

# Offline and Online Multi-Thread Polling in Long-Reach PONs: A Critical Evaluation (Extended Version)

Anu Mercian, Michael P. McGarry, and Martin Reisslein

**Abstract**—Multi-thread polling (MTP) with offline scheduling and offline excess bandwidth distribution has recently been proposed to overcome the long propagation delay of long-reach passive optical networks (LR-PONs). In this paper, we propose a complementary MTP approach with online scheduling and online excess bandwidth distribution. We evaluate the throughput-delay performance of offline and online MTP against offline and online single-thread polling (STP) with excess bandwidth distribution as well as double-phase polling (DPP) with excess bandwidth distribution. We find that online MTP and STP as well as DPP give significantly lower average packet delays than offline MTP.

**Index Terms**—Delay evaluation, dynamic bandwidth allocation, excess bandwidth distribution, long-reach PON (LR-PON), multi-thread polling (MTP).

## I. INTRODUCTION

Multi-thread polling (MTP) with offline scheduling and offline excess bandwidth, in brief *offline MTP* [1], interleaves multiple polling threads to a given set of Optical Network Units (ONUs) to mitigate the long propagation delays in Long-Reach Passive Optical Networks (LR-PONs) [2]–[7]. In offline MTP, multiple interleaved polling processes (threads) communicate bandwidth requests from the ONUs to the central Optical Line Terminal (OLT). For a given polling thread, the OLT collects the bandwidth requests from all ONUs, and then allocates upstream transmission bandwidth (windows) to the ONUs and communicates these upstream transmission windows to the ONUs. The interleaving of the polling threads aids in masking the long propagation delay between ONUs and OLT compared to offline single-thread polling (STP). Specifically, in offline STP, the upstream channel is idle from the instant when the last ONU in a polling round (cycle) ends its upstream transmission to the instant when the first ONU in the next polling cycle commences its upstream transmission. This idle time enables the OLT to collect and consider the bandwidth requests from all ONUs in the allocation of upstream transmission windows. In particular, the OLT can employ excess bandwidth distribution [8], [9] to fairly distribute the limited total upstream transmission period of a polling cycle among the ONUs according to their current bandwidth demands.

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A drawback of offline polling (also referred to as the offline scheduling framework [10] or polling with stop [5], [11]) is that the first ONU bandwidth request in a given polling cycle to reach the OLT must wait for the bandwidth requests from all other ONUs to reach the OLT, before the OLT can process the bandwidth requests. In the online scheduling framework, when a bandwidth request from an individual ONU reaches the OLT, the OLT immediately allocates an upstream transmission window to that ONU. Online scheduling thus avoids delays introduced due to ONU reports waiting for the arrival of all other ONU reports. The drawback of online scheduling is that the ONU must make bandwidth allocations to each individual ONU without knowledge of the current bandwidth demands of the other ONUs.

In this paper, we introduce *online MTP*, which features multiple polling processes (threads) to a given set of ONUs. Each polling thread employs the online scheduling framework [5], [10], [11], i.e., the OLT processes each bandwidth request immediately, thus avoiding delays due to waiting for bandwidth requests from other ONUs. Our online MTP design overcomes the challenge of making bandwidth allocation decisions without knowledge of the current bandwidth demands of the other ONUs through an online excess bandwidth distribution mechanism.

We examine the idle time reduction achieved by online MTP in comparison to offline MTP through mathematical analysis. We conduct extensive simulation evaluations for both Ethernet PONs (EPONs) based on the IEEE 802.3ah standard and Gigabit PONs (GPONs) based on the ITU-T G.984 standard. We find that online MTP achieves significantly lower average packet delays than offline MTP. However, we also find that (i) Double-Phase Polling (DPP) [12], [13] with an excess bandwidth distribution extension gives the lowest average packet delays for short polling cycle duration at low loads, and (ii) DPP, online MTP, and online STP with an online excess bandwidth distribution mechanism give very similar average packet delays at moderate to high loads.

This extended technical report complements the article [14] and is structured as follows. Section II reviews related work. Section III introduces online multi-thread polling, including the thread tuning and online excess bandwidth distribution mechanism. Section IV presents the performance evaluations of offline and online MTP with respect to STP and DPP. Section V concludes this article.

## II. BACKGROUND AND RELATED WORK

Network architecture studies have thoroughly established the feasibility of long-reach PONs [6], [15], [16] and are currently exploring advanced architectural options, such as exploiting multiple wavelength channels [17]–[20] or multiple and higher line-rate channels [21], [22]. Several studies, e.g., [23]–[28] have begun to explore DBA protocols for long-reach PONs utilizing multiple wavelength channels. We focus on long-reach PONs with a single upstream wavelength channel in this study.

DBA approaches for PONs can be classified according to the number of polling threads and three additional main dimensions [10], [11]: (i) the scheduling framework, (ii) the sizing of the upstream transmission windows (grants) for the individual ONUs, and (iii) the scheduling (along the time axis) of the grants. We focus on single-thread polling (STP) and multi-thread polling (MTP) with a statically fixed number of threads in this study. Dynamic adaptation of the number of threads, e.g., according to the traffic load [29], which can reduce delays at the expense of increased complexity, is beyond the scope of this study.

The scheduling framework is commonly characterized by the event that triggers the sizing and scheduling of upstream transmission windows. In the offline scheduling framework [10], [11], [30], the receipt of bandwidth requests from all ONUs (within a given polling thread) triggers the grant sizing and scheduling. In contrast in the online scheduling framework, the receipt of a single ONU request triggers a grant sizing and scheduling decision. To the best of our knowledge, multi-thread polling (MTP) has so far only been examined in combination with the offline scheduling framework, i.e., existing research has been limited to offline MTP. In this paper, we conduct the first study of multi-thread polling in combination with the online scheduling framework, i.e., introduce and evaluate online MTP.

Elementary grant sizing mechanisms are gated grant sizing, which allocates the full ONU request and can lead to fairness issues, and limited grant sizing, which allocates the ONU request up to a prescribed limit, thus preserving fairness [31]–[34]. Grant sizing has a significant influence on PON performance and can be aided by traffic prediction [35]–[42]. A key strategy for improving the performance of PONs employing fairness-preserving limited grant sizing is to distribute grant allocations among ONUs. The excess bandwidth from ONUs requesting less than the prescribed limit is distributed to ONUs with traffic bursts. For STP, excess bandwidth distribution has been intensely investigated within the offline scheduling framework, see e.g., [8], [9]. Excess bandwidth distribution for STP with the online scheduling framework has been examined in relatively few studies that either explored relatively complex excess management rules [43] or focused on distributing excess within the window of one preceding cycle [44] or detected gaps in the upstream transmission schedule [45]. A refined control-theory based adjustment of the prescribed limit according to service-level agreements is examined in [46].

In the context of offline MTP, grant sizing refinements employing integer linear program optimization [47] and a variety

of mechanisms for distributing grant allocations between the different threads [48]–[51] have been explored.

Since our focus is on the fundamental performance differences between MTP in combination with either the offline or online scheduling framework, we consider elementary grant sizing mechanisms for both online and offline MTP. Specifically, for offline MTP, we consider the elementary mechanism from [51], where each thread is primarily responsible for the traffic that has been newly generated since the preceding thread. For online MTP, we consider an elementary bounded excess bandwidth pool mechanism, see Section III-B. To the best of our knowledge, this article presents the first comparison of the fundamental performance differences of online and offline MTP. Comparisons that consider refinements of the grant sizing for offline and online MTP are an interesting direction for future research.

Grant scheduling has been intensely researched for increasing efficiency by avoiding voids (idle times) between ONU upstream transmissions [52]–[55] and providing quality-of-service differentiation [56], [57]. We employ the scheduling policy from [55] to mitigate idle times due to different round-trip propagation delays.

## III. ONLINE MULTI-THREAD POLLING

In this section we introduce online multi-thread polling (online MTP) for a long-reach EPON based on the IEEE 802.3ah standard. We model the EPON with the parameters in Table I. Online MTP can be analogously employed in a GPONs based on the ITU-T G.984 standard and we quantitatively examine the performance of online MTP in both an EPON and a GPON in Section IV.

### A. Multi-thread Polling Structure

Similar to offline multi-thread polling [1], which is illustrated for two threads in Fig. 1(a), the OLT launches multiple threads in online MTP. As illustrated for two threads in Fig. 1(b), in online MTP, the OLT processes the ONU bandwidth request attached to an upstream transmission immediately after receipt. In the example in Fig. 1(b), the request for an upstream transmission window for ONU  $j = 1$  of thread  $\theta = 1$  in cycle  $n$  arrives with the upstream transmission of this ONU in the preceding cycle  $n - 1$  and is processed at the instant  $\beta(n - 1, \theta = 1, j = 1)$  when the end of the upstream is received, i.e., the scheduling instant for the upstream transmission of ONU  $j = 1$  of thread  $\theta = 1$  of the cycle  $n$  is

$$\gamma_{\text{MTPon}}(n, \theta, j) = \beta(n - 1, \theta, j). \quad (1)$$

In contrast, in offline MTP, the request from the first ONU  $j = 1$  is only processed when the end of the upstream transmission of the last ONU  $j = O$  is received, i.e.,

$$\gamma_{\text{MTPoff}}(n, \theta, j) = \beta(n - 1, \theta, O). \quad (2)$$

Through the earlier processing of bandwidth requests, online MTP can reduce the idle times on the upstream channel in comparison to offline MTP as analyzed in the Appendix and in Section IV.

