Impact of EPON DBA Components on Performance

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***Abstract*—We introduce a convenient notational framework for Dynamic Bandwidth Allocation (DBA) algorithms in Ethernet Passive Optical Networks (EPONs) that uses the three principal axes of grant scheduling framework, grant sizing, and grant scheduling policy. We conduct comprehensive stability limit and packet delay investigations to determine which components have the strongest impact on these measures. We find that the grant sizing has the strongest impact on the delay and the combined grant scheduling framework and policy have the strongest impact on the stability limit. Further, we find that among the wide set of DBA algorithms we examined the shortest propagation delay first grant scheduling policy coupled with the limited with excess distribution grant sizing provides both the lowest delay and highest stability limit. The performance of shortest propagation delay first grant scheduling policy coupled with the limited with excess distribution grant sizing exceeds that of the online scheduling framework with limited grant sizing.**

***Index Terms*—Ethernet Passive Optical Network, Dynamic Bandwidth Allocation, Grant scheduling, Grant sizing, Packet delay, Propagation delay.**

I. Introduction

The design and performance evaluation of Dynamic Bandwidth Allocation (DBA) mechanisms [1], [2] for the upstream channel from the Optical Network Units (ONUs) to the Optical Line Terminal (OLT) of Ethernet Passive Optical Networks (EPONs) has received significant attention in recent years. However, a comprehensive framework for classifying and evaluating DBA mechanisms is yet to emerge. In this paper we propose a DBA notational framework and conduct performance comparisons with novel combinations of principal DBA components. More specifically, we classify and identify DBA mechanisms along the principal axes of:

- grant scheduling framework (α), which is characterized by the event triggering a bandwidth allocation,
- grant sizing (β), which determines the size (duration) of the upstream transmission window allocated to an ONU, and
- grant scheduling policy (γ), which determines the temporal order of several simultaneously scheduled transmission windows.

Thus, we identify a DBA mechanism by an (α,β,γ) triple.

Within this (α,β,γ) DBA classification we conduct throughput-delay evaluations to examine the impact of the three principal DBA classification axes. Several of these evaluations are—to the best of our knowledge—reported for the first time. For instance, we report the first (offline, limited with excess distribution, scheduling policy) DBA comparisons examining the impact of different scheduling policies within an offline scheduling framework employing limited with excess distribution grant sizing. We also examine for the first time a combination of the shortest propagation delay first (SPD) scheduling policy with limited with excess distribution grant sizing and find this combination to achieve superior throughput-delay performance in an offline scheduling framework. Throughout, we consider single-channel EPONs with different propagation distance ranges so that our results provide insights both for standard distance EPONs as well as long-reach EPONs [3], [4].

Previous studies of DBA algorithm performance have primarily examined different components of a DBA algorithm in isolation. For example, many studies have had a primary focus on grant sizing [5]–[11], while others have had a primary focus on grant scheduling [12]–[23]. In this article, we present a performance comparison that varies all three components of a DBA algorithm and examines the impact on packet delay and the maximum achievable channel utilization or stability limit.

This article is organized as follows. In Section II we discuss the problem of Dynamic Bandwidth Allocation (DBA) for EPONs. In Section III we present our experimental performance analysis. Finally, in Section IV we summarize our findings.

II. EPON Dynamic Bandwidth Allocation

A. Grant Scheduling Framework (α)

The grant scheduling framework determines when the OLT will make access decisions and send transmission grants to the ONUs. We can differentiate the scheduling frameworks according to the event that triggers the production of a grant schedule.

- Online - triggered by the receipt of a REPORT from any ONU, only that ONU is scheduled

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- Offline - triggered by the receipt of REPORTs from all ONUs, all ONUs are scheduled

Let t_g be the necessary guard time between ONU transmissions, t_i^{stall} be the delay from the end of a grant to ONU $(i-1)$ and the beginning of a grant to ONU i that results from the polling time to ONU i (see [23] for a full explanation, we omit the details due to space constraints), and t_{gap} be the delay between two arbitrary granting cycles. The delay between two arbitrary granting cycles must be at least a guard time but can be larger due to the polling time to the first ONU,

$$t_{\text{gap}} = \max\left(t_g, t_1^{\text{stall}}\right) \quad (1)$$

When using an online scheduling framework, it is clear that t_1^{stall} is less than or equal to its value when an offline scheduling framework is used. This is due to the fact that, with the online scheduling framework, the polling of the first ONU in a cycle is overlapped with transmissions from the previous cycle. Whereas, with the offline scheduling framework it is not. Therefore, t_{gap} for an online scheduling framework is less than or equal to its value for an offline scheduling framework.

