# A Comparison of Dynamic Bandwidth Allocation for EPON, GPON, and Next-Generation TDM PON

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## ABSTRACT

Dynamic bandwidth allocation in passive optical networks presents a key issue for providing efficient and fair utilization of the PON upstream bandwidth while supporting the QoS requirements of different traffic classes. In this article we compare the typical characteristics of DBA, such as bandwidth utilization, delay, and jitter at different traffic loads, within the two major standards for PONs, Ethernet PON and gigabit PON. A particular PON standard sets the framework for the operation of DBA and the limitations it faces. We illustrate these differences between EPON and GPON by means of simulations for the two standards. Moreover, we consider the evolution of both standards to their next-generation counterparts with the bit rate of 10 Gb/s and the implications to the DBA. A new simple GPON DBA algorithm is used to illustrate GPON performance. It is shown that the length of the polling cycle plays a crucial but different role for the operation of the DBA within the two standards. Moreover, only minor differences regarding DBA for current and next-generation PONs were found.

## INTRODUCTION

Passive optical networks (PONs) provide a powerful point-to-multipoint solution to satisfy the increasing capacity demand in the access part of the communication infrastructure, between service provider central offices (COs) and customer sites. A PON consists of an optical line terminal (OLT) located at the provider CO and a number of optical network units (ONUs) at the customer premises.

In a time-division multiplex (TDM) PON downstream traffic is handled by broadcasts from the OLT to all connected ONUs, while in the upstream direction an arbitration mechanism is required so that only a single ONU is allowed to transmit data at a given point in time because of the shared upstream channel. The start time and length of each transmission time slot for each ONU are scheduled using a bandwidth allocation scheme. In order to achieve flexible sharing of bandwidth among users and high bandwidth utilization, a dynamic bandwidth allocation (DBA) scheme that can adapt to the current traffic demand is required.

Two major standards for PONs have emerged, Ethernet PON (EPON) [1] and gigabit PON (GPON) [2]. Due to significant differences between the EPON and GPON standards (different control message formats, guard times, etc.), there are many implications for the DBA approaches and how an efficient bandwidth allocation scheme should be designed for these two standards. To the best of our knowledge, not much research has addressed a qualitative and quantitative comparison of DBA within EPON and GPON. Therefore, the objective of this article is to provide insight into the working mechanisms and typical performance characteristics of the DBA schemes under a variety of network conditions in these two competing standards. Furthermore, our study is extended to the next-generation TDM PONs (i.e., 10G EPON and 10G GPON).

The remainder of this article is organized as follows. In the next section we outline the key differences between the EPON and GPON standards in the context of DBA algorithms. We then discuss next-generation TDM PONs. We describe the DBA algorithms for EPON and GPON used in the article. We then define the performance parameters and methods used in this article. Results are presented in the following section, and conclusions are stated in the final section.

## EPON AND GPON STANDARDS

In this section we compare the two standards, EPON and GPON, which set the framework for the operation of DBA. The two standards


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| | EPON | | GPON | | |
|---|---|---|---|---|---|
| Line rate | Downstream | 1.25 Gb/s | Downstream | | 1.24416/ 2.48832 Gb/s |
| | Upstream | 1.25 Gb/s | Upstream | | 1.24416 Gb/s |
| | Bit rate after 8B/10B line coding | 1 Gb/s | Bit rate after scrambling line coding | | 1.24416 Gb/s |
| Guard time | Laser on-off | 512 ns | Laser on-off | | ≈25.7 ns |
| | Automatic gain control (AGC) | 96 ns, 192 ns, 288 ns, and 400 ns | Preamble and delimiter | | 70.7 ns |
| | Clock and data recovery (CDR) | 96 ns, 192 ns, 288 ns, and 400 ns | | | |
| Frame size | Ethernet frame | 64–1518 bytes | General encapsulation method (GEM) | GEM header | 5 bytes |
| | | | | Frame fragment | ≤1518 bytes |
| Overhead for bandwidth allocation | GATE/REPORT | 64 bytes (smallest size of Ethernet frame) | Status report message | | 2 bytes |

**Table 1.** *Some differences related to bandwidth allocation in standards of EPON [1] and GPON [2].*

embrace different philosophies, with EPON based on a simple standard with looser hardware requirements, and GPON based on a relatively complex standard with tighter hardware requirements and a larger focus on quality of service (QoS) assurance. On a detailed level, the two philosophies boil down to differences in guard times, overheads, and other forms of parameters influencing bandwidth utilization within the two systems. These underlying differences govern how DBA should be designed in order to cope with imposed traffic requirements and fairness policies while still maintaining efficient utilization of the PON's shared upstream channel.

Most research to date regarding DBA has addressed EPON [3–7]. However, GPON faces a series of distinct challenges, and new DBA algorithms tailored specifically to the GPON standard need to be developed. In Table 1 the differences related to bandwidth allocation in both standards are listed. The following subsections describe the differences between the EPON and GPON standards in more detail.

