EIBT: Exclusive Intervals for Bulk Transfers on EPONs

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***Abstract*—The upstream transmission of bulk data files in Ethernet passive optical networks (EPONs) arises from a number of applications, such as data backup and multimedia file upload. Existing upstream transmission approaches lead to severe delays for conventional packet traffic when best effort file and packet traffic are mixed. We propose and evaluate an exclusive interval for bulk transfer (EIBT) transmission strategy that reserves an EIBT for file traffic in an EPON polling cycle. We optimize the duration of the EIBT to minimize a weighted sum of packet and file delays. Through mathematical delay analysis and verifying simulation, we demonstrate that the EIBT approach preserves small delays for packet traffic, while efficiently serving bulk data file transfers.**

***Index Terms*—Bulk data transmission, delay analysis, Ethernet passive optical network (EPON), file transfer, packet transmission.**

I. INTRODUCTION

THE Ethernet passive optical network (EPON) is widely considered a low-cost and high-bandwidth solution for last mile Internet access [1]–[6]. An EPON has typically a point-to-multipoint network topology connecting an optical line terminal (OLT) to multiple optical network units (ONUs). Downstream transmissions are broadcast from the OLT to all ONUs on the downstream wavelength channel, while the upstream transmissions of the ONUs share a single upstream wavelength channel. Access to the shared upstream wavelength channel is controlled with the multipoint control protocol (MPCP) to avoid collisions due to multiple ONU transmissions. MPCP supports a cyclic polling procedure whereby ONUs report their queue occupancies to the OLT. The OLT dynamically allocates bandwidth to the individual ONUs [7]–[11] and schedules corresponding grants for upstream transmission windows so as to avoid collisions [12]–[16].

As reviewed in detail in Section II, a wide range of studies have examined the polling-based medium access control in EPONs for best effort packet traffic. The premise of this study is that in addition to conventional best effort packet service, e.g., for web browsing and e-mail applications, there is a growing need for a best effort bulk data (file) transfer service. For instance, the growing demand for online backup (e.g., mozy, carbonite), cloud storage (e.g., dropbox, google drive), and photo/video sharing (e.g., flickr, youtube) applications requires the upstream transmission of bulk data files. File transfer performance is emerging as one of the key evaluation metrics of access networks [17]. Thus, there is a need to investigate dynamic bandwidth allocation for EPONs to accommodate bulk data transfers.

The bulk data transfer applications are giving rise to emerging networking paradigms supporting network control and signaling based on data (file) objects, such as content centric networking (CCN) [18], [19], and network bandwidth management for bulk data transfers, such as dynamic optical circuits [20], [21]. For this study, we suppose that signaling and bandwidth management mechanisms are in place in the local and metro/wide area networks to signal and deliver bulk data files from the source node to the ONU and from the OLT to the destination node. The focus of this study is on effective medium access control and bandwidth management for best effort packet and bulk data file service in the upstream direction from ONUs to OLT in an EPON access network.

Conventional grant sizing and scheduling methods are poorly suited to simultaneously support packet traffic and bulk data file traffic. Gated grant sizing [22] grants an ONU a window large enough to transmit its entire reported queue occupancy upstream. Thus, a large file of one ONU would severely delay subsequent packets in all ONUs. Limited grant sizing constrains an ONU's upstream transmission window to a fixed maximum per polling cycle. Thus, if one ONU transmits a large file, limited grant sizing protects the packet traffic from the other ONUs from being delayed by the file transmission. However, the packet traffic at the ONU with the large file is delayed if file and packet traffic are served in first-in-first-out (FIFO) order from a single ONU queue. Separate queues for packet traffic and file traffic can overcome this problem by permitting packets that were generated after a large file to be served before the transmission of the large file is complete (while still operating each queue in simple FIFO manner).

In this paper, we propose and evaluate dynamic bandwidth allocation mechanisms for EPONs that support conventional packet traffic and bulk data file traffic which feed into two separate queues at each ONU. We limit the total upstream transmission time that is allocated to file traffic in a polling cycle to an exclusive interval for bulk transfer (EIBT) of maximum duration Δ [in seconds]. Conventional packet traffic is served

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with gated grant sizing. (Limited grant sizing for packet traffic in conjunction with a limited EIBT for file traffic is left for future research.)

Transmitting files of average size $\bar{F}$ [bit] from J ONUs in parallel over a link of bit rate C [bit/s] gives an average file delay of $J\bar{F}/C$. On the other hand, transmitting the files sequentially, i.e., one after the other, gives an average file delay of $(J+1)\bar{F}/(2C)$, almost halving the mean file delay for large J. Therefore, we serve files in FIFO order across all ONUs. (Files reported in the same polling cycle are served in smallest file first order to minimize the average file transmission completion time.) That is, reports of files enter a FIFO queue at the OLT. The currently served file receives the full EIBT of duration Δ in each cycle until the file transmission is complete.

This paper is organized as follows. In Section II, we review related work. In Section III, we present the EPON network structure, introduce the packet and file traffic models, and define the packet delay, file delay, and weighted delay metrics. In Section IV, we introduce two forms of the EIBT polling strategy, namely successive EIBT polling and interleaved EIBT polling. We also formulate the stability conditions for EIBT polling in Section IV. In Sections V and VI, we analyze the packet and file delays in successive and interleaved polling, respectively. We also identify the optimal EIBT duration Δ^* that minimizes the weighted delay metric. In Section VII, we present numerical results from our delay analysis and verifying simulation results that illustrate the packet and file delay performance of EIBT polling. Finally, in Section VIII, we summarize our conclusions.

II. RELATED WORK

Providing some prescribed level of quality of service (QoS) for packet traffic in EPONs has been the focus of a number of studies, e.g., [23]–[34]. In particular, the problem of providing differential QoS for different classes of packet traffic has attracted significant research interest; see, e.g., [35]–[46]. These existing approaches strive to provide some packet traffic flows with higher QoS, e.g., lower delays, relative to the best effort packet traffic. Our study is complementary to these existing approaches in that we focus on best effort traffic and develop polling mechanisms to accommodate both packet traffic as well as file traffic in EPONs. To the best of our knowledge, this is the first study to segregate bulk data file traffic from conventional packet traffic for distinct consideration in the dynamic bandwidth allocation in an EPON access network.

Reliable file transmission commonly employs the transmission control protocol (TCP), which has been extensively studied for large files [47]–[49]. The interactions between TCP and medium access control (polling) mechanisms in EPONs have been examined in [50]–[53], while P2P file sharing with conventional packet-based service in EPONs has been studied in [54]. This study focuses on effective EPON polling mechanisms for packet and file service.

The delay performance for conventional best effort packet service in EPONs has been analyzed in [55]–[60]. In contrast, we analyze the packet and file delays for combined packet and file best effort service in EPONs.