1) Limitations of Online Grant Scheduling Framework: With an online grant scheduling framework, the OLT considers ONU REPORTs individually. As a result, a grant scheduling policy cannot be applied. Further, grant sizing policies that require REPORTs from all ONUs (e.g., Limited with Excess Distribution) cannot be applied.

B. Grant Sizing (β)

The grant sizing policy determines the size of a grant to an ONU during a granting cycle. Let G_i be the size of a grant during an arbitrary granting cycle for ONU i, R_i be the reported queue depth during an arbitrary granting cycle for ONU i, $G_i^{\max}$ be the optional fixed grant size limit for ONU i. The following general grant sizing policies have been proposed in the literature [1], [5]:

- Fixed, $G_i = G_i^{\max}$
- Gated, $G_i = R_i$
- Limited, $G_i = \min(R_i, G_i^{\max})$

Fixed grant sizing is inefficient for ONU traffic loads with high variance. Gated grant sizing leads to unfair bandwidth allocation because the bandwidth allocated is solely a function of the request. Limited grant sizing permits fair bandwidth allocation by placing a limit on the size of a grant in any granting cycle.

1) Limited with Excess Distribution: Limited grant sizing can be augmented with a technique called excess distribution [6]. With this technique, ONUs are divided into two sets: 1) underloaded ONUs (i.e., $R_i \le G_i^{\max}$), and 2) overloaded ONUs (i.e., $R_i > G_i^{\max}$). Let $\mathcal{U}$ be the set of underloaded ONUs, and O be the set of overloaded ONUs.

The underloaded ONUs receive a grant to satisfy their REPORT,

$$G_i = R_i, \forall_{i \in \mathcal{U}} \quad (2)$$

and contribute their excess bandwidth (i.e., $G_i^{\max} - R_i$) to a pool of excess bandwidth for a granting cycle. Let E_{total} be the excess bandwidth for an arbitrary granting cycle.

$$E_{\text{total}} = \sum_{i \in \mathcal{U}} (G_i^{\max} - R_i) \quad (3)$$

The computation of E_{total} by the OLT requires that all of the reported queue depths, R_i, are received from all ONUs. An offline scheduling framework permits the OLT to collect this information. To fill in the gap between granting cycles the underloaded ONUs can be serviced without waiting for queue depth REPORTs from all ONUs [24].

The overloaded ONUs receive a grant that will include some portion of the excess bandwidth accumulated from the underloaded ONUs. Let E_i be the amount of excess bandwidth distributed to ONU i, and O the total number of overloaded ONUs. With Equitable Excess Division [6], [25],

$$E_i = \frac{E_{\text{total}}}{O}, \forall_{i \in O} \quad (4)$$

and with Controlled Excess Allocation [25],

$$G_i = \min\left(G_i^{\max} + E_i, R_i\right), \forall_{i \in O} \quad (5)$$

Let N be the number of ONUs, and η be the channel utilization for some arbitrary granting cycle,

$$\eta = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N}\left(\max\left(t_g, t_i^{stall}\right) + G_i\right)} \quad (6)$$

It is clear from Eq. (6) that a grant sizing scheme that produces larger grant sizes will result in a higher channel utilization. Eqs. (2) and (5) clearly illustrate that Limited with Excess distribution grant sizing will produce grant sizes that are greater than or equal to those produced by Limited grant sizing. As a result, Limited with Excess distribution grant sizing will result in a channel utilization that is greater than or equal to that of Limited grant sizing.

Further, a grant sizing scheme that results in larger grant sizes will serve more packets in one cycle resulting in a smaller average packet delay. The larger grant sizes will result in a larger cycle that can indirectly increase packet delays. However, Limited with Excess distribution bounds the cycle length to significantly mitigate this increase. Therefore, Limited with Excess distribution grant sizing will result in an average packet delay that is less than or equal to that of Limited grant sizing.

C. Grant Scheduling Policy (γ)

The grant scheduling policy determines how multiple ONU transmission grants are ordered in time. With the Online scheduling framework only one ONU is scheduled at a time. As a result, a grant scheduling policy can only be used within the Offline scheduling framework. The following are some scheduling policies that have been proposed and evaluated in the literature:

- Shortest Grant or Shortest Processing Time First (SPT) [15]
- Largest Number of Frames First (LNF) [19]
- Shortest Propagation Delay First (SPD) [23]

The SPD grant scheduling policy optimally minimizes the granting cycle length when using an offline scheduling framework [23]. Assuming the grant sizes are constant, Eq. 6 illustrates the minimal granting cycle length (i.e., the denominator) will produce the maximal channel utilization.

