Object-based PON Access and Tandem Networking

by

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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 back-up 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. I propose and evaluate an exclusive interval for bulk transfer (EIBT) transmission strategy that reserves an EIBT for file traffic in an EPON polling cycle. I optimize the duration of the EIBT to minimize a weighted sum of packet and file delays. Through mathematical delay analysis and verifying simulation, it is demonstrated that the EIBT approach preserves small delays for packet traffic while efficiently serving bulk data file transfers.

Dynamic circuits are well suited for applications that require predictable service with a constant bit rate for a prescribed period of time, such as demanding e-science applications. Past research on upstream transmission in passive optical networks (PONs) has mainly considered packet-switched traffic and has focused on optimizing packet-level performance metrics, such as reducing mean delay. This study proposes and evaluates a dynamic circuit and packet PON (DyCaPPON) that provides dynamic circuits along with packet-switched service. DyCaPPON provides (i) flexible packet-switched service through dynamic bandwidth allocation in periodic polling cycles, and (ii) consistent circuit service by allocating each active circuit a fixed-duration upstream transmission window during each fixed-duration polling cycle. I analyze circuit-level performance metrics, including the blocking probability of dynamic circuit requests in DyCaPPON through a stochastic knapsack-based analysis. Through this analysis I also determine the bandwidth occupied by admitted circuits. The remaining bandwidth is available for packet traffic and I analyze the resulting mean delay of packet traffic. Through extensive numerical evaluations and verifying

simulations, the circuit blocking and packet delay trade-offs in DyCaPPON is demonstrated. An extended version of the DyCaPPON designed for light traffic situation is introduced in this article as well.

DEDICATION

To my Parents, Jie Zhang and Shunhai Wei

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Chapter 1

INTRODUCTION

The Ethernet passive optical network (EPON) is widely considered a low-cost and high-bandwidth solution for last mile Internet access Andrade *et al.* (2011); Kramer *et al.* (2012); McGarry and Reisslein (2012); Roy *et al.* (2011); Turna *et al.* (2010); Zheng and Mouftah (2009), which is the improved and more developed version of network solution of Passive Optical Network (PON). 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 Choi *et al.* (2009); Jana *et al.* (2010); Luo and Ansari (2005); Sue and Cheng (2010); Lim *et al.* (2009) and schedules corresponding grants for upstream transmission windows so as to avoid collisions Kramer *et al.* (2004); Kanonakis and Tomkos (2009, 2010); Melo Pereira *et al.* (2009); Sarigiannidis *et al.* (2010).

1.1 Overview of bulk data files in PON network

As reviewed in detail in Section 1.3, 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 require the upstream transmission of bulk data files. File transfer performance is emerging as one of the key evaluation metrics of access networks Bolletta *et al.* (2011). 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 Koponen *et al.* (2007); Jacobson *et al.* (2009), and network bandwidth management for bulk data transfers, such as dynamic optical circuits Veeraraghavan *et al.* (2010); Weichenberg *et al.* (2009). For the present study, I 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 Kramer *et al.* (2002b) 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 article, I 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. I 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 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, I 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.

1.2 Overview of dynamic circuit switching in PON network

Optical networks have traditionally employed three main switching paradigms, namely circuit switching, burst switching, and packet switching, which have extensively studied respective benefits and limitations Molinero-Fernandez and McKeown (2003); Coutelen *et al.* (2005); Liu *et al.* (2006); Batayneh *et al.* (2008). In order to achieve the predictable network service of circuit switching while enjoying the some of the flexibilities of burst and packet switching, *dynamic circuit switching* has been introduced Veeraraghavan *et al.* (2010). Dynamic circuit switching can be traced back to research toward differentiated levels of blocking rates of calls Harissis and Ambler (1989). Today, a plethora of network applications ranging from high-bit rate e-science applications, e.g., for remote scientific collaborations, remote instrument control, and transfer of very large scientific data files, to big data applications of governments and private organizations, as well as tele-medicine and personal applications, such as high-quality video conferencing and distance learning, are well supported by dynamic circuit switching Veeraraghavan *et al.* (2010). Both commercial and research/education network providers have recently started to offer optical dynamic circuit switching services Mukherjee (2007); Internet2 (2014).

Dynamic circuit switching has received growing research attention in core and metro networks Zheng *et al.* (2005); Internet2 (2014); Fang and Veeraraghavan (2009); Veeraraghavan and Zheng (2004); Monga *et al.* (2011); Munir *et al.* (2009), mechanisms for supporting dynamic circuit switching in passive optical networks (PONs), which are a promising technology for network access Tomkos *et al.* (2012), are largely an open research area. As reviewed in Section 1.3, PON research to date has focused mainly on mechanisms supporting packet-switched transport. While some of these packet-switched transport mechanisms support quality of service akin to circuits through service differentiation mechanisms, to the best of my knowledge there has been no prior study of circuit-level performance in PONs, e.g., the blocking probability of circuit requests for given circuit request rate and circuit holding time.

1.3 Related Work

1.3.1 Related work of bulk data files in PON network

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. Assi *et al.* (2003a); Berisa *et al.* (2011); Chang *et al.* (2006); Dixit *et al.* (2011); Hwang *et al.* (2012); Merayo *et al.* (2007); Naser and Mouftah (2006); Radivojevic and Matavulj (2009); Shami *et al.* (2005); Vahabzadeh and Ghaffarpour Rahbar (2011); Xue *et al.* (2009); Zhang and Ansari (2010). In particular, the problem of providing differential QoS for different classes of packet traffic has attracted significant research interest, see e.g., Chen *et al.* (2009); Kramer *et al.* (2002a); Kim *et al.* (2007); Kwong *et al.* (2004); Lin *et al.* (2010, 2011a); Ma *et al.* (2005a,b); Okumura (2010); Sherif *et al.* (2004); Yin and Poo (2010); Zhu *et al.* (2006). These existing approaches strive to provide some packet traffic flows with higher QoS, e.g., lower delays, relative to the best-effort packet traffic. My study is complementary to these existing approaches in that I 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 my 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 Sailan and Hassan (2010); Wiedemeier and Tyrer (2003); Zaghloul *et al.* (2005). The interactions between TCP and medium access control (polling) mechanisms in EPONs have been examined in Chang and Liao (2006); Ikeda and Kitayama (2009); Nishiyama *et al.* (2010); Orozco and Ros (2008) while P2P file sharing with conventional packet-based service in EPONs has been studied in Maier and Herzog (2010). The present studies focus 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 Aurzada *et al.* (2008, 2011); Bharati and Saengudomlert (2010); Bhatia *et al.* (2006); Lannoo *et al.* (2007); Thanh Ngo *et al.* (2008). In contrast, I analyze the packet and file delays for combined packet and file best-effort service in EPONs.

1.3.2 Related work of dynamic circuit switching in PON network

The existing research on upstream transmission in passive optical access networks has mainly focused on packet traffic and related packet-level performance metrics. A number of studies has primarily focused on differentiating the packet-level QoS for different classes of packet traffic, e.g., Angelopoulos *et al.* (2004); Assi *et al.* (2003b); Dixit *et al.* (2011); Ghani *et al.* (2004); Luo and Ansari (2005); Radivojevic and Matavulj (2009); Sherif *et al.* (2004); Shami *et al.* (2005); Vahabzadeh and Ghaffarpour Rahbar (2011). In contrast to these studies, we consider only best effort service for the packet traffic in this article. In future work, mechanisms for differentiation of packet-level QoS could be integrated into the packet partition (see Section 3.3) of the DyCaPPON polling cycle, as well.

The needs of applications for transmission with predictable quality of service has led to various enhancements of packet-switched transport for providing quality of service (QoS). A few studies, e.g., Berisa *et al.* (2009); Holmberg (2006); Ma *et al.* (2003); Qin *et al.* (2013); Zhang *et al.* (2003); Zhang and Poo (2004), have specifically focused on providing deterministic QoS, i.e., absolute guarantees for packet-level performance metrics, such as packet delay or jitter. Several studies have had a focus on the efficient integration of deterministic QoS mechanisms with one or several lower-priority packet traffic classes in polling-based PONs, e.g.,An *et al.* (2003); Berisa *et al.* (2011); Dhaini *et al.* (2007); Hwang *et al.* (2012); Lin *et al.* (2011b); Merayo *et al.* (2011); Ngo *et al.* (2011). The resulting packet scheduling problems have received particular attention De *et al.* (2010); Melo Pereira *et al.* (2009); Yin and Poo (2010). Generally, these prior studies have found that fixed-duration polling cycles are well suited for supporting consistent QoS service. Similar to prior studies, we employ fixed-duration polling cycles in DyCaPPON, specifically on a PON with a single-wavelength upstream channel.

The prior studies commonly considered traffic flows characterized through leaky-bucket parameters that bound the long-term average bit rate as well as the size of sudden traffic bursts. Most of these studies include admission control, i.e., admit a new traffic flow only when the packet-level performance guarantees can still be met with the new traffic flow added to the existing flows. However, the circuit-level performance, i.e., the probability of blocking (i.e., denial of admission) of a new request has not been considered. In contrast, the circuits in DyCaPPON provide absolute QoS to constant bit rate traffic flows without bursts and we analyze the probability of new traffic flows (circuits) being admitted or blocked. This flow (circuit) level performance is important for network dimensioning and providing QoS at the level of traffic flows.

For completeness, we briefly note that a PON architecture that can provide circuits to ONUs through orthogonal frequency division multiplexing techniques on the physical layer has been proposed in Qian *et al.* (2007). My study, in contrast, focuses on efficient medium access control techniques for supporting circuit traffic. A QoS approach based on burst switching in a PON has been proposed in Segarra *et al.* (2005). To the best of my knowledge, circuit level performance in PONs has so far only been examined in Vardakas *et al.* (2012) for the specific context of optical code division multiplexing Kwong *et al.* (1996).

We also note for completeness that large file transmissions in optical networks have been examined in Hu *et al.* (2009), where scheduling of large data file transfers on the optical grid network is studied, in Moser *et al.* (2010), where parallel transfer over multiple network paths are examined, and in Wei *et al.* (2013), where files are transmitted in a burst mode, i.e., sequentially.

Sharing of a general time-division multiplexing (TDM) link by circuit and packet traffic has been analyzed in several studies, e.g. Bolla and Davoli (1997); Gaver and Lehoczky (1982); Ghani and Schwartz (1994); Li and Mark (1985); Maglaris and Schwartz (1982); Mankus and Tier (1992); Weinstein *et al.* (1980). These queueing theoretic analyses typically employed detailed Markov models and become computationally quite demanding for high-speed links. Also, these complex existing models considered a given node with local control of all link transmissions. In contrast, we develop a simple performance model for the distributed transmissions of the ONUs that are coordinated through polling-based medium access control in DyCaPPON. My DyCaPPON model is accurate for the circuits and approximate for the packet service. More specifically, we model the dynamics of the circuit traffic, which is given priority over packet traffic up to an aggregate circuit bandwidth of C_c in DyCaPPON, with accurate stochastic knapsack modeling techniques in Section 3.4.1. In Section 3.4.2, we present an approximate delay model for the packet traffic, which in DyCaPPON can consume the bandwidth left unused by circuit traffic.

Chapter 2

EXCLUSIVE INTERVALS FOR BULK TRANSFER (EIBT) POLLING

2.1 Network Model

2.1.1 Network structure

I consider an EPON with J ONUs attached to the OLT via a single downstream wavelength channel and a single upstream wavelength channel. C is denoted for the transmission rate of a channel [bits/s]. τ [s] here is denoted for the one-way propagation delay between OLT and ONUs, which I consider to be equidistant from the OLT. I 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 2.1.

2.1.2 Traffic model

For conventional packet traffic, 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, denote $\bar{F}$ and σ_F^2 for the mean size [bit] and variance of the files size, respectively. I here consider scenarios with $\bar{F} \gg \bar{P}$.

Here 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). I 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

Table 2.1: 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]

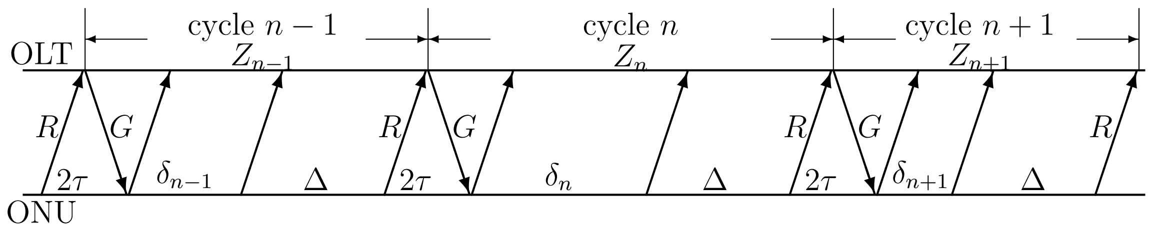


Figure 2.1: Illustration of successive EIBT polling: ONUs report bandwidth demands after the end of the EIBT of cycle $n-1$. Based on the reports (R), grants (G) are issued for upstream transmission in cycle n. There is an idle period of duration 2τ between successive cycles, which allows up-to-date reports to be used for grant sizing and scheduling.

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, (*i*) at the arrival instant the ONU needs the file size so that it can be included in the next report to the OLT, and (*ii*) 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 $\pi(j) + \phi(j)$. Here I suppose that the generation processes of the packets and files are independent. Finally, I set $\pi := \sum_j \pi(j)$ and $\phi := \sum_j \phi(j)$.

Throughout, I 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.

2.1.3 Delay Metrics

The packet delay D_P is defined 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. I also 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.

The weighted delay metric is defined as

$$D := \alpha D_P + (1 - \alpha) D_F, \tag{2.1}$$

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.

2.2 EIBT

In this section I present the detailed EIBT polling mechanisms and derive the stability limit of EIBT polling. I 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. I 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 MByte) 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 content centric networking (CCN) Koponen *et al.* (2007); Jacobson *et al.* (2009) or dynamic circuit/flow switching Veeraraghavan *et al.* (2010); Weichenberg *et al.* (2009), are beyond the scope of this study. I 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 Veeraraghavan *et al.* (2010); Weichenberg *et al.* (2009), signals and establishes a temporary circuit/flow for the transmission of a bulk date 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 Fouli and Maier (2009) 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, I augment the conventional offline scheduling framework McGarry and Reisslein (2012); Zheng and Mouftah (2009), 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 first-come-first-out (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

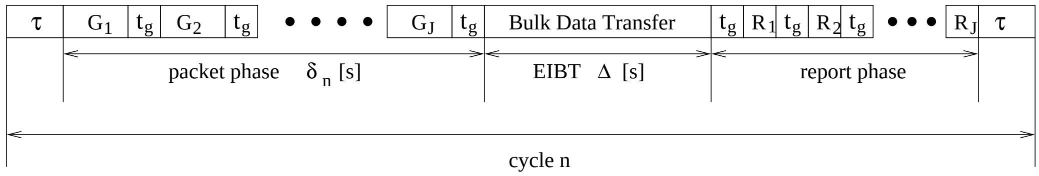


Figure 2.2: Detailed illustration of cycle n in successive EIBT polling. ONUs j with packets send them upstream during their granted transmission windows G_j in the packet phase. Bulk file data is transmitted during the EIBT of duration Δ. Then, all J ONUs report newly arrived packet and file traffic to the OLT.

the increase in OLT processing complexity is relatively low. I consider two natural strategies for embedding the EIBT in the conventional polling cycle: successive EIBT polling and interleaved EIBT polling.

I 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.

2.2.1 Successive EIBT Polling

Overview

With successive EIBT polling, as illustrated in Fig. 2.1, 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, the proposed successive EIBT polling lets all ONUs report queue occupancy information at the conclusion of the EIBT period, as illustrated in Fig. 2.2. 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.

Overhead

ω [in seconds] is noted for the mean per-cycle upstream transmission overheads, which are neglected in the illustration in Fig. 2.1. 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, I denote η for the steady-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, I conservatively set $\eta = 1$ for the remainder of this article. I 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 McGarry *et al.* (2010)) in my 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. 2.2. Thus,

$$\omega = J \cdot [t_R + (1+\eta) t_g]. \tag{2.2}$$

Cycle Duration

I observe from Fig. 2.1 that the cycle duration consists of the round-trip propagation delay, the packet phase followed by the EIBT, as well as the overhead time ω (neglected in Fig. 2.1), i.e.,

$$\mathbb{E}Z_n = 2\tau + \mathbb{E}\delta_n + \Delta + \omega. \tag{2.3}$$

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.,

$$\mathbb{E}\delta_n = \frac{\lambda \bar{P} \mathbb{E}Z_{n-1}}{C}. \tag{2.4}$$

In turn, expressing $\mathbb{E}Z_{n-1}$ with Eqn. (2.3) gives

$$\mathbb{E}\delta_n = \frac{\lambda \bar{P}}{C} \left(2\tau + \mathbb{E}\delta_{n-1} + \Delta + \omega \right). \tag{2.5}$$

I note from (2.5) 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, I obtain

$$\mathbb{E}\delta = \frac{\pi}{1-\pi} \left(2\tau + \Delta + \omega \right). \tag{2.6}$$

Inserting in (2.3) gives the mean cycle duration

$$\mathbb{E}Z = \frac{2\tau + \Delta + \omega}{1-\pi}. \tag{2.7}$$

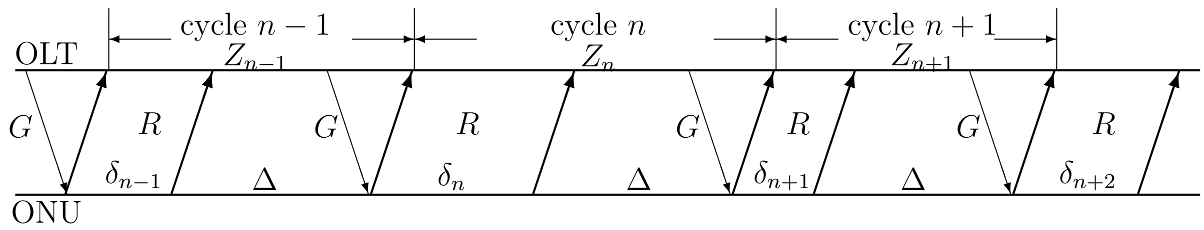


Figure 2.3: Illustration of interleaved EIBT polling: Reports (R) transmitted during the conventional packet transmission phase of cycle $n-1$ are used to determine upstream transmission grants (G) for cycle n. Idle time on the upstream channel is avoided by basing grants for cycle n on the reports from before the EIBT of cycle $n-1$.

