Low-Latency Polling Schemes for Long-Reach Passive Optical Networks

Mohammad Kiaei, Kerim Fouli, Michael Scheutzow, Martin Maier, Martin Reisslein, and Chadi Assi

***Abstract*—The increased propagation delay of future long-reach passive optical networks (LR-PONs) may lead to a significantly increased idle time and delay if optical network units (ONUs) use conventional report-grant mechanisms. Sophisticated and efficient bandwidth allocation mechanisms are required to cope with the imposed propagation delay in LR-PONs. In this study, we evaluate three dynamic bandwidth allocation (DBA) frameworks in terms of frame (packet) delay; namely, we consider conventional (interleaved) polling for traditional PON and two recently introduced scheduling paradigms for next generation LR-PON, i.e., multi-thread polling (MT-P) and real-time polling (RT-P). We enhance MT-P and RT-P by applying the just-in-time framework. Next, we provide an analytical framework for evaluating the end-to-end frame delay in our enhanced MT-P and RT-P frameworks. We compare their performance with conventional polling and double-phase polling and investigate their shortcomings and advantages in an LR-PON setting. The simulation results closely match the analysis for this framework. Also, our results indicate that RT-P significantly reduces frame delay in LR-PONs compared to MT-P and conventional polling frameworks.**

***Index Terms*—Delay analysis, ethernet PON, long-reach PON, multi-thread polling, real-time polling.**

I. Introduction

Long-reach PON is poised to be one of the major next steps in the evolution of access-metro optical networks. They essentially have the same topology as PONs and are characterized by a longer distance between the optical line terminal (OLT) and the optical network units (ONUs) as well as a larger number of ONUs. Hence, although both legacy PON and LR-PON use one upstream and one downstream channel, the maximal reach of standardized PONs is 20 km whereas LR-PONs are expected to span lengths of 100 km. Moreover, LR-PONs are expected to operate at a line rate of R = 10 Gb/s and to have 2000 to 4000 ONUs. The shift from PONs to LR-PONs translates into longer propagation delays from the OLT to the ONUs. This stipulates more sophisticated and efficient grant scheduling methods while taking care of the imposed propagation delay.

The problem of scheduling and bandwidth allocation in PONs has been widely investigated during the past few years. Several DBA methods have been introduced for various PON architectures [1]–[12]. Most of the previous studies investigate DBA methods through simulations; while a few studies employ formal mathematical analysis to uncover fundamental characteristics of various DBA approaches [13]–[16]. An analysis has been provided in [13] for evaluating the collision probability of the messages sent by ONUs to the OLT during registration which establishes the communication between new ONUs and the OLT. The analysis provides contention window sizes for an efficient registration process. Lannoo *et al.* [14] derived the mean cycle length and the approximative mean delay by using a Markov chain model for the cycle length in a multi-ONU EPON with reporting at the end of the upstream transmission. This analysis was extended in a subsequent study by Aurzada *et al.* [15], where an exact closed-form expression was derived for the delay in a gated-service single-ONU EPON with reporting at the end. Aurzada *et al.* also derived a Markov chain model for the cycle length, the exact delay in a single-ONU EPON, and an approximation of the delay in a multi-ONU EPON for gated-service EPONs with reporting at the beginning of the upstream transmission. This work was followed by [16] which provides a probabilistic analysis for the throughput and packet delay of potential next generation PONs (NG-PONs).

Most of the previous studies on delay analysis for PONs have focused on ordinary PONs which normally span less than 20 km. A formal mathematical analysis for LR-PONs is lacking in the existing literature [17]. A few polling frameworks have been introduced in recent years which can be used for LR-PONs [17]–[20]. The first candidate to address the delay problem in LR-PONs is multi-thread polling (MT-P) [21]–[23] which creates multiple interleaved polling cycle instances (i.e., "threads"). Each thread is a complete polling cycle process where all ONUs are polled once. In [21], MT-P has been compared with conventional polling in terms of average delay. The recent study [24] complements the original MT-P article [21] by comparing MT-P with "online" conventional polling, whereas [21] compared MT-P with an offline IPACT benchmark. With "offline scheduling," the OLT schedules ONUs after receiving grant requests from all ONUs on each thread, unlike "online scheduling" where the OLT schedules

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each ONU right after receiving its request. The second polling candidate for LR-PONs is real-time polling (RT-P) [25], which uses an additional separate reporting channel that allows ONUs to report increases in their queue size in real-time. These polling frameworks will be further explained in Section II.

To date, analytical investigation of the effect of different polling and system parameters on frame delay in LR-PONs has not been reported. In this study, we design an analytical framework for quantifying transmission delay and exploring the roles played by various system parameters in an LR-PON. We evaluate the advantages of MT-P and RT-P, the two recently introduced scheduling paradigms for next generation LR-PONs, and compare them with interleaved polling with adaptive cycle time (IPACT) [4], which is a benchmark algorithm for traditional PONs, and with double-phase polling (DPP) [26]. Our study is built upon previous studies on the MT-P and RT-P frameworks [21], [25], which introduced the concept of these frameworks, presented preliminary analyses, and focused on implementation issues. In this work, we first enhance MT-P and RT-P by applying the just-in-time framework [27] and introduce the adaptive MT-P and enhanced RT-P (ERT-P) frameworks. Next, we present an analytical framework for evaluating the end-to-end frame (packet) delay in the enhanced MT-P and RT-P frameworks and compare their performance with conventional polling and double-phase polling and investigate their shortcomings and advantages in a LR-PON setting. To our best knowledge, this is the first such comparison of DBA frameworks in the context of LR-PON.