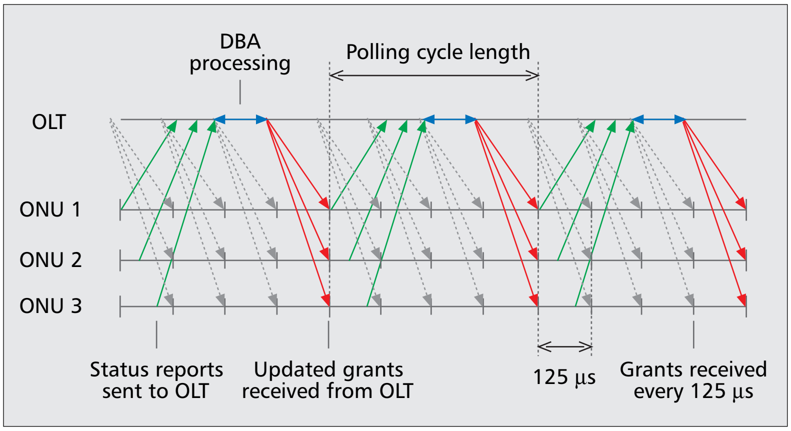
### EPON

In EPON both downstream and upstream line rates are 1.25 Gb/s, but due to the 8B/10B line encoding, the bit rate for data transmission is 1 Gb/s. Guard times between two neighboring time slots composed of laser on-off time, automatic gain control (AGC), and clock and data recovery (CDR) are used to differentiate the transmission from different ONUs in a given cycle. IEEE 802.3ah has specified values (classes) for AGC and CDR.

In EPON, Multipoint Control Protocol (MPCP) is implemented at the medium access control (MAC) layer to perform the bandwidth allocation, auto-discovery process, and ranging. As illustrated in Table 1, two control messages, REPORT and GATE, used for bandwidth allocation are defined in [1]. A GATE message carries the granted bandwidth information from the OLT to the ONU in the downstream direction, while the REPORT message is used by an ONU to report its bandwidth request to an OLT in the upstream direction. Their exchange allows the time slots to be assigned according to the traffic demand of the individual ONUs and the bandwidth available. The size of REPORT and GATE are defined as the smallest size of Ethernet frame (64 bytes).

### GPON

The GPON standard is defined in the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) G.984.x series of Recommendations sponsored by the full service access network (FSAN). Several upstream and downstream rates up to 2.48832 Gb/s are specified in the standard. Here we consider the 1.24416 Gb/s upstream rate to make it comparable with EPON. The GPON protocol is based on the standard 125 μs (~19,440 bytes at 1.24416 Gb/s) periodicity used in the telecommunications industry. This periodicity provides certain efficiency advantages over EPON, as messages (control, buffer report, and grant messages) can efficiently be integrated into the header of each 125 μs frame. In order to efficiently pack Ethernet frames into the 125 μs frame, Ethernet frame fragmentation has been introduced. Within GPON each Ethernet frame or frame fragment is encapsulated in a general encapsulation method (GEM) frame including a 5-byte GEM header. In addition, upstream QoS awareness has been integrated in the GPON standard with the introduction of the concept of transport containers (T-CONTs), where a T-CONT type represents a class of service. Hence




■ **Figure 1.** *Diagram of the bandwidth requesting algorithm used in the simulations for GPON.*

GPON provides a simple and efficient means of setting up a system for multiple service classes.

Several status reporting modes can be set within GPON. For our comparison with EPON we consider mode 0, the simplest status reporting mode. Hence, our comparison of EPON and GPON is based on a comparable type of communication mode between the OLT and ONUs where the ONUs send REPORT messages or status reports containing buffer sizes, while the OLT sends the ONUs GATE messages or grants containing the granted time slots.

## Next-Generation TDM PONs

Both the current GPON and EPON standards are on the verge of evolving to their respective next-generation standards supporting 10 Gb/s downstream bandwidth allocation along with higher upstream bandwidth support. There is an implication for the DBA problem depending on how the different forms of bandwidth overhead scale in the upgraded versions of the two standards.

1G EPON-based solutions have experienced great market penetration and been widely deployed, particularly in the Asian market. In order to cater to the ever increasing demands for bandwidth requirements from end customers, the 10G EPON Task Force was formed, known as IEEE 802.3av [8], with an initiative to standardize requirements for the next-generation 10G EPON in 2006. The IEEE 802.3av draft focuses on a new physical layer standard while still keeping changes to the logical layer at a minimum, such as maintaining all the MPCP and operations, administration, and maintenance (OAM) specifications from the IEEE 802.3ah standard. 10G EPON will use 64B/66B line coding with a line rate of 10.3125 Gb/s instead of 8B/10B line coding with a line rate of 1.25 Gb/s used in 1G EPON. For EPON we assume that the guard time is the same in time units while control messages (i.e., REPORT/GATE) are the same in byte units.

The most likely next-generation 10G GPON candidate will have a 2.48832 Gb/s upstream line rate. This upstream line rate has already been defined in ITU-T Recommendations. For larger upstream line rates, approaching 10 Gb/s, our assessment is based on estimates of the overheads for a possible future Recommendation. For GPON we assume a line rate of 9.95328 Gb/s and also that the sizes of the guard time, preamble, and delimiter remain the same in units of time, whereas the physical layer overhead (PLO) fields, GEM headers, and status report messages remain the same in units of bytes.