TABLE I
SUMMARY OF MAIN MODEL NOTATIONS

	Network structure
C	Transmission rate [bit/s] of upstream channel
J	Number of ONUs
τ	One-way propagation delay [s]
	Traffic model
$\bar{P}$, σ_P^2	Mean [bit] and variance of packet size
$\bar{F}$, σ_F^2	Mean [bit] and variance of file size
$\pi = \lambda_P \bar{P}/C$	Packet traffic intensity (load); λ_P is aggregate packet generation rate [packets/s] at all J ONUs
$\phi = \lambda_F \bar{F}/C$	File traffic intensity (load); λ_F is aggregate file generation rate [files/s] at all J ONUs
	Polling protocol
Δ	Duration [s] of Exclusive Interval for Bulk Traffic (EIBT) per polling cycle
ω	Mean per-cycle overhead time [s] for upstream transmissions (report transmission times, guard times)
$\mathbb{E}Z$	Mean cycle duration [s]
	Delay metrics
D_P	Mean packet delay [s]
D_F	Mean file delay [s]
α	Packet delay weight
$D = \alpha D_P + (1-\alpha) D_F$	Weighted delay metric [s]

III. NETWORK MODEL

A. Network Structure

We consider an EPON with J ONUs attached to the OLT via a single downstream wavelength channel and a single upstream wavelength channel. We denote C for the transmission rate of a channel [bits/s]. We denote τ [s] for the one-way propagation delay between OLT and ONUs, which we consider to be equidistant from the OLT. We denote Z_n [s] for the duration of polling cycle n and denote $\mathbb{E}Z$ for the long-run average cycle duration. The model notations are summarized in Table I.

B. Traffic Model

For conventional packet traffic, we let $\bar{P}$ denote the mean packet size [in bit] and σ_P^2 denote the variance of the packet size. For bulk data file traffic, we denote $\bar{F}$ and σ_F^2 for the mean size [bit] and variance of the files size, respectively. We consider scenarios with $\bar{F} \gg \bar{P}$.

We let $\lambda_P(j)$ denote the Poisson process arrival rate [packets/s] of conventional packet traffic at ONU j and denote by $\pi(j) := \bar{P}\lambda_P(j)/C$ the corresponding traffic intensity (load). We model the bulk data file arrival at ONU j, $j = 1, \ldots, J$, with a Poisson process with rate $\lambda_F(j)$ [files/s] and denote $\phi(j) := \bar{F}\lambda_F(j)/C$ for the corresponding traffic intensity. In this mathematical arrival model, the entire bulk data file arrives at the ONU at the arrival instant. This arrival model is consistent with real local area networks that deliver the file from a source node to the ONU at a higher bit rate than the EPON transmits the file upstream. That is, at a given arrival instant in the model, not the entire file needs to be buffered at the ONU in the corresponding real network; rather, 1) at the arrival instant, the ONU needs the file size so that it can be included in the next report to the OLT, and 2) the file needs to arrive to the ONU such that at least $C \cdot \Delta$ bit are ready for upstream transmission for each EIBT.

The total traffic intensity at ONU j is $\pi(j) + \phi(j)$. We suppose that the generation processes of the packets and files are independent. Finally, we set $\pi := \sum_j \pi(j)$ and $\phi := \sum_j \phi(j)$.

Throughout, we define the packet sizes and file sizes to include the per-packet overheads, such as the preamble for Ethernet frames and the interpacket gap, as well as the packet overheads when packetizing files for transmission.

C. Delay Metrics

We define the packet delay D_P as the time period from the instant of packet arrival at the ONU to the instant of complete delivery of the packet to the OLT. We define the file delay D_F as the maximum delay of a packet carrying a part of a given file, i.e., the file delay is the time period from the instant of file arrival to the ONU to the instant the file is completely received by the OLT.

We define the weighted delay metric

$$D := \alpha D_P + (1 - \alpha) D_F \tag{1}$$

where $\alpha,\ 0 < \alpha < 1$, is the weight assigned to packet traffic. Setting α to large values close to one favors packet traffic, while setting α to small values close to zero favors file traffic.

IV. EIBT POLLING

In this section, we present the detailed EIBT polling mechanisms and derive the stability limit of EIBT polling. We initially consider an EPON with only best effort packet service, that is, all traffic is treated as best effort traffic irrespective of timing constraints of the network applications, and explain how to introduce EIBT polling in such a best effort EPON. We define two categories of best effort traffic: bulk file traffic consists of all data files that are larger than a prescribed size threshold (e.g., a few megabytes) and are signaled as bulk files by the network application to the ONU. The detailed network signaling, which can be based on similar mechanisms as CCN [18], [19] or dynamic circuit/flow switching [20], [21], are beyond the scope of this study. We briefly outline that with CCN, a bulk data file and all packets carrying a part of the data file are identified by unique names that can be hierarchical such that packets are readily identified as part of a bulk data file. In CCN, a data file is requested through an "Interest" packet that travels from the requesting node to the source node and prepares name-based routing entries in the individual switching nodes for the transmission of the data file in the reverse (from source node to requesting node) direction. As such an Interest packet traverses the EPON downstream, the OLT and ONU can take note of the name of the data file that will arrive from one of the attached nodes (for upstream transmission from ONU to OLT), and then process the incoming data file traffic as bulk file traffic. An approach based on dynamic circuit or flow switching principles [20], [21] signals and establishes a temporary circuit/flow for the transmission of a bulk data file from a source node to the ONU (and from the OLT to the destination node). These signaling mechanisms introduce some complexity and may impact the overall network performance; evaluating the signaling complexity and performance impact is an important direction for future research.

In EIBT, conventional packet traffic encompasses all other traffic that is not bulk file traffic. The ONU has two best effort FIFO queues: one queue for bulk file traffic and another queue for conventional packet traffic. Based on the outlined signaling for bulk file traffic, tags similar to those employed in virtual LANs [61] can be used to segregate bulk file traffic from conventional packet traffic.

The introduced scheduling paradigm provides an exclusive interval for bulk data transmission (EIBT) of duration Δ in each upstream transmission cycle of duration Z_n, as long as there is file traffic to transmit upstream. In order to accommodate the EIBT, we augment the conventional offline scheduling framework [3], [6], where each ONU reports its bandwidth demands once per cycle, and scheduling decisions take the reports from all ONUs into consideration. A given cycle n contains a period of variable duration δ_n [s] for the transmission of conventional packet traffic and an EIBT of maximum duration Δ. During an EIBT, a large file (from one ONU) is transmitted (if the transmission of a file ends in an EIBT, then the transmission of a new file starts). Other files are queued in a FIFO manner. In addition to the processing of the reports and grants for conventional packet traffic, EIBT polling requires the OLT to keep track of the reported files and to issue a grant (or two) for the EIBT; hence, the increase in OLT processing complexity is relatively low. We consider two natural strategies for embedding the EIBT in the conventional polling cycle: successive EIBT polling and interleaved EIBT polling.

We remark that the proposed EIBT polling can be similarly introduced in EPONs providing packet service with QoS in addition to best effort packet service. Essentially, in such QoS EPONs, the best effort portion of the polling cycle is partitioned into a period for conventional best effort packet and an EIBT. Detailed studies of the integration of the EIBT polling with specific QoS approaches for EPONs are an important direction for future research.