The rest of this paper is structured as follows. In Section II, we address the problem statement and describe the polling frameworks which are considered in this work. The delay analysis framework for MT-P and enhanced RT-P are presented in Section III, followed by the numerical results in Section IV. We conclude our study in Section V.

II. Problem Statement and DBA Description

Generally, the bandwidth allocation procedure in PONs is carried out at the OLT, using a medium access control protocol at the MAC layer for exchanging necessary control information between the OLT and ONUs. In the downstream direction, a GATE message is used by the OLT to convey information to the ONU about the size of the allocated transmission window and the schedule of its transmission. Conversely, each ONU uses a REPORT message to transmit information to the OLT about its queue occupancies.

Fig. 1 illustrates the main differences between the existing PON and next generation LR-PON topologies. Assuming a maximum range of 100 km for LR-PON, the maximum RTT will increase to $RTT_{\max}$ = 1 ms. An LR-PON can divide ONUs into subsets and assign a separate wavelength to each subset using wavelength division multiplexing (WDM) [28].

The average frame (packet) delay is defined as the average time elapsed between a frame's generation at the ONU and its arrival at the OLT [1]. In the most general case, the different

[1]Note that an ONU might serve a single or multiple users, thus only the aggregate rate of all attached users per ONU is important.

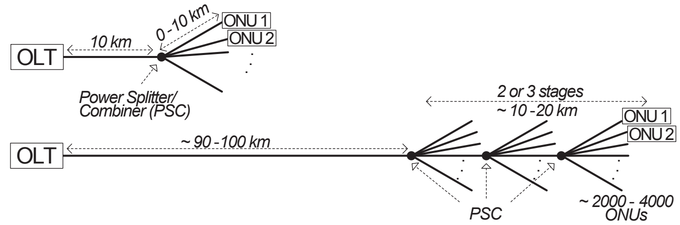


Fig. 1. Differences between PON (top) and LR-PON (bottom) topologies.

delay components experienced by a frame in polling are detailed in Fig. 2 and listed below:

- τ_R (time-to-report): Delay between frame generation and the transmission of the next REPORT message reporting it to the OLT.
- T_P (one-way propagation delay): Propagation of the REPORT message from a given ONU to the OLT. T_P may be different for each ONU.
- τ_{pr} (processing delay): Processing delay at the OLT between the arrival of the REPORT and the transmission of the GATE message.
- T_P: Propagation of the GATE message to the ONU.
- τ_G (time-to-grant): Delay between the arrival of the GATE message at the ONU and the beginning of the granted transmission window.
- τ_A (access delay): Delay between the beginning of the data transmission window and the start of frame transmission.
- T_P: Propagation of the frame to the OLT.
- τ_F (frame transmission time): Duration of the frame transmission. We have $\tau_F = F/R$, where F is the frame size in bits.

Fig. 2 explains the various delay components experienced by a single frame in a given transmission window of an ONU. This figure also illustrates the fundamental characteristics of polling. A polling cycle begins with the broadcasting of GATE messages to all ONUs and ends with the reception of their corresponding data transmissions and their REPORTs for the next cycle. If T_P is the propagation delay between a given ONU and the OLT, a frame received at the ONU experiences a minimal delay of $3T_P$, in addition to its transmission time τ_F [15]. This is due to the fact that, upon the frame's generation, a REPORT must be transmitted to the OLT and a GATE must be broadcast back to the ONU before the actual transmission of the frame becomes possible. Note that the considered frame with the transmission time τ_F is transmitted within the granted transmission window of the ONU which is shaded in the righthand side of Fig. 2.

A. Conventional Polling

Fig. 3 (a) shows an example of conventional polling in a PON with two ONUs. On the downstream channel, the OLT transmits a GATE message such that its arrival at the ONU coincides with the beginning of the granted transmission window of that ONU. It is important to note that the OLT interleaves its GATE transmissions with the reception of data so as to increase the utilization of the upstream channel.

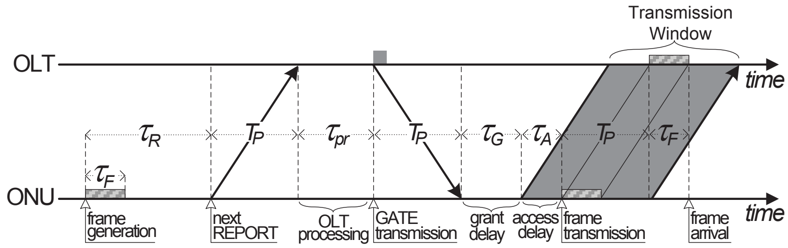


Fig. 2. Frame delay components in polling.