III. Experimental Performance Analysis

We conducted a set of simulation experiments to compare the performance of the following DBA algorithms expressed as (α, β, γ):

- (Online, Limited)
- (Offline, Limited, LNF)
- (Offline, Excess, LNF)
- (Offline, Limited, SPD)
- (Offline, Excess, SPD)

The goal of these experiments is to determine: 1) which component of a DBA algorithm has the largest impact on the average packet delay and stability limit measures, and 2) which combination of components of a DBA algorithm provides the lowest average packet delay and highest stability limit.

We use an EPON simulator that we have developed using the CSIM discrete event simulation library [26]. We simulated an EPON with a channel capacity, C, of 1 Gbps and N = 32 ONUs. We varied the maximum propagation delay to represent three different EPON reaches: 1) 1 km to 10 km (6.67 μsec to 50 μsec), 2) 1 km to 50 km (6.67 μsec to 250 μsec), and 3) 1 km to 100 km (6.67 μsec to 500 μsec) (in [23] we illustrate the feasibility of these ranges in practical EPON architectures). A quad modal packet size distribution was used for all simulation experiments: 60% 64 bytes, 4% 300 bytes, 11% 580 bytes, and 25% 1518 bytes. We set the guard time, t_g, to 1 μsec, and $G_i^{\max}$ = 7688 bytes or 61.5 μsec, $\forall_i$ (i.e., $\sum_{i=1}^{32}(G_i^{\max}+t_g)$ = 2 msec).

A. Packet Delay

Figure 1 contains plots of the average packet delay in seconds versus presented load in Gbps for the five different DBA algorithms examined with the three different propagation delay ranges examined. For all three propagation delay ranges, the DBA algorithms that use Limited with Excess Distribution grant sizing provide much lower average packet delays than those that use Limited grant sizing. As an example, with a presented load of 0.6 Gbps and maximum propagation delay of 500 μsec, the average packet delay is 327.4 msec using (Offline, Limited, LNF) and 21.91 msec using (Offline, Excess, LNF).

The average packet delay using (Offline, Limited, SPD) approaches the average packet delay of (Online, Limited) as the propagation delay range increases. As an example, with a presented load of 0.6 Gbps, the average packet delay difference is 2.09 msec or 16.34%, 2.72 msec or 10.13%, 3.06 msec or 4.8% for the three propagation delay ranges (listed in increasing order).

(Offline, Limited, LNF) produced the highest average packet delay of the five DBA algorithms with the gap between it and the others increasing as the propagation delay range increases. Finally, (Offline, Excess, SPD) produced the lowest average packet delay of all five DBA algorithms. As an example, for a propagation delay range of 6.67 μsec to 500 μsec and total presented load of 0.6 Gbps; the average packet delay is 327.38 msec using (Offline, Limited, LNF) as opposed to 7.32 msec using (Offline, Excess, SPD). The average packet delay is 60.61 msec using (Online, Limited).

In summary, the grant sizing has the largest impact on the average packet delay. Further, the grant scheduling also has a significant impact and the SPD grant scheduling policy can significantly reduce the average packet delay performance gap between the offline and online scheduling frameworks. When SPD grant scheduling is coupled with Limited with Excess distribution grant sizing, the average packet delay performance is better than with the online scheduling framework which cannot take advantage of conventional excess distribution techniques.

As we indicated in Section II-B1, the grant sizes produced by Limited with Excess distribution grant sizing are greater than or equal to those produced by Limited grant sizing, as a result more packets will be served in a single cycle. More packets served in a single cycle results in a lower average packet delay, thereby explaining our experimental observations. SPD grant scheduling, by minimizing the granting cycle length, shortens the time between grants to each ONU. A shorter time between grants also produces a lower average packet delay, further explaining our experimental observations.