A. Successive EIBT Polling

1) Overview: With successive EIBT polling, as illustrated in Fig. 1, the EIBT is appended to the conventional packet upstream transmission period. If queue occupancies are reported by each ONU during the conventional packet upstream transmission period, the queue occupancy information may be outdated after a relatively long EIBT. In order to avoid bandwidth allocation based on outdated queue information, our successive EIBT polling lets all ONUs report queue occupancy information at the conclusion of the EIBT period, as illustrated in Fig. 2. Based on these reports received at the end of a given cycle $n-1$, the OLT sizes and schedules the upstream transmission grants for the next cycle n. Note that the reporting of the queue occupancies at the end of the EIBT in cycle $n-1$ and the downstream propagation of the grants for cycle n introduces an idle time of duration 2τ between two successive cycles.

2) Overhead: We denote ω [in seconds] for the mean per-cycle upstream transmission overheads, which are neglected in the illustration in Fig. 1. Mainly, the report transmission time t_R and the guard time t_g between successive upstream transmissions from different ONUs in a cycle contribute to the per-cycle overhead. For successive polling, we denote η for the steady-

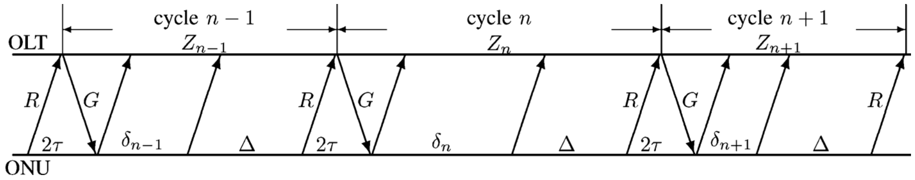


Fig. 1. Illustration of successive EIBT polling: ONUs report bandwidth demands after the end of the EIBT of cycle $n-1$. Based on the reports (R), grants (G) are issued for upstream transmission in cycle n. There is an idle period of duration 2τ between successive cycles, which allows up-to-date reports to be used for grant sizing and scheduling.

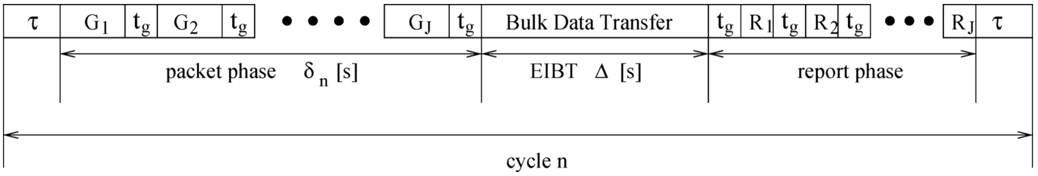


Fig. 2. Detailed illustration of cycle n in successive EIBT polling. ONUs j with packets send them upstream during their granted transmission windows G_j in the packet phase. Bulk file data are transmitted during the EIBT of duration Δ. Then, all J ONUs report newly arrived packet and file traffic to the OLT.

state probability that an ONU transmits packet traffic upstream in a given cycle. An ONU transmits packet traffic if at least one packet arrived and was reported at the end of the preceding cycle, i.e., for Poisson packet arrivals at rate λ, $\eta = 1 - e^{\lambda \mathbb{E}Z}$. For simplicity and in order not to obscure the main analysis steps, we conservatively set $\eta = 1$ for the remainder of this paper. We neglect the schedule computing time at the OLT and downstream transmission time for the first grant message of a cycle (subsequent downstream grant transmission times are masked by the upstream transmissions of the cycle [62]) in our analytical model; these overheads could be lumped into ω. Each of the ONUs transmitting packet traffic requires one guard time during the packet transmission phase. In addition, a guard time is required after the EIBT and then the J ONUs send their reports, see Fig. 2. Thus

$$\omega = J \cdot [t_R + (1+\eta)t_g]. \tag{2}$$

3) Cycle Duration: We observe from Fig. 1 that the cycle duration consists of the roundtrip propagation delay, the packet phase followed by the EIBT, as well as the overhead time ω (neglected in Fig. 1), i.e.,

$$\mathbb{E}Z_n = 2\tau + \mathbb{E}\delta_n + \Delta + \omega. \tag{3}$$

The mean duration of the packet phase $\mathbb{E}\delta_n$ corresponds for gated packet service to the transmission time for the packet traffic generated and reported in the preceding cycle of duration $\mathbb{E}Z_{n-1}$, i.e.,

$$\mathbb{E}\delta_n = \frac{\lambda \bar{P} \mathbb{E}Z_{n-1}}{C}. \tag{4}$$

In turn, expressing $\mathbb{E}Z_{n-1}$ with (3) gives

$$\mathbb{E}\delta_n = \frac{\lambda \bar{P}}{C}(2\tau + \mathbb{E}\delta_{n-1} + \Delta + \omega). \tag{5}$$

We note from (5) that in order for the network to be stable, the packet traffic amount $\lambda \bar{P} \mathbb{E}\delta_{n-1}$ that arrived during the packet phase of cycle $n-1$ must be less than the amount of packet traffic $C\mathbb{E}\delta_n$ served during the packet phase of cycle n, i.e., $\pi \mathbb{E}\delta_{n-1} < \mathbb{E}\delta_n$, which requires $\pi < 1$ for a stable network. Noting that in steady state $\mathbb{E}\delta_n = \mathbb{E}\delta_{n-1}$ and denoting $\mathbb{E}\delta$ for the steady-state mean duration of the packet phase, we obtain

$$\mathbb{E}\delta = \frac{\pi}{1-\pi}(2\tau + \Delta + \omega). \tag{6}$$

Inserting in (3) gives the mean cycle duration

$$\mathbb{E}Z = \frac{2\tau + \Delta + \omega}{1-\pi}. \tag{7}$$

B. Interleaved EIBT Polling

1) Overview: With interleaved EIBT polling, each ONU reports its queue occupancy during the conventional packet traffic upstream transmission phase of a given cycle $n-1$. The EIBT of cycle $n-1$ immediately follows the packet phase δ_{n-1} and masks the delay for the upstream propagation of the last report and downstream propagation of the grants for cycle n. Thus, at the expense of sizing and scheduling grants for cycle n based on queue occupancies that were reported before the EIBT in cycle $n-1$, interleaved EIBT polling avoids idle time on the upstream channel.

2) Overhead: With interleaved EIBT polling, each ONU sends one report and requires one guard time per cycle (plus one guard time after the EIBT), i.e., the mean overhead time per cycle is

$$\omega = J(t_R + t_g) + t_g. \tag{8}$$

3) Cycle Duration: For interleaved EIBT polling, we observe from Fig. 3 that a cycle consists of the packet phase, the EIBT, and the overhead time (neglected in Fig. 3), i.e.,

$$\mathbb{E}Z_n = \mathbb{E}\delta_n + \Delta + \omega. \tag{9}$$

Notice that in comparison to the cycle duration for successive EIBT polling (3), the cycle for interleaved EIBT polling does not include the 2τ roundtrip propagation delay. Retracing the analysis in Section IV-A3, we obtain the expected cycle duration for interleaved EIBT polling

$$\mathbb{E}Z = \frac{\Delta + \omega}{1-\pi}. \tag{10}$$

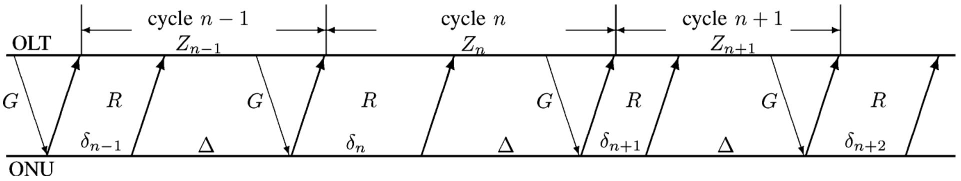


Fig. 3. Illustration of interleaved EIBT polling. Reports (R) transmitted during the conventional packet transmission phase of cycle $n-1$ are used to determine upstream transmission grants (G) for cycle n. Idle time on the upstream channel is avoided by basing grants for cycle n on the reports from before the EIBT of cycle $n-1$.