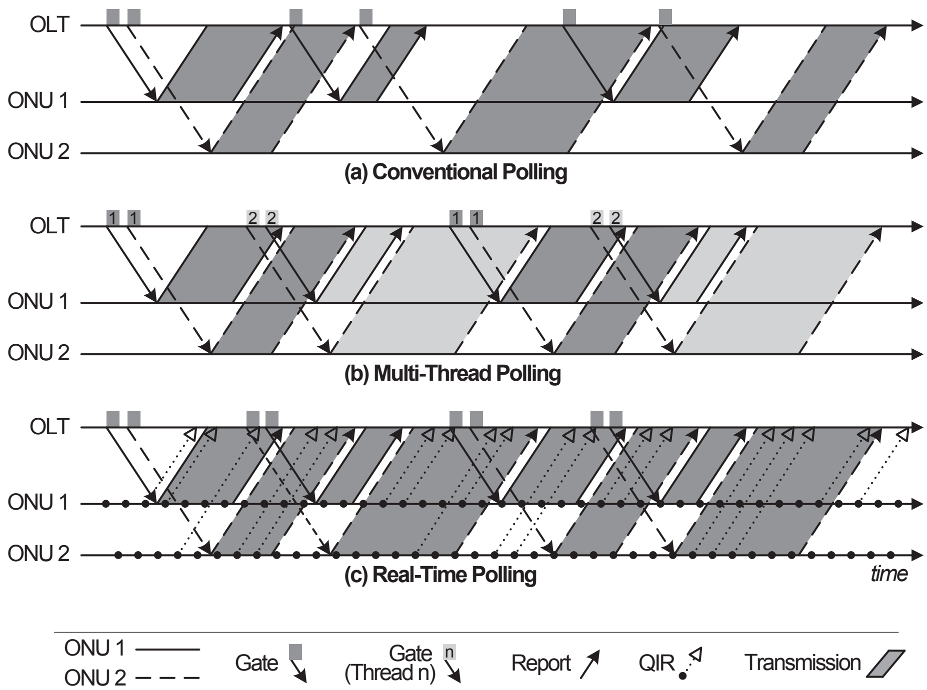


Fig. 3. Illustrations of the different LR-PON polling paradigms.

This process is called interleaved polling, and may reduce the time τ_c required by each polling cycle on the upstream channel through reducing idle time. In this scheme, GATEs are assumed to be scheduled such that their arrival at a given ONU coincides with the beginning of the granted transmission window of that ONU, hence $\tau_G = 0$. Furthermore, in the illustrations of Fig. 3, the processing delay τ_{pr} is assumed to be negligible. This is true for so-called "on-line" scheduling where the scheduling of the transmission window does not necessarily take into account the REPORT messages from all ONUs. However, other scheduling methods include "off-line" and "just-in-time (JIT)" scheduling (see [29]), where the major processing delay component, the "report-to-schedule" delay, becomes significant. The size of the allocated grant for each ONU can be determined in various ways. Among others, "gated service" and "limited service" are the two most common grant sizing techniques. In gated service, the grant size for an ONU is simply the queue size reported by that ONU. On the contrary, the limited grant-sizing technique sets the grant size to the reported queue size up to a maximum value ($W_{\max}$) for each ONU.

Conventional polling imposes a critical second constraint on the downstream transmission of GATE messages: they may not be transmitted before the arrival of the REPORT message to the OLT. Since the OLT cannot generate a GATE before receiving a REPORT, the cycle duration τ_c in conventional polling cannot fall below $RTT_{\max}$. This feature is the crucial limitation of conventional polling: it places an upper-bound on the frequency of REPORTs and data transmissions emanating from any ONU. As a result, the average frame delay increases with increasing round-trip propagation delay. To illustrate this, consider the worst-case scenario where a frame is generated an infinitesimal time after the transmission of a REPORT message. In that case the frame experiences a delay equal to the cycle time before its bandwidth is reported to the OLT. The fact that τ_c is lower-bound by $RTT_{\max}$ hence compounds the delay and capacity problem in LR-PONs. Consequently, novel bandwidth allocation methods must be explored [19], [30].

B. Multi-Thread Polling

The first candidate to alleviate the delay problem of conventional polling in LR-PONs is multi-thread polling (MT-P) [21]. MT-P creates $T \geq 1$ multiple interleaved polling cycle instances, i.e., "threads". This is illustrated in Fig. 3(b), where the REPORTs, GATEs, and data transmissions are identified by a thread number. Each thread is a complete polling cycle process where all ONUs are polled once. MT-P succeeds in reducing frame delays by giving ONUs multiple opportunities

Algorithm 1 Adaptive Multi-Thread Polling with Just-in-Time Framework

1. Initialization

(a) OLT allocates $W_{\max}/T$ to each ONU in each thread.
(b) $T_{\text{next-grant}} = N \times W_{\max}$.
(c) $GRANT_j = 0 \quad \forall j$.
(d) index = 0.

2. REPORT Collection

while $T_{\text{current}} < T_{\text{next-grant}}$ **do**
  if OLT receives REPORT from ONU_j **then**
    $GRANT_j = GRANT_j + REPORT_j$.
  end if
end while

3. Grant Allocation

(a) $GRANT_{\text{index}} = \min\left(GRANT_{\text{index}}, W_{\max}\right)$.
(b) OLT allocates $GRANT_{\text{index}}$ to ONU_{index}.
(c) $T_{\text{next-grant}} = T_{\text{next-grant}} + GRANT_{\text{index}}$.
(d) $GRANT_{\text{index}} = 0$.
(e) $\text{index} = remainder(N, \text{index} + 1)$.
(f) GOTO Step 2.

to report their queue size and to transmit data within the RTT time-period.

Threads are initially spaced $RTT_{\max}/T$ apart, hence giving the ONUs T reporting and data transmission opportunities within an $RTT_{\max}$ period. This has the effect of reducing the waiting time of frames prior to being reported and transmitted. In MT-P, fairness is achieved by allocating the excess bandwidth in each thread to overloaded ONUs. Therefore, the bandwidth allocation in each thread is performed after collecting the REPORTs from all ONUs; thus leading to the "offline scheduling" framework which results in idle time between subsequent threads. In this study, we consider the "just-in-time" (JIT) scheduling framework [29] for MT-P. This means that the OLT collects REPORTs from various threads until the channel becomes available. Then, the OLT sends the grant to the next ONU in a round-robbin fashion. We refer to this variation of MT-P as "Adaptive MT-P" as illustrated in Algorithm 1.