2.2.2 Interleaved EIBT Polling

Overview

With interleaved EIBT polling, each ONUs 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.

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

$$\omega = J(t_R + t_g) + t_g. \tag{2.8}$$

Cycle Duration

For interleaved EIBT polling, I observe from Fig. 2.3 that a cycle consists of the packet phase, the EIBT, and the overhead time (neglected in Fig. 2.3), i.e.,

$$\mathbb{E}Z_n = \mathbb{E}\delta_n + \Delta + \omega. \tag{2.9}$$

Notice that in comparison to the cycle duration for successive EIBT polling (2.3), the cycle for interleaved EIBT polling does not include the 2τ round-trip propagation delay. Re-tracing the analysis in Section 2.2.1, I obtain the expected cycle duration for interleaved EIBT polling

$$\mathbb{E}Z = \frac{\Delta + \omega}{1 - \pi}. \tag{2.10}$$

2.2.3 EIBT Stability Conditions

As noted in the analysis leading to (2.6), stability of the network requires that

$$\pi < 1. \tag{2.11}$$

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.,

$$\phi < \frac{\Delta}{\mathbb{E}Z}. \tag{2.12}$$

Inserting the expression (2.7) for $\mathbb{E}Z$ with successive EIBT (the following result follows analogously for interleaved EIBT) into (2.12) I obtain

$$\frac{\phi}{1 - \pi} < \frac{\Delta}{2\tau + \Delta + \omega}. \tag{2.13}$$

Note that the right-hand side of (2.13) is less than one. Thus, I see that (2.12) implies

$$\pi + \phi < 1. \tag{2.14}$$

2.3 Delay Analysis of Successive EIBT Polling

2.3.1 Packet Delay

The delay of a packet experienced with successive EIBT polling can be decomposed 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 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 (Heyman and Sobel, 2003, Ch. 5.5), which has mean $\frac{\mathbb{E}Z^2}{2\mathbb{E}Z}$. I obtain $\mathbb{E}Z^2$ by noting the equivalence between the round trip propagation delay 2τ in conventional offline polling, which is analyzed in Aurzada *et al.* (2008), 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 Aurzada *et al.* (2008), i.e., effectively replacing 2τ in (Aurzada *et al.*, 2008, Eqn. (33)) by $2\tau+\Delta+\omega$, so I can obtain

$$\mathbb{E}Z^2 = \frac{2\tau+\Delta+\omega}{(1-\pi)(1-\pi^2)} \cdot \left[(2\tau+\Delta+\omega)(1+\pi)+\pi\frac{\bar{P}}{C}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right)\right]. \tag{2.15}$$

Hence, I obtain for the mean reporting delay

$$D_r = \frac{2\tau+\Delta+\omega}{2(1-\pi)} + \frac{\pi\frac{\bar{P}}{C}}{2(1-\pi^2)}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right). \tag{2.16}$$

For the delay from the start of the upstream transmission to the start of the packet transmission, the analysis can be retraced steps in Aurzada *et al.* (2008) to obtain the mean of this delay as πD_r. Thus, I obtain the overall mean packet delay as

$$D_P = (1+\pi)D_r + \frac{\bar{P}}{C} + 3\tau \tag{2.17}$$

$$= \frac{1+\pi}{2(1-\pi)}(2\tau + \Delta + \omega) + \frac{\pi\frac{\bar{P}}{C}}{2(1-\pi)}\left(1 + \frac{\sigma_P^2}{\bar{P}^2}\right) + \frac{\bar{P}}{C} + 3\tau. \tag{2.18}$$

2.3.2 File Delay

I 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 queueing 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 (2.16). The time period from the report transmission to the beginning of the next EIBT period equals $2\tau + \mathbb{E}\delta = 2\tau + \frac{\pi}{1-\pi}(2\tau + \Delta + \omega)$.

I model the queueing 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 queueing delay

$$D_{M/G/1} = \frac{\rho\frac{\bar{L}}{C}\left(1 + \frac{\sigma^2}{\bar{L}^2}\right)}{2(1-\rho)}. \tag{2.19}$$

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

$$D_t = \frac{\bar{F}\mathbb{E}Z}{C\Delta} \tag{2.20}$$

$$= \frac{\bar{F}}{C\Delta}\frac{2\tau + \Delta + \omega}{1-\pi}. \tag{2.21}$$

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 (2.12) ensures that $\phi\mathbb{E}Z/\Delta < 1$.) Thus, the queuing delay is

$$D_q = \frac{\phi\frac{\bar{F}[\mathbb{E}Z]^2}{C\Delta^2}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)}{2(1-\phi\frac{\mathbb{E}Z}{\Delta})} \tag{2.22}$$

$$= \frac{\phi\bar{F}(2\tau+\Delta+\omega)^2\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)}{2(1-\pi)C\Delta[(1-\pi)\Delta - \phi(2\tau+\Delta+\omega)]}. \tag{2.23}$$

For notational convenience, I define

$$U := \Delta^2 + 2(2\tau+\omega)\Delta + (2\tau+\omega)^2$$

$$U' := \frac{dU}{d\Delta} = 2\Delta + 2(2\tau+\omega) \tag{2.24}$$

$$V := (1-\pi-\phi)\Delta^2 - \phi(2\tau+\omega)\Delta$$

$$V' := \frac{dU}{d\Delta} = 2(1-\pi-\phi)\Delta - \phi(2\tau+\omega), \tag{2.25}$$

whereby U' and V' will be used in Section 2.3.3. Summarizing,

$$D_F = (1+2\pi)\frac{2\tau+\Delta+\omega}{2(1-\pi)} + \frac{1}{2(1-\pi)C} \cdot \left[\frac{\pi\bar{P}}{1+\pi}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right) + \phi\bar{F}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)\frac{U}{V}\right] + \frac{\bar{F}}{C\Delta}\frac{2\tau+\Delta+\omega}{1-\pi} + 3\tau. \tag{2.26}$$

2.3.3 Optimal Δ^* Minimizing Weighted Delay Metric

I differentiate the weighted delay D defined in (2.1) with respect to the duration Δ of the EIBT period to identify the optimal Δ^* that minimizes the weighted delay:

$$\frac{dD(\Delta)}{d\Delta} = \alpha \frac{dD_P}{d\Delta} + (1-\alpha)\frac{dD_F}{d\Delta}. \tag{2.27}$$

For the packet delay component, I obtain from (2.18)

$$\frac{dD_P}{d\Delta} = \frac{1+\pi}{2(1-\pi)}. \tag{2.28}$$

For the file delay component, it can be obtained from (2.26) in conjunction with (2.24) and (2.25)

$$\begin{aligned} \frac{dD_F}{d\Delta} \quad = \quad & \frac{1+2\pi}{2(1-\pi)} + \frac{\phi \bar{F}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right)}{2(1-\pi)C} \cdot \frac{U'V - UV'}{V^2} \\ & -\frac{\bar{F}(2\tau+\omega)}{C(1-\pi)\Delta^2}. \end{aligned} \tag{2.29}$$

Thus, solving

$$\begin{aligned} \alpha\frac{1+\pi}{2} + (1-\alpha)\Bigg[\frac{1+2\pi}{2} + \frac{\phi\bar{F}}{2C}\left(1+\frac{\sigma_F^2}{\bar{F}^2}\right) \cdot \frac{U'V-UV'}{V^2} \\ -\frac{\bar{F}(2\tau+\omega)}{C\Delta^2}\Bigg] = 0 \end{aligned} \tag{2.30}$$

for Δ gives the optimal EIBT duration Δ^* that minimizes the weighted delay D for given weight α. While (2.30) has no closed-form solution, it can be readily solved by standard numerical methods.

Note that the stability condition (2.12) requires that

$$\Delta > \phi\frac{2\tau+\omega}{1-\pi-\phi}. \tag{2.31}$$

2.4 Delay Analysis of Interleaved EIBT Polling

2.4.1 Packet Delay

From the perspective of packet traffic, interleaved EIBT polling is equivalent to conventional offline polling with round-trip propagation delay $\Delta+\omega$ and sending the report at the end. Thus, I adapt Eqn. (2.18) by replacing $(2\tau+\Delta+\omega)$ with $(\Delta+\omega)$. I also replace the 2τ report-gate roundtrip propagation delay by the EIBT duration Δ. Thus,

$$\begin{aligned} D_P &= \frac{1+\pi}{2(1-\pi)}(\Delta+\omega)+\frac{\pi\frac{\bar{P}}{C}}{2(1-\pi)}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right) \\ &\quad +\frac{\bar{P}}{C}+\Delta+\tau. \end{aligned} \tag{2.32}$$

2.4.2 File Delay

For evaluating the reporting delay D_r it can be noted 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, I replace $2\tau+\Delta+\omega$ in (2.16) by $\Delta+\omega$ to obtain

$$D_r=\frac{\Delta+\omega}{2(1-\pi)}+\frac{\pi\frac{\bar{P}}{C}}{2(1-\pi^2)}\left(1+\frac{\sigma_P^2}{\bar{P}^2}\right). \tag{2.33}$$

The queuing delay and transmission delay with interleaved EIBT polling are equivalent to the corresponding expressions (2.23) and (2.21) for successive EIBT polling with $(2\tau+\Delta+\omega)$ replaced by $(\Delta+\omega)$ and evaluated with the overhead ω given in (2.8).

2.4.3 *Optimal Δ^* Minimizing Weighted Delay Metric*

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

$$U := \Delta^2 + 2\omega\Delta + \omega^2; \quad U' = 2\Delta + 2\omega \tag{2.34}$$

$$V := (1-\pi-\phi)\Delta^2 - \phi\omega\Delta;$$

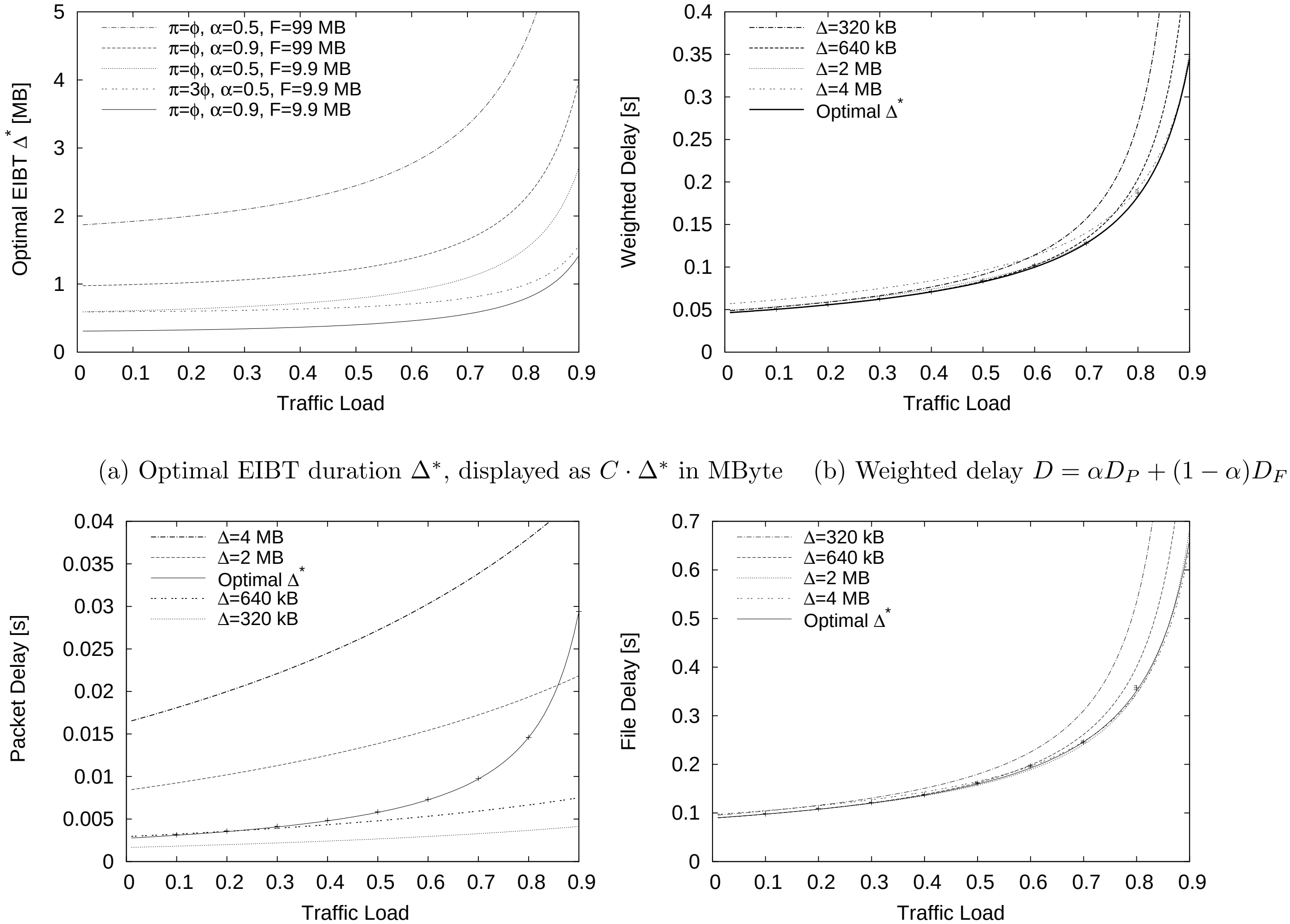
$$V' = 2(1-\pi-\phi)\Delta - \phi\omega. \tag{2.35}$$

The optimal Δ^* is obtained as the solution to (2.30) with the U and V terms defined in (2.34) and (2.35) and with $\bar{F}(2\tau+\omega)$ replaced by $\bar{F}\omega$, whereby the ω is given in (2.8).

2.5 EIBT Performance Results

2.5.1 *Evaluation Set-up*

I 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, I suppose that a signaling mechanism for bulk file traffic as outlined in Section 2.2 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 2.1.2, 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. The simulation model 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. I consider two file size scenarios, either equi-probable sizes of 3.2, 6.4, 12, and 18 MByte, which give mean file size $\bar{F} = 9.9$ MByte, or equi-probable sizes of 32, 64, 120, and 180 MByte, which give mean file size $\bar{F} = 99$ MByte. The verifying



(a) Optimal EIBT duration Δ^*, displayed as $C \cdot \Delta^*$ in MByte

(b) Weighted delay $D = \alpha D_P + (1-\alpha) D_F$

(c) Packet delay D_P

(d) File delay D_F

Figure 2.4: Successive EIBT polling: Mean delays are displayed for equal packet and file traffic loads $\pi = \phi$, mean file size $\bar{F} = 9.9$ MByte 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.

simulations were conducted with a CSIM based simulator. All simulation results are reported with 90 % confidence intervals.

2.5.2 Successive EIBT Performance

In Figure 2.4 it can be examined the performance of successive EIBT polling. In Fig. 2.4(a) I plot the optimal EIBT duration Δ^* obtained from (2.30) as a function of the total load $\pi + \phi$. I 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.

I further observe from Fig. 2.4 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.

I proceed to examine the scenario with equal portions of packet traffic load π and file traffic load ϕ, mean file size $\bar{F} = 9.9$ MByte, and packet delay weight $\alpha = 0.5$ in further detail in Figs. 2.4(b)–(d). It can be observed from the plot of the weighted delay D in Fig. 2.4(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. 2.4(a). Specifically, for the considered $\pi = \phi$, $\alpha = 0.5$, $\bar{F} = 9.9$ MB case, I can be observed from Fig. 2.4(a) that Δ^* is around 0.58 MB for low loads, but grows above 3 MB for high loads. Overall, I observe from Fig. 2.4(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. 2.4(c), I 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. It can also be observed 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. 2.4(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.

I include error bars for the 90 % confidence intervals of the simulation results only for the optimal Δ^* delay results to avoid clutter. It can be observed 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 2.2.1. Overall, I observe from Fig. 2.4(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). I further observe from

Fig. 2.4(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. 2.4(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 Eqn. (2.30). 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 2.5.1.) The OLT may base the traffic parameter estimates on a combination of traffic reports and historic traffic patterns, similar to Bianco *et al.* (2005); Gencata and Mukherjee (2003); Oki *et al.* (2002).

2.5.3 EIBT vs. Conventional Limited and Gated Polling

In Figs. 2.5 and 2.6, I 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 Kramer *et al.* (2002b). I observe from Figs. 2.5(c) and 2.6(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. 2.5(a) and 2.6(a). It can be furthermore observed from the figure that for equal packet and file traffic loads $\pi = \phi$, see Fig. 2.5(b), and for low to moderate loads of packet-dominated traffic, see Fig. 2.6(b), successive EIBT polling gives very slightly lower packet delay compared to interleaved EIBT polling. As illustrated in Fig. 2.3, 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

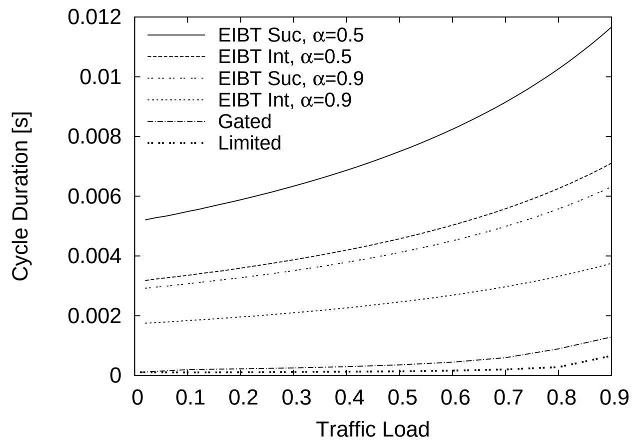
Fig.. 2.4(a), before being transmitted in the next packet phase. In contrast, with successive polling illustrated in Fig. 2.1, the packets reported at the conclusion of the EIBT are delayed only by the round-trip propagation delay 2τ until their upstream transmission commences. For high loads of packet-dominated traffic I observe from Fig. 2.6(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 the 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, I first observe from Fig. 2.5(b) and (c) as well as Fig. 2.6(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. I observe from Figs. 2.5(a) and 2.6(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 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.