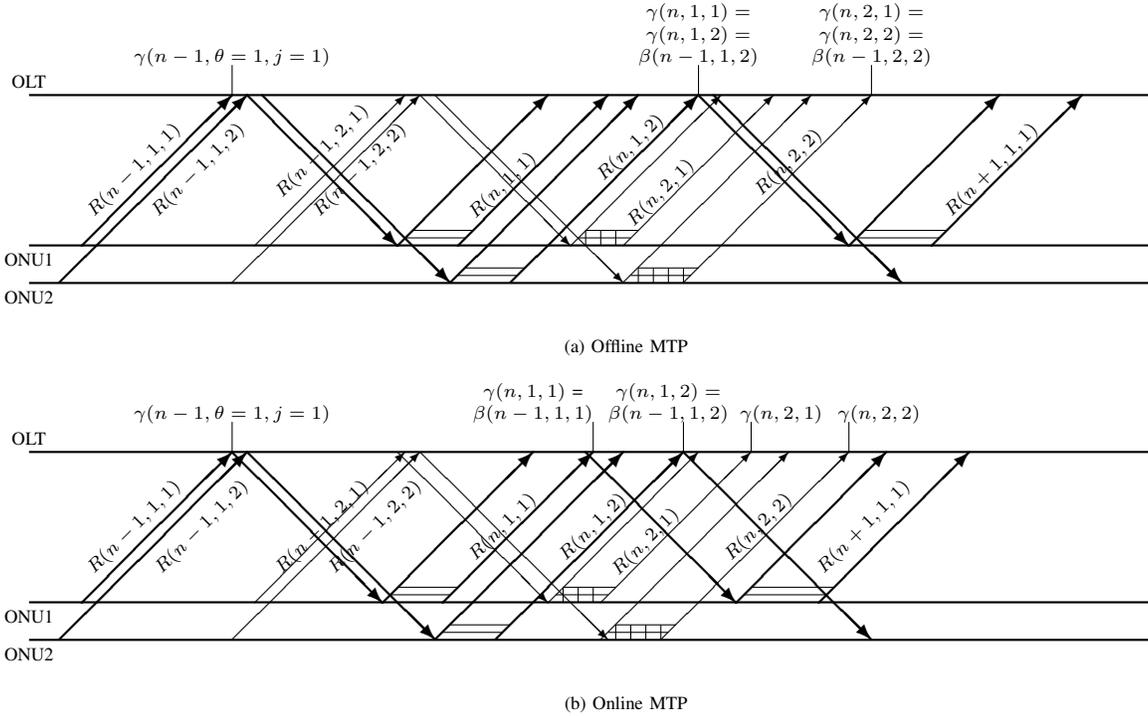


Fig. 1. Illustration of offline and online MTP for  $O = 2$  ONUs and  $\Theta = 2$  threads. ONU  $j$  appends to its upstream transmission in thread  $\theta$  of cycle  $n - 1$  its request for an upstream transmission window of duration  $R(n, \theta, j)$  in thread  $\theta$  of cycle  $n$ . When requests from all ONUs have been received at the OLT, offline MTP makes all grant sizing and scheduling decisions for thread  $\theta$  of cycle  $n$ , i.e., the scheduling instant  $\gamma_{\text{MTPoff}}(n, \theta, j)$  corresponds to the end  $\beta(n - 1, \theta, O)$  of the last upstream transmission of thread  $\theta$  of the preceding cycle  $n - 1$ . In contrast, immediately after receipt of the request by an ONU  $j$  for thread  $\theta$  in cycle  $n$  at time  $\beta(n - 1, \theta, j)$ , online MTP makes the scheduling decision.

We note that conceptually, online MTP is akin to parallel mechanisms on network processors which tend to outperform multi-thread mechanisms [58] that are akin to offline MTP.

### B. Online Excess Bandwidth Distribution Mechanism

In order to ensure fair allocation of upstream transmission windows to the ONU and prevent one ONU from monopolizing the upstream transmission channel, Limited grant sizing [31], [32] limits the duration of one contiguous upstream transmission window (grant) for an ONU to a prescribed maximum duration  $G_{\max}$ . When an ONU requests less than the maximum grant duration, i.e.,  $R(n, \theta, j) < G_{\max}$ , an excess bandwidth distribution mechanism collects the unused portion of the maximum grant duration  $G_{\max} - R(n, \theta, j)$  and distributes this “excess bandwidth” to ONUs requesting grant durations longer than  $G_{\max}$ .

We examine an elementary “bounded excess pool” approach for online excess bandwidth distribution in online MTP; adapting and examining other approaches, e.g., [43]–[45] is an interesting direction for future research. For the bounded excess pool approach, we let  $E(n, \theta, j)$  denote the excess bandwidth pool (in terms of upstream transmission window duration) available for the bandwidth allocation to the  $j$ th ONU of thread  $\theta$  in cycle  $n$ . We focus in the following explanation of the bounded excess pool approach on a given thread  $\theta$  of a given cycle  $n$  and consider the online bandwidth distribution to two successive ONUs  $j$  and  $j + 1$ ; the presented approach applies analogously for online bandwidth distribution to ONUs in successive threads or cycles.

We consider the thread reporting approach [51] where  $R(n, \theta, j)$  represents the newly generated traffic since the preceding ONU request; examining online MTP with alternate thread reporting approaches, e.g., [48] is an interesting direction for future research. For ease of exposition we initially ignore backlogged traffic from previous threads. An ONU  $j$  that requests a transmission window duration  $R(n, \theta, j)$  shorter than the maximum  $G_{\max}$  is immediately granted the requested grant duration. On the other hand, for an ONU with  $R(n, \theta, j) > G_{\max}$ , the OLT immediately allocates a transmission window duration that corresponds to the ONUs regular maximum grant size  $G_{\max}$  plus an equal share of  $1/O$  of the current excess bandwidth pool  $E(n, \theta, j)$ , not to exceed the request. In summary,

$$G(n, \theta, j) = \begin{cases} R(n, \theta, j) & \text{for } R(n, \theta, j) \leq G_{\max} \\ \min\{R(n, \theta, j), G_{\max} + \frac{E(n, \theta, j)}{O}\} & \text{for } R(n, \theta, j) > G_{\max}. \end{cases} \quad (3)$$

Any traffic amount  $R(n, \theta, j) - G(n, \theta, j)$  that can not be accommodated in the transmission window allocation becomes backlogged and adds to the transmission window request for the next thread [51].

After each bandwidth allocation, the OLT updates the excess bandwidth pool by adding in a nominal bandwidth allocation corresponding to the maximum grant duration  $G_{\max}$  and subtracting the actual just allocated grant duration  $G(n, \theta, j)$ ; moreover, the excess bandwidth pool is bounded (capped) at a prescribed maximum  $E_{\max}$ :

$$E(n, \theta, j + 1) =$$

TABLE I  
MODEL PARAMETERS FOR PON WITH MULTI-THREAD POLLING

Parameter	Meaning
Network structure	
$O$	Total number of ONUs, numbered $o = 1, 2, \dots, O$
$\tau(o)$	One-way propagation delay from OLT to ONU $o$
$Z$	Maximum cycle duration, i.e., max. aggregate duration of upstream transmission windows of all $O$ ONUs and $\Theta$ threads in a cycle
Cycle, thread, and upstream transmission indices	
$n$	Polling cycle index
$\Theta$	Total number of threads
$\theta$	Thread index, $\theta = 1, \dots, \Theta$
$j$	ONU index ordered by upstream transm. position for a given thread $\theta$ in a given cycle $n$ , i.e., ONU $j$ has $j$ th upstream transmission grant of thread $\theta$ in cycle $n$
Upstream transmission window (grant) scheduling	
$\gamma(n, \theta, j)$	Time instant when OLT makes scheduling decision for transmission window of $j$ th ONU of thread $\theta$ in cycle $n$
$T(n, \theta, j)$	Gate signaling delay: Time duration from instant of OLT scheduling decision to end of the GATE transm. for $j$ th ONU of thread $\theta$ in cycle $n$ plus round-trip prop. delay
$\alpha(n, \theta, j)$	Time instant when upstream transmission of $j$ th ONU of thread $\theta$ in cycle $n$ starts to arrive at OLT
$\beta(n, \theta, j)$	Time instant when end of upstream transm. of $j$ th ONU of thread $\theta$ in cycle $n$ arrives at OLT.
$\Omega(n, \theta, j)$	Time instant of end of upstream transm. preceding arrival of upstream transm. of $j$ th ONU of thread $\theta$ in cycle $n$
$I(n, \theta, j)$	Duration of channel idle time preceding the arrival of upstream transm. of $j$ th ONU of thread $\theta$ in cycle $n$ at OLT
Upstream transmission window (grant) sizing	
$R(n, \theta, j)$	Duration of upstream transmission window requested by $j$ th ONU of thread $\theta$ in cycle $n$
$G(j, n, \theta)$	Duration of upstream transmission window granted to $j$ th ONU of thread $\theta$ in cycle $n$
$G_{\max}$	$= \frac{Z}{\Theta}$ , Maximum duration of granted upstream transm. window size for Limited grant sizing
$E(j, n, \theta)$	Excess bandwidth pool (in terms of upstream transmission window duration) available for allocation decision to $j$ th ONU of thread $\theta$ in cycle $n$

$$\min\{E(n, \theta, j) + G_{\max} - G(n, \theta, j), E_{\max}\}. \quad (4)$$

The excess pool bound  $E_{\max}$  can be adjusted to provide a trade-off between small bandwidth allocation and frequent opportunities for ONU upstream transmission achieved for small  $E_{\max}$ ; for large  $E_{\max}$  the bandwidth allocations increase and ONU transmission opportunities may become less frequent, approaching a Gated (unbounded) bandwidth allocation [31], [32]. We examine this trade-off quantitatively in Section IV.

### C. Thread-Tuning

The variations in the traffic generation at the ONUs over time may lead to one thread carrying most (and possibly all) of the upstream traffic, effectively degrading multi-thread polling to single-thread polling. Thread tuning strives to prevent this degradation by re-distributing bandwidth, i.e., upstream transmission grant durations, among the threads. The existing thread tuning mechanism for offline MTP [1] exploits the knowledge of all ONU bandwidth requests and allocations by considering the aggregate of the upstream grant durations (after excess bandwidth distribution), i.e.,  $\sum_{j=1}^O G(n, \theta, j)$  (referred to as instantaneous cycle time in [1]).