In the initialization step, the OLT allocates a grant size of $W_{\max}/T$ to each ONU in each thread ($W_{\max}$ is the maximum grant size in limited service and T is the number of threads). The total allocated bandwidth in all threads amounts to $N \times W_{\max}$ (N is the total number of ONUs). This indicates the start time of next the grant, i.e., $T_{\text{next-grant}} = N \times W_{\max}$. The requested grant size of ONU_j ($GRANT_j$) is initialized to zero. In Step 2, the requested grant sizes are updated based on the collected REPORTs until the channel becomes available, i.e., until the current time (T_{current}) is less than $T_{\text{next-grant}}$. Note that T_{current} is automatically increased after each grant transmission. In Step 3, the grant size of the next ONU (in round robin order) is assigned using the limited service allocation scheme.

C. Real-Time Polling

The second polling candidate for LR-PONs is real-time polling (RT-P) [25], illustrated in Fig. 3(c). RT-P uses an additional separate reporting channel that allows ONUs to report increases in their queue size in real-time. By using a separate control channel, reporting can be done independently of the upstream data traffic transmission on the legacy upstream data wavelength channel, i.e., upstream data and control transmissions are decoupled. Each ONU has the opportunity to report a queue increment of Δ_Q bytes every reporting period T_s by transmitting a Queue Increment Report (QIR) to the OLT. In addition, REPORTs continue to be issued at the end of each granted data transmission window on the conventional upstream wavelength channel. RT-P can be realized by using optical coding (OC). OC-enabled ONUs apply remote encoding, reflection, and ON-OFF modulation of a pulse stream generated at the OLT. We assume that the applied codes are orthogonal and the operation is performed in an interference-free environment. The minimum queue increment size is equivalent to the minimum frame size, leading to $T_s = 5$ μs in 1 G-EPON. This means that the pulse train is generated at a frequency of 200 KHz, which is practical using off-the-shelf switches. Smaller increment sizes do not yield higher performance as the Ethernet frames are not fragmented to lower granularity [25]. These OC enhancements allow the OLT to receive out-of-band queue status updates, i.e., QIRs, every $T_s \geq 5$ μs which is much faster than in conventional PONs, thus enabling more accurate grant sizing [31].

Algorithm 2 Real-Time Polling with Just-in-Time Framework

1. Initialization

(a) OLT allocates $W_{\max}$ for each ONU.
(b) $T_{\text{next-grant}} = N \times W_{\max}$.
(c) $GRANT_j = 0 \quad \forall j$.
(d) index = 0

2. QIR Collection

while $T_{\text{current}} < T_{\text{next-grant}}$ **do**
  if OLT receives QIR from ONU_j **then**
    $GRANT_j = GRANT_j + L_{\text{QIR}}$.
  end if
end while

3. Grant Allocation

(a) OLT allocates $GRANT_{\text{index}}$ to ONU_{index}.
(b) $T_{\text{next-grant}} = T_{\text{next-grant}} + GRANT_{\text{index}}$.
(c) $GRANT_{\text{index}} = 0$.
(d) $\text{index} = remainder(N, \text{index} + 1)$.
(e) GOTO Step 2.

There are two crucial differences between QIRs and REPORT messages. First, QIRs are pulses that can be transmitted instantaneously and at significantly higher frequencies. Second, QIRs carry incremental information about the queue whereas REPORTs carry its entire size. Therefore, the OLT needs to keep track of the queue size by adding up QIRs until the arrival of the next REPORT. QIRs enable ONUs to reduce the waiting time of frames prior to their reporting to $\tau_R < T_s$. In addition, they enable the OLT to increase the granted transmission windows on shorter notice, hence significantly reducing the total frame delay. Unlike thread-specific REPORTs in MT-P, the generation of QIRs in RT-P does not trigger GATE messages.

Similar to the MT-P in Algorithm 1, we consider the JIT framework for RT-P. This means that the OLT updates the queue length of each ONU using QIR and REPORT messages while monitoring the order of REPORT messages using a REPORT list. This procedure continues until the OLT notices that the upstream channel will become free in one round-trip propagation delay ($2T_P$) from the current time. At this moment, the OLT schedules the next ONU in the REPORT list and sends a grant based on its REPORTed request and QIR messages which have been received after the REPORT. This just-in-time approach allows the OLT to collect as much information as possible before scheduling the ONUs' upstream transmissions. Our variation of RT-P is illustrated in Algorithm 2 (L_{QIR} denotes the queue increment size).

RT-P yields high reporting accuracy as queue sizes are updated approximately T_P after frame generation at the ONU (hence the term real-time). The same accuracy of queue information at the OLT can be approached by MT-P at the cost of significant complexity for the bandwidth allocation process, such as elaborate thread duration management [21] and the tagging of GATEs and REPORTs with a thread number. In addition, RT-P introduces flexibility in its polling cycle time. Since QIRs are sent in real-time and on a different channel than data, the cycle duration τ_c is not lower-bound by $RTT_{\max}$, as is the case in conventional polling. In fact, RT-P can implement a cycle duration τ_c that is on the order of a single thread duration in MT-P ($RTT_{\max}/N$) or lower, while avoiding the complexity of MT-P.

