter queue length is achieved until the load moves toward 1.0 Erlang. *ATH-DBA* achieves to shorten the queue length of multi-thread polling by allowing the ONUs to generate larger bursts if the network resources are utilizable. Fig. 5(b) further confirms the

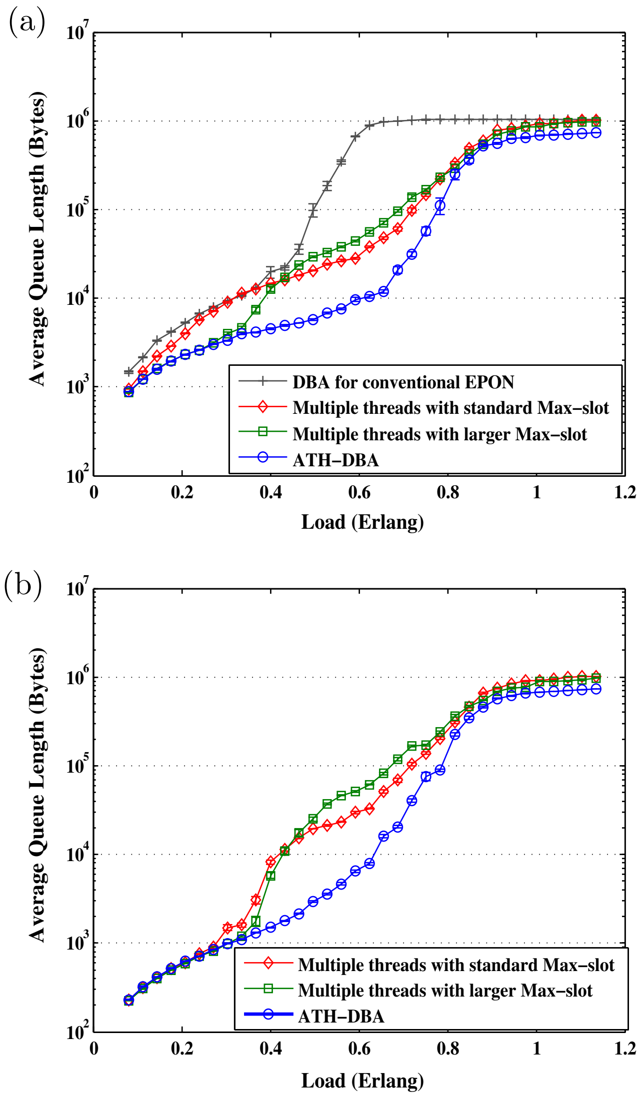

Fig. 5. Average queue length under multi-thread polling and ATH-DBA when OLT-ONU distance is (a) 100 km, (b) 20 km.

