When Are Online and Offline Excess Bandwidth Distribution Useful in EPONs?

(Invited Paper)

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Abstract. Excess bandwidth distribution techniques have recently been proposed to improve the dynamic bandwidth allocation in EPONs. We compare existing offline excess bandwidth distribution with conventional IPACT Limited in terms of packet delay performance. We identify the factors that result in packet delay reduction with excess bandwidth distribution compared to IPACT-Limited and discover that existing offline excess distribution mechanisms become unstable at moderate to high loads in long-range EPONs with large round trip propagation delays. We propose and evaluate a novel Online Excess Bandwidth Distribution (OEBD) mechanism to provide stable excess bandwidth distribution even at high loads in long-range EPONs.

Keywords: EPON, excess bandwidth distribution, IPACT Limited, packet delay.

1 Introduction

Excess bandwidth distribution for Ethernet Passive Optical Networks (EPONs) has originally been proposed in [1] as an improvement over the Limited allocation approach of Interleaved Polling with Adaptive Cycle Time (IPACT) [2,3], which we refer to as IPACT-Limited. IPACT-Limited is characterized by a maximum grant size $G_i^{\max}$ [Bytes], also frequently referred to as minimum guaranteed bandwidth, for each Optical Network Unit (ONU) i, $i = 1, \ldots, M$. Let R_i [Bytes] denote the size of the upstream transmission request from ONU i. If ONU i requests less than $G_i^{\max}$, i.e., $R_i \leq G_i^{\max}$, then IPACT-Limited grants the full request, i.e., the size of the grant to ONU i is $G_i = R_i$. If the request exceeds $G_i^{\max}$, i.e., $R_i > G_i^{\max}$, then IPACT-Limited grants an upstream transmission window for $G_i = G_i^{\max}$ Bytes.

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The intuitive reasoning behind excess bandwidth distribution is to declare the unused portions $(G_i^{\max} - G_i)$ as excess bandwidth and distribute the total excess bandwidth $\sum_{m=1}^{M}(G_i^{\max} - G_i)$ among the ONUs with $R_i > G_i^{\max}$. Thus, the basic tradeoff made with excess bandwidth distribution is to extend the cycle within which all ONUs are served once (to no more than approximately $\sum_{m=1}^{M} G_i^{\max}/C$, with C denoting the upstream transmission rate in Byte/sec) so that heavily loaded ONUs can transmit more than $G_i^{\max}$ in a cycle. In contrast, IPACT-Limited enforces shorter cycles by strictly limiting upstream transmissions to at most $G_i^{\max}$ in a cycle, resulting in heavily loaded ONUs having to use more cycles to clear backlogs.

To the best of our knowledge, IPACT with Limited allocation has not been, in detail, quantitatively compared with the various proposed excess bandwidth distribution mechanisms. That is, the outlined basic tradeoff between clearing traffic backlogs with more shorter cycles with IPACT-Limited versus fewer longer cycles with excess distribution techniques has not been quantitatively investigated to identify the factors leading to improvements with excess bandwidth distribution. Oftentimes, the excess bandwidth distribution research has focused on quantitatively comparing different excess bandwidth distribution techniques, against each other, as reviewed in Section 2.

In this paper, we conduct for the first time a detailed quantitative comparison between IPACT-Limited and excess bandwidth distribution techniques. We conduct extensive simulations to assess the packet delays. We identify the factors that influence the relative performance differences between IPACT-Limited and excess bandwidth distribution. We find that existing offline excess bandwidth distribution mechanisms achieve significant delay reductions compared to IPACT-Limited for traffic with large bursts in mid-range EPONs. However, we also find that the existing offline excess bandwidth distribution mechanisms suffer from instability problems in long-range EPONs, which are currently intensely studied [4,5,6]. We propose a novel Online Excess Bandwidth Distribution Mechanism (OEBD) to overcome the stability problems of existing offline excess bandwidth distribution mechanisms.