## DBA Schemes

Many DBA algorithms [3–7] have been developed especially for EPONs to cope with the challenges of high bandwidth utilization and QoS provisioning. However, it is difficult to pick a single best algorithm due to the multidimensional performance requirements expected of a DBA algorithm. In addition, some algorithms introduce increased complexity when supporting higher traffic demand, QoS, fairness, and so on. In order to make the comparison between GPON and EPON more general, we consider algorithms for EPON and GPON where each allocated byte corresponds to a byte residing in the buffer, a scheme we chose to refer to as *bandwidth requesting*. In contrast to traffic monitoring and predictive algorithms, bandwidth requesting algorithms have the advantage of high bandwidth utilization.

For EPON, Interleaved Polling with Adaptive Cycle Time (IPACT) [3] is considered one of the most efficient DBA algorithms in terms of bandwidth utilization. In IPACT, when the $i$th ONU is transmitting Ethernet frames in the upstream, the OLT informs the $(i + 1)$st ONU of the grant information, including the starting time and the size of the granted bandwidth. The $(i + 1)$st ONU may be polled before the transmission from the $i$th ONU is completed. Transmission slots for different ONUs are scheduled in a given cycle such that the first bit from the $(i + 1)$st ONU arrives at the OLT only after the guard time has passed (i.e., after the OLT receives the last bit from the $i$th ONU). In addition, two basic requirements need to be fulfilled:

- The GATE message carrying grant information can arrive at the $(i + 1)$st ONU in time.
- The bandwidth granted for the $i$th ONU is equal to the bandwidth requested by the $i$th ONU.

If these two requirements can be satisfied, the bandwidth in the upstream direction can be fully utilized. If the grant from the OLT is always equal to the bandwidth an ONU reported/requested, IPACT may lead to the situation that an ONU with heavy traffic load monopolizes the upstream channel so that frames from other ONUs are delayed. To solve this problem, a limited service discipline has been proposed [3] where a maximum guaranteed bandwidth ($B_i^{max}$) is predefined for each ONU. If the bandwidth requested by the $i$th ONU is less than $B_i^{max}$, the granted bandwidth from the OLT is the same as the requested bandwidth. Otherwise, the grant for the $i$th ONU is equal to $B_i^{max}$. $B_i^{max}$ sets an upper bound on the maximum bandwidth allocated to each ONU in a given cycle.

Within GPON, upstream transmission is based

| Symbol | Description | EPON | | GPON | |
|---|---|---|---|---|---|
| C | Bit rate after line coding | 1 Gb/s | 10 Gb/s | 1.24416 Gb/s | 9.95328 Gb/s |
| N | Number of ONUs | 16 | | | |
| D | Propagation delay between each ONU and the OLT | 100 μs (corresponds to a distance of 20 km) | | | |
| Q | Maximum buffer size for each ONU | 1 Mb | 10 Mb | 1.24416 Mb | 9.95328 Mb |
| $B^{guard}$ | Guard bandwidth between two neighboring slots | 125 bytes (~1 μs) | 1250 bytes (~1 μs) | 15 bytes (~96 ns) | 120 bytes (~96 ns) |
| $B^{Control}$ | Length of control message in bytes | $B^{REPORT}$ ($B^{GATE}$) = 64 bytes | | 2 bytes | |

**Table 2.** *Simulation parameters for EPON and GPON.*

on an upstream bandwidth map being broadcast to the ONUs every 125 μs. The bandwidth map is updated at regular time intervals by the DBA algorithm. Here, we propose a simple bandwidth requesting algorithm (Fig. 1) that works as follows. Within a given 125 μs upstream frame, all ONUs are scheduled to transmit buffer reports. The OLT takes the buffer reports and subtracts the previously allocated but not yet utilized grants (grants issued for the current polling cycle) to form an ONU request. This request is then used for the subsequent bandwidth allocation. The updated grants are thereafter transmitted to the ONUs together with requests for new buffer reports. The main difference between this algorithm and IPACT is that this algorithm uses a fixed polling cycle, and all the ONUs are polled essentially simultaneously (within a 125 μs frame).

## Performance Parameters and Method

### Definition of Performance Parameters

An efficient DBA algorithm strives to achieve as high bandwidth utilization as possible while still satisfying typical traffic requirement constraints such as packet delay, jitter and throughput.

In this article we define bandwidth utilization as the ratio between throughput and the system bit rate after line coding (Table 1; note the difference in bit rate after line coding between EPON and GPON). For the packet delay we refer to the waiting time for a packet in the ONU buffer (i.e., excluding the propagation delay for transmission to the OLT). Average delay as well as the corresponding 90 percent confidence interval is measured. Jitter is defined as the standard deviation of the delay. Furthermore, in this article we also introduce upstream efficiency, defined as

$$\frac{\sum_{i,j} B_{i,j}^{\text{sent}}}{\sum_{i,j} (B_{i,j}^{\text{grant}} + B^{\text{guard}} + B^{\text{Control}})},$$

where $B_{i,j}^{\text{grant}}$ denotes the size of the bandwidth granted by the OLT for the $j$th ONU in the $i$th polling cycle, while $B_{i,j}^{\text{sent}}$ denotes the size of bandwidth the $j$th ONU really used for sending Ethernet frames based on the grant issued by the OLT in the $i$th polling cycle. In EPON there is no frame fragmentation, and unused slots reminders (USRs) can be caused by the difference between $B_{i,j}^{\text{grant}}$ and $B_{i,j}^{\text{sent}}$. In GPON this type of USR is avoided by the use of frame fragmentation. The upstream efficiency as defined here provides more insight to the operation of the DBA algorithm, and the real reasons for throughput loss in EPON and GPON.