However, MT-P does not require changes at the physical-layer, whereas RT-P improves the performance at the cost of increased complexity at the physical layer which is incurred by employing OC-enabled ONUs. Furthermore, while RT-P shifts its additional signalling (QIRs) to a separate out-of-band channel, MT-P must include its REPORTs within data frames, hence creating additional overhead. On the downstream channel, since QIRs are merely live updates of the queue status that do not necessarily trigger GATE messages, RT-P transmits only one GATE per ONU in each polling cycle. In contrast, MT-P requires T GATE messages to be transmitted downstream for each polling cycle. Besides, MT-P does not remove the requirement imposed by conventional polling to wait for a REPORT before transmitting a corresponding GATE message, see Fig. 3(a). Instead, it alleviates its consequences by creating frequent REPORT and GATE instances. On the other hand, thanks to its real-time queue updating at the OLT, RT-P completely eliminates that constraint, hence simplifying downstream GATE scheduling. Due to these differences between RT-P and MT-P, RT-P yields an improved frame delay and capacity performance as verified in Section IV.

III. Delay Analysis

A. Multi-Thread Polling

In this section, we present an analytical framework for obtaining a delay expression for MT-P based on traffic intensity and guard time between the successive transmission windows. Note that this analysis only considers the average size of the transmission window of ONUs $\mathbf{E}[\theta]$, thus allowing for arbitrary frame size distributions, e.g., trimodal IP packet size distribution [32]. In doing so, our analysis becomes quite flexible and allows to be applied to a wide range of traffic models. Let N be the number of ONUs, and ε be the guard time between consecutive ONU transmission windows (ε can also model the other overhead components, such as the REPORT transmission time, as well as the preambles and interpacket gaps for the Ethernet frames). We denote $T_P = RTT/2$ as the one-way propagation delay and T as the number of threads in MT-P where $T \geq 1$ ($T = 1$ represents conventional polling).

If $N\varepsilon \geq 2T_P$, the only overhead is the guard time after each transmission window. In this case, the lower bound of the total overhead in one thread is obtained as $N\varepsilon$, which is independent of the total traffic intensity ρ. If all N ONUs generate the same traffic, then the average length of data transmission of an ONU in one thread (θ) is given by (independently of N and T):

$$\mathbf{E}[\theta] = \varepsilon \frac{\rho}{1-\rho}. \tag{1}$$

This follows because the ratio $\rho/(1-\rho)$ indicates the proportion of the utilized part of the channel to the non-utilized part. Note that under the stated condition ($N\varepsilon \geq 2T_P$), the guard time is the only time the channel is "idle". For $\varepsilon \approx 1$ μs [33] and $T_P \approx 0.5$ ms, Equation (1) holds when the number of ONUs satisfies $N \geq 2T_P/\varepsilon = 1000$. Accordingly, the expected polling cycle length is:

$$\mathbf{C} = NT\left(\mathbf{E}[\theta] + \varepsilon\right) = \frac{NT\varepsilon}{(1-\rho)}. \tag{2}$$

We note that having more than a few hundred ONUs using the same upstream channel can result in long cycle times which is not acceptable in a LR-PON setting. Therefore, we approximate the average transmission time using Equation (1) for a smaller number of ONUs. The average time between successive reports of a given ONU can be obtained as follows:

$$N\left(\mathbf{E}[\theta] + \varepsilon\right) = N\left(\frac{\rho}{1-\rho}\varepsilon + \varepsilon\right) = \frac{N\varepsilon}{1-\rho}. \tag{3}$$

According to Fig. 2, the end-to-end delay consists of the following components:

$$\Delta_T = \tau_R + 3T_P + \tau_G + \mathbf{E}[\theta], \tag{4}$$

whereby we neglect the processing delay τ_{pr}. Also, the frame transmission time τ_F has been replaced by the average transmission window size $\mathbf{E}[\theta]$. In the best (worst) case, a packet is reported at the beginning (end) of the polling cycle. Therefore, time-to-report delay τ_R in (4) can be roughly approximated as:

$$\tau_R = \frac{N}{2}\left(\mathbf{E}[\theta] + \varepsilon\right) = \frac{N\varepsilon}{2\,(1-\rho)}. \tag{5}$$

The average value of time-to-grant (τ_G) may be taken to be roughly identical to the first component as given in Equation (5). Therefore, the end-to-end delay can be obtained as

$$\Delta_T \cong 3T_P + \frac{\varepsilon(N+\rho)}{1-\rho}. \tag{6}$$

Algorithm 3 Enhanced Real-Time Polling

1. Initialization

(a) OLT allocates $W_{\max}$ for each ONU.

(b) $T_{\text{next-grant}} = N \times W_{\max}$

2. REPORT Transmission

if ONU_j receives $PACKET_p$ **then**

ONU_j generates codeword C_p corresponding to the length of $PACKET_p$ (ℓ_p)

ONU_j sends C_p to OLT via the reporting channel

end if

3. Grant Allocation

if OLT receives codeword C_p from ONU_j **then**

OLT allocates ℓ_p to ONU_j

$T_{\text{next-grant}} = T_{\text{next-grant}} + \ell_p$

end if

B. Real-Time Polling

We provide a mathematical framework for delay analysis of a modified version of RT-P where a data transmission from an ONU consists of only a single packet. In other words, instead of sending QIR messages, each ONU is sending the actual size of each packet after its generation. We call this framework enhanced RT-P (ERT-P). In ERT-P, a codeword with a fixed size of B bits is sent to the OLT over the QIR channel to report the size of the arrived packet (out-of-band reporting). The size of the codeword B depends on the maximum size of the received packet. The B bits (B pulses) are On/Off-modulated to represent the length of the packet. This architecture allows the OC-enabled ONU to use the QIR channel for reporting the exact frame size instead of queue increments. This setting is feasible and will add minor complexity to the QIR messaging approach. The ERT-P approach is explained in Algorithm 3. As can be seen in this algorithm, upon receiving a packet, the ONU generates codeword C_p of B bits corresponding to the length of the received packet. The ONU sends C_p to the OLT via the reporting channel. At the OLT, the grant allocation is done in real-time based on the received codeword. The next grant start time $T_{\text{next-grant}}$ is updated after each grant allocation.