2 Related Work

Excess bandwidth distribution as part of the dynamic bandwidth allocation process in EPONs [7] has received significant interest in recent years. Following the seminal work [1], several refinements and a range of different mechanisms have been proposed for excess bandwidth distribution. The research in [8], for instance, significantly advanced excess bandwidth allocation by introducing a weighted excess division technique that enforces fair division of the total excess bandwidth among the overloaded ONUs requesting more than $G_i^{\max}$. Several studies explored further refinements of excess bandwidth distribution to incorporate features, such as differentiated services, see e.g., [9] and traffic prediction, see e.g., [10]. The excess bandwidth allocation refinement in [11] included some limited performance comparisons with IPACT-Limited. Our comparisons are fundamentally different from [11] in that we consider a wide range of scenarios, including a range of round-trip propagation delays, to identify the factors leading to improvements with excess bandwidth distribution over IPACT-Limited.

A modification to IPACT-Limited was explored in [12], whereby the excess bandwidth of a given ONU is immediately equally distributed among the other ONUs to increase their maximum grant limits. Our Online Excess Bandwidth Distribution (OEBD) is fundamentally different from the distribution technique in [12] in that it maintains an excess bandwidth credit pool for carrying excess bandwidth across cycles, as explained in Section 4, and supports unequal weight-based excess distribution.

More recently, some excess bandwidth distribution techniques originally proposed for single-channel EPONs have been investigated in the context of Wavelength Division Multiplexing (WDM) EPONs with several upstream transmission channels [13]. The performance evaluation in [13] includes comparisons of excess bandwidth distribution with some form of IPACT, namely the Single Table extension of IPACT to WDM [14]. Specifically, the Gated allocation of IPACT, where the grant is set equal to the ONU request, without any upper limit, was considered. Gated allocation can lead to unfairness because grant sizes are determined solely as a function of reported queue depth, which is obviously unfair. IPACT with Limited allocation, which we consider in this study, avoids this fairness problem by strictly limiting the size of a granted upstream transmission.

3 Comparison of IPACT-Limited and Offline Excess Bandwidth Distribution

We initially consider IPACT-Limited bandwidth allocation in conjunction with (a) the *offline* scheduling framework, where all ONU Reports must be received before allocating bandwidth, which idles the upstream channel for one round-trip time, (b) the ONU load status *hybrid* scheduling framework, where underloaded ONUs with $R_i \leq G_i^{\max}$ are immediately granted bandwidth, and overloaded ONUs with $R_i > G_i^{\max}$ are granted bandwidth once all ONU Reports have been received, and (c) the *online* scheduling framework, where all ONUs are immediately granted bandwidth.

Among the many different excess distribution schemes, we focus on the weighted excess division dynamic bandwidth allocation scheme from [8], which enforces fair distribution of the excess bandwidth by divided the excess according to the weights of the ONUs. We combine this with the Iterative excess allocation [8] which iteratively allocates excess bandwidth to ONUs in an effort to maximize the number of satisfied ONUs. By maximizing the number of satisfied ONUs, unused slot remainders are minimized. We refer to this combined excess bandwidth distribution scheme as *Iterative.* We consider this Iterative scheme in conjunction with (a) the *offline* scheduling framework, whereby all ONU Reports need to be received at the OLT before commencing the dynamic bandwidth allocation, as well as (b) the ONU load status *hybrid* scheduling framework (referred to as DWBA-2 in [13]), whereby underloaded ONUs receive their grant (online) immediately and the excess bandwidth distribution is executed for the overloaded ONUs (offline), once all the Report messages have been received. Note that in both cases, the excess bandwidth distribution operates in offline fashion, in that the excess is allocated only after all ONU Reports for the present cycle have been received. We note that we do not consider DBA-3 from [13], which allocates overloaded ONUs (online) immediately the maximum grant size, and then additional *excess bandwidth in offline fashion*, because of its increased complexity, limited delay reductions, and increased wasted bandwidth, as evaluated in [13].