### Simulation Methods

Our performance comparison of PON systems is based on simulation studies. For EPON we have used a C++ based discrete event driven simulator developed for work presented in [7, 9], while for GPON we have used an event driven C++ based GPON simulator developed at Ericsson Research. Furthermore, both simulators have been modified and enhanced to simulate next-generation TDM PONs. Table 2 shows the primary simulation parameters for EPON and GPON. In these simulations we have used the traffic generator provided by Kramer [3] to model realistic self-similar traffic conditions. For traffic generation we used 256 pareto substreams with a hurst parameter of 0.8 and a packet size distribution taken from traffic measurements by Broadcom [10]. This traffic generator was used to generate 500,000 Ethernet frames per ONU for each value of offered load. Here the offered load is defined for the entire system and includes only the payload without any overhead. The simulation was ended after the first ONU sent the last bit of its last packet. Hence, the total simulation time of the system was determined by the ONU with the highest traffic load. For a fair comparison we set an ONU buffer size scaled according to the PON bit rate. For example, for 1G EPON the buffer size was set to 1 Mb while for 10G EPON it was set to 10 Mb (Table 2). It should be mentioned that the buffer size used in our simulations of the 1G system is on the same order of magnitude as commercial GPON products.

## Performance Evaluation

The starting point for our comparative study is to look at how the length of the polling cycle affects the performance of the DBA algorithms. The polling cycle length is a crucial design

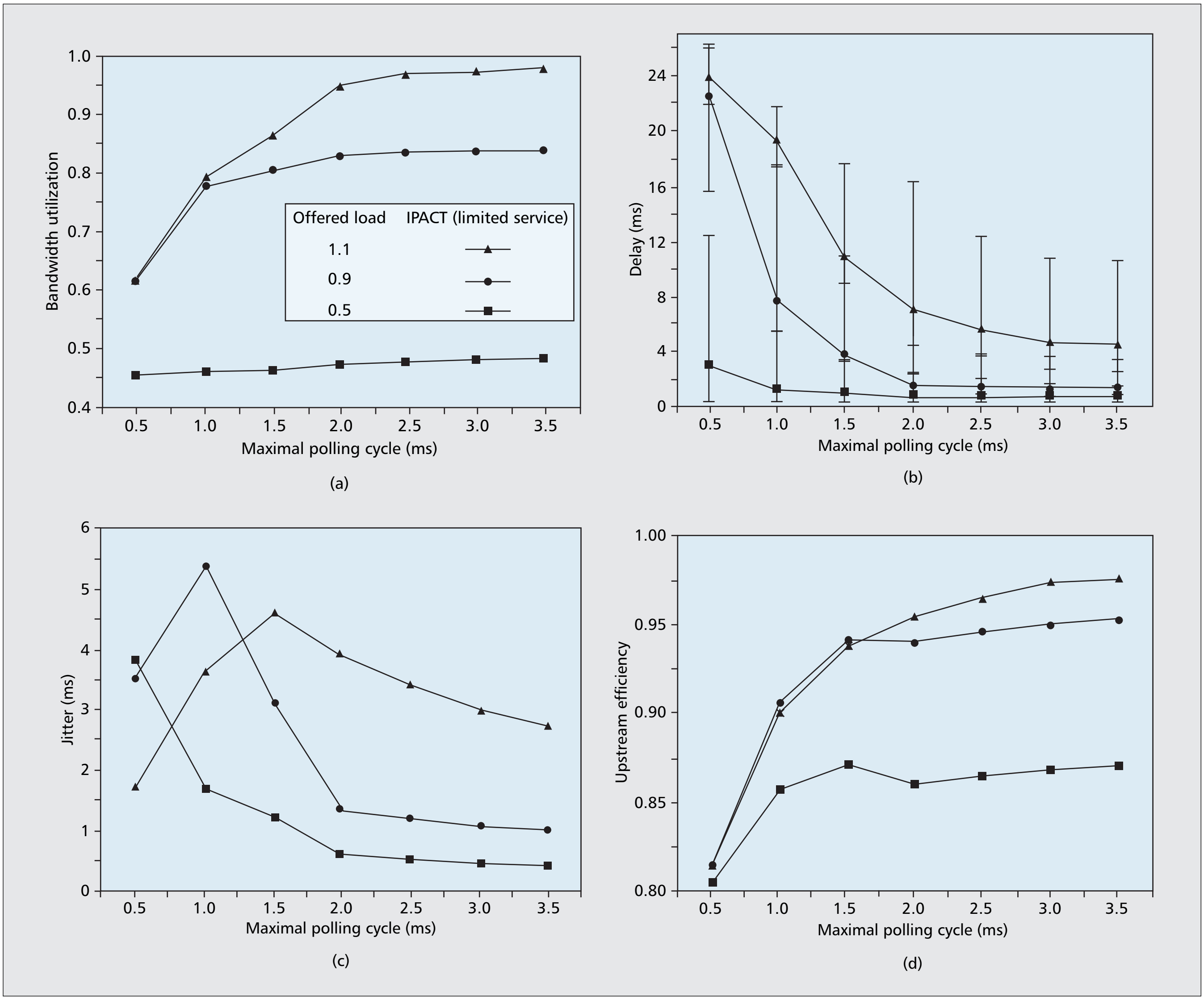



**Figure 2.** *Simulation results for 1G system (a–d): a) bandwidth utilization; b) delay with 90% confidence interval; c) jitter; d) upstream efficiency for EPON under different offered traffic loads.*