B. Stability Limit (i.e., Maximum Achievable Channel Utilization)

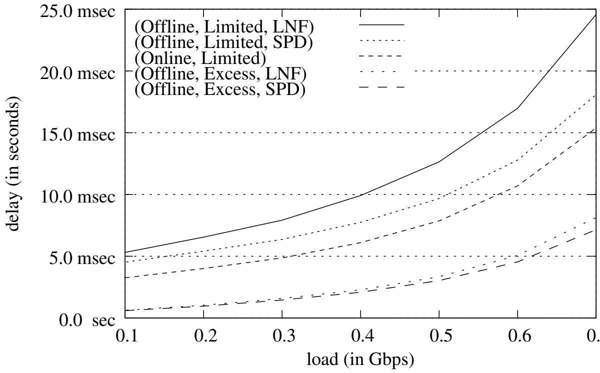
Figure 2 contains plots of the packet delay in seconds versus presented load in Gbps for high values of presented load. These plots indicate the load value at which the average packet delay approaches infinity (i.e., the stability limit or maximum achievable channel utilization). We refer to this load value as the stability limit.

The stability limit using (Online, Limited) and (Offline, Excess, SPD) is 0.91 Gbps for all three propagation delay ranges. The stability limit using (Offline, Limited, SPD) is a slightly smaller 0.9 Gbps for all three propagation delay ranges.

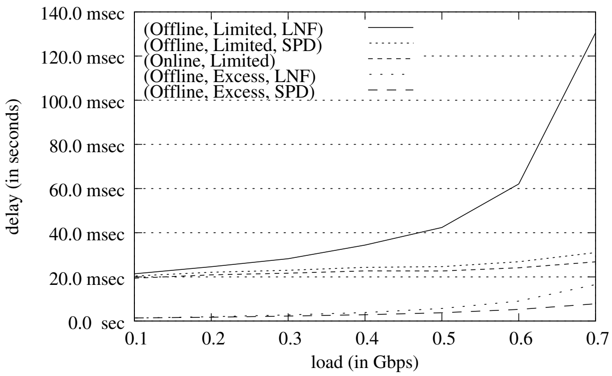
The stability limit using (Offline, Limited, LNF) and (Offline, Excess, LNF) is much lower and decreases with increasing propagation delay range. (Offline, Excess, LNF) results in a slightly higher stability limit than (Offline, Limited, LNF) for larger propagation delay ranges. As an example, with a propagation delay range of 6.67 μsec to 500 μsec, (Offline, Limited, LNF) results in a stability limit of 0.62 Gbps while (Offline, Excess, LNF) results in a stability limit of 0.63 Gbps.

In summary, the experimental data indicate the following:

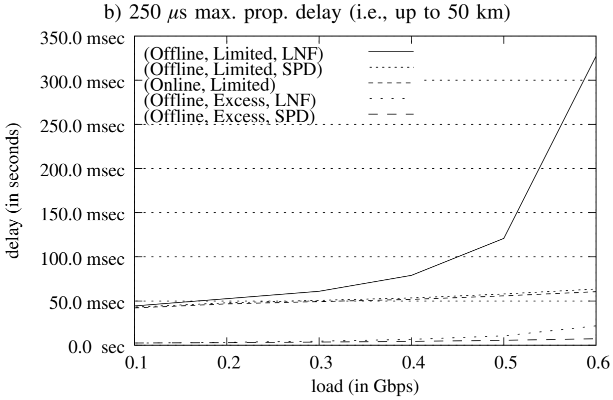
- The online grant scheduling framework can achieve the highest stability limit.



a) 50 μs max. prop. delay (i.e., up to 10 km)

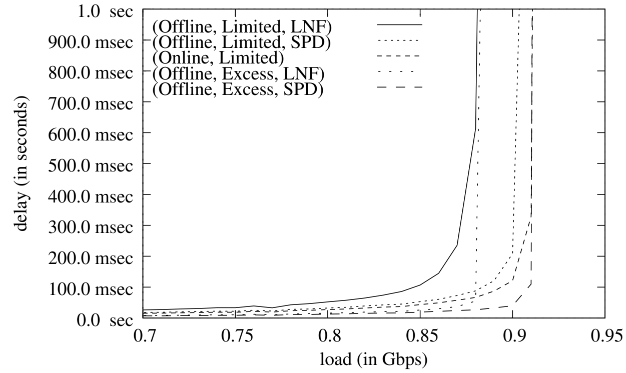


b) 250 μs max. prop. delay (i.e., up to 50 km)