We propose a Markovian model of E-RTP. Specifically, modeling packet arrivals at the ONUs as Markovian arrivals (exponential inter-arrival times (M)), we propose the following model based on the M/G/1 queuing system [34]. We acknowledge that access networks often exhibit non-Markovian traffic, which poses particular modeling challenges but can also be exploited, e.g., for traffic predictions. In order to obtain a tractable model and gain basic fundamental insights into the E-RTP behaviors, we focus on the Markovian traffic model in this study. We model the service time of each packet by a general distribution (G), that accounts for reporting, scheduling, granting, and transmission. The system includes one server which is a single channel carrying one packet at a time. The offered service consists of reporting, scheduling, granting, and transmission of packets. Our analysis assumes the stability condition, i.e., that the arrival rate λ is less than the service rate μ, ensuring that there is no packet loss. The traffic intensity ρ is defined as λ/μ. We note that a key step in the modeling of the service time is to represent the round-robin service provided by RTP, where packets recently generated at a given ONU are served in an allocated transmission grant, through the first-come-first-served model that underlies the M/G/1 model.

TABLE I
NETWORK PARAMETERS

Upstream data rate	1 Gb/s
Number of ONUs	16
ONU buffer size	10 Mbytes
Guard bandwidth between adjacent slots	1 μs
Queue increment size	64 bytes
QIR period	5 μs

We define Δ as the delay component at the OLT, from the arrival of the REPORT to transmission of the GATE messages. Assuming that all ONUs are equally loaded, the average end-to-end delay is (approximately) given by

$$\Delta_T = 3T_P + \Delta, \tag{7}$$

where T_P is the one-way propagation delay from ONU to OLT and Δ is the time from REPORT arrival at the OLT until the GATE message is sent to the ONU. Note that the beginning of the transmission is immediately placed at the arrival of the GATE message to the ONU. In this case, Δ is the average waiting time in an M/G/1-queue and can be obtained from the following equation which is a variation of the Pollaczek-Khinchine formula [34]

$$\Delta = \rho \frac{(\mu_p + \varepsilon)\left(1 + \frac{\sigma_p^2}{(\mu_p+\varepsilon)^2}\right)}{2\,(1-\rho)}. \tag{8}$$

Here, ρ is the traffic intensity including the overhead ε, $\mu_p = \mathbf{E}[P]$ is the average packet transmission time, and $\sigma_p^2 = \mathbf{E}\left[(P - \mathbf{E}[P])^2\right]$ is its variance. In ERT-P, we can assume that the overhead ε per transmission is actually an overhead per packet and thus add ε to the packet length. Equation (8) is obtained under the stability condition whereby each of the N ONUs generates packets at a rate $\lambda > 0$. Substituting Equation (8) in (7), we find the average frame delay (in seconds):

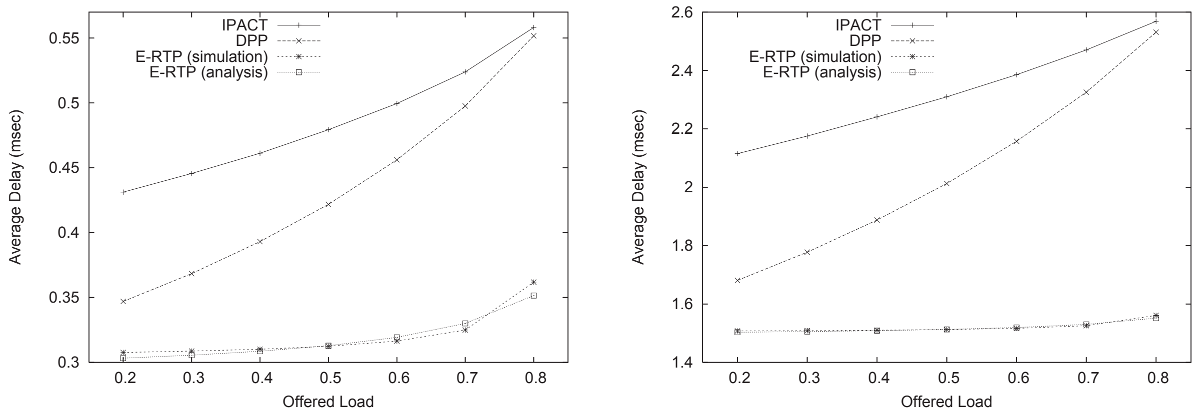
$$\Delta_T = 3T_P + \left[\frac{(\mu_p+\varepsilon)^2 + \sigma_p^2}{2(\mu_p+\varepsilon)}\right]\frac{\rho}{1-\rho} \tag{9}$$

where $\rho = \lambda N\,(\mu_p + \varepsilon)$.