parameter. It influences almost all performance parameters such as bandwidth utilization, delay, and jitter. It also has implications on hardware requirements such as the processing power for the DBA, buffer sizes, and the complexity of the algorithm. Deciding the length of polling cycle is a matter of finding an optimal balance between different performance requirements. This balance will now be sought for EPON and GPON.

## EPON AND GPON

In Fig. 2 we present the results for bandwidth utilization, upstream efficiency, delay, and jitter for both EPON and GPON. Note that for EPON the results are given as a function of an imposed maximum polling cycle, while for GPON results are given as a function of fixed polling cycle. The considered EPON algorithm has an adaptive polling cycle where the average polling cycle is always smaller than the maximum polling cycle.

Let us first summarize the main conclusions that can be drawn from Fig. 2. For the EPON algorithm, performance is more strongly dependent on the polling cycle than for GPON. Furthermore, as shown in Figs. 2a and 2b, in EPON both bandwidth utilization and delay are seen to improve as the maximum polling cycle is increased. This trend continues until a saturation point above 2 ms is reached. For GPON, as seen in Figs. 2e and 2f, there is instead a degradation in performance with increasing polling cycle.

Three key characteristics have been identified to influence the bandwidth utilization and delay performance of the DBA algorithms for EPON and GPON in the figures:

- The protocol overhead related to the polling cycle
- Propagation delay making the OLT and ONUs wait for reception of DBA messages
- The algorithms' ability to avoid buffer overflows for single queues

The first two parameters affect the performance more severely for the EPON algorithm under consideration, whereas the third problem is more severe for the considered GPON algorithm.

Regarding the first characteristic, there are larger overhead related bandwidth losses (over-