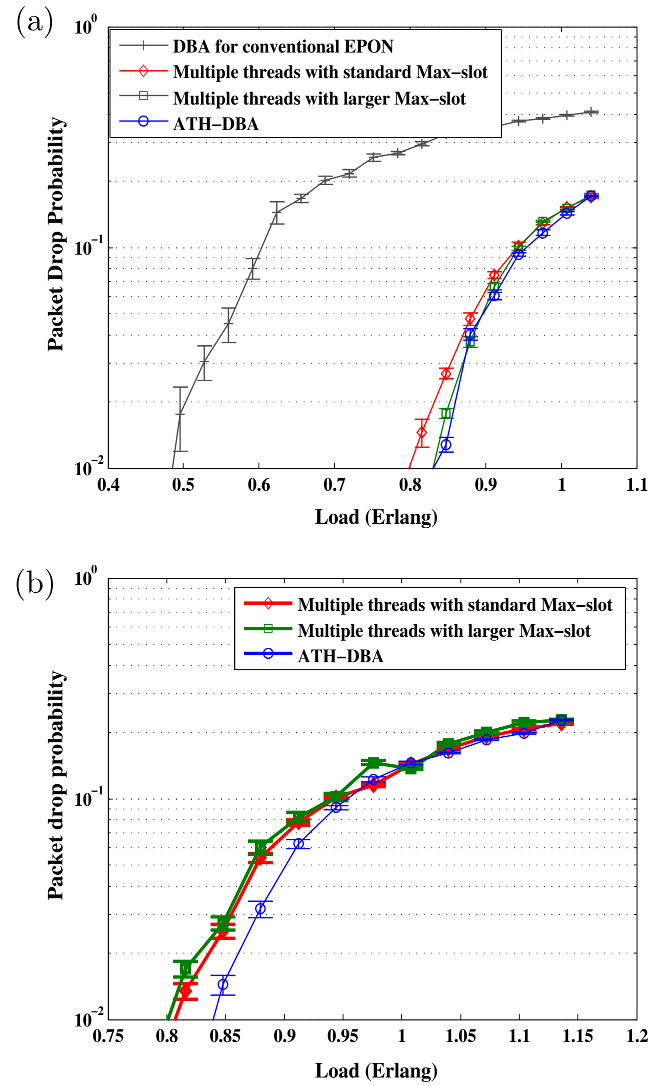

Fig. 6. Packet drop probability under multi-thread polling and Adaptive threshold-based OBS-DBA when OLT-ONU distance is (a) 100 km, (b) 20 km.

delay performance of *ATH-DBA* by illustrating the results under the OLT-ONU distance of 20 km. Since our proposed scheme achieves keeping the queue length lower in each load level, it introduces shorter delay to the incoming packets as we have shown in Figs. 3(a)–(b).

Average packet delay is basically the ratio of the total delay of the packets received by the OLT from the ONUs to the total number of packets received at the OLT. Hence, a bandwidth distribution scheme, which tends to drop more packets is more likely to introduce less average packet delay. However, relying on its queue length performance in Fig. 5(a) and (b), *ATH-DBA* is not expected to lead to higher packet loss ratio at the ONUs. Fig. 6(a) and (b) illustrate the packet loss ratio behavior. As seen in Fig. 6(a), limited DBA for the conventional EPON starts to drop packets around the load level of 0.5 Erlang which is the point where it leads to a sharp growth in the queue length and delay. Multi-thread polling (MT) starts to drop packets at the load level of 0.8 Erlang when larger maximum timeslot is used, and at a load level between 0.8 Erlang and 0.9 Erlang when standard maximum timeslot is used. Nevertheless, *ATH-DBA* does not increase packet loss probability although it allows the ONU to generate large bursts. The reason of this behavior is that the size of the ONU bursts is controlled by keeping track of the packet delay behavior, i.e., varying the size and time thresholds. Fig. 6(b) demonstrates the same behavior assuring that *ATH-DBA* does not violate the packet loss performance of multi-thread polling although the propagation delay changes due to the OLT-ONU distance.

Maximum packet delay is another performance metric which complements the success of average packet delay. Fig. 7 illustrates maximum packet delay under multi-thread polling and *ATH-DBA* for 100 km and 20 km OLT-ONU distances. Under the light load levels, *ATH-DBA* does not introduce an enhancement to multi-thread polling since ONU requests do not lead to a congested upstream link. As the load increases from 0.3 Erlang to the moderate loads, *ATH-DBA* leads to reduced maximum delay until 1.0 Erlang. At 1.0 Erlang, maximum delay of the schemes coincide. Adapting the thresholds dynamically allows *ATH-DBA* to generate larger bursts which may further lead to longer maximum delay, e.g., higher time and size thresholds increase the waiting time of the other ONUs in the network. However, by controlling the threshold increase trigger ratio (δ), *ATH-DBA* avoids to generate enormous bursts; hence as seen in the figure, maximum delay of multi-thread polling is reduced as well. Another phenomenon in this figure is the high maximum delay under the far-light load levels. The reason of this behavior can be explained as follows: Low utilization of the

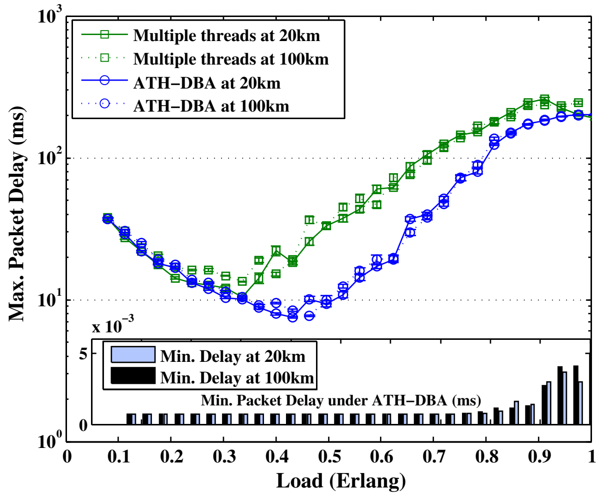

Fig. 7. Maximum packet delay under multi-thread polling and ATH-DBA for the OLT-ONU distances of 100 km and 20 km.

upstream channel and the tendency to offer full-grant for the incoming requests make the buffered packets of some ONUs (that experience less intense input traffic than the average) suffer in terms of buffering delay. Since this lasts for a short period, it does not reflect the overall behavior of the system (i.e., average packet delay) but instantaneously increases the experienced maximum delay in the network.