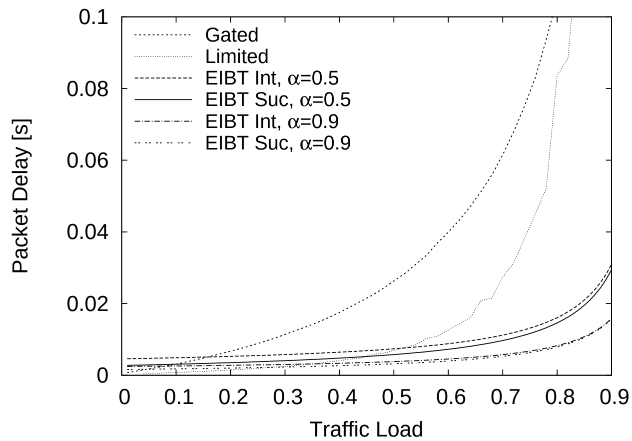
It can next be observed from Figs. 2.5 and 2.6 that limited polling has low packet delays for low traffic loads; while for moderate to high traffic loads the packet delays with limited polling are substantially higher than for EIBT, and still lower than for gated polling. I also observe that limited 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. 2.5(a) and 2.6(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. 2.5(b) and 2.6(b). I observe from comparing Figs. 2.5(c) and 2.6(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 counter-balanced by the increased number of ONUs using their maximum sized transmission window of duration 2 ms/J to transmit packet traffic.

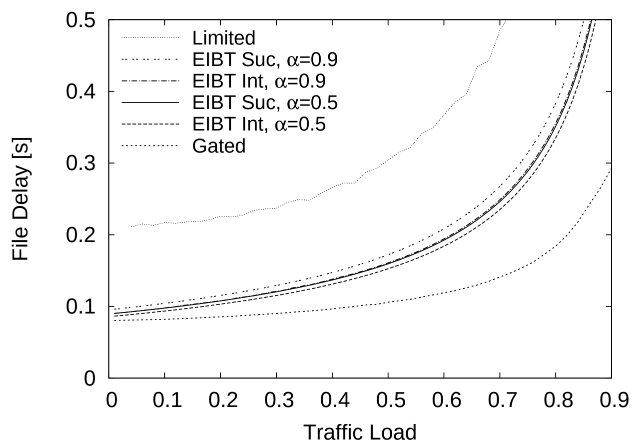
Next, I observe from Fig. 2.5(a) that the packet delay weight α in EIBT provides an effective control mechanism for the mean packet delay. For a total traffic load of 0.84, for instance, increasing α from 0.5 to 0.9 reduces the mean packet delay from 20 to 10 ms; the corresponding increase in mean file delay is approximately 25 ms, see Fig. 2.5(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.



(a) Cycle duration $\mathbb{E}Z$

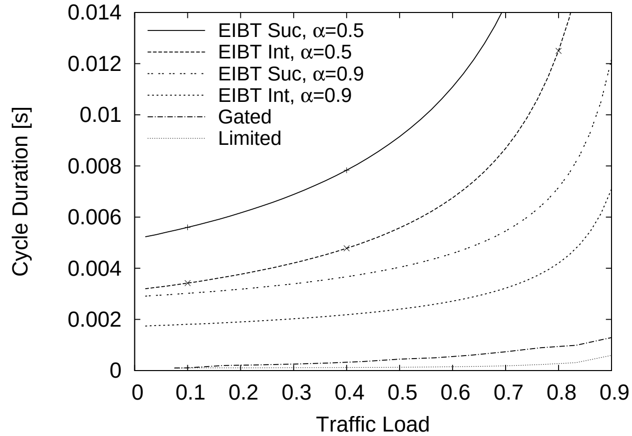


(b) Packet delay D_P

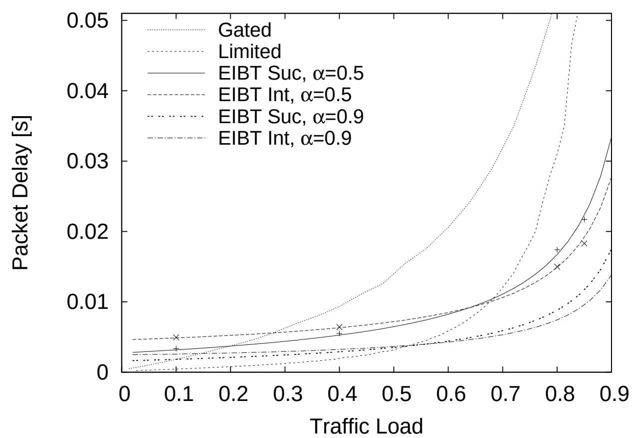


(c) File delay D_F

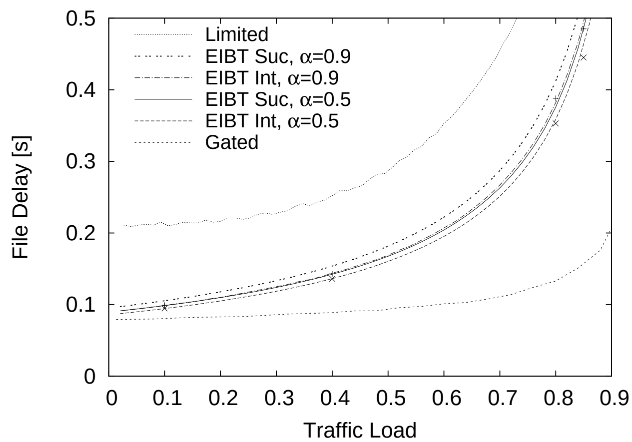
Figure 2.5: Comparison of EIBT polling using optimal EIBT duration Δ^* with conventional limited and gated polling for equal packet and file traffic loads $\pi = \phi$ and mean file size $\bar{F} = 9.9$ MB.



(a) Cycle duration $\mathbb{E}Z$



(b) Packet delay D_P



(c) File delay D_F

Figure 2.6: 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.

Chapter 3

DYNAMIC CIRCUIT AND PACKET PON (DYCAPPON)

3.1 Introduction of DyCaPPON

Today, a plethora of network applications ranging from the migration of data and computing work loads to cloud storage and computing Satyanarayanan *et al.* (2009) as well as high-bit rate e-science applications, e.g., for remote scientific collaborations, to big data applications of governments, private organizations, and households are well supported by dynamic circuit switching Veeraraghavan *et al.* (2010). Moreover, gaming applications benefit from predictable low-delay service Bredel and Fidler (2010); Fitzek *et al.* (2002); Maier and Herzog (2010); Schaefer *et al.* (2002) provided by circuits, as do emerging virtual reality applications Kurillo and Bajcsy (2013); Pallot *et al.* (2012); Vasudevan *et al.* (2010). Also, circuits can aid in the timely transmission of data from continuous media applications, such as live or streaming video. Video traffic is often highly variable and may require smoothing before transmission over a circuit Ghazisaidi *et al.* (2012); Oh *et al.* (2008); Qiao and Koutsakis (2011); Reisslein *et al.* (2002); Rexford and Towsley (1999); Shuaib *et al.* (2011); Van der Auwera and Reisslein (2009) or require a combination of circuit transport for a constant base bit stream and packet switched transport for the traffic burst exceeding the base bit stream rate. Both commercial and research/education network providers have recently started to offer optical dynamic circuit switching services Mukherjee (2007); Internet2 (2014).

While dynamic circuit switching has received growing research attention in core and metro networks Internet2 (2014); Charbonneau *et al.* (2012); Fang and Veeraraghavan (2009); Li *et al.* (2008); Monga *et al.* (2011); Munir *et al.* (2009); Skoog *et al.* (2012); Van Breusegem *et al.* (2005); Veeraraghavan and Zheng (2004), mechanisms for supporting dynamic circuit switching in passive optical networks (PONs), which are a promising technology for network access Mahloo *et al.* (2013); McGarry and Reisslein (2012); McGarry *et al.* (2010); Sivakumar *et al.* (2013); Tomkos *et al.* (2012); Zanini *et al.* (2013), are largely an open research area. As reviewed in Section 1.3.2, PON research on the upstream transmission direction from the distributed Optical Network Units (ONUs) to the central Optical Line Terminal (OLT) has mainly focused on mechanisms supporting packet-switched transport Aurzada *et al.* (2008, 2011); Zheng and Mouftah (2009). While some of these packet-switched transport mechanisms support quality of service akin to circuits through service differentiation mechanisms, to the best of my knowledge there has been no prior study of circuit-level performance in PONs, e.g., the blocking probability of circuit requests for a given circuit request rate and circuit holding time.

In this chapter, I present the first circuit-level performance study of a PON with polling-based medium access control. Three main original contributions are made here towards the concept of efficiently supporting both **Dy**namic **C**ircuit **a**nd **P**acket traffic in the upstream direction on a **PON**, which is referred to as **DyCaPPON**:

- I propose a novel DyCaPPON polling cycle structure that exploits the dynamic circuit transmissions to mask the round-trip propagation delay for dynamic bandwidth allocation to packet traffic.

- I develop a stochastic knapsack-based model of DyCaPPON to evaluate the circuit-level performance, including the blocking probabilities for different classes of circuit requests.

- I analyze the bandwidth sharing between circuit and packet traffic in DyCaP-

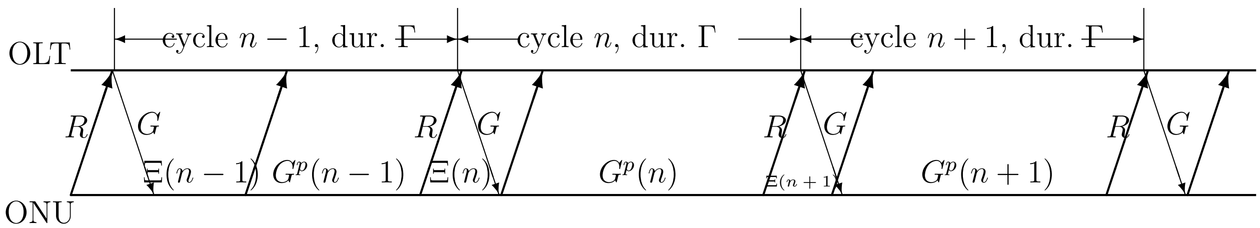


Figure 3.1: An upstream cycle n has fixed duration Γ and has a circuit partition of duration $\Xi(n)$ (that depends on the bandwidth demands of the accepted circuits) while a packet partition occupies the remaining cycle duration $\Gamma - \Xi(n)$. Each ONU sends a report during each packet partition. Packet traffic reported in cycle $n-1$ is served in the packet partition of cycle n (if there is no backlog). A circuit requested in cycle $n-1$ starts in the circuit partition of cycle $n+1$. Thus, the 2τ round-trip propagation delay (RTT) between the last ONU report (R) of a cycle $n-1$ and the first packet transmission following the grant (G) of the next cycle n is masked by the circuit partition, provided as $\Xi(n) > 2\tau$.

PON and evaluate packet-level performance, such as mean packet delay, as a function of the circuit traffic.

3.2 System Model

3.2.1 Network structure

I consider a PON with J ONUs attached to the OLT with a single downstream wavelength channel and a single upstream wavelength channel. I denote C for the transmission bit rate (bandwidth) of a channel [bits/s]. I denote τ [s] for the one-way propagation delay between the OLT and the equidistant ONUs. I denote Γ [s] for the fixed duration of a polling cycle. The model notations are summarized in Table 3.1. Please notice that there are some differences with the previous previous chapter's notations regarding EIBT, in order to distinguish them.

3.2.2 Traffic Models

For circuit traffic, I consider K classes of circuits with bandwidths $\mathbf{b} = (b_1,\ b_2, \ldots, b_K)$. I denote λ_c [requests/s] for the aggregate Poisson process arrival rate of circuit re-

Table 3.1: Main model notations

Network architecture	
C	Transmission rate [bit/s] of upstream channel
C_c	Transmission rate limit for circuit service, $C_c \leq C$
J	Number of ONUs
τ	One-way propagation delay [s]
Traffic model	
$\mathbf{b} = (b_1, \ldots, b_K)$	Bit rates [bit/s] for circuit classes $k = 1, 2, \ldots, K$
λ_c	Aggregate circuit requests arrival rate [circuits/s]
p_k	Prob. that a request is for circuit type k
$\bar{b} = \sum_{k=1}^{K} p_k b_k$	Mean circuit bit rate [bit/s]
$1/\mu$	Mean circuit holding time [s/circuit]
$\chi = \frac{\lambda_c \bar{b}}{\mu C}$	Offered circuit traffic intensity (load)
$\bar{P}$, σ_p^2	Mean [bit] and variance of packet size
$\pi = \frac{\lambda_p \bar{P}}{C}$	Packet traffic intensity (load); λ_p is agg. packet generation rate [packets/s] at all J ONUs
Polling protocol	
Γ	Total cycle duration [s], constant
Ξ	Cycle duration (rand. var.) occupied by circuit traffic
ω	Mean per-cycle overhead time [s] for upstream transmissions (report transm. times, guard times)
Stochastic knapsack model for circuits	
$\mathbf{n} = (n_1, \ldots, n_K)$	State vector of numbers of circuits of class k
$\beta = \mathbf{n} \cdot \mathbf{b}$	Aggregate bandwidth of active circuits
$q(\beta)$	Equilibrium probability for active circuits having aggregate bandwidth β
Performance metrics	
B_k	Blocking probability for circuit class k
D	Mean packet delay [s]

quests. A given circuit request is for a circuit of class k, $k = 1, 2, \ldots, K$, with probability p_k. I model the circuit holding time (duration) as an exponential random variable with mean $1/\mu$.

For packet traffic, I denote $\bar{P}$ and σ_p^2 for the mean and the variance of the packet size [in bit], respectively. I denote λ_p for the aggregate Poisson process arrival rate [packets/s] of packet traffic across the J ONUs and denote $\pi := \bar{P}\lambda_p/C$ for the packet traffic intensity (load).

Throughout, I define the packet sizes and circuit bit rates 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 circuit traffic for transmission.

3.2.3 Performance Metrics

For circuit traffic, I consider the blocking probability B_k, $k = 1, 2, \ldots, K$, i.e., the probability that a request for a class k circuit is blocked, i.e., cannot be accommodated within the transmission rate limit for circuit service C_c. I define the average circuit blocking probability as $\bar{B} = \sum_{k=1}^{K} p_k B_k$. For packet traffic, I consider the mean packet delay D defined 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.

3.3 DyCaPPON Upstream Bandwidth Management

3.3.1 Overview of Cycle and Polling Structure

In order to provide circuit traffic with consistent upstream transmission service with a fixed circuit bandwidth, DyCaPPON employs a polling cycle with a fixed duration Γ [s]. An active circuit with bandwidth b is allocated an upstream transmission window of duration $b\Gamma/C$ in every cycle. Thus, by transmitting at the full upstream channel bit rate C for duration $b\Gamma/C$ once per cycle of duration Γ, the circuit experiences a transmission bit rate (averaged over the cycle duration) of b. I let $\Xi(n)$ denote the aggregate of the upstream transmission windows of all active circuits in the PON in cycle n, and refer to $\Xi(n)$ as the circuit partition duration. I refer to the remaining duration $\Gamma - \Xi(n)$ as the packet partition of cycle n.

As illustrated in Fig. 3.1, a given cycle n consists of the circuit partition followed by the packet partition. During the packet partition of each cycle, each ONU sends a report message to the OLT. The report message signals new circuit requests as well as the occupancy level (queue depth) of the packet service queue in the ONU to the OLT. The signaling information for the circuit requests, i.e., requested circuit bandwidth and duration, can be carried in the Report message of the MPCP protocol in EPONs with similar modifications as used for signaling information for operation on multiple wavelength channels McGarry *et al.* (2006).

Specifically, for signaling dynamic circuit requests, an ONU report in the packet partition of cycle $n-1$ carries circuit requests generated since the ONU's preceding report in cycle $n-2$. The report reaches the OLT by the end of cycle $n-1$ and the OLT executes circuit admission control as described in Section 3.3.2. The ONU is informed about the outcome of the admission control (circuit is admitted or blocked) in the gate message that is transmitted on the downstream wavelength channel at the beginning of cycle n. In the DyCaPPON design, the gate message propagates downstream while the upstream circuit transmissions of cycle n are propagating upstream. Thus, if the circuit was admitted, the ONU commences the circuit transmission with the circuit partition of cycle $n+1$.

For signaling packet traffic, the ONU report in the packet partition of cycle $n-1$ carries the current queue depth as of the report generation instant. Based on this queue depth, the OLT determines the effective bandwidth request and bandwidth

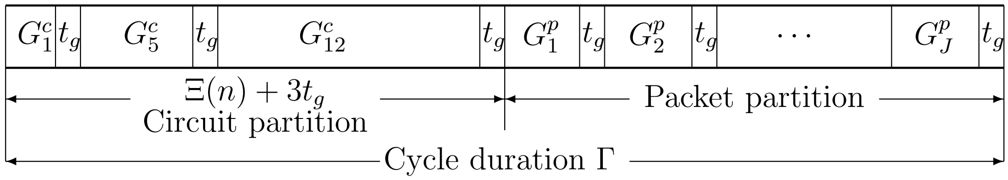


Figure 3.2: Detailed example illustration of an upstream transmission cycle n: ONUs 1, 5, and 12 have active circuits with bandwidths resulting in circuit grant durations G_1^c, G_5^c, and G_{12}^c. Each of the J ONUs is allocated a packet grant of duration G_j^p according to the dynamic packet bandwidth allocation based on the reported packet traffic; the packet grant accommodates at least the ONU report (even if there is not payload packet traffic).

allocation as described in Section 3.3.3. The gate message transmitted downstream at the beginning of cycle n informs the ONU about its upstream transmission window in the packet partition of cycle n.