IV. NUMERICAL RESULTS

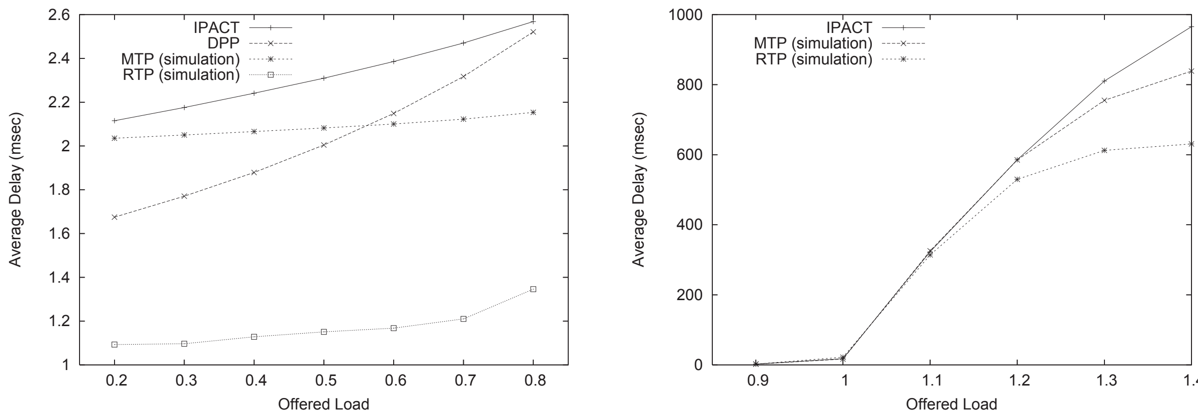
We evaluate the average frame delay of each polling framework using the OMNeT++ simulation environment [35] for a PON with an OLT-ONU distance of 20km and 100km, i.e., one-way propagation delay of 100μs and 500μs, respectively. Other network parameters are listed in Table I. We consider Ethernet frames (packets) uniformly distributed between 64 bytes and 1518 bytes. In this setting, we have $\mu_p \simeq 6.33 \times 10^{-6}$ μs and $\sigma_p^2 \simeq 1.35 \times 10^{-10}$ μs^2, and the end-to-end delay in Equation (9) is (in μs):

$$\Delta_T \cong 3T_P + 12.874 \times \frac{\rho}{1-\rho}. \tag{10}$$



(a) One-way propagation delay is $100\mu s$ (20km) (b) One-way propagation delay is $500\mu s$ (100km)

Fig. 4. Delay comparison for ERT-P with conventional polling and DPP, for gated service.



(a) Low load (b) High load (extended time-scale)

Fig. 5. Delay performance of polling frameworks with gated service when $T_P = 500\mu s$ (100km).

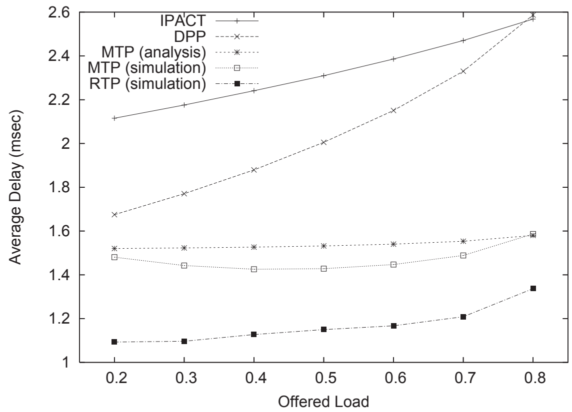
This equation presents the average frame delay in ERT-P where each packet is reported individually. Note that 11 bits (pulses) are required to report the exact packet size up to 1518 bytes. This is comparable to the average number of QIR pulses which are required for RT-P. The average size of Ethernet packets is 791 bytes. Assuming one QIR message for every 64 bytes, 13 QIR pulses are required on average for reporting each packet, i.e., a 65 μs pulse train when $T_s = 5$ μs.

We compare the LR-PON DBA frameworks with conventional polling (IPACT) for two main reasons. First, IPACT is widely used as a benchmark algorithm for traditional PONs [2], [4]. Second, this comparison highlights the shortcomings of typical report-grant based DBA algorithms in LR-PONs. Note that our goal is not to suggest any improvements for IPACT, but rather to include it in a benchmark comparison to highlight the shortcomings of traditional report-grant based DBA algorithms and show the potential performance gain. We also compare the MT-P and RT-P LR-PON DBA frameworks with Double Phase Polling (DPP) [26], since DBA algorithms based on DPP have recently been found to give the best delay-throughput performance among single-thread polling mechanisms in LR-PONs [36].

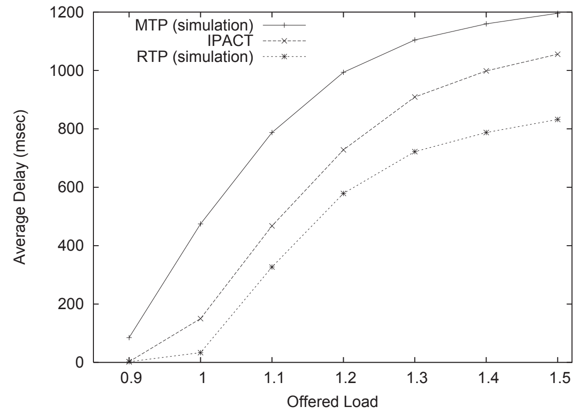
Fig. 4 illustrates the average frame delay for the IPACT and ERT-P frameworks in a short-range PON and an LR-PON with 16 ONUs. We employ "gated service", i.e., the OLT grants the entire request of each ONU. This setting results in the best performance for conventional polling [4]. Similar to [25], the 95% confidence intervals of our simulation results were smaller than 5% of the mean value. We notice that the simulation results for ERT-P match closely the analytical results derived from Eqn. (10); for both short-range PON and LR-PON, the analysis results are within 4% of the simulation results. We observe a significant delay reduction for ERT-P compared to both IPACT and DPP. The interleaving of single-thread polling processes to two ONU groups in DPP [26] significantly reduces the mean frame delay for low to moderate loads compared to IPACT single-thread polling. For high loads, the ONU transmission windows grow large such that the relative gain of the interleaving of the two ONU groups diminishes and the DPP delays approach the IPACT delays.