We have also tested the minimum packet delay experienced by ATH-DBA under each load level. At the bottom of Fig. 7, minimum packet delay under ATH-DBA is illustrated for the ONU-OLT distances of 20 km and 100 km. As seen in the figure, minimum packet delay is at the level of a few microseconds and it is lower when the network experiences light delay. In fact, minimum packet delay is not a critical service quality metric in performance evaluation. However, test results related to the minimum packet delay have been included here in order to demonstrate the earliest possible time that a packet can be delivered to the OLT. Furthermore, results at the bottom of Fig. 7 together with the main plot in the figure and Fig. 3(a) provide an idea on the delay bounds of the packet delay under ATH-DBA.

Finally, we illustrate the effect of the threshold increase trigger ratio (δ) on the performance of *ATH-DBA*. We set the load to five different values varying from 0.6 Erlang to 1.0 Erlang and the OLT-ONU distance to 100 km. We apply four different δ values in the following set: {0.1,0.3,0.6,0.9}. As we have mentioned above, threshold increase trigger ratio (δ) denotes a reduction ratio in the idle upstream time which lets the ONU increment the time and size threshold. As seen in Fig. 8(a), δ has an impact when the load is equal to or lighter than 0.8 Erlang. Otherwise, any change in the idle period of the ONU (increase/decrease) can trigger the threshold update. In Fig. 8(b), we have evaluated ATH-DBA in terms of packet loss ratio under various load levels varying between 0.80 and 1.0 Erlang. Here, since packet loss does not occur for the loads lighter than 0.8 Erlang. δ has an impact on the packet drop probability for the load levels above 0.8 Erlang. Based on the results presented in the figure and considering the delay performance in the previous plots, setting δ to 0.3 seems reasonable as decreasing δ to 0.1 tends to increase packet loss and the average packet delay.

Here, we have to include a further discussion on the selection of δ. According to the results, selecting $\delta = 0.6$ or $\delta = 0.9$ is also possible as those values introduce lower delays under 0.8 Erlang and 0.9 Erlang network loads, respectively. However, these trigger ratios are not advantageous in terms of packet drop probability as seen