As illustrated in Fig. 3.1, in the DyCaPPON design, the circuit partition is positioned at the beginning of the cycle, in an effort to mitigate the idle time between the end of the packet transmissions in the preceding cycle and the beginning of the packet transmissions of the current cycle. In particular, when the last packet transmission of cycle $n-1$ arrives at the OLT at the end of cycle $n-1$, the first packet transmission of cycle n can arrive at the OLT at the very earliest one roundtrip propagation delay (plus typically negligible processing time and gate transmission time) after the beginning of cycle n. If the circuit partition duration $\Xi(n)$ is longer than the roundtrip propagation delay 2τ, then idle time between packet partitions is avoided. On the other hand, if $\Xi(n) < 2\tau$, then there an idle channel period of duration $2\tau - \Xi(n)$ between the end of the circuit partition and the beginning of the packet partition in cycle n.

Note that this DyCaPPON design trades off lower responsiveness to circuit requests for the masking of the roundtrip propagation delay. Specifically, when an ONU signals a dynamic circuit request in the report message in cycle $n-1$, it can at the earliest transmit circuit traffic in cycle $n+1$. On the other hand, packet traffic signaled in the report message in cycle $n-1$ can be transmitted in the next cycle, i.e., cycle n.

Fig. 3.2 illustrates the structure of a given cycle in more detail, including the overheads for the upstream transmissions. Each ONU that has an active circuit in the cycle requires one guard time of duration t_g in the circuit partition. Thus, with η denoting the number of ONUs with active circuits in the cycle, the duration of the circuit partition is $\Xi(n)+\eta t_g$. In the packet partition, each of the J ONUs transmits at least a report message plus possibly some data upstream, resulting in an overhead of $J(t_R+t_g)$. Thus, the overhead per cycle is

$$\omega_o = \eta t_g + J(t_R + t_g). \tag{3.1}$$

The resulting aggregate limit of the transmission windows for packets in cycle n is

$$G^p(n) = \Gamma - \max\{2\tau,\ \Xi(n)\} - \omega_o. \tag{3.2}$$

Low-Packet-Traffic Mode Polling

If there is little packet traffic, the circuit partition $\Xi(n)$ and the immediately following packet transmission phase denoted P1 in Fig. 3.3 may leave significant portions of the fixed-duration cycle idle. In such low-packet-traffic cycles, the OLT can launch additional polling rounds denoted P2, P3, and P4 in Fig. 3.3 to serve newly arrived packets with low delay. Specifically, if all granted packet upstream transmissions have arrived at the OLT and there is more than $J(t_R+t_g)+2\tau$ time remaining until the end of the cycle (i.e., the beginning of the arrival of the next circuit partition Ξ_{n+1}) at the OLT, then the OLT can launch another polling round.

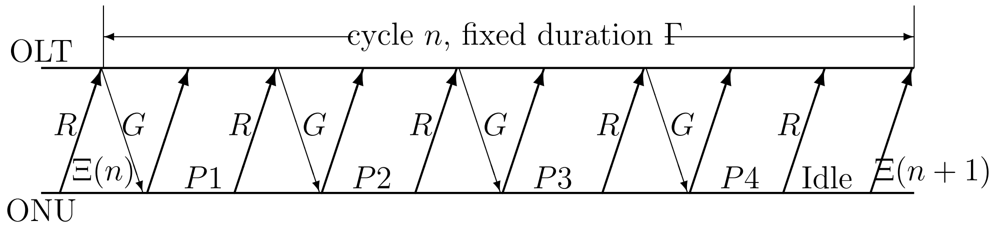


Figure 3.3: Illustration of low-packet-traffic mode polling: If transmissions from all ONUs in the packet phase P1 following the circuit partition $\Xi(n)$ reach the OLT more than 2τ before the end of the cycle, the OLT can launch additional packet polling rounds P2, P3, and P4 to serve newly arrived packet traffic before the next circuit partition $\Xi(n+1)$.

3.3.2 Dynamic Circuit Admission Control

For each circuit class k, $k = 1, 2, \ldots, K$, the OLT tracks the number n_k of currently active circuits, i.e., the OLT tracks the state vector $\mathbf{n} := (n_1, ..., n_k)$ representing the numbers of active circuits. Taking the inner product of $\mathbf{n}$ with the vector $\mathbf{b} := (b_1, ..., b_k)$ representing the bit rates of the circuit classes gives the currently required aggregate circuit bandwidth

$$\beta = \mathbf{b} \cdot \mathbf{n} = \sum_{k=1}^{K} b_k n_k, \tag{3.3}$$

which corresponds to the circuit partition duration

$$\Xi(n) = \frac{\beta\Gamma}{C}. \tag{3.4}$$

For a given limit C_c, $C_c \leq C$, of bandwidth available for circuit service, I let $\mathcal{S}$ denote the state space of the stochastic knapsack model Ross (1995) of the dynamic circuits, i.e.,

$$\mathcal{S} := \{\mathbf{n} \in I^K : \mathbf{b} \cdot \mathbf{n} \leq C_c\}, \tag{3.5}$$

where I is the set of non-negative integers.

For an incoming ONU request for a circuit of class k, I let $\mathcal{S}_k$ denote the subset of the state space $\mathcal{S}$ that can accommodate the circuit request, i.e., has at least spare bandwidth b_k before reaching the circuit bandwidth limit C_c. Formally,

$$\mathcal{S}_k := \{\mathbf{n} \in \mathcal{S} : \mathbf{b} \cdot \mathbf{n} \leq C_c - b_k\}. \tag{3.6}$$

Thus, if presently $\mathbf{n} \in \mathcal{S}_k$, then the new class k circuit can be admitted; otherwise, the class k circuit request must be rejected (blocked).

3.3.3 Packet Traffic Dynamic Bandwidth Allocation

With the offline scheduling approach Zheng and Mouftah (2009) of DyCaPPON, the reported packet queue occupancy corresponds to the duration of the upstream packet transmission windows $R_j, j = 1, 2, \ldots, J$, requested by ONU j. Based on these requests, and the available aggregate packet upstream transmission window G^p (3.2), the OLT allocates upstream packet transmission windows with durations $G_j^p,\ j = 1, 2, \ldots, J$, to the individual ONUs.

The problem of fairly allocating bandwidth so as to enforce a maximum cycle duration has been extensively studied for the Limited grant sizing approach Assi *et al.* (2003b); Bai *et al.* (2006), which I adapt as follows. I set the packet grant limit for cycle n to

$$G_{\max}(n) = \frac{G^p(n)}{J}. \tag{3.7}$$

If an ONU requests less than the maximum packet grant duration $G_{\max}(n)$, it is granted its full request and the excess bandwidth (i.e., difference between $G_{\max}(n)$ and allocated grant) is collected by an excess bandwidth distribution mechanism. If an ONU requests a grant duration longer than $G_{\max}(n)$, it is allocated this maximum grant duration, plus a portion of the excess bandwidth according to the equitable distribution approach with a controlled excess allocation bound Assi *et al.* (2003a); Bai *et al.* (2006).

With the Limited grant sizing approach, there is commonly an unused slot remainder of the grant allocation to ONUs Kramer *et al.* (2002a); Hajduczenia *et al.* (2006); Naser and Mouftah (2006) due to the next queued packet not fitting into the remaining granted transmission window. I model this unused slot remainder by half of the average packet size $\bar{P}$ for each of the J ONUs. Thus, the total mean unused transmission window duration in a given cycle is

$$\omega_u = \frac{J\bar{P}}{2C}. \tag{3.8}$$

3.4 Performance Analysis

3.4.1 Circuit Traffic

Request Blocking

In this section, I employ techniques from the analysis of stochastic knapsacks Ross (1995) to evaluate the blocking probabilities B_k of the circuit class. I also evaluate the mean duration of the circuit partition Ξ, which governs the mean available packet partition duration G^p, which in turn is a key parameter for the evaluation of the mean packet delay in Section 3.4.2.

The stochastic knapsack model Ross (1995) is a generalization of the well-known Erlang loss system model to circuits with heterogeneous bandwidths. In brief, in the stochastic knapsack model, objects of different classes (sizes) arrive to a knapsack of fixed capacity (size) according to a stochastic arrival process. If a newly arriving object fits into the currently vacant knapsack space, it is admitted to the knapsack and remains in the knapsack for some random holding time. After the expiration of the holding time, the object leaves the knapsack and frees up the knapsack space that it occupied. If the size of a newly arriving object exceeds the currently vacant knapsack space, the object is blocked from entering the knapsack, and is considered dropped (lost).

I model the prescribed limit C_c on the bandwidth available for circuit service as the knapsack capacity. The requests for circuits of bandwidth $b_k,\ k = 1, 2, \ldots, K$, arriving according to a Poisson process with rate $p_k\lambda_c$ are modeled as the objects seeking entry into the knapsack. An admitted circuit of class k occupies the bandwidth (knapsack space) b_k for an exponentially distributed holding time with mean $1/\mu$.

I denote $\mathcal{S}(\beta)$ for the set of states $\mathbf{n}$ that occupy an aggregate bandwidth $\beta,\ 0 \leq \beta \leq C_c$, i.e.,

$$\mathcal{S}(\beta) := \{\mathbf{n} \in \mathcal{S} : \mathbf{b} \cdot \mathbf{n} = \beta\}. \tag{3.9}$$

Let $q(\beta)$ denote the equilibrium probability of the currently active circuits occupying an aggregate bandwidth of β. Through the recursive Kaufman-Roberts algorithm (Ross, 1995, p. 23), which is given in the Appendix, the equilibrium probabilities $q(\beta)$ can be computed with a time complexity of $O(C_cK)$ and a memory complexity of $O(C_c + K)$.

The blocking probability $B_k,\ k = 1, 2, \ldots, K$ is obtained by summing the equilibrium probabilities $q(\beta)$ of the sets of states that have less than b_k available circuit bandwidth, i.e.,

$$B_k = \sum_{\beta=C_c-b_k+1}^{C_c} q(\beta). \tag{3.10}$$

I define the average circuit blocking probability

$$\bar{B} = \sum_{k=1}^{K} p_k B_k. \tag{3.11}$$

Aggregate Circuit Bandwidth

The performance evaluation for packet delay in Section 3.4.2 requires taking expectations over the distribution $q(\beta)$ of the aggregate bandwidth β occupied by circuits. In preparation for these packet evaluations, I define $\mathbb{E}_\beta[f(\beta)]$ to denote the expectation of a function f of the random variable β over the distribution $q(\beta)$, i.e., I define

$$\mathbb{E}_\beta[f(\beta)] = \sum_{\beta=0}^{C_c} f(\beta) q(\beta). \tag{3.12}$$

With this definition, the mean aggregate bandwidth of the active circuits is obtained as

$$\bar{\beta} = \mathbb{E}_\beta[\beta] = \sum_{\beta=0}^{C_c} \beta q(\beta). \tag{3.13}$$

Note that by taking the expectation of (3.4), the corresponding mean duration of the circuit partition is $\bar{\Xi} = \mathbb{E}_\beta[\beta\Gamma/C] = \bar{\beta}\Gamma/C$.

Delay and Delay Variation

In this section I analyze the delay and delay variations experienced by circuit traffic as it traverses a DyCaPPON network from ONU to OLT. Initially I ignore delay variations, i.e., I consider that a given circuit with bit rate b has a fixed position for the transmission of its $b\Gamma$ bits in each cycle. Three delay components arise: The "accumulation/dispersal" delay of Γ for the $b\Gamma$ bits of circuit traffic that are transmitted per cycle. Note that the first bit arriving to form a "chunk" of $b\Gamma$ bits experiences the delay Γ at the ONU, waiting for subsequent bits to "fill up (accumulate)" the chunk. The last bit of a chunk experiences essentially no delay at the ONU, but has to wait for a duration of Γ at the OLT to "send out (disperse)" the chunk at the circuit bit rate b. The other delay components are the transmission delay of $b\Gamma/C$ and the propagation delay τ. Thus, the total delay is

$$\Gamma\left(1 + \frac{b}{C}\right) + \tau. \tag{3.14}$$

Circuit traffic does not experience delay variations (jitter) in DyCaPPON as long as the positions (in time) of the circuit transmissions in the cycle are held fixed.

When an ongoing circuit is closing down or a new circuit is established, it may become necessary to rearrange the transmission positions of the circuits in the cycle in order to keep all circuit transmissions within the circuit partition at the beginning of the cycle and avoid idle times during the circuit partition. Adaptations of packing algorithms Dyckhoff (1990) could be employed to minimize the shifts in transmission positions. Note that for a given circuit service limit C_c, the worst-case delay variation for a given circuit with rate b is less than $\Gamma(C_c - b)/C$ as the circuit could at the most shift from the beginning to the end of the circuit partition of maximum duration $\Gamma C_c/C$.

3.4.2 Packet Traffic

Stability Limit

Inserting the circuit partition duration Ξ from (3.4) into the expression for the aggregate limit G^p on the transmission window for packets in a cycle from (3.2) and taking the expectation $\mathbb{E}_\beta[\cdot]$ with respect to the distribution of the aggregate circuit bandwidth β, I obtain

$$\bar{G^p} = \Gamma - \mathbb{E}_\beta\left[\max\left\{2\tau,\ \frac{\beta\Gamma}{C}\right\}\right] - \omega_o. \tag{3.15}$$

Considering the unused slot remainder ω_u (3.8), the mean portion of a cycle available for upstream packet traffic transmissions is limited to

$$\pi_{\max} = 1 - E_\beta\left[\max\left\{\frac{2\tau}{\Gamma},\ \frac{\beta}{C}\right\}\right] - \frac{\omega_o + \omega_u}{\Gamma}. \tag{3.16}$$

That is, the packet traffic intensity π must be less than $\pi_{\max}$ for stability of the packet service, i.e., for finite packet delays.

Mean Delay

In this section, I present for stable packet service an approximate analysis of the mean delay D of packets transmitted during the packet partition. In DyCaPPON, packets are transmitted on the bandwidth that is presently not occupied by admitted circuits. Thus, fluctuations in the aggregate occupied circuit bandwidth β affect the packet delays. If the circuit bandwidth β is presently high, packets experience longer delays than for presently low circuit bandwidth β. The aggregated occupied circuit bandwidth β fluctuates as circuits are newly admitted and occupy bandwidth and as existing circuits reach the end of their holding time and release their occupied bandwidth. The time scale of these fluctuations of β increases as the average circuit holding time $1/\mu$ increases, i.e., as the circuit departure rate μ decreases (and correspondingly, the circuit request arrival rate λ decreases for a given fixed circuit traffic load χ) Gaver and Lehoczky (1982).

For circuit holding times that are orders of magnitude larger than the typically packet delays (service times) in the system, the fluctuations of the circuit bandwidth β occur at a significantly longer (slower) time scale than the packet service time scale. That is, the bandwidth β occupied by circuits exhibits significant correlations over time which in turn give rise to complex correlations with the packet queueing delay Weinstein *et al.* (1980); Tham and Hume (1983). For instance, packets arriving during a long period of high circuit bandwidth may experience very long queueing delays and are possibly only served after some circuits release their bandwidth. As illustrated in Section 3.5.3, the effects of these complex correlations become significant for scenarios with moderate to long circuit holding times $1/\mu$ when the circuit traffic load is low to moderate relative to the circuit bandwidth limit C_c (so that pronounced circuit bandwidth fluctuations are possible), and the packet traffic load on the remaining bandwidth of approximately $C - C_c$ is relatively high, so that substantial packet queue build-up can occur. I leave a detailed mathematical analysis of the complex correlations occurring in these scenarios in the context of DyCaPPON for future research.

In the present study, I focus on an approximate packet delay analysis that neglects the outlined correlations. I base my approximate packet delay analysis on the expectation $E_\beta[f(\beta)]$ (3.12), i.e., I linearly weigh packet delay metrics $f(\beta)$ with the probability masses $q(\beta)$ for the aggregate circuit bandwidth β. I also neglect the "low-load" operating mode of Section 3.3.1 in the analysis.

In the proposed DyCaPPON cycle structure, a packet experiences five main components, namely (*i*) the reporting delay from the generation instant of the packet to the transmission of the report message informing the OLT about the packet, which for the fixed cycle duration of DyCaPPON equals half the cycle duration, i.e., $\Gamma/2$, (*ii*) the report-to-packet partition delay $D_{\mathrm{r-p}}$ from the instant of report transmission to the beginning of the packet partition in the next cycle, (*iii*) the queuing delay D_q from the reception instant of the grant message to the beginning of the transmission of the packet, as well as (*iv*) the packet transmission delay with mean $\bar{P}/C$, and (*v*) the upstream propagation delay τ.