3.1 Simulation Set-Up

We developed an EPON simulation engine using the CSIM simulation library. We set the upstream transmission bit rate to $C = 1$ Gbps. We initially consider an EPON with $M = 16$ ONUs, each with a 10 MByte buffer. We consider round trip (RTT) propagation delays (ONU to OLT and back to ONU) for short-range ($[8,\ 10]\mu$s corresponding to OLT-to-ONU distances up to 1 km), mid-range ($[13.36,\ 100]\mu$s corresponding to OLT-to-ONU distances up to 10 km), long-range ($[0.8,\ 1]$ms corresponding to OLT-to-ONU distances up to 100 km), and extra long-range ($[1.6,\ 2]$ms corresponding to OLT-to-ONU distances up to 200 km) EPONs; for each range the different ONUs draw their RTT independently randomly from a uniform distribution over the respective intervals.

Each ONU independently generates self-similar traffic with a Hurst parameter of 0.75 [15] using 32 traffic sources. The burst size (number of data packets) and time between bursts were independently randomly drawn from Pareto distributions. Following common packet size models, 60% of the packets have 64 Byte, 4% have 300 Byte, 11% have 580 Byte, and 25% have 1518 Byte. Each of the 32 sources of a given ONU has initially a maximum burst size of $B = 10$ MByte, which is achieved by truncating the Pareto distribution to produce a maximum burst size no greater than $B/1518$ Bytes $= 6907$ packets. Each ONU contributed equally to the overall traffic load.

For upstream transmission, each data packet is sent with a Preamble of 8 Bytes and an Inter-packet Gap of 12 Bytes (which count toward the upstream transmission grant). Gate and Report messages each have 64 Bytes and there is a $t_{\text{guard}} = 1\ \mu$s guard time between upstream transmissions. For the IPACT-Limited and Hybrid-Iterative bandwidth allocation schemes, we initially set the maximum grant size to $G_{\max} = G_i^{\max} = 15,500$ Bytes for each ONU; the corresponding cycle time is $MG_{\max}/C + Mt_{\text{guard}} = 2$ ms.

As primary performance metric we consider in this paper the packet queuing delay, defined as the time interval from the generation of a packet at an ONU to the instant the upstream transmission of the packet commences. We note that the total packet delay in the network would be obtained by adding the packet transmission delay and the one-way propagation delay to the packet queuing delay.

Table 1. Packet delay in ms as function of load in Mbps for different scheduling frameworks. Fixed Parameters: mid-range RTT, $M = 16$ ONUs, $B = 10$ MByte max. burst size, $G_{\max} = 15,500$ Byte.

Load	200	400	600	800
Offline-Limited	0.30	0.44	0.78	2.34
Offline-Iterative	0.21	0.31	0.55	1.47
Online-Limited	0.25	0.33	0.54	1.39
Hybrid-Iterative	0.20	0.28	0.45	1.10

3.2 Impact of Offline, Hybrid, and Online Scheduling

As expected, we observe from Table 1 that Online-Limited substantially reduces the delay compared to Offline-Limited since the extra round trip time (between the last ONU completing the upstream transmission of a cycle and the first ONU commencing the upstream transmission of the next cycle) is eliminated for *all* grants. (Hybrid-Limited, where only overloaded ONUs are scheduled in offline fashion, performed very similarly to Online-Limited.) With Hybrid-Iterative the extra round trip time is avoided only for the underloaded ONUs, resulting in a relatively smaller delay reduction compared to Offline-Iterative.

We further observe from Table 1 that for online/hybrid scheduling the difference between Limited and Iterative is relatively smaller than for offline scheduling. This is mainly because the cycles in Online-Limited are much shorter than in Offline-Limited reducing the impact of the larger number of cycles needed to work off large traffic bursts. At the same time, it is more likely that upstream transmissions from ONUs requesting less than $G_{\max}$ mask the shorter delay between the upstream transmissions working off a large burst from a given ONU.