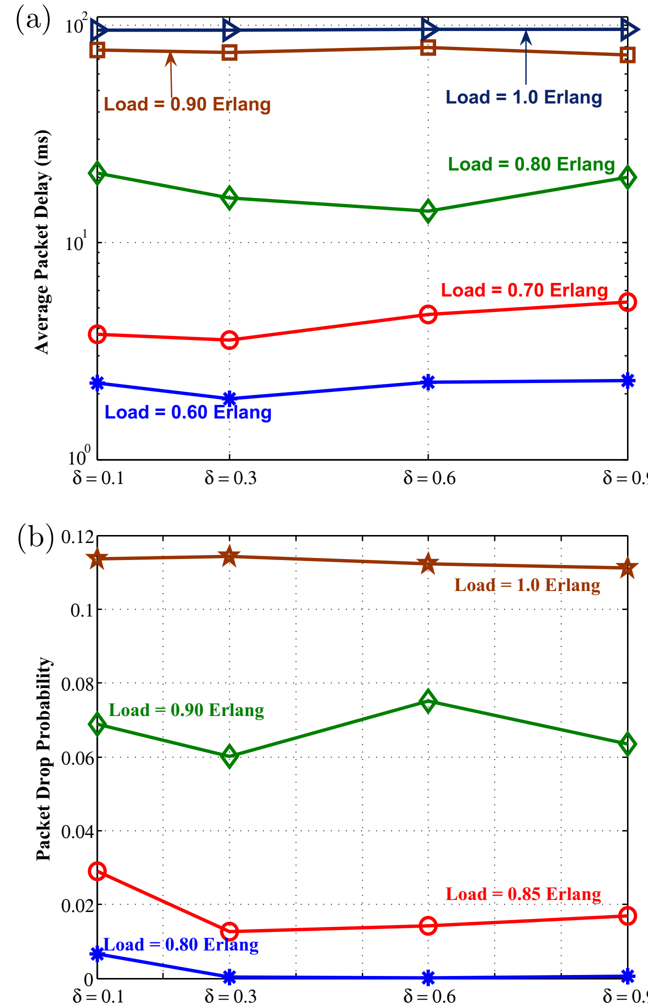

Fig. 8. (a) Average packet delay, and (b) average packet drop probability of *ATH-DBA* for various threshold increase trigger ratios (δ).

in Fig. 8(b). Furthermore, under light load levels ($\leqslant$0.6 Erlang), these δ values lead to higher packet delays that are almost 1 ms above the packet delay of multi-thread polling. The reason of this behavior is as follows: Letting the REPORT generator increment the *STh* and *TTh* values causes larger grants to be generated which result in longer cycle durations under light load levels. Besides, through simulations we have seen that lower thresholds perform better in terms of average packet delay under the light loads. Hence, we set $\delta = 0.3$ and let the REPORT generator increase the *STh* and *TTh* when the decreasing idle time is 0.3 times of its previous value.

5. Conclusion

In this article, we have proposed a novel bandwidth allocation scheme that combines multi-thread polling of Long-Reach Ethernet Passive Optical Networks (LR-EPON) and adaptive threshold-based optical burst assembly to improve the delay performance of the bandwidth distribution process in LR-EPON. The proposed bandwidth allocation framework is named as *Adaptive Threshold-based Optical Burst Assembly in Dynamic Bandwidth Allocation (ATH-DBA)*. In *ATH-DBA*, each ONU maintains a burst assembly queue between the input buffer and the REPORT generator while being polled through multiple threads. Upon receiving a GATE message, an ONU measures its idle time in the upstream direction and modifies the time and size thresholds. Based on these threshold values, packets are dequeued from the input queue and enqueued into the burst assembly queue. REPORT message requests bandwidth for the packets that have already been enqueued into the burst assembly queue. We have shown that *ATH-DBA* enhances the average packet delay performance of multi-thread polling under both short reach and long-reach scenarios. *ATH-DBA*, can further enhance the service quality of multi-thread polling in terms of maximum packet delay up to 70% as it avoids generation of large bursts by the employment of a control mechanism, namely the threshold increase ratio. *ATH-DBA* also leads to more than 95% utilization under heavy loads. Besides, two-stage buffering-based REPORT generation can achieve keeping the input buffer less occupied compared to the predecessor schemes. Furthermore, using adaptive thresholds in REPORT generation lets *ATH-DBA* keep the average packet drop probability in the acceptable range of the multi-thread polling. The simulation results imply that adopting *ATH-DBA* in LR-EPON will enhance the service quality of various types of access network traffic while inheriting advantages introduced by extending the reach of PON. Last but not least, two-stage REPORT generation in *ATH-DBA* reduces the computational load on the OLT since OLT does not need to determine the size of each bandwidth allocation since this information is reported by the secondary buffers.

ATH-DBA can easily be adapted to a multi-priority classes of service concept by defining multiple burst assembly queues before the report generator module. Hence, *ATH-DBA* with multiple priority queues is planned to be included in the future extension of this study.