In the report-to-packet partition delay I include a delay component of half the mean duration of the packet partition $\bar{G^p}/2$ to account for the delay of the reporting of a particular ONU to the end of the packet partition. The delay from the end of the packet partition in one cycle to the beginning of the packet partition of the next cycle is the maximum of the roundtrip propagation delay 2τ and the mean duration of the circuit partition Ξ. Thus, I obtain overall for the report-to-packet partition delay as

$$D_{\mathrm{r-p}} = \frac{\bar{G^p}}{2} + \mathbb{E}_\beta\left[\max\left\{2\tau,\ \frac{\beta\Gamma}{C}\right\}\right] \quad (3.17)$$

$$= \frac{1}{2}\left(\Gamma + \mathbb{E}_\beta\left[\max\left\{2\tau,\ \frac{\beta\Gamma}{C}\right\}\right] - \omega_o\right). \quad (3.18)$$

I model the queueing delay 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 queueing delay Kleinrock (1975)

$$D_{M/G/1} = \frac{\rho\frac{\bar{L}}{C}\left(1 + \frac{\sigma^2}{\bar{L}^2}\right)}{2(1-\rho)}. \quad (3.19)$$

For DyCaPPON, I model the aggregate packet traffic from all J ONUs as feeding into one M/G/1 queue with mean packet size $\bar{P}$ and packet size variance σ_p^2. I model the circuit partitions, when the upstream channel is not serving packet traffic, through scaling of the packet traffic intensity. In particular, the upstream channel is available for serving packet traffic only for the mean fraction $(\bar{G^p} - \omega_u)/\Gamma$ of a cycle. Thus, for large backlogs served across several cycles, the packet traffic intensity during the packet partition is effectively

$$\pi_{\mathrm{eff}} = \frac{\pi}{\pi_{\max}}. \quad (3.20)$$

Hence, the mean queueing delay is approximately

$$D_q = \frac{\frac{\pi_{\mathrm{eff}}\bar{P}}{C}\left(1 + \frac{\sigma_p^2}{\bar{P}^2}\right)}{2(1-\pi_{\mathrm{eff}})}. \quad (3.21)$$

Thus, the overall mean packet delay is approximately

$$D = \frac{\Gamma}{2} + D_{\mathrm{r-p}} + D_q + \frac{\bar{P}}{C} + \tau. \quad (3.22)$$

Table 3.2: Circuit bandwidths b_k and request probabilities p_k for $K = 3$ classes of circuits in performance evaluations.

	Class k		
	1	2	3
b_k [Mb/s]	52	156	624
p_k [%]	53.56	28.88	15.56

3.5 DyCaPPON Performance Results

3.5.1 Evaluation Setup

I consider an EPON with $J = 32$ ONUs, a channel bit rate $C = 10$ Gb/s, and a cycle duration $\Gamma = 2$ ms. Each ONU has abundant buffer space and a one-way propagation delay of $\tau = 96$ μs to the OLT. The guard time is $t_g = 5$ μs and the report message has 64 Bytes. I consider $K = 3$ classes of circuits as specified in Table 3.2. A packet has 64 Bytes with 60% probability, 300 Bytes with 4% probability, 580 Bytes with 11% probability, and 1518 bytes with 25% probability, thus the mean packet size is $\bar{P} = 493.7$ Bytes. The verifying simulations were conducted with a CSIM based simulator and are reported with 90 % confidence intervals which are too small to be visible in the plots.

3.5.2 Impact of Packet Traffic Load π

In Table 3.3 I present circuit blocking probability results. In Fig. 3.4 I plot packet delay results for increasing packet traffic load π. I consider three levels of offered circuit traffic load χ, which are held constant as the packet traffic load π increases. DyCaPPON ensures consistent circuit service with the blocking probabilities and delay characterized in Section 3.4.1 irrespective of the packet traffic load π, that is,

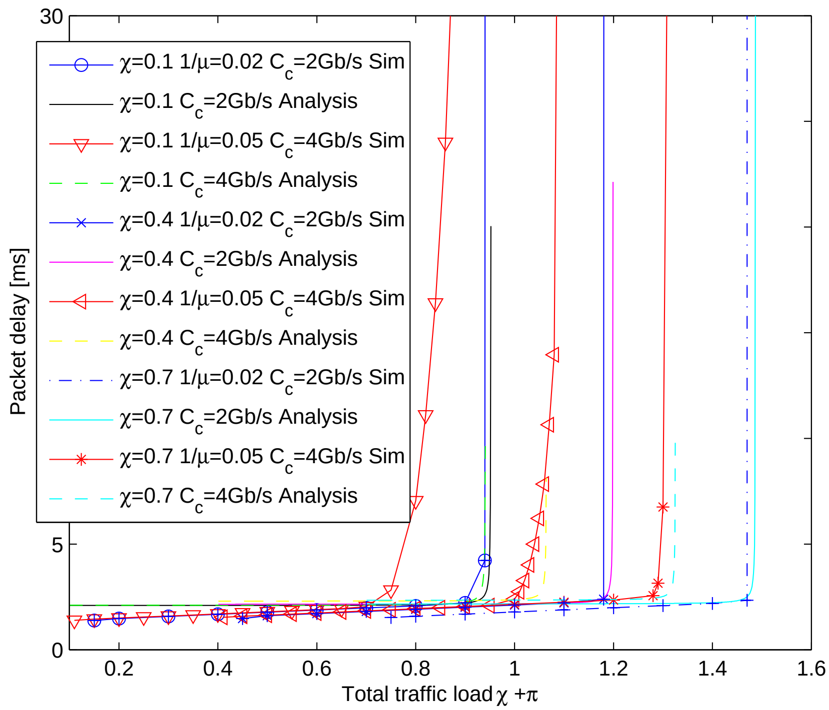


Figure 3.4: Impact of packet traffic load π: Mean packet delay D from simulations (S) and analysis (A) as a function of total traffic load $\chi + \pi$, which is varied by varying π for fixed circuit traffic load $\chi = 0.1$, 0.4, or 0.7, with different $C_c = 2$ and $1/\mu$ settings.

the packet traffic does *not* degrade the circuit service at all. Specifically, Table 3.3 gives the blocking probabilities B_k as well as the average circuit blocking probability $\bar{B} = \sum_{k=1}^{K} p_k B_k$ for the different levels of offered circuit traffic load; these blocking probability values hold for the full range of packet traffic loads π. Similarly, Fig. 3.5, 3.6, 3.7, 3.8 demonstrate the impact of π under more different scenarios.

I observe from Table 3.3 that for a given offered circuit traffic load level χ, the blocking probability increases with increasing circuit bit rate b_k as it is less likely that sufficient bit rate is available for a higher bit rate circuit. Moreover, I observe that the blocking probabilities increase with increasing offered circuit traffic load χ. This is because the circuit transmission limit C_c becomes increasingly saturated with

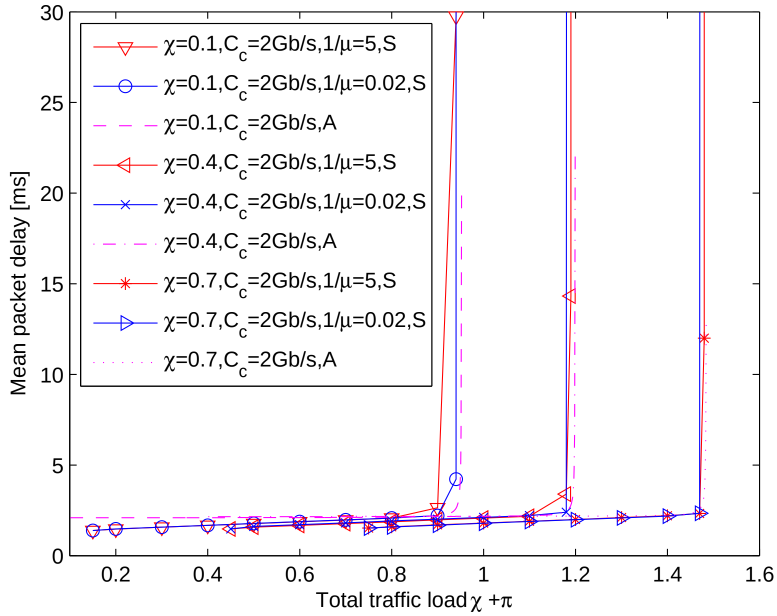


Figure 3.5: Impact of packet traffic load π: Mean packet delay D from simulations (S) and analysis (A) as a function of total traffic load $\chi+\pi$, which is varied by varying π for fixed circuit traffic load $\chi = 0.1$, 0.4, or 0.7, with $C_c = 2$ Gb/s, and two different $1/\mu$ values

increasing offered circuit load χ, resulting in more blocked requests. The representative simulation results in Table 3.3 indicate that the stochastic knapsack analysis is accurate, as has been extensively verified in the context of general circuit switched systems Ross (1995).

In Fig. 3.4 I plot the mean packet delay as a function of the total traffic load, i.e., the sum of offered circuit traffic load χ plus the packet traffic load π. I initially exclude the scenario with $\chi = 0.1$, $C_c = 4$ Gbps, and $1/\mu = 0.5$ s from consideration; this scenario is discussed in Section 3.5.3. I observe from Fig. 3.4 that for low packet traffic load π (i.e., for a total traffic load $\chi + \pi$ just above the offered circuit traffic load χ), the packet delay is nearly independent of the offered circuit traffic load χ. For low packet traffic load, the few packet transmissions fit easily into the packet partition of the cycle.

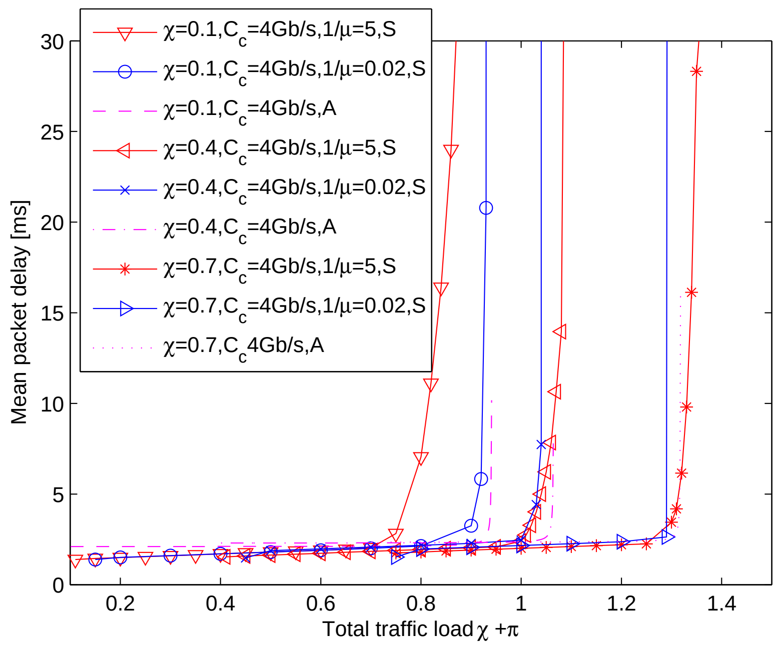


Figure 3.6: Impact of packet traffic load π: Mean packet delay D from simulations (S) and analysis (A) as a function of total traffic load $\chi+\pi$, which is varied by varying π for fixed circuit traffic load $\chi = 0.1$, 0.4, or 0.7, with $C_c = 4$ Gb/s, and two different $1/\mu$ values

I observe from Fig. 3.4 sharp packet delay increases for high packet traffic loads π that approach the maximum total traffic load, i.e., offered circuit traffic load χ plus maximum packet traffic load $\pi_{\max}$. For $C_c = 2$ Gb/s, the maximum packet traffic load $\pi_{\max}$ is 0.85 for $\chi = 0.1$ and 0.78 for $\chi = 0.7$, see Table 3.3. Note that the maximum packet traffic load $\pi_{\max}$ depends on the offered circuit traffic load χ and the circuit traffic limit C_c. For a low offered circuit traffic load χ relative to C_c/C, few circuit requests are blocked and the admitted circuit traffic load (equivalently mean aggregate circuit bandwidth $\bar{\beta}$) is close to the offered circuit load χ. On the other hand, for high offered circuit traffic load χ, many circuit requests are blocked, resulting in an admitted circuit traffic load (mean aggregate circuit bandwidth $\bar{\beta}$) significantly below the offered circuit traffic load χ. Thus, the total (normalized)

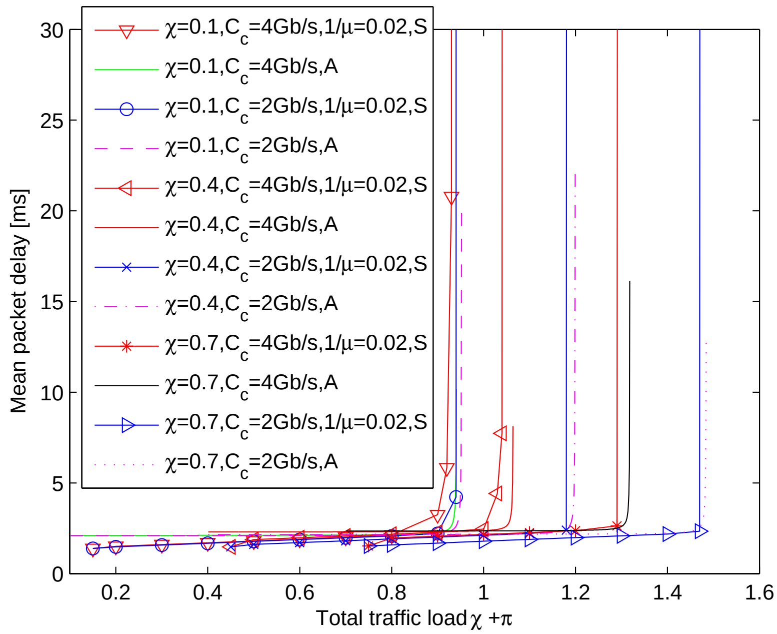


Figure 3.7: Impact of packet traffic load π: Mean packet delay D from simulations (S) and analysis (A) as a function of total traffic load $\chi+\pi$, which is varied by varying π for fixed circuit traffic load $\chi = 0.1$, 0.4, or 0.7, with $1/\mu = 0.02$ s, and two different C_c values

traffic load, i.e., offered circuit load χ plus packet traffic load π, in a stable network can exceed one for high offered circuit traffic load χ.

3.5.3 Impact of Mean Circuit Holding Time

I now turn to the packet delay results for the scenario with low circuit traffic load $\chi = 0.1$ relative to the circuit bandwidth limit $C_c = 4$ Gbps and moderately long mean circuit holding time $1/\mu = 0.5$ s in Fig. 3.4. I observe for this scenario that the mean packet delays obtained from the simulations begin to increase dramatically as the total load $\chi + \pi$ approaches 0.8. In contrast, for the circuit traffic load $\chi = 0.1$ in conjunction with the lower circuit bandwidth limit $C_c = 2$ Gbps and short mean circuit holding times $1/\mu = 0.02$ s, the mean packet delays remain low for total loads up to close to the total maximum load $\chi + \pi_{\max} = 0.95$ and then increase sharply.

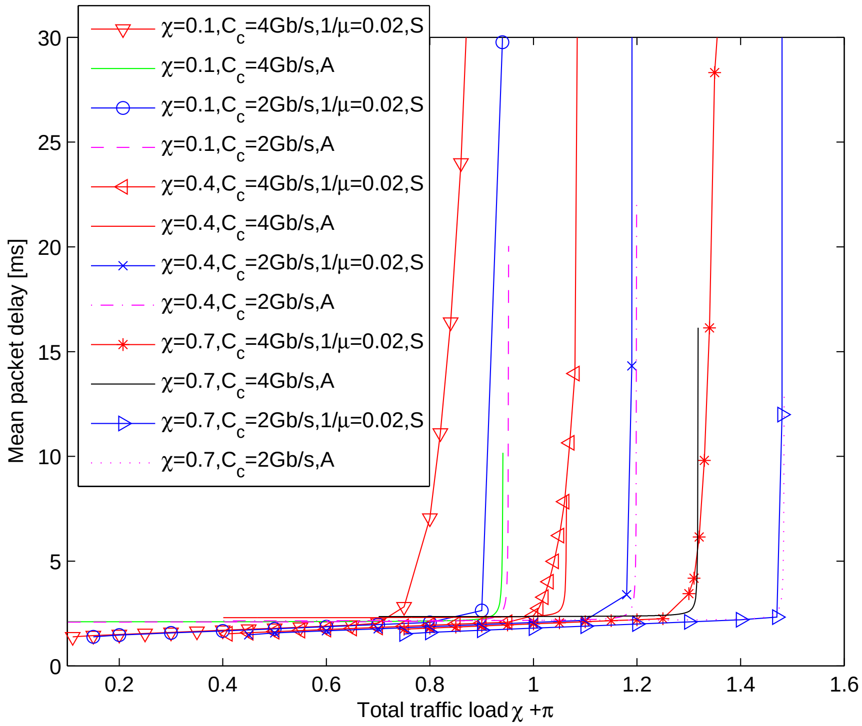


Figure 3.8: Impact of packet traffic load π: Mean packet delay D from simulations (S) and analysis (A) as a function of total traffic load $\chi + \pi$, which is varied by varying π for fixed circuit traffic load $\chi = 0.1$, 0.4, or 0.7, with $1/\mu = 0.5$ s, and two different C_c values

The pronounced delay increases at lower loads (in the 0.75–0.92 range) for the $\chi = 0.1$, $C_c = 4$ Gbps, $1/\mu = 0.5$ s scenario are mainly due to the higher-order complex correlations between the pronounced slow-time scale fluctuations of the circuit bandwidth and the packet queueing as explained in Section 3.4.2. The high circuit bandwidth limit $C_c = 4$ Gbps relative to the low circuit traffic load $\chi = 0.1$ allows pronounced fluctuations of the aggregate occupied circuit bandwidth β. For the moderately long mean circuit holding time $1/\mu = 0.5$ s, these pronounced fluctuations occur at a long time scale relative to the packet service time scales, giving rise to pronounced correlation effects. That is, packets arriving during periods of high circuit bandwidth β may need to wait (queue) until some circuits end and release

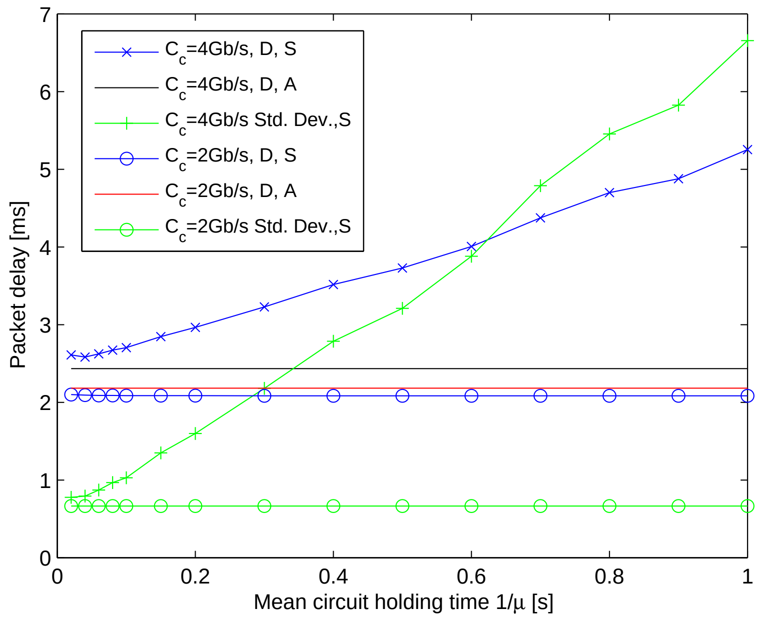


Figure 3.9: Mean packet delay D and standard deviation of packet delay as a function of mean circuit holding time $1/\mu$; fixed parameters $\chi = 0.5$, $\pi = 0.6$.

sufficient bandwidth to serve the queued packet backlog. These correlation effects are neglected in my approximate packet delay analysis in Section 3.4.2 giving rise to the large discrepancy between simulation and analysis observed for the $\chi = 0.1$, $C_c = 4$ Gb/s, $1/\mu = 0.5$ s scenario in Fig. 3.4.