C. EIBT Stability Conditions

As noted in the analysis leading to (6), stability of the network requires that

$$\pi < 1. \tag{11}$$

Moreover, large files are only served during the EIBT of fixed duration Δ within a cycle of expected duration $\mathbb{E}Z$. The amount [in bit] of file traffic generated during a cycle $\lambda_F \bar{F} \mathbb{E}Z$ must be less than the file traffic amount ΔC transmitted during a cycle, i.e.,

$$\phi < \frac{\Delta}{\mathbb{E}Z}. \tag{12}$$

Inserting the expression (7) for $\mathbb{E}Z$ with successive EIBT (the following result follows analogously for interleaved EIBT) into (12), we obtain

$$\frac{\phi}{1-\pi} < \frac{\Delta}{2\tau + \Delta + \omega}. \tag{13}$$

Note that the right-hand side of (13) is less than one. Thus, we see that (12) implies

$$\pi + \phi < 1. \tag{14}$$

V. DELAY ANALYSIS OF SUCCESSIVE EIBT POLLING

A. Packet Delay

We decompose the delay of a packet experienced with successive EIBT polling into five main components, namely the reporting delay from the instant of packet generation to the transmission of the report (R) containing the packet, the roundtrip propagation delay 2τ for the upstream propagation of the report (R) and the downstream propagation of the grants (G), the delay from the beginning of the upstream transmission containing the considered packet to the beginning of the transmission of the packet, as well as the packet transmission delay with mean $\bar{P}/C$ and the upstream propagation delay τ.

The reporting delay corresponds to the backward recurrence time of the cycle [63, Ch. 5.5], which has mean $(\mathbb{E}Z^2)/(2\mathbb{E}Z)$. We obtain $\mathbb{E}Z^2$ by noting the equivalence between the roundtrip propagation delay 2τ in conventional offline polling, which is analyzed in [55], and $2\tau + \Delta + \omega$ in successive EIBT polling. That is, from the perspective of packet traffic, EIBT polling is equivalent to conventional offline polling with reporting at the end of the upstream transmission in a network with roundtrip propagation delay $2\tau + \Delta + \omega$. By retracing the derivation of $\mathbb{E}Z^2$ in [55], i.e., effectively replacing 2τ in ([55, eq. (33)] by $2\tau + \Delta + \omega$, we obtain

$$\mathbb{E}Z^2 = \frac{2\tau + \Delta + \omega}{(1-\pi)(1-\pi^2)} \cdot \left[(2\tau + \Delta + \omega)(1+\pi) + \pi \frac{\bar{P}}{C} \left(1 + \frac{\sigma_P^2}{\bar{P}^2} \right) \right]. \tag{15}$$

Hence, we obtain for the mean reporting delay

$$D_r = \frac{2\tau + \Delta + \omega}{2(1-\pi)} + \frac{\pi \frac{\bar{P}}{C}}{2(1-\pi^2)} \left(1 + \frac{\sigma_P^2}{\bar{P}^2} \right). \tag{16}$$

For the delay from the start of the upstream transmission to the start of the packet transmission, we retrace the analysis steps in [55] to obtain the mean of this delay as πD_r. Thus, we obtain the overall mean packet delay as

$$\begin{aligned} D_P &= (1+\pi) D_r + \frac{\bar{P}}{C} + 3\tau & (17)\\ &= \frac{1+\pi}{2(1-\pi)} (2\tau + \Delta + \omega) \\ &\quad + \frac{\pi \frac{\bar{P}}{C}}{2(1-\pi)} \left(1 + \frac{\sigma_P^2}{\bar{P}^2} \right) + \frac{\bar{P}}{C} + 3\tau. & (18) \end{aligned}$$

B. File Delay

We decompose the file delay D_F into five main components: the reporting delay D_r, the delay from the report transmission to the beginning of the next EIBT, the queuing delay D_q, the transmission delay D_t, and the propagation delay τ. The reporting delay accounts for the time period from the instant of file arrival to the transmission of the report containing the information about the file and has the mean given in (16). The time period from the report transmission to the beginning of the next EIBT period equals $2\tau + \mathbb{E}\delta = 2\tau + \pi(2\tau + \Delta + \omega)/(1-\pi)$.

We model the queuing of the bulk data files with an M/G/1 queue. Generally, for messages with mean service time $\bar{L}/C$, normalized message size variance $\sigma^2/\bar{L}^2$, and traffic intensity ρ, the M/G/1 queue has expected queuing delay

$$D_{M/G/1} = \frac{\rho \frac{\bar{L}}{C} \left(1 + \frac{\sigma^2}{\bar{L}^2} \right)}{2(1-\rho)}. \tag{19}$$

The transmission of a file with mean size $\bar{F}$ [bit] requires on average $\bar{F}/(C\Delta)$ EIBTs, since $C\Delta$ [bit] of a file are transmitted in each EIBT. Each cycle of duration $\mathbb{E}Z$ contains one EIBT of duration Δ; thus, the mean service time (transmission delay) for a file is

$$D_t = \frac{\bar{F}\mathbb{E}Z}{C\Delta} \tag{20}$$

$$= \frac{\bar{F}}{C\Delta}\frac{2\tau+\Delta+\omega}{1-\pi}. \tag{21}$$

The corresponding normalized variance of the file size is $\sigma_F^2/\bar{F}^2$. For each EIBT period of duration Δ, the server needs to work on average for a duration of $\mathbb{E}Z$; thus, the traffic intensity is effectively $\phi\mathbb{E}Z/\Delta$. (Note that stability condition (12) ensures that $\phi\mathbb{E}Z/\Delta < 1$.) Thus, the queuing delay is

$$D_q = \frac{\phi\frac{\bar{F}[\mathbb{E}Z]^2}{C\Delta^2}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)}{2(1-\phi\frac{\mathbb{E}Z}{\Delta})} \tag{22}$$

$$= \frac{\phi\bar{F}(2\tau+\Delta+\omega)^2\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)}{2(1-\pi)C\Delta[(1-\pi)\Delta-\phi(2\tau+\Delta+\omega)]}. \tag{23}$$