References

[1] J. Zheng, H.T. Mouftah, Optical WDM Networks: Concepts and Design Principles, Wiley-IEEE Press, Hoboken, NJ, 2004.
[2] T. Koonen, Fiber to the home/fiber to the premises: what, where, and when?, Proceedings of the IEEE 94 (5) (May 2006) 911–934
[3] M. Mcgarry, M. Reisslein, M. Maier, Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms, IEEE Communications Surveys Tutorials 10 (3) (2008) 46–60.
[4] J. Zheng, H.T. Mouftah, Optical Access Networks and Advanced Photonics: Technologies and Deployment Strategies, in: I.P. Chochliouros, G.A. Helliotis (Eds.), Chapter: Dynamic Bandwidth Allocation for Ethernet Passive Optical Networks, IGI Global, 2010. pp. 146–161.
[5] G. Kramer, B. Mukherjee, G. Pesavento, Ethernet PON(ePON): design and analysis of an optical access network, Photonic Network Communications 3 (2001) 307–319.
[6] IEEE 802.3ah – Ethernet in the First Mile working group archives. <http://www.ieee802.org/3/efm>
[7] G. Kramer, B. Mukherjee, G. Pesavento, IPACT: a dynamic protocol for an ethernet PON (EPON), IEEE Communications Magazine 40 (2) (2002) 74–80.
[8] J. Zheng, H.T. Mouftah, Media access control for ethernet passive optical networks: an overview, IEEE Communications Magazine 43 (2) (2005) 145–150.
[9] L. Yuanqiu, N. Ansari, Bandwidth allocation for multiservice access on EPONs, IEEE Communications Magazine 43 (2) (2005) S16–S21.
[10] J. Zheng, H.T. Mouftah, A survey of dynamic bandwidth allocation algorithms for ethernet passive optical networks, Optical Switching and Networking 6 (3) (2009) 151–162. July.
[11] R. Davey, D. Nesset, A. Rafel, D. Payne, A. Hill, Designing long reach optical access networks, BT Technology Journal 24 (2006) 13–19.
[12] R.P. Davey, D.B. Grossman, M. Rasztovits-Wiech, D.B. Payne, Long-reach passive optical networks, IEEE/OSA, Journal of Lightwave Technology 27 (3) (2009) 273–291. February.
[13] P. Darren, E. Shea John, A Mitchell, 10-Gb/s 1024-way-split 100-km long-reach optical-access network, IEEE/ OSA, Journal of Lightwave Technology 25 (3) (2007) 685–693. March.
[14] H. Song, B.-W. Kim, B. Mukherjee, Long-reach optical access networks: a survey of research challenges, demonstrations, and bandwidth assignment mechanisms, IEEE Communications Surveys & Tutorials 12 (1) (2010) 112–123. First Quarter.
[15] L. Gutierrez, M. de andrate, S. Sallent, New trends on optical access networks: DBAs for 10G EPON and long-reach PON, in: European Conference on Networks and Optical, Communications, June 2009, pp. 487–494.
[16] A.M. Ragheb, M. Elnamaky, H. Fathallah, H. Mouftah, Performance evaluation of standard IPACT for future long reach passive optical networks (LR-PON), in: International Conference on Communication Technologies, January 2010.
[17] Huan Song, A. Banerjee, Byoung-Whi Kim, B. Mukherjee, "Multi-thread polling: a dynamic bandwidth distribution scheme in long-reach PON", in: IEEE Global Telecommunications Conference, 2007, pp. 2450–2454.
[18] H. Song, B.-W. Kim, B. Mukherjee, Multi-thread polling: a dynamic bandwidth distribution scheme in long-reach PON, IEEE Journal on Selected Areas in Communications 27 (2) (February 2009) 134–142.
[19] J. Segarra, V. Sales, J. Prat, "OLT design approach for resilient extended PON with OBS dynamic bandwidth allocation sharing the OLT optical resources",in: International Conference on Transparent Optical Networks, 2008, vol. 4, pp. 139–144.
[20] J. Segarra, V. Sales, J. Prat, An all-optical access-metro interface for hybrid WDM/TDM PON based on OBS, IEEE/OSA Journal of Lightwave Technology 25 (4) (2007) 1002–1016. April.
[21] Y. Chen, C. Qiao, X. Yu, Optical burst switching (OBS): a new area in optical networking research, IEEE Network Magazine 18 (3) (2004) 16–23. May–June.
[22] B. Kantarci, S. Oktug, T. Atmaca, Performance of obs techniques under self-similar traffic based on various burst assembly techniques, Computer Communications 30 (2) (2007) 315–325.
[23] S. Choudhury, G. Chakraborty, A.K. Mal, Impact of burst assembly algorithms on data loss in OBS networks under time-correlated traffic input, IEEE/OSA Journal of Optical Communications and Networking 2 (12) (2010) 1063–1076. December.
[24] B. Kantarci, S. Oktug, Loss rate-based burst assembly to resolve contention in optical burst switching networks, IET Communications 2 (1) (2008) 137–143.
[25] B. Kantarci, S. Oktug, Adaptive threshold based burst assembly in OBS networks, in: Canadian Conference on Electrical and Computer Engineering (CCECE), May 2006, pp. 1419–1422.
[26] S. Ozsarac, E. Karasan, Congestion window-based adaptive burst assembly for TCP traffic in OBS networks, Photonic Network Communications 20 (2) (2010) 138–150. October.
[27] M.A. Toksoz, N. Akar, Dynamic threshold-based assembly algorithms for optical burst switching networks subject to burst rate constraints, Photonic Network Communications 20 (2) (2010) 120–130. October.
[28] B. Kantarci, H.T. Mouftah, Bandwidth distribution with adaptive threshold-based optical burst assembly in long-reach EPON, in: OSA Advanced Photonics Congress, May 2011.
[29] C.-H. Chang, N.M. Alvarez, P. Kourtessis, R.M. Lorenzo, J.M. Senior, Full-service mac protocol for metro-reach GPONs, IEEE/OSA Journal of Lightwave Technology 28 (7) (April 2010) 1016–1022.
[30] B. Skubic, Jiajia Chen, J. Ahmed, Biao Chen, L. Wosinska, B. Mukherjee, Dynamic bandwidth allocation for long-reach PON: overcoming performance degradation, IEEE Communications Magazine 48 (11) (2010) 100–108. November.
[31] T. Jimenez, N. Merayo, J.D. Ramon, P. Fernandez, R.M. Lorenzo, I. de Miguel, N. Fernandez, E.J. Abril, Interleaved polling algorithm with inserted cycles to support service level agreement in long-reach EPONs, in: International Conference on Transparent Optical Networks (ICTON), June 2009, pp. Th.B3.5.1–Th.B3.5.4.
[32] B. Kantarci, H.T. Mouftah, Periodic GATE optimization (PGO) in long-reach passive optical networks, in: 25th Biennial Symposium on Communications (QBSC), May 2010, pp. 230–233.
[33] B. Kantarci, H.T. Mouftah, Periodic GATE optimization (PGO): a new service scheme for long-reach passive optical networks, IEEE Systems Journal 4 (4) (2010) 440–448.
[34] B. Kantarci, H.T. Mouftah, "Periodic GATE optimization with QoSawareness for long-reach passive optical networks", in: IEEE Symposium on Computers and Communications (ISCC), 2010, pp. 879–884.
[35] B. Kantarci, H.T. Mouftah, On SLA-constraints in dynamic bandwidth allocation for long-reach passive optical networks, in: International Conference on Transparent Optical Networks (ICTON), June 2010, Tu.B1.3.1–Tu.B1.3.7.
[36] B. Kantarci, H.T. Mouftah, Delay-constrained admission and bandwidth allocation for long-reach EPON, Journal of Networks 7 (5) (2012) 812–820. May.
[37] N. Merayo, T. Jimenez, P. Fernandez, R.J. Duran, R.M. Lorenzo, I. de Miguel, E.J. Abril, A bandwidth assignment polling algorithm to enhance the efficiency in QoS long-reach EPONs, in: European Transactions on Telecommunications, November 2010. <http://dx.doi.org/10.1002/ett.1449>.
[38] H-T. Lin, Z-H. Ho, H-C. Cheng, W-R. Chang, SPON: a slotted long-reach PON architecture for supporting internetworking capability, in: IEEE Military Communications Conference (MILCOM), October 2009, pp. 1–8.
[39] M. Mcgarry, M. Reisslein, F. Aurzada, M. Scheutzow, Shortest propagation delay (SPD) first scheduling for EPONs with heterogeneous propagation delays, IEEE Journal on Selected Areas in Communications 28 (6) (Aug. 2010) 849–862.
[40] H. Song, A. Banerjee, B. Mukherjee, B-W. Kim, S. Yang, Y. Park, LA-Aware protocol for efficient tunable laser utilization to support incremental upgrade in long-reach passive optical networks, IEEE/OSA Journal of Optical Communications and Networking 1 (5) (2009) 512–520.
[41] C.A. Chan, M. Attygalle, N. Ampalavanapillai, Remote repeater-based EPON with MAC forwarding for long-reach and high-split-ratio passive optical networks, IEEE/OSA Journal of Optical Communications and Networking 2 (1) (2010) 28–37.
[42] B. Kantarci, H.T. Mouftah, Bandwidth distribution solutions for performance enhancement in long-reach passive optical networks, IEEE Communications Surveys & Tutorials 14 (3) (2012) 714–733.
[43] N. Antunes, C. Fricker, P. Robert, J. Roberts, GATE-driven dynamic wavelength and bandwidth allocation for WDM-EPONs, in: IEEE Global Telecommunications Conference, 2010, pp. 1–5.