I observe from Fig. 3.4 for the scenarios with relatively high circuit traffic loads $\chi = 0.4$ and 0.7 relative to the considered circuit bandwidth limits $C_c = 2$ and 4 Gbps that the mean packet delays remain low up to levels of the total load close to the total stability limit $\chi + \pi_{\max}$ predicted from the stability analysis in Section 3.4.2. The relatively high circuit traffic loads χ lead to high circuit blocking probabilities (see Table 3.3) and the admitted circuits utilize the available circuit traffic bandwidth C_c nearly fully for most of the time. Vacant portions of the circuit bandwidth C_c are quickly occupied by the frequently arriving new circuit requests. Thus, there are only relatively minor fluctuations of the bandwidth available for packet service and the approximate packet delay analysis is quite accurate.

Returning to the scenario with relatively low circuit traffic load $\chi = 0.1$ in Fig. 3.4, I observe that for the short mean circuit holding time $1/\mu = 0.02$, the mean packet delays remain low up to load levels close to the stability limit $\chi + \pi_{\max}$. For these relatively short circuit durations, the pronounced fluctuations of the occupied circuit bandwidth occur on a sufficiently short time scale to avoid significant higher-order correlations between the circuit bandwidth and the packet service.

I examine these effects in more detail in Fig. 3.9, which shows means and standard deviations of packet delays as a function of the mean circuit holding time $1/\mu$ for fixed traffic load $\chi = 0.5$, $\pi = 0.6$. I observe that for the high $C_c = 4$ Gbps circuit bandwidth limit, the mean packet delay as well as the standard deviation of the packet delay obtained from simulations increase approximately linearly with increasing mean circuit holding time $1/\mu$. The $C_c = 4$ Gbps circuit bandwidth limit permits sufficiently large fluctuations of the circuit bandwidth β for the $\chi = 0.5$ load, such that for increasing circuit holding time, the packets increasingly experience large backlogs that can only be cleared when some circuits end and release their bandwidth. In contrast, for the lower circuit bandwidth limit $C_C = 2$ Gbps, which severely limits fluctuations of the circuit bandwidth β for the high circuit traffic load $\chi = 0.5$, the mean and standard deviation of the packet delay remain essentially constant for increasing $1/\mu$.

3.5.4 Impact of Offered Circuit Traffic Load χ

In Table. 3.4, I examine the impact of the circuit traffic load χ on the DyCaPPON performance more closely. I keep the packet traffic load fixed at $\pi = 0.7$ and examine the average circuit blocking probability $\bar{B}$ and the mean packet delay D as a function of the circuit traffic load χ. I observe from Table. 3.4 that, as expected, the mean circuit blocking probability $\bar{B}$ increases with increasing circuit traffic load χ, whereby analysis closely matches the simulations.

For the packet traffic, I observe from Table 3.4 a very slight increase in the mean packet delays D as the circuit traffic load χ increases. This is mainly because the transmission rate limit C_c for circuit service bounds the upstream transmission bandwidth the circuits can occupy to no more than C_c in each cycle. As the circuit traffic load χ increases, the circuit traffic utilizes this transmission rate limit C_c more and more fully. However, the packet traffic is guaranteed a portion $1 - C_c/C$ of the upstream transmission bandwidth. Formally, as the circuit traffic load χ grows large ($\chi \to \infty$), the mean aggregate circuit bandwidth $\bar{\beta}$ approaches the limit C_c, resulting in a lower bound for the packet traffic load limit (3.16) of $\pi_{\max} = 1 - \max\{2\tau/\Gamma,\ C_c/C\} - (\omega_o + \omega_u)/\Gamma$ and corresponding upper bounds for the effective packet traffic intensity π_{eff} and the mean packet delay D.

3.5.5 Impact of Limit C_c for Circuit Service

In Fig. 3.10 I examine the impact of the transmission rate limit C_c for circuit traffic. I consider different compositions χ, π of the total traffic load $\chi + \pi = 1.05$. I observe from Fig. 3.10(a) that the average circuit blocking probability $\bar{B}$ steadily decreases for increasing C_c. In the example in Fig. 3.10, the average circuit blocking probability $\bar{B}$ drops to negligible values below 1 % for C_c values corresponding to roughly twice the offered circuit traffic load χ. For instance, for circuit load $\chi = 0.25$, $\bar{B}$ drops to 0.9 % for $C_c = 5$ Gb/s. The limit C_c thus provides an effective parameter for controlling the circuit blocking probability experienced by customers.

From Fig. 3.10(b), I observe that the mean packet delay abruptly increases when the C_c limit reduces the packet traffic portion $1 - C_c/C$ of the upstream transmission bandwidth to values near the packet traffic intensity π. I also observe from Fig. 3.10(b) that the approximate packet delay analysis is quite accurate for small to moderate C_c values (the slight delay overestimation is due to neglecting the low packet traffic polling), but underestimates the packet delays for large C_c. Large circuit traffic limits C_c give the circuit traffic more flexibility for causing fluctuations of the occupied circuit bandwidth, which deteriorate the packet service. Summarizing, I see from Fig. 3.10(b) that as the effective packet traffic intensity $\pi/(1 - C_c/C)$ approaches one, the mean packet delay increases sharply. Thus, for ensuring low-delay packet service, the limit C_c should be kept sufficiently below $(1 - \pi)C$.

When offering circuit and packet service over shared PON upstream transmission bandwidth, network service providers need to trade off the circuit blocking probabilities and packet delays. As I observe from Fig. 3.10, the circuit bandwidth limit C_c provides an effective tuning knob for controlling this trade-off.

3.5.6 Low-traffic load model polling of DyCaPPON

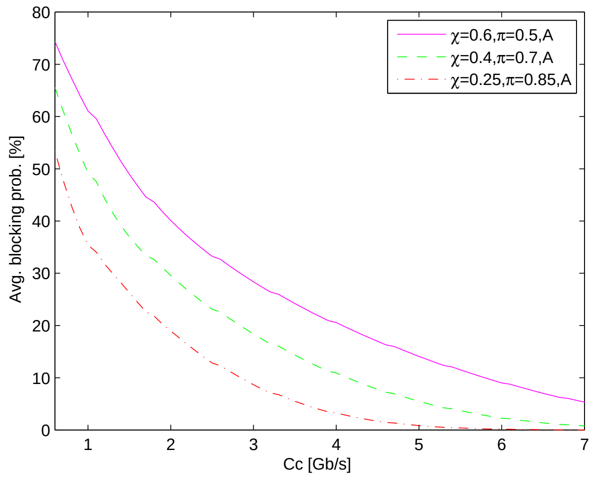
In Table. 3.4, I have introduced the low-traffic mode of DyCaPPON. The simulation shown in Fig. 3.11 has verified the efficient improvement provided by this low-traffic mode. As I can see, under a certain C_c conditions ($C_c = 4$ Gb/s in this case), the Low-traffic mode can help to make a dramatic improvement on the mean packet delay over normal mode. This improvement is deal to the more frequent polling mechanism in each cycle to reduce the waiting time of packets between their generation and reported to the OLT. I also notice that the lighter both traffic loads have, the better improvement can be achieved. Thus the circuit load $\chi = 0.4$ has greater traffic delay than the case of $\chi = 0.2$. A range of packet traffic load until $\pi = 0.6$ seems to have desired performance to replace the normal mode with low-traffic mode of DyCaPPON. Therefore, the low-traffic mode of DyCaPPON should be a better choice under most circumstances for practical uses.

Table 3.3: Circuit blocking probabilities B_k from analysis (A) Eqn. (3.10) with representative verifying simulations (S) for given offered circuit traffic load χ, circuit bandwidth limit $C_c = 2$ or 4 Gb/s and mean circuit holding time $1/\mu$. The blocking probabilities are independent of the packet traffic load π. Table also gives average circuit traffic bit rate $\bar{\beta}$ from (3.13), mean duration of packet phase $\bar{G}_p$ (3.15), and packet traffic load limit $\pi_{\max}$ (3.16).

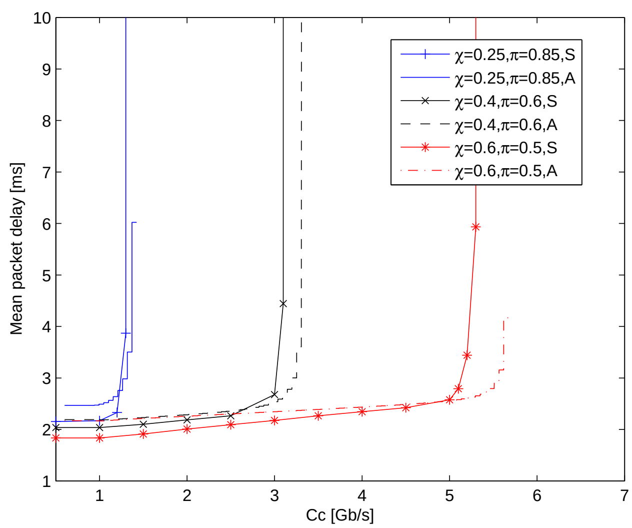
χ	C_c [Gb/s]	$1/\mu$ [s]	B_1 [%]	B_2 [%]	B_3 [%]	$\bar{B}$ [%]	$\bar{\beta}$ [$10^9 Gbps$]	$\bar{G}_p$ [ms]	$\pi_{\max}$
0.1	4	A	$8.5 \cdot 10^{-3}$	0.031	0.28	0.057	1.05	1.68	0.842
0.1	2	A	0.93	3.2	21	4.6	0.93	1.70	0.852
0.1	2	0.5 S	0.72	2.9	21	4.4	0.90		
0.1	2	0.02 S	1.1	3.7	22	5.1	0.95		
0.4	4	A	3.34	10.6	39.6	10.9	3.02	1.33	0.665
0.4	4	0.5 S	3.4	11	41	11	3.0		
0.4	4	0.02 S	4.4	12	42	13	3.2		
0.4	2	A	12.1	33.1	85.7	29.6	1.68	1.60	0.799
0.4	2	0.5 S	12	35	85	30	1.6		
0.4	2	0.02 S	13	35	87	31	1.7		
0.7	4	A	9.55	26.5	74.6	24.6	3.49	1.24	0.618
0.7	4	0.5 S	10	27	75	25	3.5		
0.7	4	0.02 S	13	29	75	28	3.6		
0.7	2	A	23.5	56.6	98.3	44.7	1.83	1.57	0.785
0.7	2	0.5 S	23	57	98	45	1.8		
0.7	2	0.02 S	28	57	98	47	1.8		

Table 3.4: Mean circuit blocking probability $\bar{B}$ and mean packet delay D as a function of circuit traffic load χ; fixed parameters: circuit bandwidth limit C_c = 2 Gb/s, packet traffic load $\pi = 0.7$.

χ	0.0001	0.05	0.1	0.20	0.40	0.60	$\chi \to \infty$
$\bar{B}$, S [%]	0	1.2	5.1	16	31	43	
$\bar{B}$, A [%]	0.016	1.08	4.81	14.9	29.6	40.1	100
D, S [ms]	1.9	2.0	2.0	2.1	2.2	2.2	
D, A [ms]	2.10	2.11	2.13	2.16	2.21	2.23	2.42

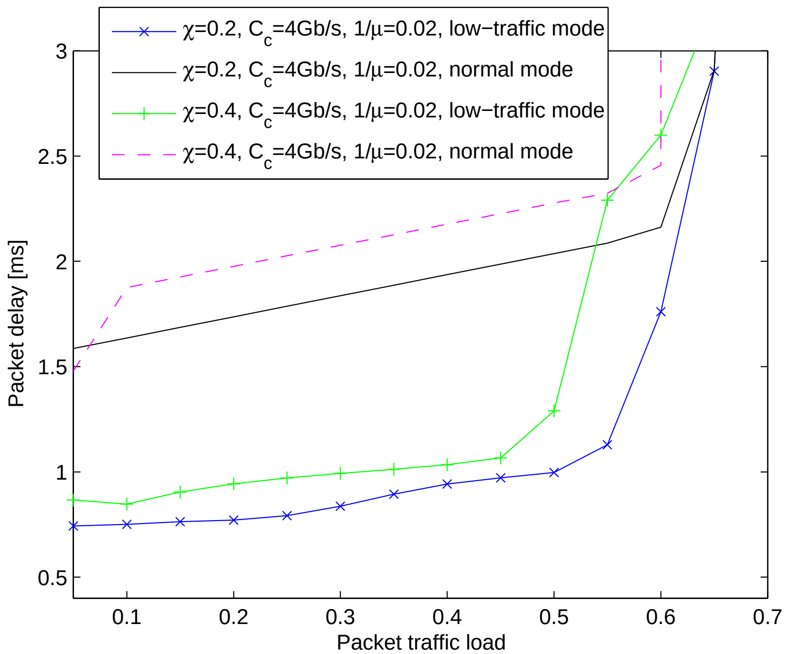


(a) Mean request blocking probability $\bar{B}$



(b) Mean packet delay D

Figure 3.10: Impact of circuit service limit C_c: Mean circuit blocking probability $\bar{B}$ (from analysis, Eqn. (3.10)) and mean packet delay D (from analysis and simulation) as a function of transmission rate limit for circuit service C_c; fixed mean circuit holding time $1/\mu = 0.02$ s.



(b) Mean packet delay D

Figure 3.11: Mean packet delay comparison, implementing both normal mode and low-traffic mode of polling of DyCaPPON

Chapter 4

FUTURE WORK

In this chapter, I will briefly discuss the issues that were faced in my results and the future to the presented work. Both EIBT and DyCaPPON are designed for large bandwidth users with priority. 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 Jung *et al.* (2010); Kazovsky *et al.* (2012); Yang *et al.* (2009) as well as metro networks Ahmed and Shami (2012); Maier *et al.* (2003); White *et al.* (2003); Yang *et al.* (2003) so as to efficiently transmit packet and file traffic from a mobile wireless node to the ONU, onwards to the OLT, and across a metropolitan area network.

There are also several promising directions for future research on access networks that flexibly provide both circuit and packet service. One important future research direction is to broadly examine cycle-time structures and wavelength assignments in PONs providing circuit and packet service. In particular, the present study focused on a single upstream wavelength channel operated with a fixed polling cycle duration. Future research should examine the trade-offs arising from operating multiple upstream wavelength channels and combinations of fixed- or variable-duration polling cycles. An exciting future research direction is to extend the PON service further toward the individual user, e.g., by providing circuit and packet service on integrated PON and wireless access networks, such as Aurzada *et al.* (2014); Coimbra *et al.* (2013); Dhaini *et al.* (2011); Lim *et al.* (2013); Maier *et al.* (2009); Moradpoor *et al.* (2013), that reach individual mobile users or wireless sensor networks Hossen and Hanawa (2011); Seema and Reisslein (2011); Yu *et al.* (2012). Further, exploring combined circuit and packet service in long-reach PONs with very long round trip propagation delays, which may require special protocol mechanisms, see e.g., Kantarci and Mouftah (2012); Mercian *et al.* (2013); Song *et al.* (2010), is an open research direction. Another direction is to examine the integration and interoperation of circuit and packet service in the PON access network with metropolitan area networks Bianco *et al.* (2013); Maier and Reisslein (2004); Maier *et al.* (2003); Scheutzow *et al.* (2003); Yang *et al.* (2003); Yuang *et al.* (2010) and wide area networks to provide circuit and packet service Veeraraghavan and Zheng (2004).

Chapter 5

SUMMARY AND CONCLUSION

I 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 traffic (EIBT). I analytically characterized the optimal EIBT duration that minimizes a weighted mean packet and file delay metric. Through numerical evaluations based on my analysis and simulations, I 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.

I have also proposed and evaluated DyCaPPON, a passive optical network that provides dynamic circuit and packet service. DyCaPPON is based on fixed duration cycles, ensuring consistent circuit service, that is completely unaffected by the packet traffic load. DyCaPPON masks the round-trip propagation delay for polling of the packet traffic queues in the ONUs with the upstream circuit traffic transmissions, providing for efficient usage of the upstream bandwidth. I have analyzed the circuit level performance, including the circuit blocking probability and delay experienced by circuit traffic in DyCaPPON, as well as the packet level performance, including the bandwidth available for packet traffic after serving the circuit traffic as well as the resulting packet delays.

Through extensive numerical investigations based on the analytical performance characterization of DyCaPPON as well as verifying simulations, I have demonstrated the circuit and packet traffic performance and trade-offs in DyCaPPON. The provided analytical performance characterizations as well as the identified performance trade-offs provide tools and guidance for dimensioning and operating PON access networks that provide a mix of circuit and packet oriented service. Low-traffic mode polling of DyCaPPON is also proposed in this article, as an optional improved version of DyCaPPON, targeting the low to moderate overall traffic load scenarios. Simulation result of the low-traffic mode DyCaPPON is also provided.

REFERENCES

Ahmed, A. and A. Shami, “RPR-EPON-WiMAX hybrid network: A solution for access and metro networks”, IEEE/OSA Journal of Optical Communications and Networking **4**, 3, 173–188 (2012).