To further examine the impact of the larger number of cycles, we simulated a hypothetical EPON with all transmission overhead directly associated with an upstream transmission (guard time as well as Report message transmission time) set to zero. For this hypothetical EPON with a load of 800 Mbps, Online-Limited achieves a delay of 1.01 ms compared to Hybrid-Iterative giving 0.94 ms, i.e., the gap has significantly narrowed compared to the 1.39 ms vs. 1.10 ms with all the overheads. This significant narrowing of the gap indicates that the delay difference between Online-Limited and Hybrid-Iterative is to a large degree due to the upstream transmission overheads (guard time, Report message transmission time), which are experienced more often when transmitting large bursts in more, but shorter cycles with Online-Iterative. Note in particular, that each cycle in a real EPON contains a guard time and a Report message transmission for each ONU, even if only one or a few ONUs have data to send. These delays can not be masked by the interleaved transmissions of several ONUs.

We proceed to examine Online-Limited and Hybrid-Iterative, the best performing approaches from this section, in more detail in the subsequent section.

Table 2. Packet delay in ms as function of load in Mbps for different maximum burst sizes B. Fixed Parameters: $M = 16$ ONUs, mid-range RTT.

Load	200	400	600	800
$B = 65$k, $G_{\max} = 15,500$ B, On.-Lim.	0.135	0.147	0.179	0.313
$B = 65$k, $G_{\max} = 15,500$ B, Hyb.-It.	0.135	0.147	0.179	0.309
$B = 4$M, $G_{\max} = 15,500$ B, On.-Lim.	0.206	0.271	0.421	0.974
$B = 4$M, $G_{\max} = 15,500$ B, Hyb.-It.	0.180	0.237	0.363	0.790
$B = 10$M, $G_{\max} = 31,125$ B, $M = 16$, On.-Lim.	0.213	0.289	0.473	1.16
$B = 10$M, $G_{\max} = 31,125$ B, $M = 16$, Hyb.-It.	0.199	0.271	0.440	1.06
$B = 10$M, $G_{\max} = 15,500$ B, $M = 32$, On.-Lim.	0.281	0.410	0.689	1.80
$B = 10$M, $G_{\max} = 15,500$ B, $M = 32$, Hyb.-It.	0.213	0.312	0.526	1.31

3.3 Impact of Burst Size B and Maximum Grant Size $G_{\max}$

We examine in Table 2 the impact of smaller burst sizes as well as larger maximum transmission grants. Recall that the results in Table 1 were obtained with a maximum burst size of 10 MBytes for each of the 32 traffic streams producing the load at a given ONU. We observe from Table 2 that reducing the maximum burst size to 4 MBytes and further to 65 kBytes reduces the delay difference between Online-Limited and Hybrid-Iterative, with both giving essentially the same delays for the 65 kByte maximum burst size. This is because smaller bursts require fewer cycles for transmission, both with Online-Limited and Hybrid-Iterative.

Further, we observe from Table 2 that a larger maximum grant size of $G_{\max} = 31,125$ Byte compared to the $G_{\max} = 15500$ Byte considered in Table 1 narrows the gap between Online-Limited and Hybrid-Iterative for the large $B = 10$ MByte maximum burst size. This is again mainly because of the fewer cycles required to work off bursts, which are this time due to the larger maximum grant size, and correspondingly longer cycle.

Finally, we observe from Table 2 that a larger number of ONUs makes the delay differences between Online-Limited and Hybrid-Iterative more pronounced. This is primarily due to the increased upstream transmission overheads (guard time and Report transmission time) which are incurred for each ONU once in each cycle.

3.4 Impact of Round Trip Time RTT and Maximum Grant Size $G_{\max}$

In this section we focus on the impact of the round trip time, in conjunction with the maximum grant size, on the relative delay performance of Online-Limited and Hybrid-Iterative. (Ignore for now the OEBD results in Table 3; these are discussed in the next section.) We first observe that for the short round trip time up to 10 μs, the delays for high loads are very similar to the delays for high loads for round trip times up to 100 μs in Table 2.

Importantly, we observe from Table 3 that Hybrid-Iterative exhibits a pronounced threshold behavior. For loads below a critical threshold, Hybrid-Iterative gives substantially smaller delays than Online-Limited. In fact, the

Table 3. Packet delay in ms as function of load in Mbps for different round trip times. Fixed Parameters: $M = 16$ ONUs, $B = 10$ MByte maximum burst size.