For online MTP, which immediately processes each individual ONU request, we introduce the following online thread tuning mechanism. We base the thread tuning on the allocated

grant durations for each individual ONU  $j$ . Specifically, we compare the ratio of allocated grant durations (after excess bandwidth distribution) to the  $j$ th ONU in the present thread  $\theta$  and the immediately preceding thread  $\theta - 1$  with a prescribed tuning threshold  $T_{\text{tune}}$ , i.e., we check whether

$$\frac{G(n, \theta, j)}{G(n, \theta - 1, j)} > T_{\text{tune}}. \quad (5)$$

(For the case  $\theta = 1$ , we consider the grant durations  $G(n, 1, j)$  and  $G(n - 1, \Theta, j)$ ). If the present to preceding grant duration ratio exceeds the tuning threshold, then we shift the bandwidth (transmission window duration)

$$\Phi = \frac{G(n, \theta, j) - G(n, \theta - 1, j)}{2} \quad (6)$$

from the present thread  $\theta$  to the succeeding thread  $\theta + 1$ . (If the present thread is the last thread of the cycle  $\theta = \Theta$ , we shift the bandwidth  $\Phi$  to thread  $\theta = 1$  of the next cycle.) For instance, consider a given ONU  $j$  in multi-thread polling with  $\Theta = 2$  threads: If in a given cycle  $n$ , the grant  $G(n, 2, j)$  for the second thread becomes more than  $T_{\text{tune}}$  times larger than the preceding grant  $G(n, 1, j)$ , then we shift the grant duration  $\Phi = [G(n, 2, j) - G(n, 1, j)]/2$  by reducing the grant for the second thread to  $G(n, 2, j) - \Phi$  and adding  $\Phi$  to the grant for thread  $\theta = 1$  in the next cycle  $n + 1$ , i.e., we allocate the grant  $G(n + 1, 1, j) + \Phi$ .

We note that the outlined online thread tuning mechanism immediately responds to thread imbalances by adjusting the grant allocations to the present thread and the next thread (which could be in the present or next cycle). In contrast, in the offline thread tuning mechanism [1], the OLT records the imbalances among the threads in a given cycle  $n$  and makes the corresponding grant allocation adjustments in the next cycle  $n + 1$ .

## IV. PERFORMANCE EVALUATION

### A. Simulation Set-up

1) *Network and Traffic Parameters:* We evaluate the MTP algorithms with CSIM based simulators for both an LR-EPON based on the IEEE 802.3ah standard and an LR-GPON based on the ITU-T G.984 standard. We consider these PONs with  $O = 32$  ONUs (ONTs) and a one-way propagation distance  $\tau(o)$  uniformly randomly distributed between 90 and 100 km. Thus, the mean round-trip propagation delay is about  $2\tau = 0.95$  ms; for illustrative explanatory explanations of the results we write that approximately  $2\tau = 1$  ms for simplicity of exposition.

We consider PONs with one upstream transmission channel with a bit rate of  $C = 1$  Gb/s. Each ONU (ONT) has an infinite buffer in the simulation model and independently generates self-similar packet traffic with a Hurst parameter of 0.75. We employ a common quad-mode packet size distribution with 60 % 64 byte packets, 4 % 300 byte packets, 11 % 580 byte packets, and 25 % 1518 byte packets. We define the traffic load as the long-run average packet traffic (payload) bit rate.

2) *Transmission Window Signaling*: For signalling the upstream transmission window requests and grants between the ONUs and OLT, the EPON employs REPORT and GATE messages, which are 64 Bytes, following the IEEE 802.3ah standard. The guard time in the EPON is set to  $t_g = 1 \mu\text{s}$ . In addition, the EPON incurs the standard overheads due to frame preambles and inter-packet gaps.

In a GPON, transmission window requests and grants are signalled through dynamic bandwidth reports upstream (DBRu) and Bandwidth Maps (BWMaps) that are embedded in periodic  $125 \mu\text{s}$  frames [59]. In our simulations, we consider the XGPON overheads following the ITU-T G.987 standard and set the GPON guard band to  $t_g = 30 \text{ ns}$ .

3) *DBA Approaches*: We compare the online MTP approach introduced in Section III with offline MTP [1] with an adapted form of the thread tuning mechanism of Section III.C., double-phase polling (DPP) [12], as well as single-thread polling (STP) with offline and online scheduling. We consider MTP with  $\Theta = 2$  threads for a consistent comparison with DPP, which partitions the set of  $O$  ONUs into two subsets. Thus, the evaluation provides insights into the effectiveness of interleaving two polling threads to each ONU compared to interleaving single-thread polling to two subsets of the ONUs. We set the thread tuning threshold to  $T_{\text{tune}} = 5$ . We define  $Z$  as the maximum aggregate duration of the upstream transmission windows (grants) allocated to the  $O$  ONUs (and  $\Theta$  threads, if MTP is considered) of a given cycle  $n$ , and refer for brevity to  $Z$  as the maximum cycle length. Throughout, we employ a grant size limit  $G_{\text{max}}$  that is based on maximum cycle duration  $Z = 2, 4, \text{ or } 8 \text{ ms}$ , and number of threads  $\Theta$  ( $\Theta = 1$  for STP and  $\Theta = 2$  for MTP):

$$G_{\text{max}} = \frac{Z}{\Theta}. \quad (7)$$

In particular, offline STP and offline MTP employ limited grant sizing based on  $G_{\text{max}}$  with offline excess bandwidth distribution using equitable distribution with a controlled excess allocation bound [8], [9], while DPP employs an excess share mechanism among its two ONU groups [10]. We consider online STP with limited grant sizing based on  $G_{\text{max}}$  without excess bandwidth distribution (denoted by ‘‘online STP, lim.’’) as well as online STP with limited grant sizing and the bounded excess pool approach from Section III-B (denoted by ‘‘online STP, exc.’’). For all considered DBA approaches with offline grant scheduling, i.e., offline MTP, offline STP, and DPP, we employ shortest propagation delay first scheduling [55].

4) *Performance Metrics*: We define the average packet delay as the mean time period from the instant of packet generation at an ONU to the complete delivery of the packet to the OLT. We define the mean cycle duration as the mean time span from the arrival instant  $\alpha(n, 1, 1)$  of the first ONU in thread 1 in a cycle  $n$  to the corresponding instant  $\alpha(n+1, 1, 1)$  in the next cycle  $n+1$ . Moreover, we examine the average grant duration, which we define as the mean of the durations of the contiguous transmission windows (grants)  $G(n, \theta, j)$ . We also examine the average idle time, which we define as the mean of the channel idle times  $I(n, \theta, j)$ .

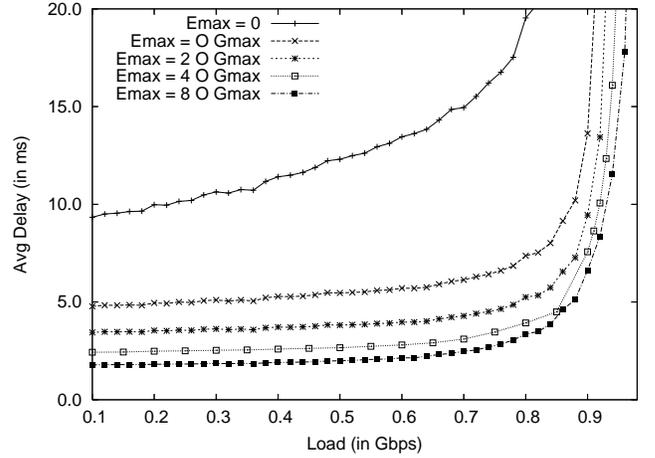


Fig. 2. Mean packet delay as a function of traffic load for different bounds  $E_{\text{max}}$  on the excess bandwidth pool in the online excess bandwidth distribution mechanism (see Section III-B) of online MTP.

We note that the utilization of the upstream transmission channel during a given cycle  $n$  due to packet data (payload) traffic is

$$\rho(n) = \frac{\sum_{\theta=1}^{\Theta} \sum_{j=1}^O G(n, \theta, j)}{\sum_{\theta=1}^{\Theta} \sum_{j=1}^O [I(n, \theta, j) + G(n, \theta, j)]}, \quad (8)$$

which leads to the long-run utilization through averaging over a long time horizon.

## B. Performance Results

1) *Impact of Maximum Excess Bandwidth Pool Size  $E_{\text{max}}$* : In Fig. 2, we plot the mean packet delay for a range of bounds  $E_{\text{max}}$  in Eqn. (4) of the online excess bandwidth distribution mechanism. For this evaluation, we consider an EPON with maximum cycle length  $Z = 4 \text{ ms}$ . The bound  $E_{\text{max}} = 0$  corresponds to Limited grant sizing [31], [32], which limits each grant duration to  $G_{\text{max}}$ ; with  $E_{\text{max}} = xOG_{\text{max}}$ , the excess bandwidth pool is limited to  $x$  times the aggregate of the maximum grant duration  $G_{\text{max}}$  for all  $O$  ONUs. We observe from Fig. 2(a) that the mean packet delay decreases with increasing excess bandwidth pool bound  $E_{\text{max}}$ . Larger excess bandwidth pools permit longer contiguous upstream transmission windows for the transmission of bursts of traffic generated at an ONU, thus reducing the mean packet delay. We observe from Fig. 2 that a small excess bandwidth pool of  $E_{\text{max}} = OG_{\text{max}}$  reduces the mean packet delays substantially compared to Limited grant sizing without any excess bandwidth distribution ( $E_{\text{max}} = 0$ ). Further increases of the bound on the excess bandwidth pool  $E_{\text{max}}$  result in smaller and smaller delay reductions. Even a small excess bandwidth pool of  $E_{\text{max}} = OG_{\text{max}}$  greatly increases the flexibility of the dynamic bandwidth allocation in transmitting traffic bursts in fewer longer upstream transmissions. When  $E_{\text{max}}$  is fairly large, further increases benefit only traffic burst that are larger than  $G_{\text{max}} + E_{\text{max}}/O$ .