Henceforth, we consider the original RT-P deployment proposed in [25] and compare it with our enhanced version of MT-P (adaptive MT-P) as well as conventional polling and DPP. The number of threads in our MT-P implementation is three which yields the highest performance [21]. As mentioned in Section II, we consider the JIT framework for MT-P. Similarly, our RT-P implementation is based on the JIT scheduling framework in a round-robin fashion.

Fig. 5 illustrates the obtained average delay for the three polling frameworks when "gated service" is applied. We notice that MT-P achieves only somewhat lower delay than IPACT in this gated service setting, as the multiple threads tend to



(a) Low load



(b) High load (extended time-scale)

Fig. 6. Delay performance of polling frameworks with limited service when $T_P = 500\mu$s (100km).

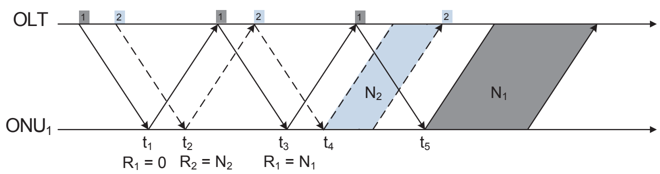


Fig. 7. Low load effect on delay performance in MT-P.

degenerate to a single thread. That is, one thread carries the bulk of the requested grants and the other threads send only small grants or empty REPORTs. This can be resolved by using thread control at the expense of higher complexity [21]. DPP provides some delay reduction compared to IPACT and MT-P in this gated service scenario if the traffic load is low to moderate; for high loads the DPP delay approaches the IPACT delay (and is therefore not plotted in Fig. 5(b) to avoid clutter). RT-P achieves the smallest delays across all loads compared to the other polling frameworks.

Recall that the delay analysis of MT-P presented in Section III-A assumes balanced bandwidth allocation among threads. Therefore, we compare analysis and simulation results for MT-P when "limited service" is in use as presented in Fig. 6. In Fig. 6, we observe remarkable improvement in MT-P and RT-P for low loads over IPACT and DPP; and for high loads we observe the excellent delay performance of RT-P. Also, the simulation results for MT-P are fairly close to the analytical values derived from expression (6). Note that the analysis presented in Section III holds under stability conditions where $\rho < 1$, as considered in Fig. 6(a). However, we extend our simulation results to higher loads in order to provide a better insight into the behavior of various polling frameworks under overload conditions.

An interesting observation in this figure is that the frame delay can be below $3T_P$ for low loads in MT-P and RT-P. This is due to the "post-reporting" condition which is illustrated in Fig. 7 for MT-P [37]. Assume that ONU_1 sends a request of $R_1 = 0$ for thread 1 and $R_2 = N_2$ for thread 2 at times t_1 and t_2, respectively. Using the just-in-time framework, the OLT receives the requests and sends gates with size 0 for thread 1 and N_2 for thread 2. Then, the ONU sends the new request of $R_1 = N_1 > N_2$ at time t_3. However, N_2 bytes of this new request have already been reported in the previous thread 2 and will be sent at time t_4. Therefore, when the OLT grants the full $R_1 = N_1$ request, the first thread can start transmitting N_1 bytes at time t_5, i.e., it can transmit N_2 bytes from packets which have been generated in the interval between t_3 and t_5, thus resulting in delays less than $3T_P$. A similar "post-reporting" effect arises with RT-P, where it can be more pronounced due to the higher frequency of sending incremental reports.

V. Conclusion

We studied the delay performance of polling frameworks for next generation long-reach passive optical networks (LR-PONs) with large propagation delay. We integrated the just-in-time framework into the multi-thread polling (MT-P) and real-time polling (RT-P) frameworks. We compared these enhanced polling frameworks with conventional interleaved and double-phase polling in terms of average upstream frame delay in traditional and long-reach PONs. Also, we introduced an enhanced real-time polling (ERT-P) method and derived an analytical framework for its delay based on an M/G/1 queuing system. We conducted the first evaluation study of RT-P for LR-PONs, which has previously only been examined for short-range PONs. We observed that the derived analytical delay characterization closely matches the simulation results for ERT-P for both short- and long-reach PONs. We found that RT-P consistently achieved the lowest frame delays in the considered LR-PON scenarios and that MT-P with proper grant sizing can achieve significantly lower frame delay than IPACT.

The presented explicit delay equations can be used to derive the bandwidth utilization efficiency of LR-PONs using either the MT-P or RT-P polling framework. More importantly, they are intended to be used in future benchmark comparison of alternative DBA algorithms by being able to quantify the performance gap, thus representing a reference for future LR-PON DBA algorithm design, similar to the benchmark role that IPACT has for conventional PONs. The obtained expressions may also be used for LR-PON network dimensioning and performance optimization under different given traffic scenarios.

Directions for future research include the delay performance analysis of LR-PONs that are integrated with metro-level networks [38]–[42] as well as LR-PONs for wireless backhaul [43].

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