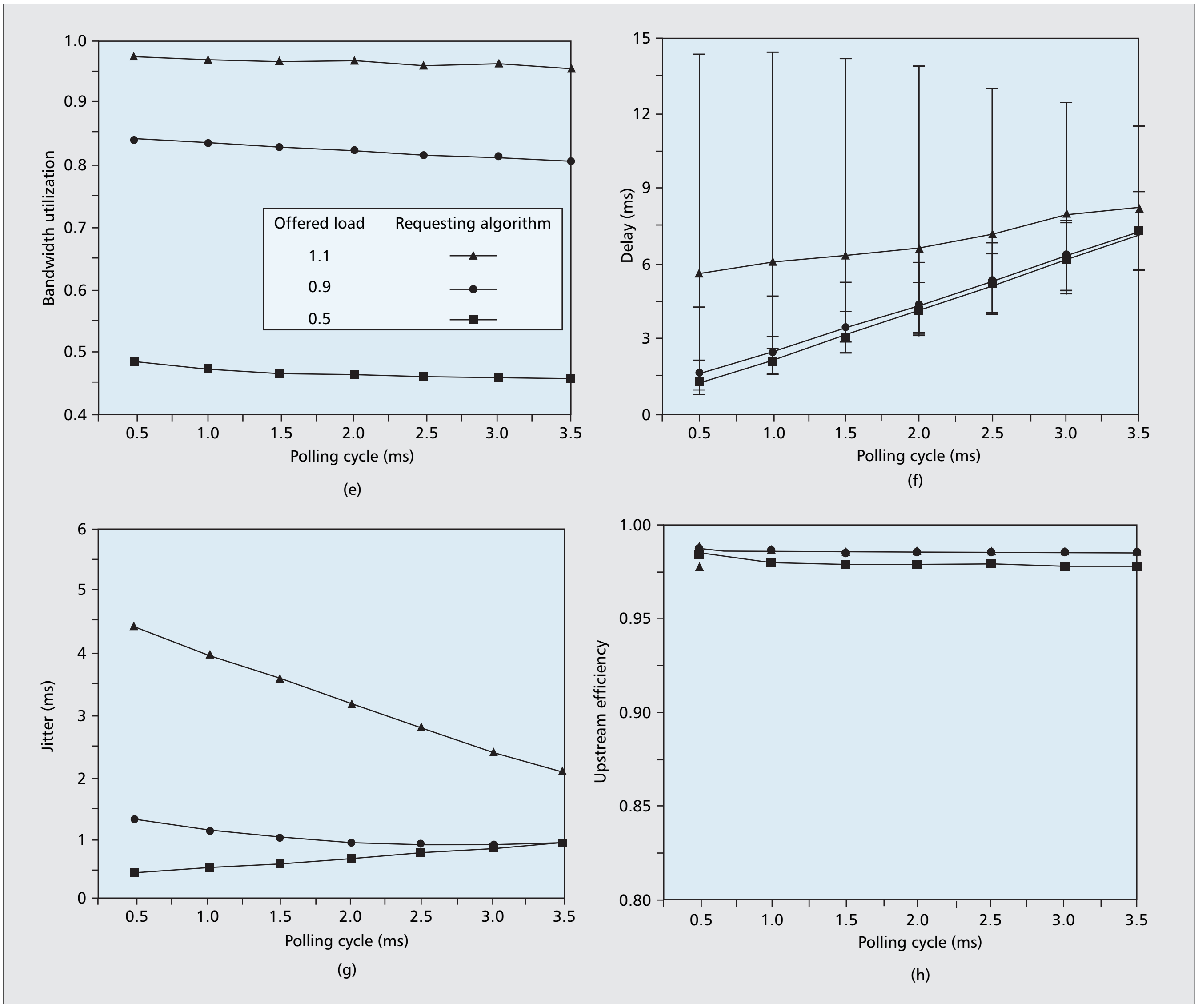



**Figure 2.** *Simulation results for 1G system (e–h): e) bandwidth utilization; f) delay with 90 percent confidence interval; g) jitter; h) upstream efficiency for GPON under different offered traffic loads.*

head, guard time, and control messages for DBA) in EPON than in GPON. This makes EPON more sensitive to changes involving the occurrence of overhead related bandwidth loss. In EPON the total size of overhead related bandwidth loss is constant per polling cycle. Hence, a smaller polling cycle leads to a larger amount of overhead related bandwidth loss. For GPON the overhead related bandwidth loss is relatively small and constant during the fixed 125 μs frame. Hence, the bandwidth overhead does not depend on the polling cycle. This characteristic provides a partial explanation of the increasing bandwidth utilization with increasing polling cycle for EPON in Fig. 2a and the rather stable bandwidth utilization for GPON in Fig. 2e.

The propagation delay has a strong influence on EPON performance. Because of the adaptive polling cycle and the bursty nature of Ethernet traffic, the polling cycle will sometimes be smaller than the fiber propagation delay. The smaller the given maximum polling cycle, the higher probability that the grant information from the OLT will not reach an ONU in time, and consequently more bandwidth will be lost. This is the main explanation of the poor bandwidth utilization and large delay for EPON seen in Figs. 2a and 2b for small polling cycles. In GPON the polling cycle is typically fixed. If the fixed polling cycle is chosen sufficiently large (i.e., larger than 0.5 ms), the corresponding loss of bandwidth can be completely avoided.

Finally, the ability of the algorithm to avoid single queue buffer overflows is related to the ability of the temporal bandwidth prioritization for buffers that are almost full. An algorithm that strongly prioritizes full buffers will achieve high throughput, possibly at the expense of delay and fairness between queues. In EPON, by increasing the maximum polling cycle, the maximum guaranteed bandwidth $B_i^{max}$ for each ONU is automatically increased so that the larger bandwidth is allocated to queues that request more bandwidth. Therefore, in EPON higher throughput can be obtained by increasing the maximum polling cycle and giving higher priori-