A drawback of increasing the bound  $E_{\text{max}}$  on the excess bandwidth pool is that successive upstream transmission opportunities for the individual ONUs become spaced

further apart. With Limited grant sizing, an ONU has an upstream transmission opportunity at least every  $OG_{\max}$  seconds (whereby we neglect the overheads in this illustrative discussion). Excess bandwidth distribution increases the spacing between successive transmission opportunities of an ONU by up to  $E_{\max}$  seconds.

We consider  $E_{\max} = 4OG_{\max}$  for the remainder of this article.

2) *Online MTP vs. Offline MTP*: In Figs. 3 and 4, we plot the mean packet delay as a function of traffic load for maximum cycle durations  $Z = 2$  ms, 4 ms, and 8 ms for the EPON. The means of the cycle durations, grant durations  $G(n, \theta, j)$ , and idle times  $I(n, \theta, j)$  for the  $Z = 4$  ms maximum cycle duration are plotted in Figs. 5–10. For interpreting Figs. 7–10, note that the grant duration and idle time applies for each individual ONU upstream transmission, i.e., for MTP with  $\Theta = 2$ , there are twice as many grants and idle times in a cycle than with STP.

We observe from Fig. 3 that online MTP generally achieves significantly lower delays than offline MTP. However, for the short  $Z = 2$   $\mu$ s maximum cycle duration, we observe from Fig. 3(a) that for low loads up to about 0.25, offline MTP achieves very slightly lower mean packet delays than online MTP. At low loads, the offline excess bandwidth distribution mechanism in offline MTP, which bases decisions on knowledge of the requests from all ONUs, achieves larger grant sizes for the short cycle (small  $G_{\max}$ ) than the online mechanism in online MTP. With a longer cycle,  $G_{\max}$  is less restricting, diminishing the benefit of the more informed grant sizing decisions of offline MTP relative to online MTP. Importantly, with increasing load, the waiting in offline MTP for all ONU requests of a given thread increases with overall increasing grant durations, resulting in substantial delay reductions with online MTP compared to offline MTP.

For high loads, it is instructive to first consider offline STP with excess distribution grant sizing. We observe from Fig. 3(a) that offline excess STP with maximum cycle duration  $Z = 2$  ms gives very large delays as the load approaches 0.6 Gbps. This is because offline excess STP has an idle period of one round-trip propagation delay ( $2\tau$ ), i.e., approximately 1 ms in the considered scenario, between successive cycles, limiting the utilization of the upstream channel to less than approximately  $Z/(2\tau + Z)$ .

Offline MTP can mask the  $2\tau$  channel idle time by interleaving the multiple polling threads. However, for short cycles and a small number of threads, nearly full loading and perfect balancing of the threads is required to mask the  $2\tau$  channel idle time. Specifically, with  $\Theta = 2$  polling threads and a maximum cycle duration of  $Z = 2$  ms, each thread needs essentially all grant sizes to be at the maximum  $G_{\max} = Z/(\Theta O)$  so that each thread takes up one half (1 ms) of the cycle duration, and the interleaving of the two threads perfectly masks the  $2\tau = 1$  ms round-trip time. As we observe from Fig. 3, with increasing maximum cycle duration  $Z$ , offline MTP achieves moderate delays below 10 ms up to increasingly higher loads; up to a load of approximately 0.58 Gbps for a maximum cycle duration of  $Z = 2$  ms, up to almost 0.8 Gbps for  $Z = 4$  ms, and up to approximately 0.87 Gbps for  $Z = 8$  ms.

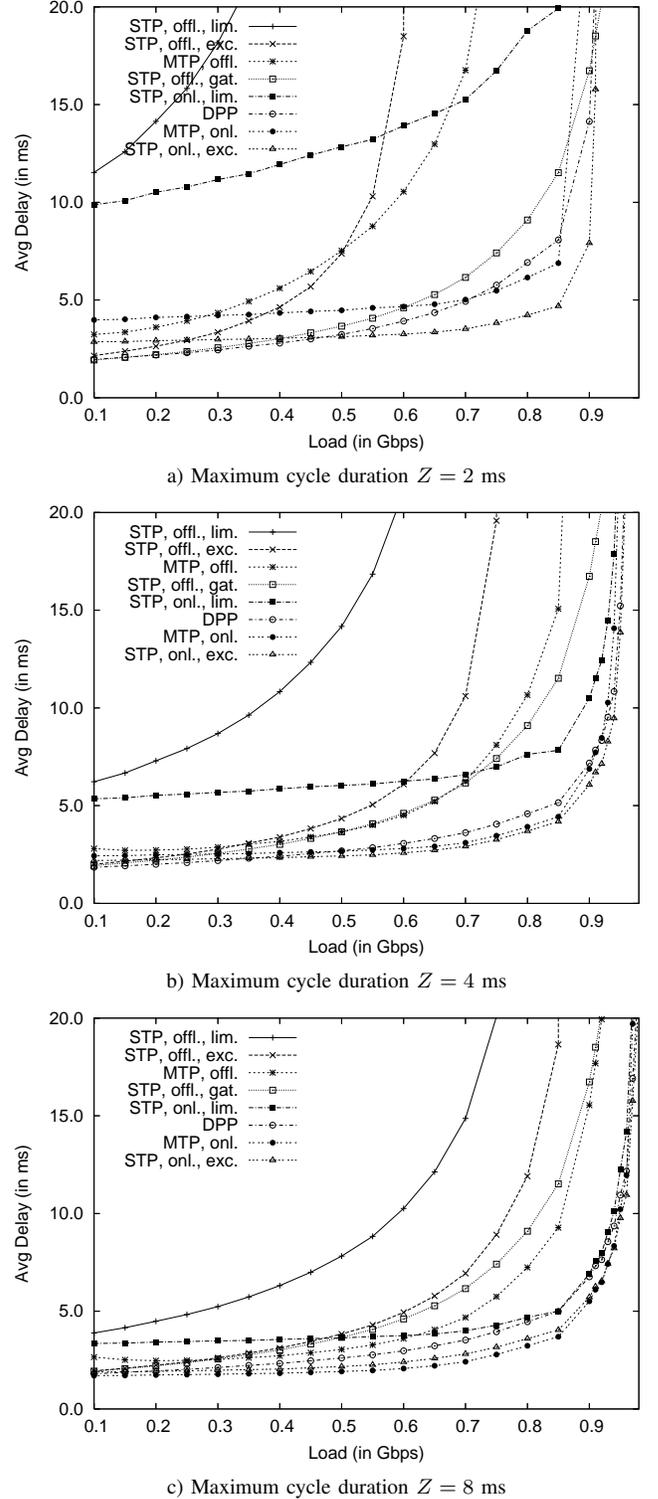


Fig. 3. Average packet delay in EPON as a function of traffic load

In contrast, online polling does not incur the  $2\tau$  channel idle period as the polling processing to the individual ONUs are interleaved. As a result, online MTP achieves moderate mean packet delays below 10 ms already for the short  $Z = 2$  ms cycle duration up to a high load of approximately 0.9 Gbps, and up to loads around 0.95 for longer cycles.

Turning to the mean grant durations in Fig. 7 we observe

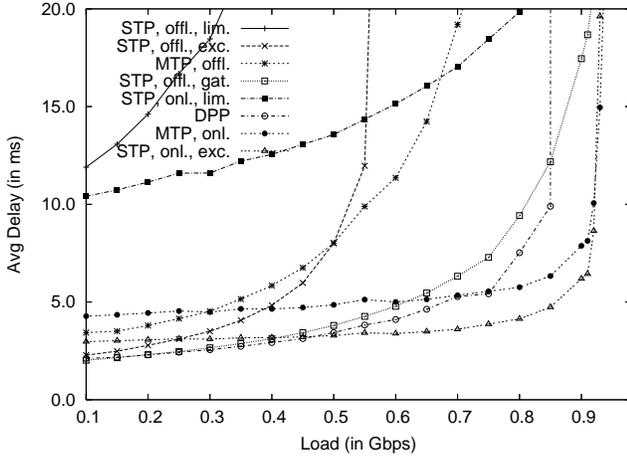
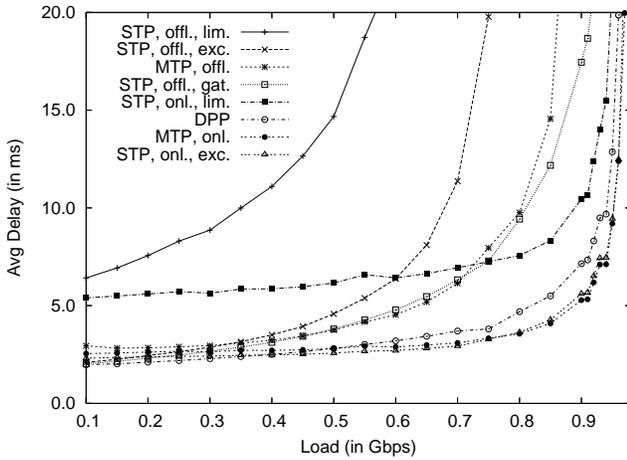
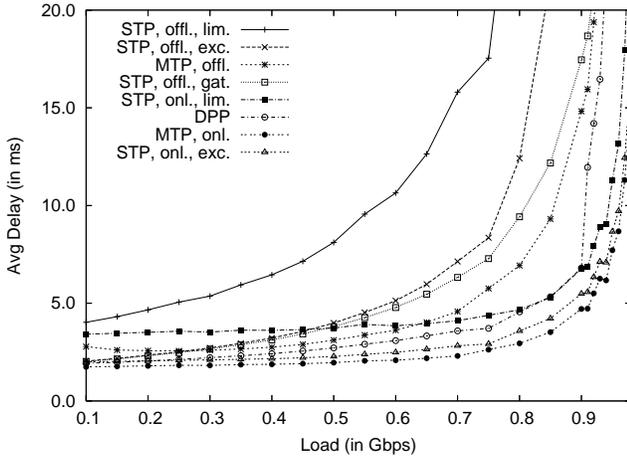
a) Maximum cycle duration  $Z = 2$  msb) Maximum cycle duration  $Z = 4$  msc) Maximum cycle duration  $Z = 8$  ms

Fig. 4. Average packet delay in GPON as a function of traffic load

that offline MTP has longer mean grant durations than online MTP. The longer grant durations are mainly due to the offline scheduling, which results in overall longer mean cycle durations, as Reports from all ONUs are collected before scheduling decisions. On average, online MTP gives smaller grant durations and shorter cycles (see Fig 5), i.e., more frequent upstream transmissions of each ONU.