For notational convenience, we define

$$\begin{aligned} U &:= \Delta^2 + 2(2\tau+\omega)\Delta + (2\tau+\omega)^2 \\ U' &:= \frac{dU}{d\Delta} = 2\Delta + 2(2\tau+\omega) \end{aligned} \tag{24}$$

$$\begin{aligned} V &:= (1-\pi-\phi)\Delta^2 - \phi(2\tau+\omega)\Delta \\ V' &:= \frac{dU}{d\Delta} = 2(1-\pi-\phi)\Delta - \phi(2\tau+\omega) \end{aligned} \tag{25}$$

whereby U' and V' will be used in Section V-C. Summarizing,

$$\begin{aligned} D_F = {} & (1+2\pi)\frac{2\tau+\Delta+\omega}{2(1-\pi)} + \frac{1}{2(1-\pi)C} \\ & \cdot\left[\frac{\pi\bar{P}}{1+\pi}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right) + \phi\bar{F}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)\frac{U}{V}\right] \\ & + \frac{\bar{F}}{C\Delta}\frac{2\tau+\Delta+\omega}{1-\pi} + 3\tau. \end{aligned} \tag{26}$$

C. Optimal Δ^* Minimizing Weighted Delay Metric

We differentiate the weighted delay D defined in (1) with respect to the duration Δ of the EIBT period to identify the optimal Δ^* that minimizes the weighted delay

$$\frac{dD(\Delta)}{d\Delta} = \alpha\frac{dD_P}{d\Delta} + (1-\alpha)\frac{dD_F}{d\Delta}. \tag{27}$$

For the packet delay component, we obtain from (18)

$$\frac{dD_P}{d\Delta} = \frac{1+\pi}{2(1-\pi)}. \tag{28}$$

For the file delay component, we obtain from (26) in conjunction with (24) and (25)

$$\begin{aligned} \frac{dD_F}{d\Delta} = {} & \frac{1+2\pi}{2(1-\pi)} + \frac{\phi\bar{F}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)}{2(1-\pi)C}\cdot\frac{U'V-UV'}{V^2} \\ & - \frac{\bar{F}(2\tau+\omega)}{C(1-\pi)\Delta^2}. \end{aligned} \tag{29}$$

Thus, solving

$$\begin{aligned} \alpha\frac{1+\pi}{2} + (1-\alpha) & \left[\frac{1+2\pi}{2} + \frac{\phi\bar{F}}{2C}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)\right. \\ & \left.\cdot\frac{U'V-UV'}{V^2} - \frac{\bar{F}(2\tau+\omega)}{C\Delta^2}\right] = 0 \end{aligned} \tag{30}$$

for Δ gives the optimal EIBT duration Δ^* that minimizes the weighted delay D for a given weight α. While (30) has no closed-form solution, it can be readily solved by standard numerical methods.

We note that the stability condition (12) requires that

$$\Delta > \phi\frac{2\tau+\omega}{1-\pi-\phi}. \tag{31}$$

VI. DELAY ANALYSIS OF INTERLEAVED EIBT POLLING

A. Packet Delay

From the perspective of packet traffic, interleaved EIBT polling is equivalent to conventional offline polling with roundtrip propagation delay $\Delta + \omega$ and sending the report at the end. Thus, we adapt (18) by replacing $(2\tau+\Delta+\omega)$ with $(\Delta+\omega)$. We also replace the 2τ report-gate roundtrip propagation delay by the EIBT duration Δ. Thus

$$\begin{aligned} D_P = {} & \frac{1+\pi}{2(1-\pi)}(\Delta+\omega) + \frac{\pi\frac{\bar{P}}{C}}{2(1-\pi)}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right) \\ & + \frac{\bar{P}}{C} + \Delta + \tau. \end{aligned} \tag{32}$$

B. File Delay

For evaluating the reporting delay D_r, we note that the roundtrip propagation delay in conventional offline polling is equivalent to the EIBT duration (plus overhead) $\Delta + \omega$ in interleaved EIBT polling (which in turn is equivalent to $2\tau + \Delta + \omega$ in successive EIBT polling). Thus, we replace $2\tau + \Delta + \omega$ in (16) by $\Delta + \omega$ to obtain

$$D_r = \frac{\Delta+\omega}{2(1-\pi)} + \frac{\pi\frac{\bar{P}}{C}}{2(1-\pi^2)}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right). \tag{33}$$

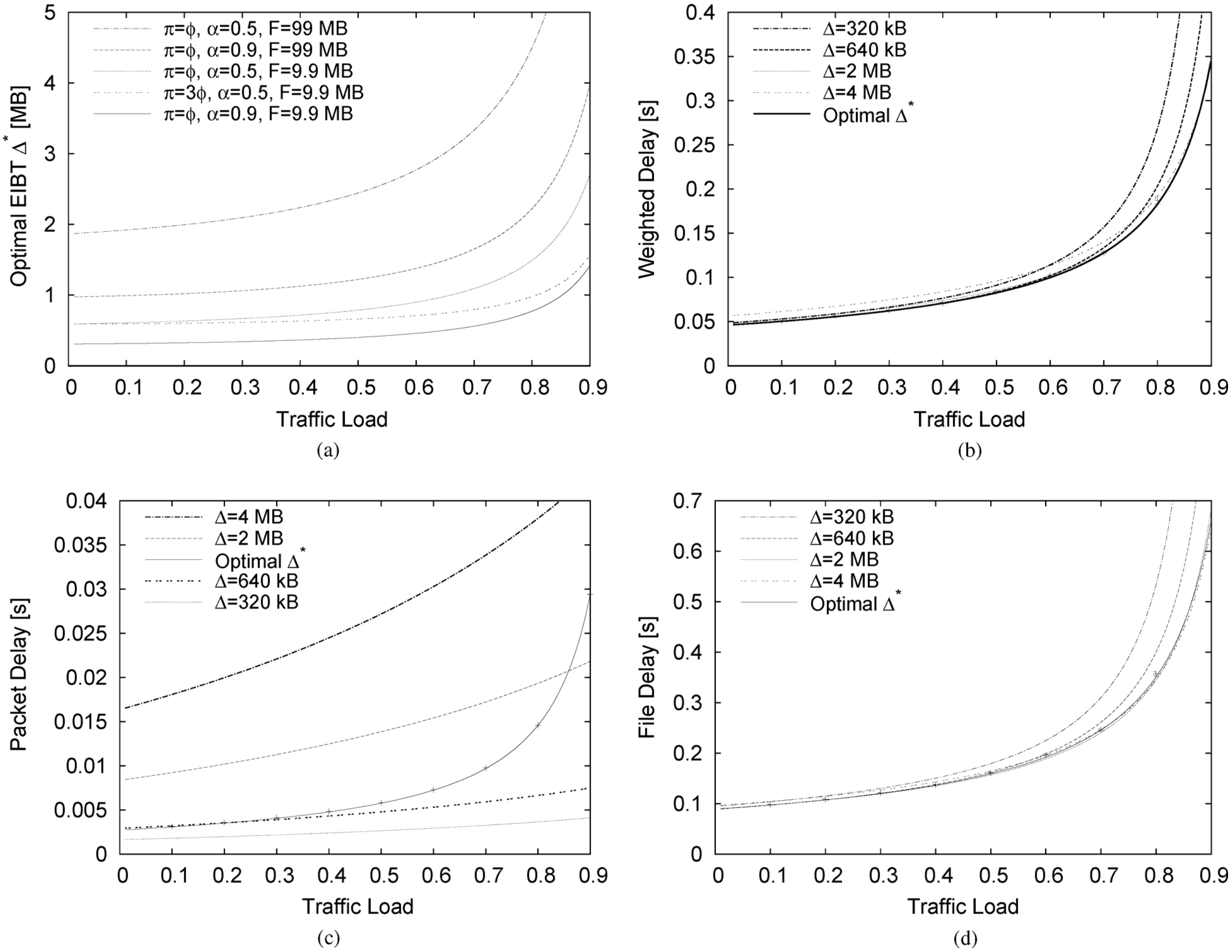
The queuing delay and transmission delay with interleaved EIBT polling are equivalent to the corresponding expressions (23) and (21) for successive EIBT polling with $(2\tau+\Delta+\omega)$ replaced by $(\Delta+\omega)$ and evaluated with the overhead ω given in (8).