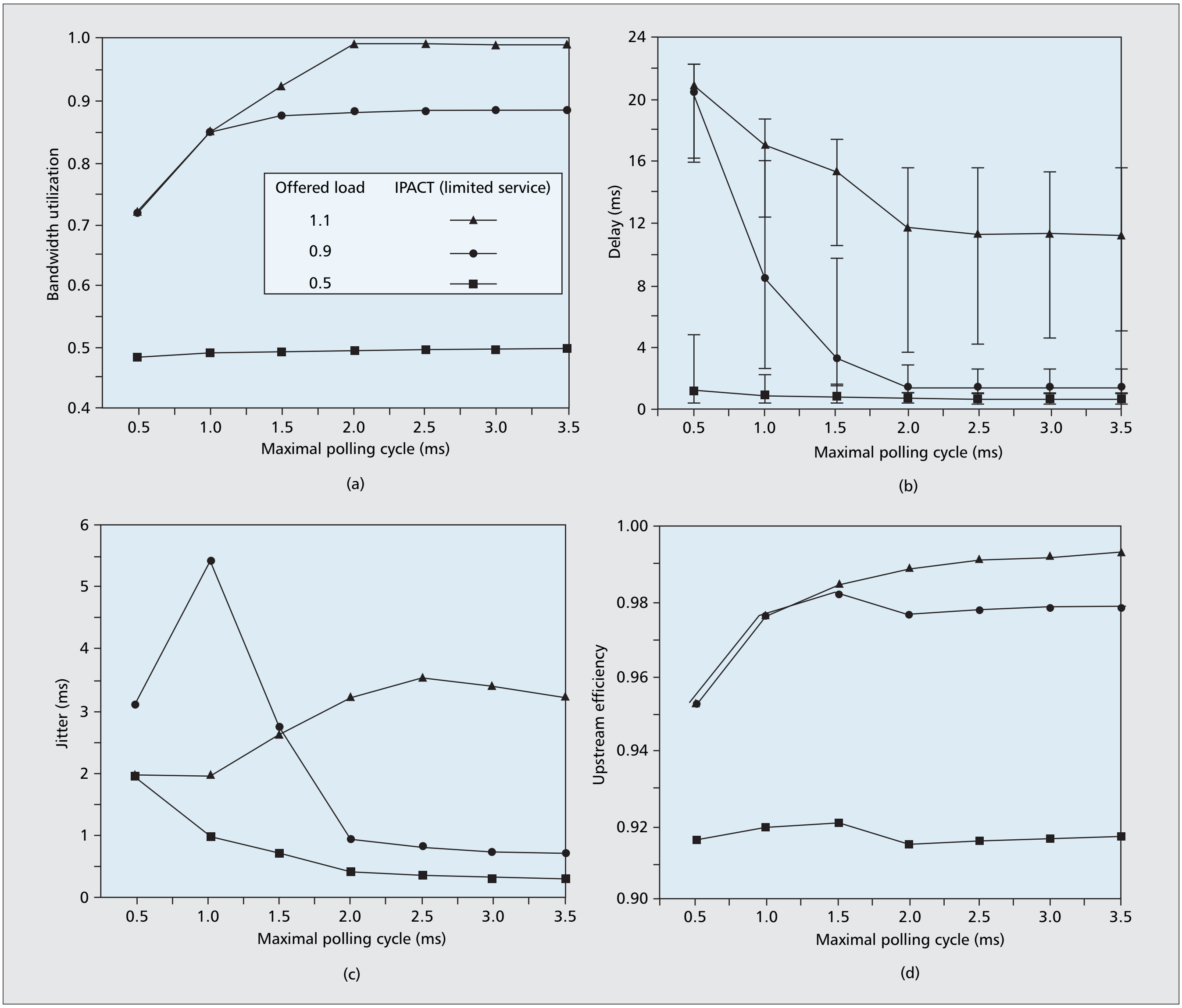


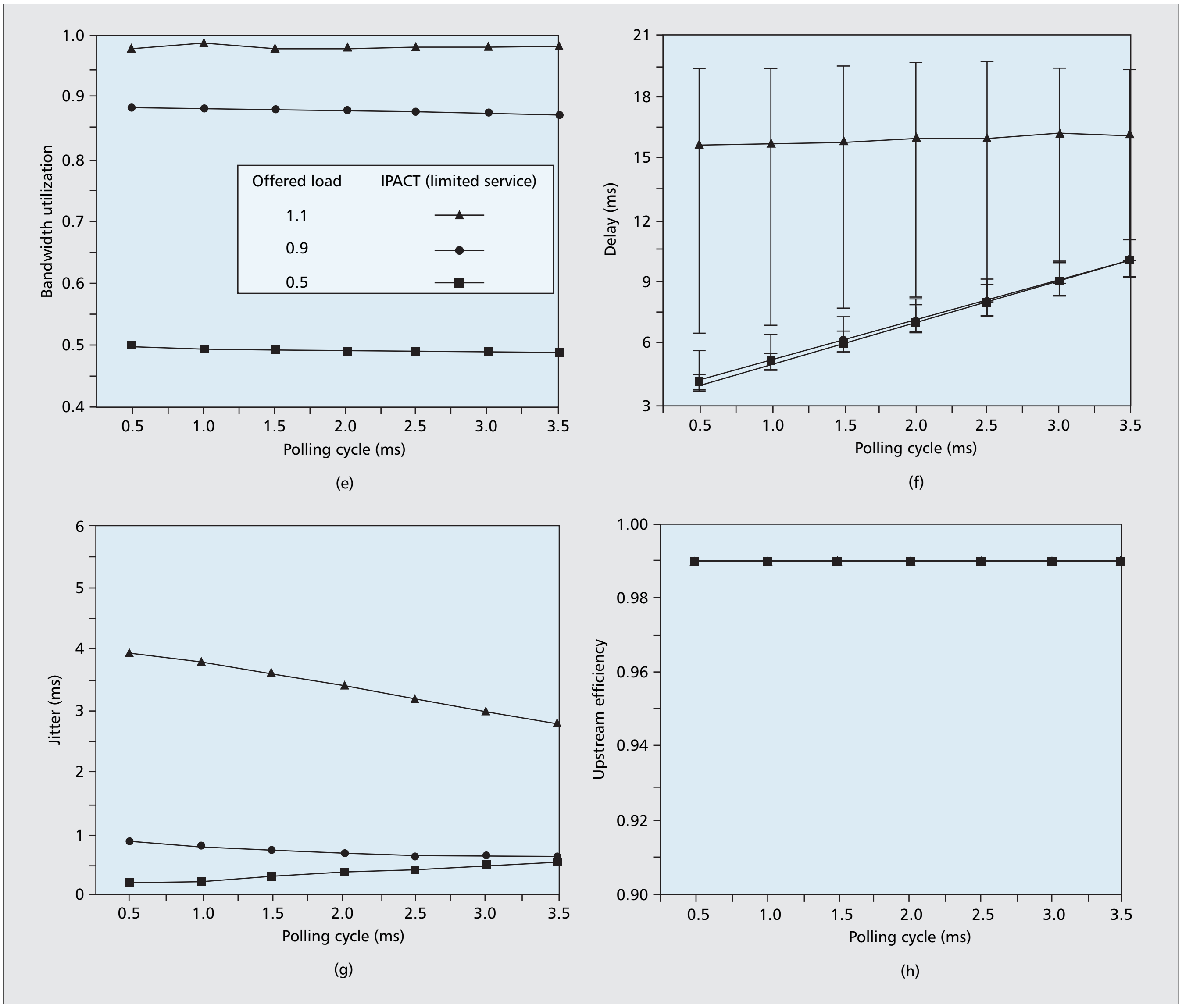

**Figure 3.** *Simulation results for the next generation TDM PONs (a–d): a) bandwidth utilization; b) delay with 90 percent confidence range; c) jitter; d) upstream efficiency for EPON under different offered traffic loads.*