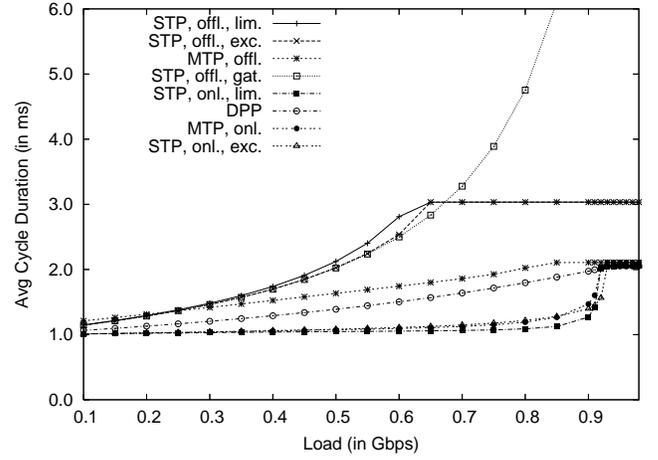
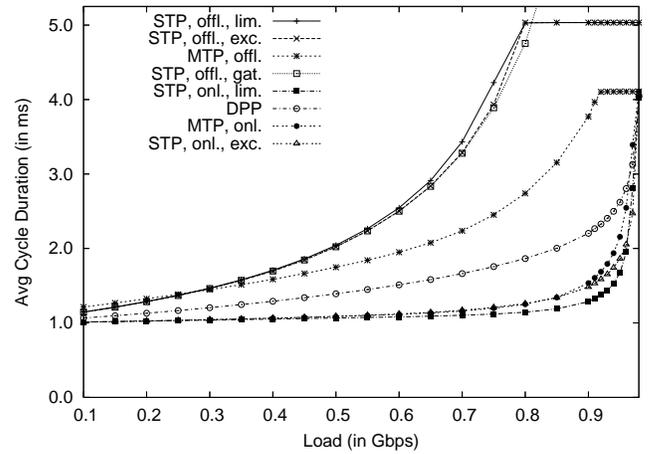
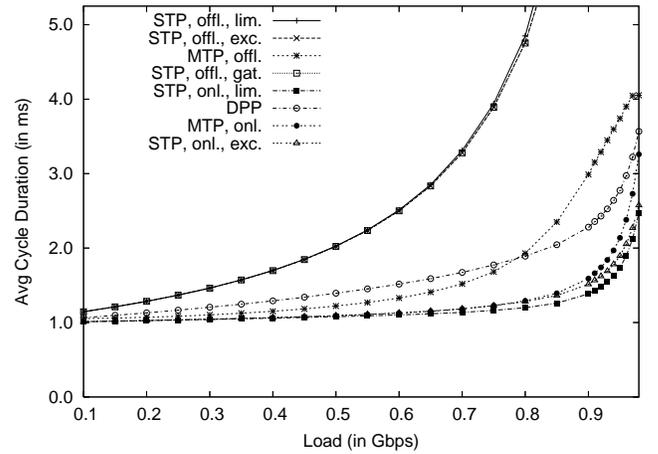
a) Maximum cycle duration  $Z = 2$  msb) Maximum cycle duration  $Z = 4$  msc) Maximum cycle duration  $Z = 8$  ms

Fig. 5. Average cycle duration in EPON as a function of traffic load

Importantly, as we observe from Fig. 9, online MTP achieves substantially shorter mean idle times than offline MTP; except for very high loads, where both MTP approaches achieve a mean idle time close to the guard time  $t_g$ . The interleaving of the multiple polling processes with online scheduling substantially reduces the mean idle time for low to moderately high loads (up to around 0.9 Gbps).

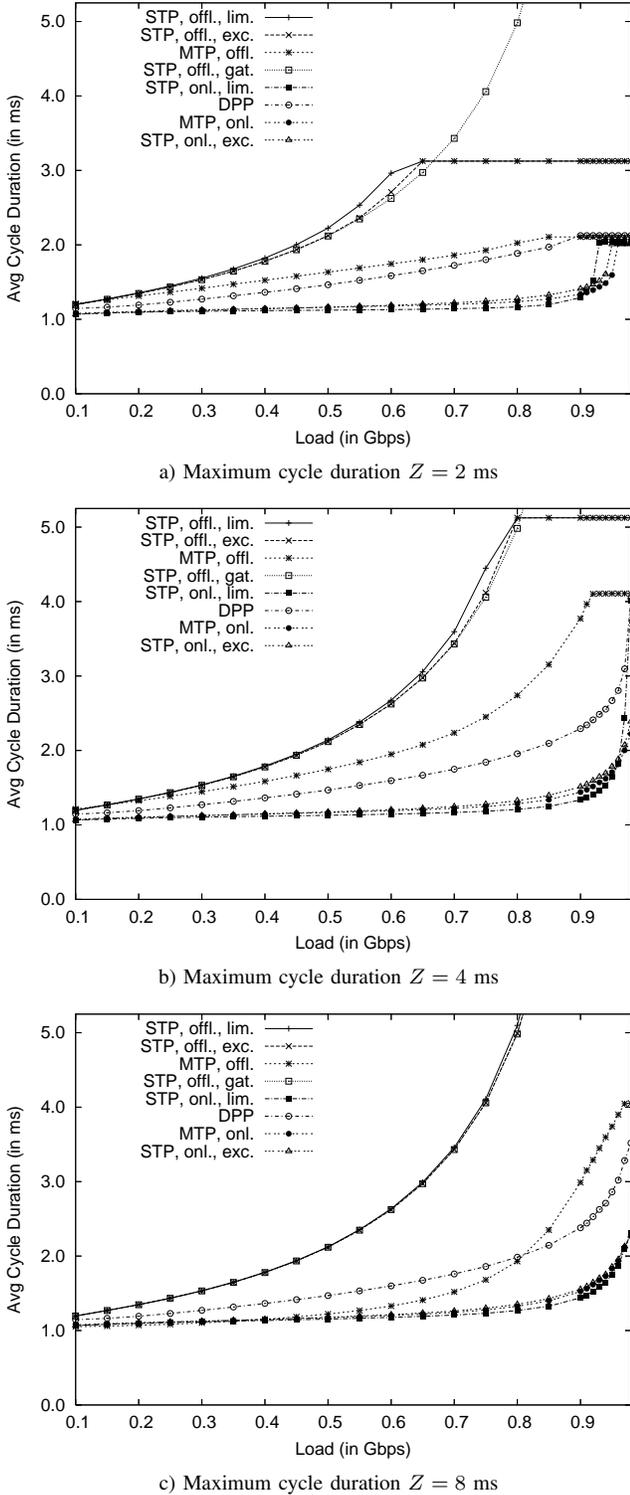


Fig. 6. Average cycle duration in GPON as a function of traffic load

For higher loads (above 0.9 Gbps), online MTP still achieves lower packet delays even though it has essentially the same mean idle time as offline MTP. This delay reduction with online MTP is mainly due to the online excess bandwidth distribution mechanism. The offline excess bandwidth distribution re-distributes bandwidth among ONUs in a given cycle. In contrast, online excess bandwidth distribution re-

distributes bandwidth temporally across cycles. That is, the online approach saves up the unused bandwidth portions  $G_{\max} - R(n, \theta, j)$  from past cycles and can allocate this “saved” bandwidth in future cycles with traffic bursts. When many ONUs have simultaneous traffic bursts, as is likely for high loads of self-similar traffic, offline MTP with its offline excess bandwidth distribution is frequently restricted by the maximum grant size, see Fig. 7. The traffic bursts are often backlogged, resulting in large mean packet delays with offline MTP that extend well beyond the range plotted in the corresponding Fig. 3(b). In contrast, online excess bandwidth distribution quickly serves colluding traffic bursts from many ONUs by temporarily extending the cycle duration with the “saved up” bandwidth. These few long grants and cycles are counter-balanced by many short cycles and grants, resulting in lower mean cycle and grant duration with online MTP (see Figs. 5 and 7).

3) *EPON v. GPON*: From our extensive evaluations we have observed that EPON and GPON give very similar delay performance and have generally very similar behaviors of the cycle, grant, and idle time durations see Figs 4, 6, 8, and 10. Only for the short  $Z = 2$  ms cycle duration and for low loads does the GPON give slightly noticeably higher delays than the EPON, as observed by comparing Fig. 4 with Fig. 3. We refer to [60], [61] for comparisons specifically focused on the EPON and GPON overheads. We observe from Figs. 3 and 4, that for a load of 0.1 Gbps, online limited STP gives a mean delay of approximately 10 ms in an EPON compared to about 11 ms in a GPON. This slightly higher GPON delay is mainly due to the static periodic signaling of bandwidth requests and upstream transmission windows within the GPON frame structure. This GPON signalling according to a static period frame structure results in slightly higher traffic backlog and delays than the flexible adaptive signaling in the EPON. With increasing traffic load and longer cycle durations this slight difference between GPON and EPON becomes negligible.

#### 4) *MTP vs. STP and DPP benchmarks*:

a) *Offline STP with excess bandwidth distribution*: We observe from Fig. 3 that offline STP with excess bandwidth distribution (henceforth referred to as offline excess STP for brevity) throughout achieves vastly lower delays than offline STP with limited grant sizing underscoring the importance of excess bandwidth distribution for low-delay service in PONs with a limited cycle duration (i.e., PONs that do not permit gated grant sizing).