C. Optimal Δ^* Minimizing Weighted Delay Metric

Similar to successive EIBT polling, we define for interleaved EIBT polling

$$U := \Delta^2 + 2\omega\Delta + \omega^2, \quad U' = 2\Delta + 2\omega \tag{34}$$

$$\begin{aligned} V &:= (1-\pi-\phi)\Delta^2 - \phi\omega\Delta, \\ V' &= 2(1-\pi-\phi)\Delta - \phi\omega. \end{aligned} \tag{35}$$



(a) (b)

(c) (d)

Fig. 4. Successive EIBT polling: mean delays are displayed for equal packet and file traffic loads $\pi = \phi$, mean file size $\bar{F} = 9.9$ MB, and packet delay weight $\alpha = 0.5$ as a function of total traffic load $\pi + \phi$. All curves are obtained from the delay analysis; verifying simulation results are plotted as error bars at discrete load values. (a) Optimal EIBT duration Δ^*, displayed as $C \cdot \Delta^*$ in megabyte. (b) Weighted delay $D = \alpha D_P + (1 - \alpha) D_F$. (c) Packet delay D_P. (d) File delay D_F.

The optimal Δ^* is obtained as the solution to (30) with the U and V terms defined in (34) and (35) and with $\bar{F}(2\tau + \omega)$ replaced by $\bar{F}\omega$, whereby the ω is given in (8).

VII. EIBT PERFORMANCE RESULTS

A. Evaluation Setup

We consider an EPON with $J = 32$ ONUs with abundant buffer space, a one-way propagation delay of $\tau = 48$ μs of the ONUs from the OLT, and bit rate $C = 1$ Gb/s. For the simulation evaluations, we suppose that a signaling mechanism for bulk file traffic as outlined in Section IV is in place and provides instant signaling that does not introduce signaling delay for the bulk file traffic. Also, following the file traffic model in Section III-B, the local area network delivers a file fast enough to the ONU such that at least $C \cdot \Delta$ bit of the file are ready for upstream transmission for each EIBT. The guard time is set to $t_g = 5$ μs and the report message has 64 bytes. 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 consider two file size scenarios, either equiprobable sizes of 3.2, 6.4, 12, and 18 MB, which give mean file size $\bar{F} = 9.9$ MB, or equiprobable sizes of 32, 64, 120, and 180 MB, which give mean file size $\bar{F} = 99$ MB. The verifying simulations were conducted with a CSIM-based simulator. All simulation results are reported with 90% confidence intervals.

B. Successive EIBT Performance

In Fig. 4, we examine the performance of successive EIBT polling. In Fig. 4(a), we plot the optimal EIBT duration Δ^* obtained from (30) as a function of the total load $\pi + \phi$. We first observe that Δ^* stays relatively constant for low to moderate loads, and then increases for high loads. The considered gated bandwidth allocation for packet traffic sets the duration of the packet phase δ_n so as to accommodate all reported packets. High loads lead to increasingly more reported packets and consequently longer packet phases δ_n. From the perspective of file service, the longer packet phases lead to longer interruptions of file transmission. In order to compensate for these longer interruptions, the optimal EIBT duration grows, so files suffer fewer of these longer interruptions. For packet-dominated traffic with $\pi = 3\phi$, this growth of the optimal EIBT duration is less pronounced as there is a lower proportion of file traffic.

We further observe from Fig. 4 that for decreasing packet delay weight α [and consequently increasing file delay weight

$(1-\alpha)]$ as well as for increasing mean file size $\bar{F}$, the optimal EIBT duration Δ^* increases. The longer EIBTs accommodate larger portions of the files and reduce the file delay relative to the packet delay, hence leading to lower weighted delay as $(1-\alpha)$ increases. As file sizes increase for a fixed Δ, more EIBTs are required to serve a file, i.e., more packet service periods interrupt the file transmission. Thus, the optimal EIBT duration increases to compensate for the more numerous interruptions of the file transmission.

We proceed to examine the scenario with equal portions of packet traffic load π and file traffic load ϕ, mean file size $\bar{F} = 9.9$ MB, and packet delay weight $\alpha = 0.5$ in further detail in Fig. 4(b)–(d). We observe from the plot of the weighted delay D in Fig. 4(b) that the delay curve for $\Delta = 2$ MB is very close to the delay curve for the optimal Δ^* across the entire load range. The delay curves for the smaller $\Delta = 320$ and 640 kB are close to the optimal delay curve for low loads, but give substantially higher delays at high loads. In contrast, the delay curve for $\Delta = 4$ MB is only slightly above the optimal delay curve for low loads and approaches the optimal curve for high loads. These behaviors are due to the increasing Δ^* for increasing traffic load, as plotted in Fig. 4(a). Specifically, for the considered $\pi = \phi$, $\alpha = 0.5$, $\bar{F} = 9.9$ MB case, we observe from Fig. 4(a) that Δ^* is around 0.58 MB for low loads, but grows above 3 MB for high loads. Overall, we observe from Fig. 4(b) that the weighted delay is relatively insensitive to the Δ setting, as long as Δ is large enough to accommodate the average file size within a few EIBTs.