Load	200	400	600	800
$G_{\max} = 15,500$ Bytes, 2 ms cycle				
short RTT, Online-Limited	0.158	0.259	0.486	1.36
short RTT, Hybrid-Iterative	0.123	0.209	0.398	1.08
short RTT, OEBD	0.131	0.218	0.412	1.11
long RTT, Online-Limited	2.43	2.60	2.93	3.85
long RTT, Hybrid-Iterative	1.31	1.44	1.76	> 2 s
long RTT, OEBD	1.82	1.88	2.03	2.61
X-long RTT, Online-Limited	5.37	6.64	10.13	34.23
X-long RTT, Hybrid-Iterative	2.57	3.01	> 2 s	> 2 s
X-long RTT, OEBD	3.65	3.91	4.62	8.91
$G_{\max} = 31,125$ Bytes, 4 ms cycle				
long RTT, Online-Limited	1.66	1.70	1.81	2.30
long RTT, Hybrid-Iterative	1.25	1.33	1.51	2.11
long RTT, OEBD	1.68	1.73	1.87	2.43

delay differences become more pronounced with increased round trip time, with Hybrid-Iterative achieving delays less than half as large as Online-Limited for low loads and the extra long round trip time up to 2 ms. However, for loads above a critical load threshold, which decreases for increasing round trip time, Hybrid-Iterative becomes unstable and gives excessively large delays. On the other hand, Online-Limited robustly continues to provide low delays even at very high loads.

The explanation for this behavior is as follows. Consider an extreme scenario in Hybrid-Iterative where only one ONU has upstream traffic, namely a very large burst. Then, this overloaded ONU receives all the upstream transmission bandwidth in the cycles, namely $MG_{\max}$ per cycle (neglecting the grants for Report messages to the other ONUs). A given cycle consists of an upstream transmission of $MG_{\max}$ [Byte], lasting $MG_{\max}/C$ [s], plus one round trip time RTT for reporting the remaining size of the backlog and receiving the next grant. In addition, the cycle contains M guard times and the Report transmission times of the other $M-1$ ONU's Report messages (which we neglect in this approximate analysis). Thus, the maximum sustainable upstream transmission rate is approximately

$$\frac{MG_{\max}}{RTT + \frac{MG_{\max}}{C} + Mt_{\text{guard}}} = \frac{G_{\max}}{\frac{RTT}{M} + \frac{G_{\max}}{C} + t_{\text{guard}}}. \tag{1}$$

We note that this threshold is approximate in that upstream transmissions from underloaded ONUs may mask some of the round trip time incurred due to offline excess bandwidth distribution, leading to a higher threshold in an actual EPON. On the other hand, the neglected overheads may slightly reduce the threshold for a actual EPON. For the specific realizations of the randomly drawn RTT which gave an average RTT of 0.871 ms for the long range EPON simulation and an average RTT of 1.74 ms for the extra long range EPON simulation, the approximate theoretical thresholds are 691.3 Mbps for the long range EPON and 530.5 Mbps for the extra long range EPON. Our simulations indicate that these theoretical approximation are very close to the actual thresholds found in simulations, which are around 690 Mbps for the long range and 513 Mbps for the extra long range scenario. For loads well below the derived threshold, Hybrid-Iterative is able to provide small delays and to fairly allocate excess bandwidth to overloaded ONUs in offline fashion. When the load grows well above the threshold, then waiting for the excess bandwidth distribution until all Report messages are received for a cycle, reduces the capacity so much to render the network effectively unstable.

In order to overcome the stability problems due to the offline excess bandwidth distribution in Hybrid-Iterative, we propose and examine a novel Online Excess Bandwidth Distribution (OEBD) approach in the next section.