We observe from Fig. 5 and 7 that all offline STP approaches have essentially the same mean cycle and grant duration, with offline limited STP having very slightly higher mean cycle and grant duration at high loads (before the cycle duration reaches its maximum at about  $Z + 2\tau = 5$  ms, the maximum grant duration  $G_{\max} = Z/O = 0.125$  ms is outside the plotted range). This is because gated and excess grant sizing accommodate traffic bursts in fewer longer grants and have then more (empty) grants without payload that only provide an ONU Report message. Thus, the gated and excess approaches go through slightly more polling cycles, slightly reducing average grant duration.

We also observe from Figs. 7 that offline MTP has roughly

half the average grant durations of the offline STP approaches. This is due to splitting the traffic load into the two threads. Corresponding to the  $G_{\max} = Z/(\Theta O) = 0.0625$  ms setting, the offline MTP mean grant size reaches its maximum at high loads.

Examining closer the mean packet delays, we observe from Fig. 3(a) that for the  $Z = 2$  ms cycle duration, offline excess STP achieves somewhat lower delays than offline MTP for loads up to about 0.5 Gbps; for longer cycles, offline excess STP gives (very slightly) lower delays than offline MTP only for very low loads. This is mainly because STP incurs relatively lower per-cycle overhead. Specifically, STP requires only one Report transmission and one guard time per ONU per cycle. On the other hand, MTP requires  $\Theta = 2$  Report transmissions and guard times per ONU per cycle. However, both approaches can transmit an aggregated grant size of at most  $OG_{\max}$  upstream per cycle.

For moderate to high traffic loads, we observe from Fig. 3 that offline MTP achieves substantially lower delays than offline excess STP. This substantial delay reduction is mainly due to the upstream transmissions of each thread growing longer for increasing traffic load. The interleaving of these increasingly longer upstream transmission threads then masks increasing portions of the  $2\tau$  channel idle period, resulting in the observed substantial delay reductions. Correspondingly, we observe from Fig. 9 that the offline STP approaches experience throughout a mean idle time of approximately  $2\tau/O = 31.25 \mu\text{s}$ . That is, within a given cycle, the offline STP upstream transmissions are spaced only a guard time ( $t_g = 1 \mu\text{s}$ ) apart, but then there is a  $2\tau$  channel idle period before the next cycle's upstream transmissions. We observe from Fig. 9(c) that the interleaving of the offline polling threads effectively reduces the idle time. As the upstream transmission threads grow long for high loads, the mean idle time of offline MTP approaches the  $t_g = 1 \mu\text{s}$  guard time.

*b) Offline STP with gated grant sizing:* We observe from Fig. 3(a) and (b) that offline STP with gated grant sizing (henceforth, offline gated STP, for brevity) gives lower delays than offline MTP for the  $Z = 2$  ms and 4 ms cycle durations. For these shorter cycle durations, gated grant sizing achieves the lower delays by permitting the uninterrupted transmission of large traffic bursts. In contrast, limited grant sizing with excess bandwidth distribution limits that total aggregate of the grant sizes in a cycle to at most  $OG_{\max}$ . Therefore, a large traffic burst needs to be transmitted over several cycles, each incurring an overhead of one Report transmission and guard time per ONU per thread. Also, as the traffic load grows very high, the upstream transmissions with gated grant sizing grow very long. As a result, the  $2\tau$  channel idle period becomes negligible compared to the very long cycle durations, allowing gated grant sizing to give relatively very good delay performance at high loads.

We observe from Fig. 3(c) that for the  $Z = 8$  ms cycle duration, offline MTP gives lower delays than offline gated STP, except for very low loads (less than 0.25 Gbps) and very high loads (above approximately 0.925 Gbps). For moderate traffic loads with the  $Z = 8$  ms cycle duration, the grant durations in each MTP thread can be sufficiently large to ac-

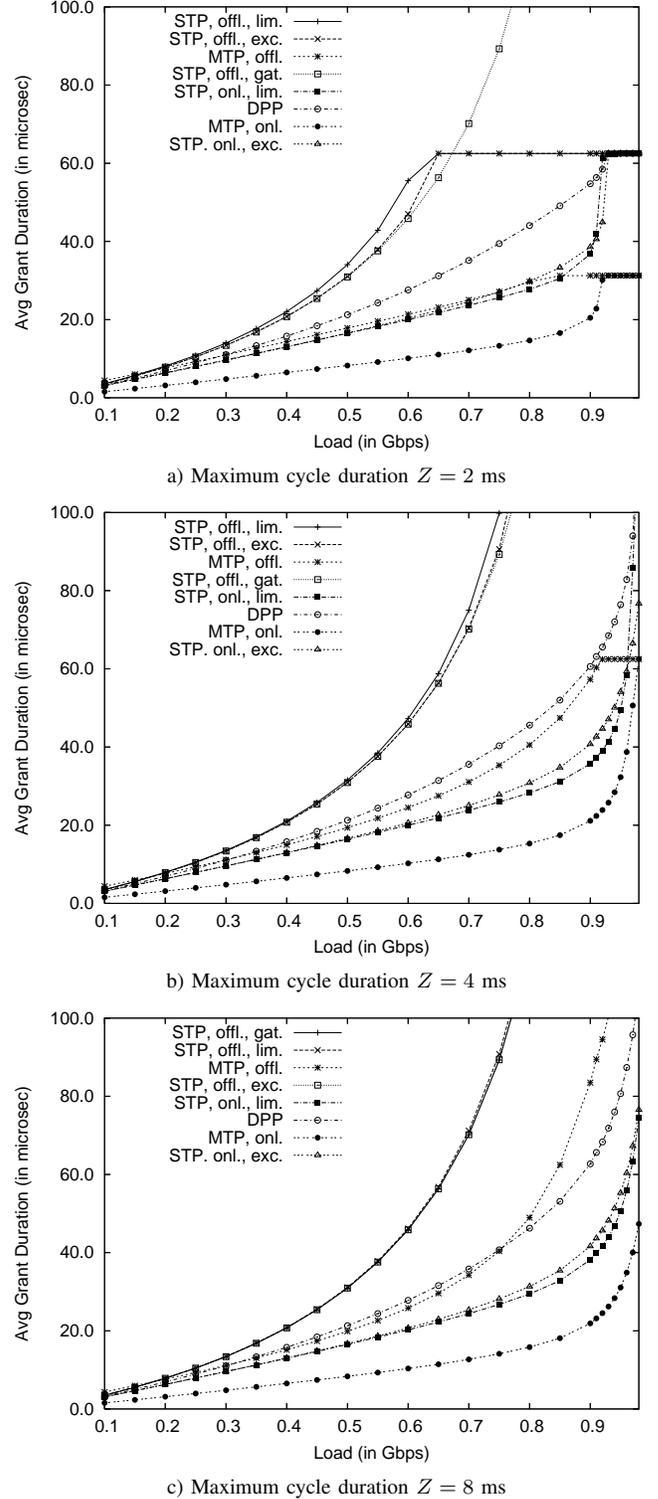


Fig. 7. Mean of grant durations  $G(n, \theta, j)$  in EPON as a function of traffic load

commodate small to moderate traffic bursts (with overhead not significantly higher than gated grant sizing) and to mask the  $2\tau$  channel idle period (which is not yet negligible compared to the gated grant sizes at these moderate load levels).

*c) Online STP with limited grant sizing:* We observe from Fig. 3 that for loads up to around 0.6–0.7 Gbps, online

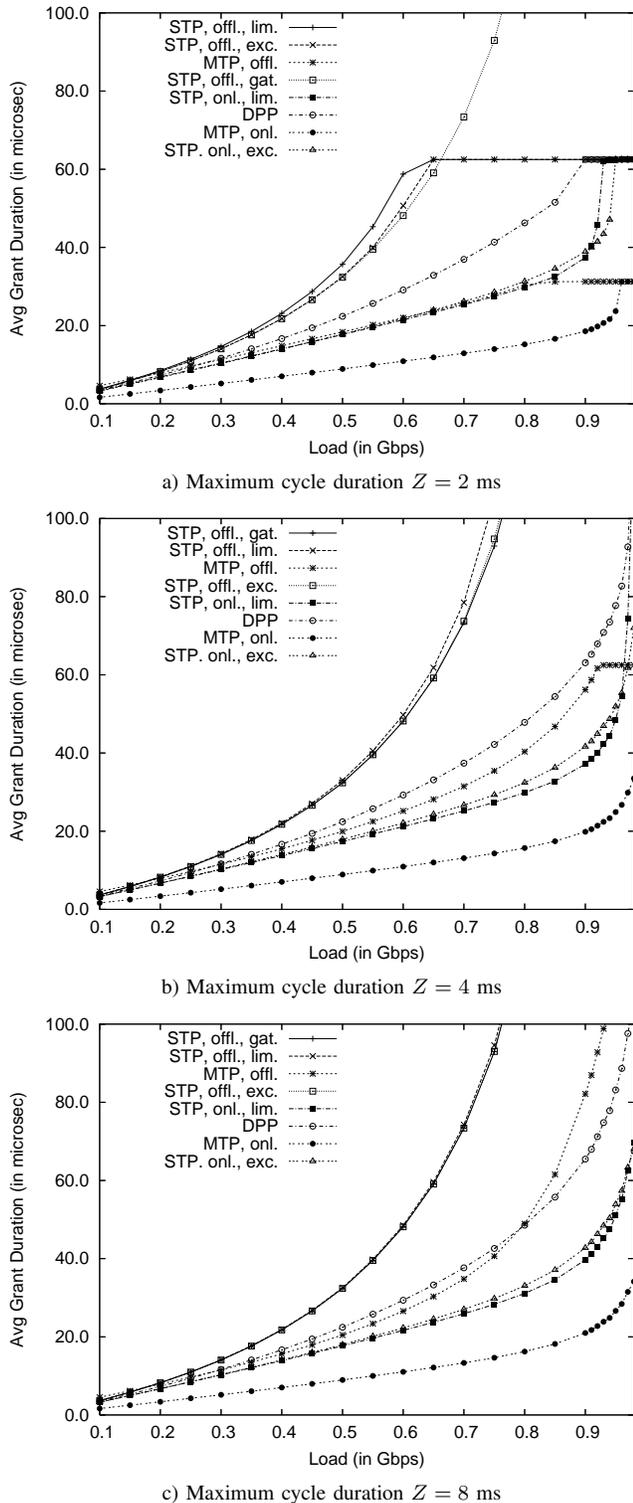


Fig. 8. Mean of grant durations  $G(n, \theta, j)$  in GPON as a function of traffic load