ty to queues with heavy traffic load. This explains the very high bandwidth utilization and small delay for EPON seen in Figs. 2a and 2b for large polling cycles. Because of the fixed polling cycle in GPON, the bandwidth allocation loses some of its dynamics. This shortcoming could be overcome by introducing load-dependent priorities to the queues. The slight drop in bandwidth utilization for GPON in Fig. 2e for larger polling cycles is due to such buffer overflows and could be avoided by changing the prioritization scheme. For the considered GPON algorithm, delay is a result of the fixed polling cycle. For low load, the delay increases proportionally with the polling cycle. For high load the buffers are filled up, and the delay approaches a more constant dependence with respect to the polling cycle.

Next, we consider jitter. For EPON, in Fig. 2c one can observe a load-dependent peak in the jitter. There are two mechanisms that explain this behavior. In general, as the nature of Ethernet traffic is bursty, the delay variation increases with decreasing average polling cycle. However, when the number of dropped frames increases, the range of the delay variation is reduced. This reduces jitter for smaller polling cycles where bandwidth utilization is poor, thus producing the observed peak. For GPON it is shown in Fig. 2g that for low load, jitter increases slightly with an increase in the length of the polling cycle. This behavior is consistent with jitter being dependent on increased waiting time. For the higher load when buffers are being filled up, jitter decreases with increasing length of the polling cycle.

Figures 2d and 2h show the results for upstream efficiency in the EPON and GPON, respectively. According to the definition of upstream efficiency, it depicts to what extent the protocol related overhead influences EPON and GPON.

In EPON it can be observed from the simulation results that the upstream efficiency first




■ **Figure 3.** *Simulation results for the next generation TDM PONs (e–h): e) bandwidth utilization; f) delay with 90 percent confidence range; g) jitter; h) upstream efficiency for GPON under difference offered traffic loads.*

gradually increases and then gets saturated for different traffic loads. It should be noted that a valley point appears around the maximum polling cycle of 2 ms in the case of offered load of 0.5 and 0.9. According to the previous analysis, if the maximum polling cycle is larger than 2 ms, the bandwidth utilization reaches its maximum; hence, the amount of dropped packets decreases to the lowest level (i.e., less packets in the buffer). This means that the bandwidth request of an ONU in each polling cycle becomes smaller, so the real polling cycle may also be smaller. Therefore, the curve of upstream efficiency has a valley point for the maximum polling cycle of 2 ms. In GPON the curves for upstream efficiency for different offered traffic loads are nearly constant.

Comparing EPON and GPON, we find that their optimal upstream efficiency performance is similar, although frame fragmentation is not supported by EPON. This means that the efficiency of both EPON and GPON standards supporting the different DBA schemes is similar.

### NEXT-GENERATION TDM PONS

Figures 3a–3h show the bandwidth utilization, delay, jitter, and upstream efficiency for next-generation TDM PONs. We find that in 10G EPON the changes caused by different maximum polling cycles for all the performance parameters, including bandwidth utilization, delay, jitter, and upstream efficiency, are similar to EPON. However, one can observe that the overall performance of both EPON and GPON has improved. The main reason for this improvement is the higher bit rate. The polling cycle, which still has a similar value in time to the 1G TDM PON, is increased in bytes, while the fixed bytes used for the control message and similar USRs caused by the absence of frame fragmentation maintain the same length in bytes in 10G TDM PON.

## CONCLUSION

We have identified performance limiting parameters for DBA within EPON and GPON. For

For the next generation TDM PONs, if the overheads of control messages are still similar in bytes and guard time does not change in time significantly, the performance trends as a function of maximum polling cycle can be maintained while the optimal performance is improved.

EPON, the crucial performance parameters that must be managed are large overheads and effects of propagation delay. Starting from a small value and increasing the maximum polling cycle, one observes an improvement of all the performance parameters up to a saturation level. This optimal value of the maximum polling cycle is a result of configuration parameters (e.g., the buffer size at each ONU, the propagation delay from the OLT to the ONU, and the DBA message processing time).

GPON performance depends crucially on the ability of the DBA to quickly respond to the momentary traffic load on the PON in order to avoid single buffer overflows. From the simulation results it is evident that in GPON it is preferable to set as small a polling cycle as possible. This increases throughput and reduces delay. A lower limit to the polling cycle in GPON is in reality enforced by hardware parameters such as propagation delay and DBA message processing time. Compared to the very dynamic IPACT scheme for EPON, GPON algorithms are slightly more static in the sense that the polling cycle is fixed. The fixed polling cycle is advantageous for QoS assurance, which, while not considered in this article, is integrated in the GPON protocol. For QoS in EPON the algorithm must be modified in a way that might imply a more static polling cycle.

For next-generation TDM PONs, if the overheads of control messages are still similar in bytes and guard time does not change significantly, the performance trends as a function of maximum polling cycle can be maintained while the optimal performance is improved.

## Acknowledgment

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