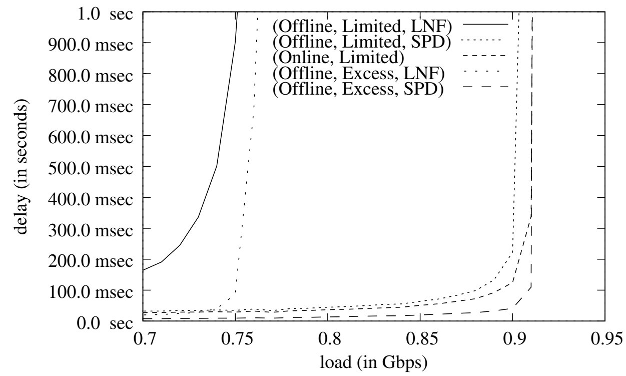


c) 500 μs max. prop. delay (i.e., up to 100 km)

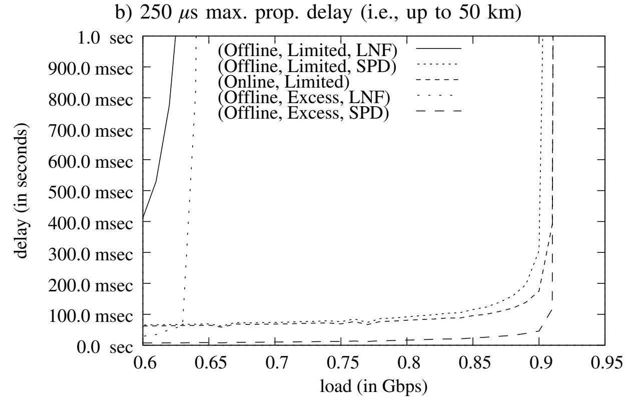
Fig. 1. Average packet delay for five DBA algorithms used for bandwidth allocation in EPONs with three different propagation delay ranges.



a) 50 μs max. prop. delay (i.e., up to 10 km)



b) 250 μs max. prop. delay (i.e., up to 50 km)



c) 500 μs max. prop. delay (i.e., up to 100 km)

Fig. 2. Stability limit for five DBA algorithms used for bandwidth allocation in EPONs with three different propagation delay ranges.

- The Shortest Propagation Delay grant scheduling policy can significantly narrow the stability limit gap between the offline and online scheduling frameworks.
- The Shortest Propagation Delay grant scheduling policy coupled with Limited with Excess Distribution grant sizing closes the stability limit gap between the offline and online scheduling frameworks.
- Limited with Excess Distribution grant sizing provides only a modestly higher stability limit compared to Limited grant sizing.

Therefore, the grant scheduling has the largest impact on the stability limit. While the grant sizing has only a modest impact on the stability limit. Further, when SPD grant scheduling is coupled with Limited with Excess distribution grant sizing, the stability limit is the same as with the online scheduling framework. SPD grant scheduling optimally minimizes the granting cycle length for an offline scheduling framework. As indicated in Section II-B1, a minimal granting cycle length will produce the maximal channel utilization.

IV. Conclusion

In conclusion, we presented a novel notational framework for identifying DBA algorithms and have conducted a performance evaluation that varies all three components of a DBA algorithm.

We have found that grant sizing has the strongest impact on average packet delay. Specifically, Limited with Excess distribution grant sizing produces significantly lower average packet delay compared to Limited grant sizing. We have also found that the grant scheduling also has a significant impact on the average packet delay. When SPD grant scheduling is coupled with Limited with Excess distribution grant sizing, the average packet delay is less than with the online scheduling framework.

We have found that grant scheduling has the strongest impact on the stability limit or maximum achievable channel utilization. Whereas the grant sizing only has a modest impact on the stability limit. When SPD grant scheduling is coupled with Limited with Excess distribution grant sizing, the stability limit is the same as with the online scheduling framework.

Of the five DBA algorithms examined the SPD grant scheduling policy in the offline grant scheduling framework coupled with Limited with Excess distribution grant sizing produced both the lowest average packet delay and the highest stability limit.

Note that our simulation evaluations provide insights into the relative impact of the principal DBA components (α, β, γ) on the mean packet delays and stability limits. Mathematical analysis can provide insights into the relative impact of different approaches for the individual DBA components, e.g., showing that Limited with Excess grant sizing gives larger stability limit and smaller delay than Limited grant sizing. However, to the best of our knowledge, examining the relative impact of the principal DBA components is mathematically not tractable.

This paper has been focused on EPONs with a single upstream wavelength channel. A promising avenue of future investigation is to develop a similar notational framework and conduct comprehensive performance evaluations for WDM EPONs with multiple upstream channels.

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