STP with limited grant sizing (online limited STP) gives higher delay than offline MTP, whereby the difference is more pronounced for shorter cycle durations. Bursty self-similar traffic at these lower load levels, typically produces traffic bursts in only few ONUs out of the  $O$  ONUs. Limited grant sizing without any excess bandwidth distribution strictly

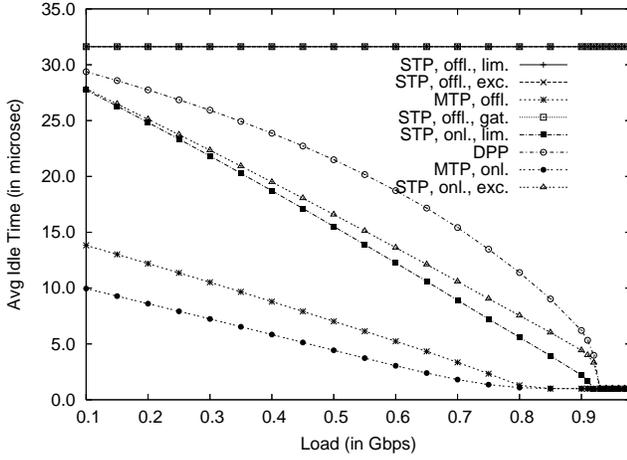
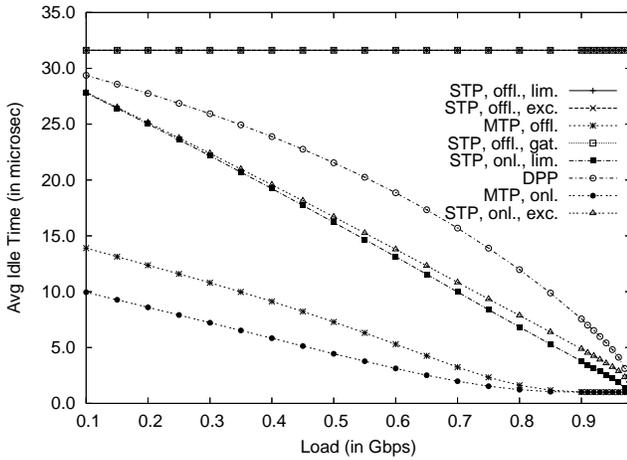
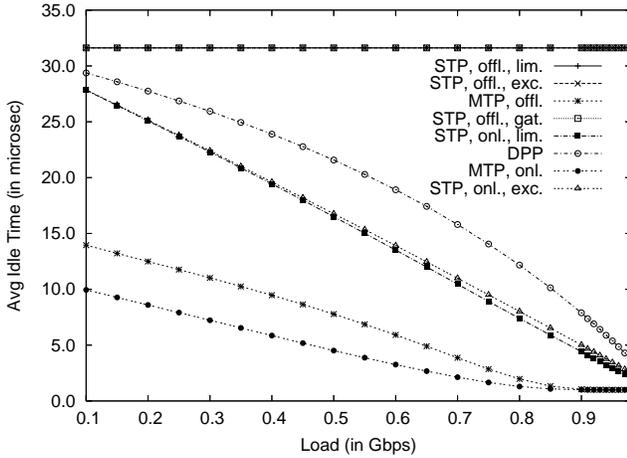
limits an ONU's grant duration to  $G_{\max} = Z/O$ . Thus, for short cycle durations, each ONU is restricted to one short upstream transmission of duration at most  $G_{\max}$  per cycle. Hence, many cycles, each incurring overhead, are required to serve traffic bursts. Importantly, the interleaving of STP processes containing only short upstream transmissions by only a few ONUs is not sufficient to mask the long  $2\tau$  round-trip propagation delay that a given ONU experiences between its successive upstream transmissions.

For loads above the 0.6–0.7 Gbps level, online limited STP gives substantially lower delays than offline MTP. At these higher loads levels, the ONUs have generally more traffic backlog, thus more ONUs are utilizing their maximum permitted  $G_{\max}$  upstream transmission window. The interleaving of a sufficient number of sufficiently long ONU upstream transmissions effectively masks the long round-trip propagation delay. At the same time, STP avoids the extra overheads of MTP as well as the thread tuning required in offline MTP to mask the  $2\tau$  channel idle period [49].

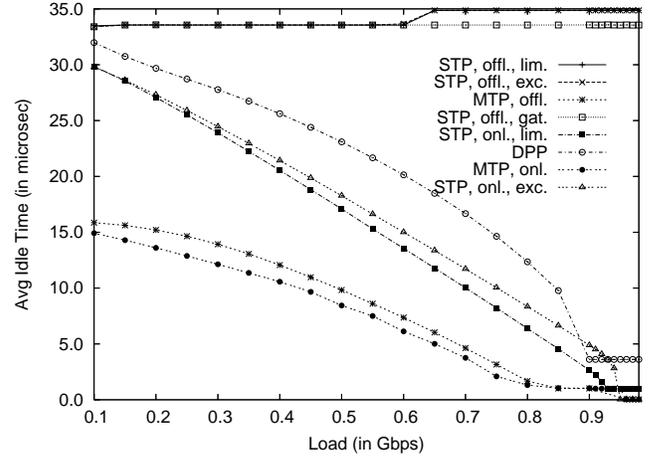
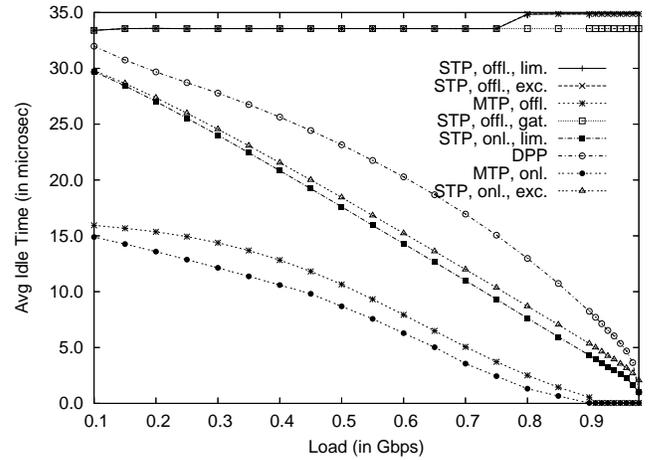
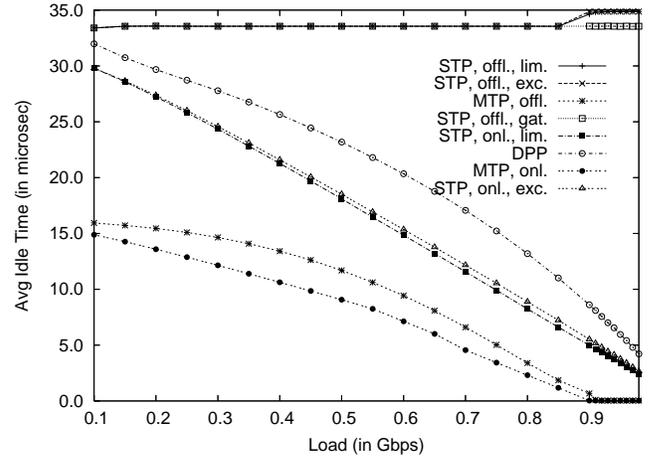
Comparing online limited STP and online STP with online excess bandwidth distribution (online excess STP), we observe from Fig. 3 that the online excess bandwidth distribution reduces the delay to less than half compared to online limited STP, whereby the delay reduction is more pronounced for short cycles. Short cycle durations  $Z$  correspond to smaller grant size limits  $G_{\max} = Z/O$ , requiring online limited STP to serve traffic burst over more successive cycles. Excess bandwidth distribution relaxes the grant size limit by accumulating unused portions of the grant size limit  $G_{\max}$  from ONUs with little or no traffic in the excess bandwidth pool and allocating this excess to ONUs serving traffic bursts. Thus, traffic burst can be served with fewer, longer upstream transmissions. (see Fig. 7).

We observe from Figs. 5, 7, and 9 that online limited STP gives generally cycle, grant, and idle time durations similar to online excess STP. The slight differences between online limited and excess STP arise mainly from excess bandwidth distribution extending some cycles to serve traffic bursts, whereas limited grant sizing taking more cycles to serve traffic bursts.

d) *Double-phase polling and online STP with excess bandwidth distribution:* We observe from Fig. 3 that double-phase polling (DPP) and online STP with online excess bandwidth distribution (online excess STP) give generally very similar delays as online MTP, especially for the longer  $Z = 4$  ms and 8 ms cycle durations. We also observe from Fig. 3(a) that DPP achieves the lowest delays at low loads for the short  $Z = 2$  ms cycle. DPP makes offline excess bandwidth allocation decisions with knowledge of the bandwidth requests of half of the ONUs (whereby each half forms an ONU group), and shares excess bandwidth across the two ONU groups [10]; thus DPP achieves almost as effective excess bandwidth distribution as offline excess STP. At the same time, DPP interleaves the single polling processes to the two ONU groups, thus striving to mask the  $2\tau$  channel idle period of offline polling and avoiding the extra overheads of MTP. For low loads, when only one or a few ONUs have traffic bursts, this ONU group-interleaving masking strategy is essentially as effective as interleaving individual online ONU polling

a) Maximum cycle duration  $Z = 2$  msb) Maximum cycle duration  $Z = 4$  msc) Maximum cycle duration  $Z = 8$  msFig. 9. Mean of idle times  $I(n, \theta, j)$  in EPON as a function of traffic load

processes. However, for high loads, when many ONUs are backlogged, the finer-grained interleaving of individual online ONU polling processes achieves somewhat more effective masking of the  $2\tau$  round-trip propagation delay than the coarse-grained interleaving of the polling processes to the two ONU groups, resulting in somewhat lower delays with the online polling approaches with excess bandwidth distribution

a) Maximum cycle duration  $Z = 2$  msb) Maximum cycle duration  $Z = 4$  msc) Maximum cycle duration  $Z = 8$  msFig. 10. Mean of idle times  $I(n, \theta, j)$  in GPON as a function of traffic load

(online excess STP and online MTP).