An, F., Y. Hsueh, K. Kim, I. White and L. Kazovsky, “A new dynamic bandwidth allocation protocol with quality of service in Ethernet-based passive optical networks”, in “Proc. IASTED WOC”, vol. 3, pp. 165–169 (2003).

Andrade, M., G. Kramer, L. Wosinska, J. Chen, S. Sallent and B. Mukherjee, “Evaluating strategies for evolution of passive optical networks”, IEEE Communications Magazine **49**, 7, 176–184 (2011).

Angelopoulos, J., H.-C. Leligou, T. Argyriou, S. Zontos, E. Ringoot and T. Van Caenegem, “Efficient transport of packets with QoS in an FSAN-aligned GPON”, IEEE Comm. Mag. **42**, 2, 92–98 (2004).

Assi, C., Y. Ye, S. Dixit and M. Ali, “Dynamic bandwidth allocation for Quality-of-Service over Ethernet PONs”, IEEE Journal on Selected Areas in Communications **21**, 9, 1467–1477 (2003a).

Assi, C., Y. Ye, S. Dixit and M. Ali, “Dynamic bandwidth allocation for quality-of-service over Ethernet PONs”, IEEE Journal on Selected Areas in Communications **21**, 9, 1467–1477 (2003b).

Aurzada, F., M. Levesque, M. Maier and M. Reisslein, “FiWi access networks based on next-generation PON and gigabit-class WLAN technologies: A capacity and delay analysis”, IEEE/ACM Trans. Netw., in print (2014).

Aurzada, F., M. Scheutzow, M. Herzog, M. Maier and M. Reisslein, “Delay analysis of Ethernet passive optical networks with gated service”, OSA Journal of Optical Networking **7**, 1, 25–41 (2008).

Aurzada, F., M. Scheutzow, M. Reisslein, N. Ghazisaidi and M. Maier, “Capacity and delay analysis of next-generation passive optical networks (NG-PONs)”, IEEE Trans. on Communications **59**, 5, 1378–1388 (2011).

Bai, X., C. Assi and A. Shami, “On the fairness of dynamic bandwidth allocation schemes in Ethernet passive optical networks”, Comp. Commun. **29**, 11, 2125–2135 (2006).

Batayneh, M., D. Schupke, M. Hoffmann, A. Kirstaedter and B. Mukherjee, “Link-rate assignment in a WDM optical mesh network with differential link capacities: A network-engineering approach”, in “Proc. HONET”, pp. 216–219 (2008).

Berisa, T., A. Bazant and V. Mikac, “Bandwidth and delay guaranteed polling with adaptive cycle time (BDGPACT): A scheme for providing bandwidth and delay guarantees in passive optical networks”, J. of Opt. Netw. **8**, 4, 337–345 (2009).

Berisa, T., Z. Ilic and A. Bazant, “Absolute delay variation guarantees in passive optical networks”, IEEE/OSA Journal of Lightwave Technology **29**, 9, 1383–1393 (2011).

Bharati, S. and P. Saengudomlert, “Analysis of mean packet delay for dynamic bandwidth allocation algorithms in EPONs”, IEEE/OSA J. of Lightwave Technology **28**, 23, 3454–3462 (2010).

Bhatia, S., D. Garbuzov and R. Bartos, “Analysis of the gated IPACT scheme for EPONs”, in “Proc. of IEEE ICC”, pp. 2693–2698 (2006).

Bianco, A., T. Bonald, D. Cuda and R.-M. Indre, “Cost, power consumption and performance evaluation of metro networks”, IEEE/OSA J. Opt. Comm. Netw. **5**, 1, 81–91 (2013).

Bianco, A., J. M. Finochietto, G. Giarratana, F. Neri and C. Piglione, “Measurement-based reconfiguration in optical ring metro networks”, IEEE/OSA Journal of Lightwave Technology **23**, 10, 3156–3166 (2005).

Bolla, R. and F. Davoli, “Control of multirate synchronous streams in hybrid TDM access networks”, IEEE/ACM Trans. Netw. **5**, 2, 291–304 (1997).

Bolletta, P., A. Del Grosso, L. Rea, A. Luisi, S. Pompei, A. Valenti and D. Del Buono, “Monitoring of the user Quality of Service: Network architecture for measurements, role of the user operating system with consequences for optical accesses”, in “Proc. of Int. Conf. on Optical Network Design and Modeling (ONDM)”, pp. 1–5 (2011).

Bredel, M. and M. Fidler, “A measurement study regarding quality of service and its impact on multiplayer online games”, in “Proc. NetGames”, (2010).

Chang, C.-H., P. Kourtessis and J. Senior, “GPON service level agreement based dynamic bandwidth assignment protocol”, Electronics Letters **42**, 20, 1173–1174 (2006).

Chang, K.-C. and W. Liao, “On the throughput and fairness performance of TCP over Ethernet Passive Optical Networks”, IEEE Journal on Selected Areas in Communications **24**, 12, Part Supplement, 3–12 (2006).

Charbonneau, N., A. Gadkar, B. H. Ramaprasad and V. Vokkarane, “Dynamic circuit provisioning in all-optical WDM networks using lightpath switching”, Opt. Sw. Netw. **9**, 2, 179 – 190 (2012).

Chen, J., B. Chen and L. Wosinska, “Joint bandwidth scheduling to support differentiated services and multiple service providers in 1G and 10G EPONs”, IEEE/OSA J. of Opt. Commun. and Netw. **1**, 4, 343–351 (2009).

Choi, S. Y., S. Lee, T. J. Lee, M. Y. Chung and H. Choo, “Double-phase polling algorithm based on partitioned ONU subgroups subgroups for high utilization in EPONs”, IEEE/OSA Journal of Optical Communications and Networking **1**, 5, 484–497 (2009).

Coimbra, J., G. Schtz and N. Correia, “A game-based algorithm for fair bandwidth allocation in Fibre-Wireless access networks”, Optical Switching and Networking **10**, 2, 149 – 162 (2013).

Coutelen, T., H. Elbiaze and B. Jaumard, “Performance comparison of OCS and OBS switching paradigms”, in “Proc. Transparent Optical Networks”, (2005).

De, S., V. Singh, H. M. Gupta, N. Saxena and A. Roy, “A new predictive dynamic priority scheduling in Ethernet passive optical networks (EPONs)”, Opt. Switch. Netw. **7**, 4, 215–223 (2010).

Dhaini, A., C. Assi, M. Maier and A. Shami, “Per-stream QoS and admission control in Ethernet passive optical networks (EPONs)”, IEE/OSA J. Lightwave Tech. **25**, 7, 1659–1669 (2007).

Dhaini, A., P.-H. Ho and X. Jiang, “QoS control for guaranteed service bundles over fiber-wireless (FiWi) broadband access networks”, IEEE/OSA J. Lightwave Techn. **29**, 10, 1500–1513 (2011).

Dixit, A., G. Das, B. Lannoo, D. Colle, M. Pickavet and P. Demeester, “Jitter performance for QoS in Ethernet passive optical networks”, in “Proceedings of ECOC”, pp. 1–3 (2011).

Dyckhoff, H., “A typology of cutting and packing problems”, Eu. J. Op. Res. **44**, 2, 145–159 (1990).

Fang, X. and M. Veeraraghavan, “A hybrid network architecture for file transfers”, IEEE Transactions on Parallel and Distributed Systems **20**, 12, 1714–1725 (2009).

Fitzek, F., G. Schulte and M. Reisslein, “System architecture for billing of multiplayer games in a wireless environment using GSM/UMTS and WLAN services”, in “Proc. ACM NetGames”, pp. 58–64 (2002).

Fouli, K. and M. Maier, “The road to carrier-grade ethernet”, IEEE Communications Magazine **47**, 3, S30–S38 (2009).

Gaver, D. and J. Lehoczky, “Channels that cooperatively service a data stream and voice messages”, IEEE Trans. Commun. **30**, 5, 1153–1162 (1982).

Gencata, A. and B. Mukherjee, “Virtual-topology adaptation for WDM mesh networks under dynamic traffic”, IEEE/ACM Transactions on Networking **11**, 2, 236–247 (2003).

Ghani, N., A. Shami, C. Assi and M. Raja, “Intra-ONU bandwidth scheduling in Ethernet passive optical networks”, IEEE Communications Letters **8**, 11, 683–685 (2004).

Ghani, S. and M. Schwartz, “A decomposition approximation for the analysis of voice/data integration”, IEEE Transactions on Communications **42**, 7, 2441–2452 (1994).

Ghazisaidi, N., M. Maier and M. Reisslein, "VMP: A MAC protocol for EPON-based video-dominated FiWi access networks", IEEE Trans. Broadcasting **58**, 3, 440–453 (2012).

Hajduczenia, M., H. J. A. da Silva and P. P. Monteiro, "EPON versus APON and GPON: a detailed performance comparison", OSA Journal of Optical Networking **5**, 4, 298–319 (2006).

Harissis, A. and A. Ambler, "A new multiprocessor interconnection network with wide sense nonblocking capabilities", in "Proc. Midwest Symp. Circuits and Systems", pp. 923–926 (1989).

Heyman, D. P. and M. J. Sobel, *Stochastic Models in Operations Research: Volume 1: Stochastic Processes and Operating Characteristics* (Courier Dover, 2003).

Holmberg, T., "Analysis of EPONs under the static priority scheduling scheme with fixed transmission times", in "Proc. NGI", pp. 1–8 (2006).

Hossen, M. and M. Hanawa, "Network architecture and performance analysis of MULTI-OLT PON for FTTH and wireless sensor networks", Int. J. Wireless & Mobile Networks **3**, 6, 1–15 (2011).

Hu, M., W. Guo and W. Hu, "Dynamic scheduling algorithms for large file transfer on multi-user optical grid network based on efficiency and fairness", in "Proc. ICNS", pp. 493–498 (2009).

Hwang, I., J. Lee, K. Lai and A. Liem, "Generic QoS-aware interleaved dynamic bandwidth allocation in scalable EPONs", IEEE/OSA J. of Optical Commun. and Netw. **4**, 2, 99–107 (2012).

Ikeda, H. and K. Kitayama, "Dynamic bandwidth allocation with adaptive polling cycle for maximized TCP throughput in 10G-EPON", IEEE/OSA J. of Lightwave Techn. **27**, 23, 5508–5516 (2009).

Internet2, "Dynamic circuit network", Http://www.internet2.edu/network/dc/ (2014).

Jacobson, V., D. Smetters, J. Thornton, M. Plass, N. Briggs and R. Braynard, "Networking named content", in "Proc., ACM CoNEXT", (2009).

Jana, N., G. Sankaran, K. Sivalingam and G. Parr, "Performance analysis of dynamic bandwidth allocation algorithms for long-reach PONs", in "Proceedings of IEEE Int. Symposium on Advanced Networks and Telecommunication Systems (ANTS)", pp. 28–30 (2010).

Jung, B., J. Choi, Y.-T. Han, M.-G. Kim and M. Kang, "Centralized scheduling mechanism for enhanced end-to-end delay and QoS support in integrated architecture of EPON and WiMAX", IEEE/OSA Journal of Lightwave Technology **28**, 16, 2277–2288 (2010).

Kanonakis, K. and I. Tomkos, “Offset-based scheduling with flexible intervals for evolving gpon networks”, IEEE/OSA Journal of Lightwave Technology **27**, 15, 3259 –3268 (2009).

Kanonakis, K. and I. Tomkos, “Improving the efficiency of online upstream scheduling and wavelength assignment in hybrid wdm/tdma epon networks”, IEEE Journal on Selected Areas in Communications **28**, 6, 838 –848 (2010).

Kantarci, B. and H. Mouftah, “Bandwidth distribution solutions for performance enhancement in long-reach passive optical networks”, IEEE Commun. Surv. Tut. **14**, 3, 714–733 (2012).

Kazovsky, L., S.-W. Wong, T. Ayhan, K. Albeyoglu, M. Ribeiro and A. Shastri, “Hybrid optical-wireless access networks”, Proceedings of the IEEE **100**, 5, 1197–1225 (2012).

Kim, N., H. Yun and M. Kang, “Analysis of effect of load-based excess bandwidth reservation on performances of differentiated services in E-PON”, IET Commun. **1**, 3, 382–390 (2007).

Kleinrock, L., *Queueing systems. volume 1: Theory* (Wiley, 1975).

Koponen, T., M. Chawla, B. Chun, A. Ermolinskiy, K. Kim, S. Shenker and I. Stoica, “A data-oriented (and beyond) network architecture”, in “Proc., ACM SIGCOMM”, (2007).

Kramer, G., A. Banerjee, N. Singhal, B. Mukherjee, S. Dixit and Y. Ye, “Fair queueing with service envelopes (FQSE): a cousin-fair hierarchical scheduler for subscriber access networks”, IEEE Journal on Selected Areas in Communications **22**, 8, 1497–1513 (2004).

Kramer, G., M. DeAndrade, R. Roy and P. Chowdhury, “Evolution of optical access networks: Architectures and capacity upgrades”, Proceedings of the IEEE **100**, 5, 1188–1196 (2012).

Kramer, G., B. Mukherjee, S. Dixit, Y. Ye and R. Hirth, “Supporting differentiated classes of service in Ethernet passive optical networks”, OSA J. of Optical Netw. **1**, 9, 280–298 (2002a).

Kramer, G., B. Mukherjee and G. Pesavento, “Interleaved polling with adaptive cycle time (IPACT): A dynamic bandwidth distribution scheme in an optical access network”, Photonic Network Communications **4**, 1, 89–107 (2002b).

Kurillo, G. and R. Bajcsy, “3D teleimmersion for collaboration and interaction of geographically distributed users”, Virtual Reality **17**, 1, 29–43 (2013).

Kwong, K., D. Harle and I. Andonovic, “Dynamic bandwidth allocation algorithm for differentiated services over WDM EPONs”, in “Proc. of Int. Conf. on Communications Systems”, pp. 116–120 (2004).

Kwong, W., G.-C. Yang and J.-G. Zhang, "2^n prime-sequence codes and coding architecture for optical code-division multiple-access", IEEE Transactions on Communications **44**, 9, 1152–1162 (1996).

Lannoo, B., L. Verslegers, D. Colle, M. Pickavet, M. Gagnaire and P. Demeester, "Analytical model for the IPACT dynamic bandwidth allocation algorithm in EPONs", OSA Journal of Optical Networking **6**, 6, 677–688 (2007).

Li, S.-Q. and J. W. Mark, "Performance of voice/data integration on a TDM system", IEEE Transactions on Communications **33**, 12, 1265–1273 (1985).

Li, Z., Q. Song and I. Habib, "CHEETAH virtual label switching router for dynamic provisioning in IP optical networks", Optical Switching and Netw. **5**, 23, 139–149 (2008).

Lim, W., K. Kanonakis, P. Kourtessis, M. Milosavljevic, I. Tomkos and J. M. Senior, "Flexible QoS differentiation in converged OFDMA-PON and LTE networks", in "Proc. OFC", (2013).

Lim, W., C. Yun, Y.-M. Yang, H. Lee and K. Kim, "Burst-polling-based dynamic bandwidth allocation using adaptive minimum guaranteed bandwidth for EPONs", IEEE/OSA J. of Opt. Comm. & Netw. **1**, 7, 594–599 (2009).

Lin, H.-T., C.-L. Lai, W.-R. Chang and S.-J. Hong, "Design and analysis of a WDM EPON for supporting private networking and differentiated services", IEEE/OSA J. of Optical Commun. and Netw. **2**, 5, 266–282 (2010).

Lin, H.-T., C.-L. Lai, W.-R. Chang and C.-L. Liu, "FIPACT: A frame-oriented dynamic bandwidth allocation scheme for triple-play services over EPONs", in "Proc. ICCCN", (2011a).

Lin, H.-T., C.-L. Lai, W.-R. Chang and C.-L. Liu, "FIPACT: A frame-oriented dynamic bandwidth allocation scheme for triple-play services over EPONs", in "Proc. ICCCN", pp. 1–6 (2011b).

Liu, X., C. Qiao, X. Yu and W. Gong, "A fair packet-level performance comparison of OBS and OCS", in "Proc. OFC", (2006).

Luo, Y. and N. Ansari, "Limited sharing with traffic prediction for dynamic bandwidth allocation and QoS provioning over EPONs", OSA Journal of Optical Networking **4**, 9, 561–572 (2005).

Ma, M., L. Liu and T. Cheng, "Adaptive scheduling for differentiated services in an Ethernet passive optical network", OSA Journal of Optical Networking **4**, 10, 661–67 (2005a).

Ma, M., Y. Zhu and T. Cheng, "A bandwidth guaranteed polling MAC protocol for Ethernet passive optical networks", in "Proceedings of IEEE INFOCOM", vol. 1, pp. 22–31 (2003), San Francisco, CA.

Ma, M., Y. Zhu and T. Cheng, “A systematic scheme for multiple access in Ethernet passive optical access networks”, IEEE/OSA Journal of Lightwave Technology **23**, 11, 3671–3682 (2005b).

Maglaris, B. and M. Schwartz, “Optimal fixed frame multiplexing in integrated line- and packet-switched communication networks”, IEEE Trans. Inf. Th. **28**, 2, 263–273 (1982).

Mahloo, M., C. M. Machuca, J. Chen and L. Wosinska, “Protection cost evaluation of WDM-based next generation optical access networks”, Optical Switching and Netw. **10**, 1, 89–99 (2013).

Maier, M., N. Ghazisaidi and M. Reisslein, “The audacity of fiber-wireless (FiWi) networks”, in “Proc. of AccessNets”, vol. 6 of *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pp. 16–35 (Springer, 2009).

Maier, M. and M. Herzog, “Online gaming and P2P file sharing in next-generation EPONs”, IEEE Communications Magazine **48**, 2, 48–55 (2010).

Maier, M. and M. Reisslein, “AWG-based metro WDM networking”, IEEE Commun. Mag. **42**, 11, S19–S26 (2004).

Maier, M., M. Reisslein and A. Wolisz, “A hybrid MAC protocol for a metro WDM network using multiple free spectral ranges of an arrayed-waveguide grating”, Computer Networks **41**, 4, 407–433 (2003).