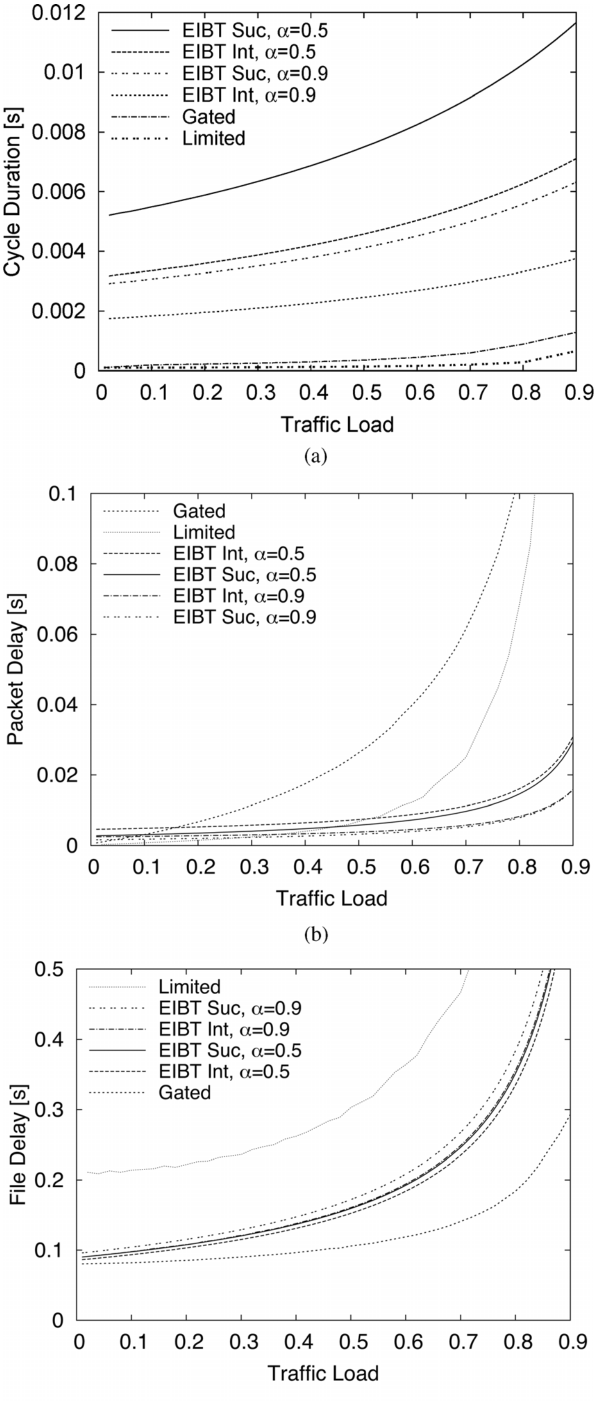
Turning to the mean packet delay D_P in Fig. 4(c), we observe that smaller Δ give smaller packet delays. This is mainly because packets are served more frequently and thus incur lower delays when the EIBT is shorter. We also observe that with increasing traffic load, the packet delay curves for fixed Δ increase relatively slowly (almost linearly), especially for small Δ, in contrast to the essentially exponentially growing packet delay with the optimal Δ^*. For small $\Delta = 320$ or 640 kB, the packet traffic, which constitutes here half of the total traffic load, is fully served after each of the short EIBTs. This ensures low delays even at high total loads close to 0.9, which corresponds to a packet traffic load $\pi = \lambda_P \bar{P}/C = 0.45$. Concomitantly, the file delay for short EIBTs rapidly increases at these high loads above the file delays for long or the optimal EIBT, as observed in Fig. 4(d). The optimal Δ^* balances packet and file delays such that both packet and file delay increase exponentially for increasing total traffic load, while minimizing at any given load level the weighted delay.

We include error bars for the 90% confidence intervals of the simulation results only for the optimal Δ^* delay results to avoid clutter. We observe that the analytical results match the simulation results closely. The very slight overestimation of the mean delays by the analysis is due to the conservative setting of $\eta = 1$, i.e., counting two guard times for each ONU, in Section IV-A2. Overall, we observe from Fig. 4(a) that the optimal EIBT duration Δ^* is sensitive to the traffic parameters, such as file size and traffic load (especially at high traffic load levels). We further observe from Fig. 4(c) that the packet delay is influenced by the setting of the EIBT duration Δ across the entire range of load levels, whereas the file delay in Fig. 4(d) is relatively insensitive to the Δ setting at low to moderate traffic loads, but becomes sensitive to Δ at high traffic loads. Thus, the traffic parameters should be monitored and the optimal EIBT duration Δ^* be evaluated according to (30). In particular, from the received ONU reports, the OLT should periodically estimate the current traffic parameters, i.e., the packet and file traffic load levels π and ϕ as well as file size mean $\bar{F}$ and variance σ_F^2. (Packet size mean $\bar{P}$ and variance σ_P^2 can be based on common packet size models, see Section VII-A.) The OLT may base the traffic parameter estimates on a combination of traffic reports and historic traffic patterns, similar to [64]–[66].

C. EIBT Versus Conventional Limited and Gated Polling

In Figs. 5 and 6, we compare the mean packet and file delays of successive and interleaved EIBT polling with online gated and online limited (with cycle length 2 ms) bandwidth allocation [22]. We observe from Figs. 5(c) and 6(c) that interleaved EIBT polling gives throughout very slightly lower file delay than successive EIBT polling. This is mainly because the cycle in interleaved EIBT polling does not contain a 2τ idle period and has a smaller overhead ω, resulting in a shorter mean cycle duration compared to successive EIBT polling, as observed in Figs. 5(a) and 6(a). We furthermore observe from the figure that for equal packet and file traffic loads $\pi = \phi$, see Fig. 5(b), and for low to moderate loads of packet-dominated traffic, see Fig. 6(b), successive EIBT polling gives very slightly lower packet delay compared to interleaved EIBT polling. As illustrated in Fig. 3, interleaved EIBT polling forces all packets reported by the end of the packet transmission phase to wait for a full EIBT of duration Δ^* (whereby typically $\Delta^* \gg 2\tau$), see Fig. 4(a), before being transmitted in the next packet phase. In contrast, with successive polling illustrated in Fig. 1, the packets reported at the conclusion of the EIBT are delayed only by the roundtrip propagation delay 2τ until their upstream transmission commences. For high loads of packet-dominated traffic, we observe from Fig. 6(b) that interleaved EIBT polling achieves slightly lower packet delay than successive EIBT polling. For the high load, the packet phase becomes long, and due to the dominance of packets, the packet phase becomes disproportionately longer than the EIBT. Thus, the effect of waiting for the full EIBT duration becomes relatively weaker. This reduced EIBT waiting effect and the lower overhead of interleaved polling, which does not have the 2τ idle period, result in slightly reduced packet delays with interleaved EIBT polling.

Turning to the comparison with gated and limited polling, we first observe from Fig. 5(b) and (c) as well as Fig. 6(b) and (c) that gated polling gives the highest packet delay (for traffic loads above approximately 0.16 for $\pi = \phi$ and above about 0.28 for $\pi = 3\phi$) and the lowest file delay (for all load levels) among the considered mechanisms. Gated polling allows an ONU to send a file in one continuous upstream transmission window. This ensures minimal file delay, but blocks all packets from upstream transmission until the transmission of the earlier reported files is completed, causing high packet delays. We observe from Figs. 5(a) and 6(a) that despite the high packet delays, gated polling has relatively short mean cycle duration $\mathbb{E}Z$. This is because files are rare compared to packets; specifically, for equal packet and file loads $\pi = \phi$, there is in the long run one file