4 Online Excess Bandwidth Distribution (OEBD)

In this section we introduce and evaluate online excess bandwidth distribution (OEBD) for an *online* scheduling framework that makes grant decisions based on a single report; extensions to online Just-in-Time (JIT) scheduling [16] are left for future work. Recall that we let R_i denote the bandwidth requested by the considered report from a given ONU $i,\ i = 1, \ldots, M$, whereby bandwidth is measured in units of Bytes of transmitted data (i.e., corresponds to an upstream transmission window in seconds times the upstream bandwidth in Byte/sec), and that we let $G_i^{\max}$ [Bytes] be a constant denoting the maximum bandwidth that can be allocated to ONU i in a grant. We let $w_i,\ 0 \le w_i \le 1,\ \sum_{i=1}^{M} w_i = 1$ denote the weight of ONU i in a weighted fair excess division [8]. We define an excess bandwidth credit pool and let E_t [Bytes] denote the current total amount of bandwidth credits in the excess pool. In addition, we let $\delta,\ 0 \le \delta \le 1$, be a constant aging factor.

The OEBD bandwidth allocation proceeds as follows. If the considered ONU i is underloaded, i.e., requests less than the prescribed maximum allocation ($R_i \le G_i^{\max}$), then the bandwidth R_i is granted and the excess $G_i^{\max} - R_i$ is added to the excess bandwidth pool E_t. If the considered ONU is overloaded, i.e., requests more than its prescribed maximum allocation ($R_i > G_i^{\max}$), then the ONU is allocated its prescribed maximum $G_i^{\max}$ plus up to $w_i E_t$ excess bandwidth from the pool. With a controlled excess allocation technique, the allocation is capped at R_i, i.e., the ONU is allocated $\min\{G_i^{\max} + w_i E_t,\ R_i\}$. Accordingly, the excess pool is reduced by $\min\{G_i^{\max} + w_i E_t,\ R_i\}$. In addition, after every N grants, we "age" the pool, E_t, using the multiplicative constant δ.

4.1 Simulation Results

We conducted initial simulations to identify good settings for the parameters N and δ. We found that generally larger δ reduces the delays and set $\delta = 0.75$

for the results presented here. We have set $N = M$ to "age" the pool after a full grant cycle. A $\delta = 1$ may cause OEBD to degenerate in the long run to Gated bandwidth allocation. We observe from the OEBD results for $G_{\max}$ in Table 3 that OEBD gives delays that are generally between Online-Limited and Hybrid-Iterative, typically closer to the Hybrid-Iterative delays. Importantly, for the long-range and extra-long range scenarios with moderate to high load, for which Hybrid-Iterative becomes unstable, OEBD remains stable and consistently provides significantly lower delays than Online-Limited.

We also observe from Table 3 that for $G_{\max} = 31,125$ Bytes, OEBD gives delays slightly larger than Online-Limited.

5 Conclusion

We have examined the delay and fairness performance of conventional IPACT with Limited allocation and existing excess bandwidth allocation strategies, which allocate excess in an offline fashion. We discovered that offline excess bandwidth allocation significantly reduces the delay compared to IPACT-Limited for traffic with large bursts and EPONs with mid-range round-trip times. For traffic with small bursts or EPONs with short round-trip times, IPACT-Limited achieves delays almost as low as with offline excess bandwidth distribution.

Importantly, we found that for long-range EPONs with large round-trip times, offline excess bandwidth distribution exhibits a pronounced threshold behavior: For loads below a critical threshold, offline excess bandwidth distribution provides lower delays than IPACT-Limited. For loads above the threshold, offline excess bandwidth distribution becomes unstable, resulting in excessively large delays, whereas IPACT-Limited continues to achieve small delays.

We introduced Online Excess Bandwidth Distribution (OEBD) to overcome the stability problems of the existing offline excess bandwidth distribution mechanisms. We found that OEBD generally achieves delays between offline excess bandwidth distribution and IPACT-Limited below the stability limit of offline excess bandwidth distribution, and below IPACT-Limited for load levels above the stability limit.

There are numerous important avenues for future research on OEBD. One important direction is to further comprehensively study the parameter setting for OEBD to ensure robust, good performance across a wide range of scenarios. Another avenue is to examine the compatibility of OEBD with emerging dynamic bandwidth allocation strategies for long-range EPONs, such as multi-thread polling [6]. Furthermore, not only the delay performance, but also the fairness performance of OEBD requires careful evaluation.

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