[44] N. Antunes, C. Fricker, P. Robert, J. Roberts, Upstream traffic capacity of a WDM EPON under online GATE-driven scheduling, internal report, 2010.
[45] H-T. Lin, W-R. Chang, C-L. Lai, S-J. Hong, "Supporting private networking with wavelength spatial-reuse over WDM EPONs", in: IEEE Global Telecommunications Conference (GLOBECOM), 2008, p. 30.
[46] J.R. Ferguson, M. Reisslein, M.P. McGarry, Online excess bandwidth distribution for ethernet passive optical networks, Journal of Optical Networking 8 (2009) 358–369. April.
[47] B. Kantarci, H.T. Mouftah, Energy efficiency in the extended-reach fiber-wireless access networks, IEEE Network 26 (2) (2012) 28–35. March/April.
[48] G. Kramer, DESL: discrete event simulation library. <http://glenkramer.com/ucdavis/deslresearch.shtml>, Last Access July 2012.
[49] M.S. Taqqu, W. Willinger, R. Sherman, Proof of a fundamental result in self-similar traffic modeling, SIGCOMM Computing Communications Review 27 (April 1997) 5–23.
[50] L. Yuanqiu, Y. Si, N. Ansari, W. Ting, Resource management for broadband access over time-division multiplexed passive optical networks, IEEE Network 21 (5) (2007) 20–27. September–October.
[51] J. Zhang, N. Ansari, Utility max-min fair resource allocation for diversified applications in EPON, in: Access Networks 37 of Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Springer, Berlin, Heidelberg, 2010, pp. 14–24.