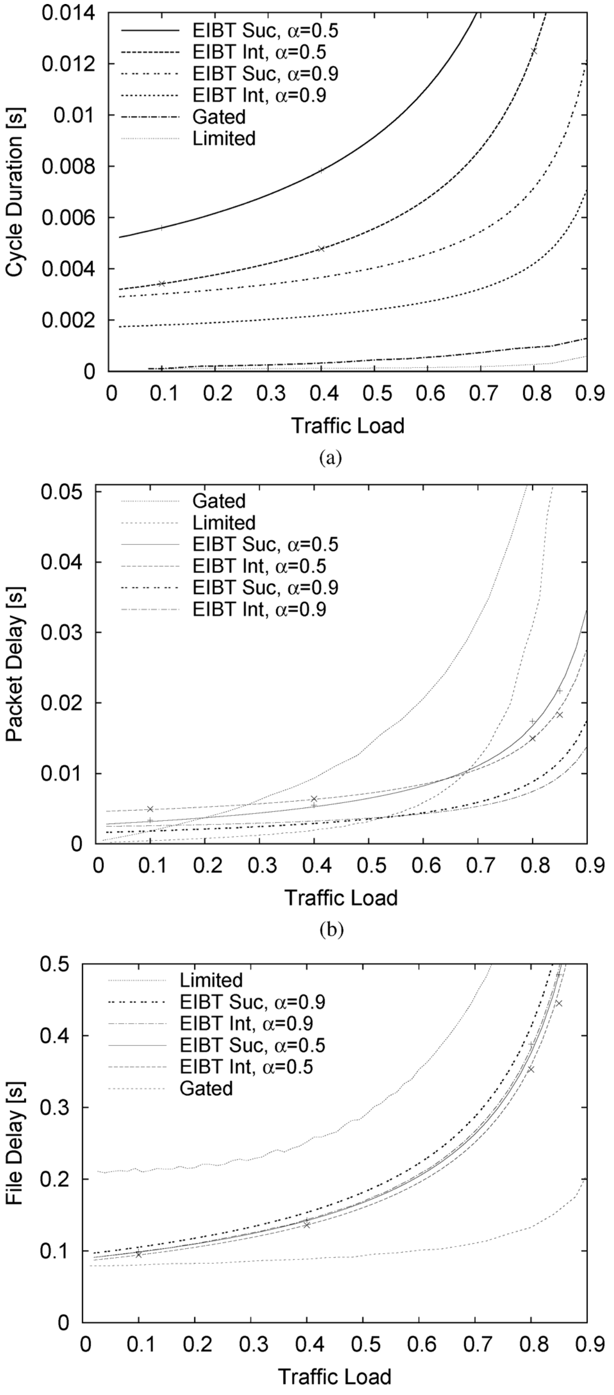


(a)

(b)

(c)

Fig. 5. Comparison of EIBT polling using optimal EIBT duration Δ^* with conventional limited and gated polling for equal packet and file traffic loads $\pi = \phi$ and mean file size $\bar{F} = 9.9$ MB. (a) Cycle duration $\mathbb{E}Z$. (b) Packet delay D_P. (c) File delay D_F.



(a)

(b)

(c)

Fig. 6. Comparison of EIBT polling using optimal EIBT duration Δ^* with conventional limited and gated polling for packet-dominated traffic load $\pi = 3\phi$ and mean file size $\bar{F} = 9.9$ MB. (a) Cycle duration $\mathbb{E}Z$. (b) Packet delay D_P. (c) File delay D_F.

for every $\bar{F}/\bar{P}$ packets. Since gated polling serves a file completely in one cycle, relatively few cycles contain file transmissions, which cause large backlog of packet traffic. Gated polling clears all backlog in the next cycle. Thus, relatively few cycles become long due to file transmissions, which are averaged with many short cycles containing only packets, leading to a low mean cycle duration. On the other hand, the few long cycles contain many packets that experience a high delay, leading to a relatively high mean packet delay.

We next observe from Figs. 5 and 6 that limited polling has low packet delays for low traffic loads, while for moderate to high traffic loads, the packet delays with limited polling are substantially higher than for EIBT, and still lower than for gated polling. We also observe that limited polling has the shortest cycle durations and the highest file delays among the considered mechanisms. Limited polling grants each of the J ONUs at most an upstream transmission window of duration 2 ms/J. This limits the amount of file data that an ONU can transmit per cycle and allows other ONUs to transmit their packets with low delay, leading to lower mean packet delay and shorter cycle duration than gated polling. However, EIBT polling has two fundamental advantages over limited polling that allow EIBT polling to achieve substantially lower delays than limited polling. First, for ONUs that have received a file and subsequently some packets for transmission, limited polling (with a single queue) forces the packets to wait until the file transmission at the ONU is completed. With EIBT polling, the packets are transmitted in the packet phase, independently from the file transmissions. Second, with limited polling, files from multiple ONUs are transmitted in parallel, i.e., each ONU with a file sends a 2 ms$\cdot C/J$ sized chunk of its file in a cycle. In contrast, EIBT polling transmits the files sequentially, i.e., the EIBTs in successive cycles are dedicated to a given file, until the file transmission is complete.

For packet-dominated traffic with $\pi = 3\phi$, the EIBT cycle duration grows faster with increasing total traffic load than for equal packet and file traffic with $\pi = \phi$, see Figs. 5(a) and 6(a), to accommodate the increased proportion of packet traffic in each cycle, while keeping the relation between packet and file delays approximately constant. For the $\pi = 3\phi$ packet-dominated scenario, the packet traffic in gated and limited polling slightly benefits from the fewer interruptions by files, see Figs. 5(b) and 6(b). We observe from comparing Figs. 5(c) and 6(c) that file traffic in the packet-dominated $\pi = 3\phi$ scenario experiences slightly lower delays with gated polling compared to the $\pi = \phi$ scenario, mainly due to the reduced chance of large files queuing for transmission while another large file is transmitted. For limited polling, the reduced chance of transmitting multiple files in parallel is counterbalanced by the increased number of ONUs using their maximum sized transmission window of duration 2 ms/J to transmit packet traffic.

Next, we observe from Fig. 5(a) that the packet delay weight α in EIBT provides an effective control mechanism for the mean packet delay. For a total traffic load of 0.84, for instance, increasing α from 0.5 to 0.9 reduces the mean packet delay from 20 to 10 ms; the corresponding increase in mean file delay is approximately 25 ms, see Fig. 5(b). One potential application scenario of the packet delay control is to set the packet delay weight α for a given set of traffic parameters so as to minimize the weighted delay D subject to the mean packet delay D_P meeting a prescribed tolerable mean packet delay. This application would minimize the file delay subject to meeting the tolerable mean packet delay.

VIII. CONCLUSION

We developed and analyzed polling-based dynamic bandwidth allocation mechanisms for jointly serving conventional packet traffic and bulk data file traffic on the shared upstream wavelength channel of an EPON. The proposed approaches partition the polling cycle into a packet transmission phase and an exclusive interval for bulk transfer (EIBT). We analytically characterized the optimal EIBT duration that minimizes a weighted mean packet and file delay metric. Through numerical evaluations based on our analysis and simulations, we found that EIBT effectively shields packet traffic from the high delay increases that arise when mixing packet and file traffic in conventional dynamic bandwidth allocation mechanisms.

There are a number of important directions for future research. One interesting direction is to expand the EIBT concept to converged fiber-wireless (FiWi) networks [67]–[69] as well as metro networks [70]–[73] so as to efficiently transmit packet and file traffic from a mobile wireless node to the ONU, onward to the OLT, and across a metropolitan area network.

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