With the longer cycle durations, see Fig. 3(c) and (e), the larger grant size limit  $G_{\max}$  somewhat relaxes the demands for excess bandwidth distribution. Thus, the online polling approaches with online excess bandwidth distribution give similarly low delays as DPP and the offline polling approaches with offline excess bandwidth distribution at low loads.

Also, for the long  $Z = 8$  ms cycle, see Fig. 3(e), online MTP gives very slightly lower delays than online excess STP (and DPP) in the mid-load range. With this long cycle duration, the MTP grants can become sufficiently to diminish the extra MTP overhead and the improved interleaving (reduced idle time) with MTP can very slightly reduce the mean delay.

Although this evaluation study is focused on long-reach PONs, we briefly note that for conventional short-reach PONs, the propagation delay effects are less pronounced. Hence, the delay reduction effect due to the improved interleaving with online MTP diminishes compared to DPP and online STP. At the same time, online STP and DPP have lower overhead and complexity than MTP; thus online STP and DPP are well-suited DBA approaches for conventional PONs where they achieve low delay with low complexity.

## V. CONCLUSION

We have introduced online multi-thread polling (online MTP) employing multiple polling threads with online scheduling and online excess bandwidth distribution. Through online scheduling decisions immediately after receipt of each individual ONU bandwidth request, online MTP reduces the channel idle time compared to offline MTP [1].

We have compared the mean packet delay performance of offline and online MTP against single-thread polling (STP) benchmarks and double-phase polling (DPP) [12] in long-reach PONs. We have found that offline MTP gives lower delays than the offline STP benchmarks for long polling cycle durations; and lower delays than online STP with limited grant sizing [32] for short polling cycles.

We found that online MTP, DPP, and online STP with online excess bandwidth distribution give generally very similar low-delay performance with the following slight differences: (i) At low loads in short-cycle PONs, DPP gives somewhat lower delays than online STP and MTP. (ii) At high loads, online STP and MTP with excess distribution achieve slightly lower delays than DPP. (iii) In PONs with the long  $Z = 8$  ms cycle, online MTP gives very slight delay reductions compared to online STP and DPP.

Overall, based on the results of our mean delay performance evaluations, we can formulate the following recommendations for dynamic bandwidth allocation (DBA) in long-reach PONs with a round-trip propagation delay between OLT and ONUs (ONTs) on the order of 1 ms: For long-reach PONs with a short polling cycle duration of  $Z = 2$  ms, which gives the individual ONUs frequent transmission opportunities, DPP gives the lowest mean packet delays up to a traffic load around 50 % of the upstream link capacity. At higher loads, online STP (and to a lesser degree online MTP) provide some delay reduction compared to DPP at the expense of reducing the frequency of ONU transmission opportunities (due to the use of excess bandwidth and correspondingly extending temporarily the cycle duration).

For long-reach PONs with longer  $Z = 4$  ms or 8 ms cycle duration, DPP, online STP, and online MTP give very similar low-delay performance. Thus, the DBA selection can be largely based on features other than the mean delay performance. DPP ensures consistent maximum cycle durations,

i.e., minimum frequencies of ONU transmission opportunities and has only a single polling process per ONU, but requires the splitting of the ONUs into two static groups. Online STP and MTP achieve some slight delay reductions compared to DPP, but may increase the maximum cycle duration up to a bound that can be controlled through the bound on the excess bandwidth pool  $E_{\max}$  (4). Online MTP achieves some very slight delay reductions compared to online STP and DPP for the long  $Z = 8$  ms cycle duration, but increases complexity due to multiple polling threads and thread tuning compared to online STP.

There are several important directions for future research on dynamic bandwidth allocation on long-reach PONs. One direction is to examine DBA approaches providing specific quality-of-service assurances to some traffic classes, while providing overall low average delays to best effort traffic. Another direction is to examine efficient approaches for interfacing long-reach PONs with complementary networks, such as wireless local and access networks [62]–[66] as well as metropolitan and wide-area networks [67]–[73] while maintaining specific quality of service levels [74], [75].

## APPENDIX: IDLE TIME EVALUATION FOR MTP

In this appendix, we analyze the duration  $I(n, \theta, j)$  of the channel idle time preceding the arrival of the upstream transmission of the  $j$ th ONU of thread  $\theta$  in cycle  $n$ . We first determine the time instant of the end of the arrival of the preceding upstream transmission at the OLT. In case we consider the first ONU  $j = 1$  of the first thread  $\theta = 1$  of a given cycle  $n$ , then the preceding upstream transmission is that of the last ONU  $j = O$  of the last thread  $\theta = \Theta$  of the preceding cycle  $n - 1$ . On the other hand, in case of the first ONU  $j = 1$  of the second through last thread  $\theta$ ,  $\theta = 2, 3, \dots, \Theta$ , of a given cycle  $n$ , the preceding upstream transmission is that of the last ONU  $j = O$  of the preceding thread  $\theta - 1$  in this cycle  $n$ . Finally, in case of the second through last ONU  $j$ ,  $j = 2, 3, \dots, O$ , of any thread  $\theta$ ,  $\theta = 1, 2, \dots, \Theta$  of a give cycle  $n$ , the preceding upstream transmission is that of the preceding ONU  $j - 1$  in this thread  $\theta$  and cycle  $n$ . In summary, we express the instant of the arrival of the end of the upstream transmission that precedes the arrival of the upstream transmission of the  $j$ th ONU of thread  $\theta$  in cycle  $n$  at the OLT as

$$\Omega(n, \theta, j) = \begin{cases} \beta(n - 1, \Theta, O) & \text{for } \theta = 1; j = 1 \\ \beta(n, \theta - 1, O) & \text{for } \theta = 2, \dots, \Theta; j = 1 \\ \beta(n, \theta, j - 1) & \text{for } \theta = 1, \dots, \Theta; \\ & j = 2, \dots, O. \end{cases} \quad (9)$$

There must be a guard time of duration  $t_g$  between the instant  $\Omega(n, \theta, j)$  of the end of the arrival of the preceding upstream transmission at the OLT and the instant of the beginning of the arrival of the upstream transmission of the  $j$ th ONU of thread  $\theta$  in cycle  $n$ . On the other hand, this upstream transmission of the  $j$ th ONU of thread  $\theta$  in cycle  $n$  can at the earliest arrive a gate signaling delay  $T(n, \theta, j)$  after its scheduling instant  $\gamma(n, \theta, j)$ , i.e.,

$$\alpha(n, \theta, j) = \max\{\Omega(n, \theta, j) + t_g, \gamma(n, \theta, j) + T(n, \theta, j)\}. \quad (10)$$

The duration of the idle time  $I(n, \theta, j)$  preceding the arrival

of the upstream transmission of the  $j$ th ONU of thread  $\theta$  of cycle  $n$  is

$$I(n, \theta, j) = \alpha(n, \theta, j) - \Omega(n, \theta, j). \quad (11)$$

Inserting (10) into (11), we obtain for the idle time

$$I(n, \theta, j) = \max\{t_g, \gamma(n, \theta, j) + T(n, \theta, j) - \Omega(n, \theta, j)\}. \quad (12)$$

Recall from Section III-A that for online MTP, the scheduling instant  $\gamma_{\text{MTPon}}(n, \theta, j)$  of the  $j$ th upstream transmission of thread  $\theta$  for cycle  $n$  corresponds to the instant when the end of the upstream transmission of the  $j$ th ONU of thread  $\theta$  of the preceding cycle  $n - 1$  arrives at the OLT, i.e., neglecting processing delays at the OLT the scheduling instant  $\gamma_{\text{MTPon}}(n, \theta, j)$  is given by Eqn. (1). In contrast, offline MTP collects the bandwidth requests of all  $O$  ONUs of a given thread  $\theta$  from a given cycle  $n - 1$  before making scheduling decisions for all ONUs  $j$ ,  $j = 1, 2, \dots, O$ , for thread  $\theta$  in the next cycle  $n$ , resulting in the later scheduling instant  $\gamma_{\text{MTPoff}}(n, \theta, j)$  given by Eqn. (2).

The gate signaling delay  $T(n, \theta, j)$  of online scheduling is the transmission time for one GATE message plus the round-trip propagation delay to the  $j$ th ONU. For offline scheduling, the gate signaling delay for the  $j$ th ONU consists of the transmission time for  $j$  GATE messages (as the GATE messages are sent back-to-back after the scheduling decision) plus the round-trip propagation delay to the  $j$ th ONU. Note that for a given set of ONUs with heterogeneous propagation delays, the online polling processes can be launched in the shortest-propagation-delay (SPD) first order to achieve equivalent scheduling order as SPD offline scheduling [55].

In summary, we note from (12) that for a given end time of the preceding upstream transmission  $\Omega(n, \theta, j)$ , the earlier scheduling instant  $\gamma_{\text{MTPon}}$  of online MTP compared to the scheduling instant  $\gamma_{\text{MTPoff}}$  for offline MTP (as well as the slightly shorter gate signaling delay of online scheduling) imply shorter idle times for online MTP. The shorter idle times decrease the cycle duration. Decreased cycle duration generally reduces the packet delay of MTP [1]; specific simulation results demonstrating the delay reduction are presented in Section IV.

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