Burak Kantarci is a postdoctoral fellow at the School of Electrical Engineering and Computer Science of the University of Ottawa. He received the M.Sc, and Ph.D degrees in Computer Engineering at Istanbul Technical University in 2005, and 2009, respectively. He received the Siemens Excellence Award in 2005 for his studies in optical burst switching. During his Ph.D study, he studied as a visiting scholar under the supervision of Prof. Mouftah at the UoOttawa. Dr. Kantarci has co-authored over five-dozen refereed papers in established journals and conferences, and contributed four book chapters. His research interests are energy-efficient network planning, broadband access networks, WDM networks, optical switching, survivable network design, green communications, and cloud computing.

Hussein T. Mouftah joined the School of Information Technology and Engineering (SITE) of the University of Ottawa in 2002 as a Tier 1 Canada Research Chair Professor, where he became a University Distinguished Professor in 2006. He has been with the ECE Dept. at Queen's University (1979–2002), where he was prior to his departure a Full Professor, and the Department Associate Head. He has six years of industrial experience, mainly at Bell Northern Research of Ottawa (became Nortel Networks). He served IEEE ComSoc as Editor-in-Chief of the IEEE Communications Magazine (1995–97), Director of Magazines (1998–99), Chair of the Awards Committee (2002–03), Director of Education (2006–07), and Member of the Board of Governors (1997–99 and 2006–07). He has been a Distinguished Speaker of the IEEE Communications Society (2000–07). Currently he serves IEEE Canada (Region 7) as Chair of the Awards and Recognition Committee. He is the author or coauthor of 8 books, 53 book chapters, and more than 1100 technical papers, 12 patents, and 140 industrial reports. He is the joint holder of 12 Best Paper and/or Outstanding Paper Awards. He has received numerous prestigious awards, such as the 2008 ORION Leadership Award of Merit, the 2007 Royal Society of Canada Thomas W. Eadie Medal, the 2007–2008 University of Ottawa Award for Excellence in Research, the 2006 IEEE Canada McNaughton Gold Medal, the 2006 EIC Julian Smith Medal, the 2004 IEEE ComSoc Edwin Howard Armstrong Achievement Award, the 2004 George S. Glinski Award for Excellence in Research of the U of O Faculty of Engineering, the 1989 Engineering Medal for Research and Development of the Association of Professional Engineers of Ontario (PEO), and the Ontario Distinguished Researcher Award of the Ontario Innovation Trust. Dr. Mouftah is a Fellow of the IEEE (1990), the Canadian Academy of Engineering (2003), the Engineering Institute of Canada (2005), and the Royal Society of Canada RSC: The Academy of Science (2008).