Mankus, M. L. and C. Tier, “Asymptotic analysis of an integrated digital network”, SIAM J. Appl. Math. **52**, 1, 234–269 (1992).

McGarry, M. and M. Reisslein, “Investigation of the DBA algorithm design space for EPONs”, IEEE/OSA Journal of Lightwave Technology **30**, 14, 2271–2280 (2012).

McGarry, M., M. Reisslein, F. Aurzada and M. Scheutzow, “Shortest propagation delay (SPD) first scheduling for EPONs with heterogeneous propagation delays”, IEEE J. on Selected Areas in Commun. **28**, 6, 849–862 (2010).

McGarry, M., M. Reisslein and M. Maier, “WDM ethernet passive optical networks”, IEEE Commun. Mag. **44**, 2, 15–22 (2006).

Melo Pereira, F., N. L. S. Fonseca and D. S. Arantes, “A fair scheduling discipline for Ethernet passive optical networks”, Computer Networks **53**, 11, 1859–1878 (2009).

Merayo, N., R. Duran, P. Fernandez, I. de Miguel, J. Aguado, R. Lorenzo and E. Abril, “Interleaved polling algorithm with service level agreement (SLA) to improve QoS in Ethernet PONs”, in “Proc. of Int. Conf. on Transparent Optical Networks”, vol. 4, pp. 28–31 (2007).

Merayo, N., T. Jimenez, P. Fernandez, R. Duran, R. Lorenzo, I. de Miguel and E. Abril, “A bandwidth assignment polling algorithm to enhance the efficiency in QoS long-reach EPONs”, Eu. Trans. Telecommun. **22**, 1, 35–44 (2011).

Mercian, A., M. McGarry and M. Reisslein, "Offline and online multi-thread polling in long-reach PONs: A critical evaluation", IEEE/OSA J. Lightwave Techn. **31**, 12, 2018–2228 (2013).

Molinero-Fernandez, P. and N. McKeown, "The performance of circuit switching in the internet", OSA J. Opt. Netw. **2**, 4, 83–96 (2003).

Monga, I., C. Guok, W. Johnston and B. Tierney, "Hybrid networks: lessons learned and future challenges based on ESnet4 experience", IEEE Commun. Mag. **49**, 5, 114–121 (2011).

Moradpoor, N., G. Parr, S. McClean and B. Scotney, "IIDWBA algorithm for integrated hybrid PON with wireless technologies for next generation broadband access networks", Opt. Switching. Netw. **10**, 4, 439–457 (2013).

Moser, D., E. Cano and P. Racz, "Secure large file transfer over multiple network paths", in "Proc. IEEE Network Operations and Management Symposium (NOMS)", pp. 777–792 (2010).

Mukherjee, B., "Architecture, control, and management of optical switching networks", in "Proc. Photonics in Switching", pp. 43–44 (2007).

Munir, A., S. Tanwir and S. Zaidi, "Requests provisioning algorithms for Dynamic Optical Circuit Switched (DOCS) networks: A survey", in "Proc. IEEE Int. Multitopic Conference (INMIC)", pp. 1–6 (2009).

Naser, H. and H. Mouftah, "A fast class-of-service oriented packet scheduling scheme for EPON access networks", IEEE Communications Letters **10**, 5, 396–398 (2006).

Ngo, M., A. Gravey and D. Bhadauria, "Controlling QoS in EPON-based FTTX access networks", Telec. Sys. **48**, 1-2, 203–217 (2011).

Nishiyama, H., Z. Fadlullah and N. Kato, "Inter-layer fairness problem in TCP bandwidth sharing in 10G-EPON", IEEE Systems Journal **4**, 4, 432–439 (2010).

Oh, S., B. Kulapala, A. Richa and M. Reisslein, "Continuous-time collaborative prefetching of continuous media", IEEE Transactions on Broadcasting **54**, 1, 36–52 (2008).

Oki, E., K. Shiomoto, S. Okamoto, W. Imajuku and N. Yamanaka, "Heuristic multi-layer optimum topology design scheme based on traffic measurement for IP + photonic networks", in "Proc., Optical Fiber Communication Conf. and Exhibit (OFC)", pp. 104–105 (2002).

Okumura, Y., "Traffic control algorithm offering multi-class fairness in PON based access networks", IEICE Transactions on Communications **93**, 3, 712–715 (2010).

Orozco, J. and D. Ros, "TCP performance over gigabit-capable passive optical networks", in "Proc. of AccessNets", pp. 264–279 (2008).

Pallot, M., P. Daras, S. Richir and E. Loup-Escande, “3D-live: live interactions through 3D visual environments”, in “Proc. Virtual Reality Int. Conf.”, (2012).

Qian, D., J. Hu, J. Yu, P. Ji, L. Xu, T. Wang, M. Cvijetic and T. Kusano, “Experimental demonstration of a novel OFDM-A based 10 Gb/s PON architecture”, Proc. ECOC pp. 1–2 (2007).

Qiao, L. and P. Koutsakis, “Adaptive bandwidth reservation and scheduling for efficient wireless telemedicine traffic transmission”, IEEE Trans. Vehicular Technology **60**, 2, 632–643 (2011).

Qin, Y., D. Xue, L. Zhao, C. K. Siew and H. He, “A novel approach for supporting deterministic quality-of-service in WDM EPON networks”, Optical Switching and Networking **10**, 4, 378–392 (2013).

Radivojevic, M. and P. Matavulj, “Implementation of intra-ONU scheduling for Quality of Service support in Ethernet passive optical networks”, IEEE/OSA J. Lightw. Techn. **27**, 18, 4055–4062 (2009).

Reisslein, M., J. Lassetter, S. Ratnam, O. Lotfallah, F. Fitzek and S. Panchanathan, “Traffic and quality characterization of scalable encoded video: a large-scale trace-based study, Part 1: overview and definitions”, Tech. rep., Arizona State Univ. (2002).

Rexford, J. and D. Towsley, “Smoothing variable-bit-rate video in an internetwork”, IEEE/ACM Transactions on Networking **7**, 2, 202–215 (1999).

Ross, K. W., *Multiservice Loss Models for Broadband Telecommunication Networks* (Springer, 1995).

Roy, R., G. Kramer, M. Hajduczenia and H. Silva, “Performance of 10G-EPON”, IEEE Communications Magazine **49**, 11, 78–85 (2011).

Sailan, M. and R. Hassan, “Network file transfer performance: Effect of IP address, TCP window size and file size”, in “Proceedings of Int. Conference on Network Applications, Protocols and Services (NETAPPS)”, pp. 114–118 (2010).

Sarigiannidis, P., S. Petridou, G. Papadimitriou and M. Obaidat, “IGFS: A New MAC Protocol Exploiting Heterogeneous Propagation Delays in the Dynamic Bandwidth Allocation on WDM-EPON”, IEEE Systems Journal **4**, 1 (2010).

Satyanarayanan, M., P. Bahl, R. Caceres and N. Davies, “The case for VM-based cloudlets in mobile computing”, IEEE Pervasive Comp. **8**, 4, 14–23 (2009).

Schaefer, C., T. Enderes, H. Ritter and M. Zitterbart, “Subjective quality assessment for multiplayer real-time games”, in “Proc. ACM NetGames”, pp. 74–78 (2002).

Scheutzow, M., M. Maier, M. Reisslein and A. Wolisz, “Wavelength reuse for efficient packet-switched transport in an AWG-based metro WDM network”, IEEE/OSA Journal of Lightwave Technology **21**, 6, 1435–1455 (2003).

Seema, A. and M. Reisslein, "Towards efficient wireless video sensor networks: A survey of existing node architectures and proposal for a Flexi-WVSNP design", IEEE Comm. Surv. & Tut. **13**, 3, 462–486 (2011).

Segarra, J., C. Bock and J. Prat, "Hybrid WDM/TDM PON based on bidirectional reflective ONUs offering differentiated QoS via OBS", in "Proc. Transparent Optical Networks", vol. 1, pp. 95–100 (2005).

Shami, A., X. Bai, N. Ghani, C. Assi and H. Mouftah, "QoS control schemes for two-stage Ethernet passive optical access networks", IEEE J. on Sel. Areas in Commun. **23**, 8, 1467–1478 (2005).

Sherif, S., A. Hadjiantonis, G. Ellinas, C. Assi and M. Ali, "A novel decentralized ethernet-based PON access architectureg for provisioning differentiated QoS", IEEE/OSA J. of Lightwave Technology **22**, 11, 2483–2497 (2004).

Shuaib, K., F. Sallabi and L. Zhang, "Smoothing and modeling of video transmission rates over a QoS network with limited bandwidth connections", Int. Journal of Computer Networks and Communications **3**, 3, 148–162 (2011).

Sivakumar, A., G. Sankaran and K. Sivalingam, "Performance analysis of ONU-wavelength grouping schemes for efficient scheduling in long reach-PONs", Opt. Switching Netw. **10**, 4, 465–474 (2013).

Skoog, R., G. Clapp, J. Gannett, A. Neidhardt, A. Von Lehman and B. Wilson, "Architectures, protocols and design for highly dynamic optical networks", Opt. Switch. Netw. **9**, 3, 240–251 (2012).

Song, H., B. W. Kim and B. Mukherjee, "Long-reach optical access networks: A survey of research challenges, demonstrations, and bandwidth assignment mechanisms", IEEE Communications Surveys and Tutorials **12**, 1, 112–123 (2010).

Sue, C. C. and H. W. Cheng, "A fitting report position scheme for the gated IPACT dynamic bandwidth algorithm in EPONs", IEEE/ACM Transactions on Networking **18**, 2, 624–637 (2010).

Tham, Y. and J. Hume, "Analysis of voice and low-priority data traffic by means of brisk periods and slack periods", Comp. Commun. **6**, 1, 14–22 (1983).

Thanh Ngo, M., A. Gravey and D. Bhadauria, "A mean value analysis approach for evaluating the performance of EPON with Gated IPACT", in "Proc. of Int. Conf. on Optical Network Design and Modeling", pp. 1–6 (2008).

Tomkos, I., L. Kazovsky and K.-I. Kitayama, "Next-generation optical access networks: dynamic bandwidth allocation, resource use optimization, and QoS improvements", IEEE Netw. **26**, 2, 4–6 (2012).

Turna, O. C., M. A. Aydin, T. Atmaca and A. Zaim, "A novel dynamic bandwidth allocation algorithm based on half cycling for EPONs", in "Proceedings of Int. Conf. on Emerging Network Intelligence", pp. 38–43 (2010).

Vahabzadeh, M. and A. Ghaffarpour Rahbar, "Modified smallest available report first: New dynamic bandwidth allocation schemes in QoS-capable EPONs", Optical Fiber Technolgy **17**, 1, 7–16 (2011).

Van Breusegem, E., J. Cheyns, D. De Winter, D. Colle, M. Pickavet, P. Demeester and J. Moreau, "A broad view on overspill routing in optical networks: a real synthesis of packet and circuit switching?", Optical Switching and Networking **1**, 1, 51–64 (2005).

Van der Auwera, G. and M. Reisslein, "Implications of smoothing on statistical multiplexing of H. 264/AVC and SVC video streams", IEEE Trans. on Broadcasting **55**, 3, 541–558 (2009).

Vardakas, J., I. Moscholios, M. Logothetis and V. Stylianakis, "Blocking performance of multi-rate OCDMA PONs with QoS guarantee", Int. J. Adv. Telecom. **5**, 3 and 4, 120–130 (2012).

Vasudevan, R., Z. Zhou, G. Kurillo, E. Lobaton, R. Bajcsy and K. Nahrstedt, "Real-time stereo-vision system for 3D teleimmersive collaboration", in "Proc. IEEE ICME", pp. 1208–1213 (2010).

Veeraraghavan, M., M. Karol and G. Clapp, "Optical dynamic circuit services", IEEE Commun. Mag. **48**, 11, 109–117 (2010).

Veeraraghavan, M. and X. Zheng, "A reconfigurable Ethernet/SONET circuit-based metro network architecture", IEEE J. Selected Areas on Communications **22**, 8, 1406–1418 (2004).

Wei, X., F. Aurzada, M. McGarry and M. Reisslein, "EIBT: Exclusive intervals for bulk transfers on EPONs", IEEE/OSA J. Lightwave Technology **31**, 1, 99–110 (2013).

Weichenberg, G., V. Chan and M. Medard, "Design and analysis of optical flow-switched networks", IEEE/OSA Journal of Optical Communications and Networking **1**, 3, B81–B97 (2009).

Weinstein, C., M. Malpass and M. Fisher, "Data traffic performance of integrated circuit-and packet-switched multiplex structure", IEEE Trans. Commun. **28**, 6, 873–878 (1980).

White, I. M., M. S. Rogge, K. Shrikhande and L. G. Kazovsky, "A summary of the HORNET project: A next-generation metropolitan area network", IEEE Journal on Selected Areas in Communications **21**, 9, 1478–1494 (2003).

Wiedemeier, P. and H. Tyrer, "Large file transmissions over high delay data communication channels using TCP", in "Proceedings of IEEE Aerospace Conference", vol. 3, pp. 1237–1243 (2003).

Xue, D., Y. Qin and C. K. Siew, "Deterministic QoS provisioning with network calculus based admission control in WDM EPON networks", in "Proc. of IEEE ICC", pp. 1–6 (2009).

Yang, H.-S., M. Maier, M. Reisslein and M. Carlyle, "A genetic algorithm-based methodology for optimizing multiservice convergence in a metro WDM network", IEEE/OSA Journal of Lightwave Technology **21**, 5, 1114–1133 (2003).

Yang, K., S. Ou, K. Guild and H.-H. Chen, "Convergence of ethernet PON and IEEE 802.16 broadband access networks and its QoS-aware dynamic bandwidth allocation scheme", IEEE Journal on Selected Areas in Communications **27**, 2, 101–116 (2009).

Yin, Y. and G. Poo, "User-oriented hierarchical bandwidth scheduling for ethernet passive optical networks", Comp. Comm. **33**, 8, 965–975 (2010).

Yu, X., Y. Zhao, L. Deng, X. Pang and I. Monroy, "Existing PON infrastructure supported hybrid fiber-wireless sensor networks", in "Proc. OFC", pp. 1–3 (2012).

Yuang, M., I.-F. Chao and B. Lo, "HOPSMAN: An experimental optical packet-switched metro WDM ring network with high-performance medium access control", IEEE/OSA Journal of Optical Communications and Networking **2**, 2, 91–101 (2010).

Zaghloul, S., V. Frost and A. Mohammad, "Modeling TCP long file transfer latency over long delay wireless multilink PPP", IEEE Communications Letters **9**, 11, 988–990 (2005).

Zanini, F., L. Valcarenghi, D. P. Van, M. Chincoli and P. Castoldi, "Introducing cognition in TDM PONs with cooperative cyclic sleep through runtime sleep time determination", Opt. Switching Netw., in print (2013).

Zhang, J. and N. Ansari, "An application-oriented fair resource allocation scheme for EPON", IEEE Systems Journal **4**, 4, 424–431 (2010).

Zhang, L., E.-S. An, H.-G. Yeo and S. Yang, "Dual DEB-GPS scheduler for delay-constraint applications in Ethernet passive optical networks", IEICE Trans. Commun. **86**, 5, 1575–1584 (2003).

Zhang, L. and G.-S. Poo, "Delay constraint dynamic bandwidth allocation in Ethernet Passive Optical Networks", in "Proc. ICCS", pp. 126–130 (2004).

Zheng, J. and H. Mouftah, "A survey of dynamic bandwidth allocation algorithms for Ethernet Passive Optical Networks", Optical Switching and Networking **6**, 3, 151–162 (2009).

Zheng, X., M. Veeraraghavan, N. Rao, Q. Wu and M. Zhu, "CHEETAH: circuit-switched high-speed end-to-end transport architecture testbed", IEEE Commun. Mag. **43**, 8, S11–S17 (2005).

Zhu, Y., M. Ma and T. Cheng, "Hierarchical scheduling to support differentiated services in Ethernet passive optical networks", Computer Networks **50**, 3, 350–366 (2006).

APPENDIX A

APPENDIX: EVALUATION OF EQUILIBRIUM PROBABILITIES $Q(\beta)$

In this Appendix, we present the recursive Kaufman-Roberts algorithm (Ross, 1995, p. 23) for computing the equilibrium probabilities $q(\beta)$, $0 \leq \beta \leq C_c$ that the currently active circuit occupy an aggregated bandwidth β. For the execution of the algorithm, the given circuit bandwidths $b_1, b_2, \ldots, b_K$ and limit C_c are suitably normalized so that incrementing β in integer steps covers all possible combinations of the circuit bandwidth. For instance, in the evaluation scenario considered in Section 3.5.1, all circuit bandwidth are integer multiples of 52 Mb/s. Thus, we normalize all bandwidths by 52 Mb/s and for $C_s = 5$ Gb/s execute the following algorithm for $\beta = 0, 1, 2, \ldots, 96$. (The variables b_k, C_c, and β refer to their normalized values, e.g., $C_c = 96$, in the algorithm below).

The algorithm first evaluates unnormalized occupancy probabilities $g(\beta)$ that relate to a product-form solution of the stochastic knapsack Ross (1995). Subsequently the normalization term G for the occupancy probabilities is evaluated, allowing then the evaluation of the actual occupancy probabilities $q(\beta)$.

1. Set $g(0) \leftarrow 1$ and $g(\beta) \leftarrow 0$ for $\beta < 0$.
2. For $\beta = 1, 2, \ldots, C_c$, set

$$g(\beta) \leftarrow \frac{1}{\beta} \sum_{k=1}^{K} \frac{b_k p_k \lambda_c}{\mu} g(\beta - b_k). \tag{A.1}$$

3. Set

$$G = \sum_{\beta=0}^{C_c} g(\beta). \tag{A.2}$$

4. For $\beta = 0, 1, \ldots, C_c$, set

$$q(\beta) \leftarrow \frac{g(\beta)}{G}. \tag{A.3}$$