Dynamic Bandwidth Allocation with Multi-ONU Customer Support for Ethernet Passive Optical Networks

Oscar J. Ciceri, Carlos A. Astudillo, and Nelson L.S. da Fonseca
Institute of Computing - University of Campinas
Campinas 13089-971, SP, Brazil
Email: oscar@lrc.ic.unicamp.br, castudillo@lrc.ic.unicamp.br, nfonseca@ic.unicamp.br

***Abstract*—This paper introduces a mechanism for the support of multi-ONU service level agreements (SLAs) in dynamic bandwidth allocation (DBA) algorithms for Ethernet passive optical networks (EPON). The employment of SLAs for multiple optical network units (ONUs) instead of individual ONUs allows better utilization of the bandwidth reserved for these ONUs. The proposed DBA mechanism allows customers owning multiple ONUs to redistribute the aggregated bandwidth of the group of ONUs to better balance the bandwidth utilization. The proposed DBA can be employed in different use cases such as mobile backhauling/fronthauling, PON virtualization, and multi-site enterprise networking. Simulation results show that the proposed DBA improves the network performance.**

Keywords*—*Dynamic Bandwidth Allocation, Passive Optical Networks, Mobile Backhauling/Fronthauling, Network Virtualization, Quality of Service.

I. INTRODUCTION

Passive optical networks (PONs) have been deployed in broadband access networks for the past two decades. Two different technologies share the optical access networks market; Ethernet PON (EPON) and gigabit-capable PON (GPON), being EPON the less expensive solution. Moreover, in order to further reduce costs and maximize revenues, service providers employing PONs can offer new services such as mobile backhauling/fronthauling and PON virtualization.

New scenarios are thus envisioned in which customers owning multiple optical network units (ONUs) are connected to a single PON (multi-ONU customers). These customers can be mobile network operators (MNOs), multi-site enterprises, or virtual service providers renting multiple ONUs from the infrastructure provider. An MNO using PON for backhauling/fronthauling macrocells and smallcells is a typically use case of multi-ONU customers [1]. Another example is PON virtualization [2] [3], which allows to share the network with various virtual service providers, each one owning a subset of ONU in the PON. Moreover, long-reach PONs [4] increases the geographical coverage of a PON, increasing the chance of a business customer to have more than one ONU within the footprint of a single PON.

However, service providers are currently able to support only guaranteed bandwidth to individual ONUs with the existing dynamic bandwidth allocation (DBA) algorithms. Consequently, peaks of bandwidth demand may surpass the guaranteed bandwidth for some ONUs and, at the same time, underutilize guaranteed bandwidth to other ONUs. Such multi-ONU customer scenario creates opportunities for infrastructure providers to employ new business models such as *multi-ONU service level agreements (SLAs)*. In this paper, we call *multi-ONU SLA* a scheme which considers the aggregate SLAs of a group of ONUs as a single SLA. In such approach, the optical line terminator (OLT) is able to share the unused guaranteed bandwidth of an ONU with the other ONUs belonging to the same customer by taking advantage of statistical multiplexing while maintaining isolation from the other customers.

This paper introduces *MOS-IPACT*, a novel EPON DBA scheme that supports *multi-ONU SLAs* for customers such as MNOs, virtual service providers and multi-site enterprises, as well as *individual SLAs* for traditional customers. The offering of a single SLA to multiple ONUs belonging to the same customer increases overall network utilization and improves quality of service (QoS) provisioning. *MOS-IPACT* allows network providers to distribute the non-utilized reserved bandwidth of an ONU to the others ONUs of the group it belongs to.

The rest of the paper is organized as follows. Section II discusses the related work. Section III describes the proposed DBA mechanism. Section IV details the simulation model, the scenarios used and analyze the results derived via simulations. Finally, Section V concludes the paper.

II. EPON DYNAMIC BANDWIDTH ALLOCATION

In PONs, resource allocation in the upstream depends on the multiple access technique used for sharing the optical infrastructure. There are two main multiple access techniques; time division multiple access (TDMA) and time and wavelength division multiple access (TWDMA). The first generation of EPONs, which comprises 1G-EPON (IEEE 802.3ah) and 10G-EPON (IEEE 802.3av), uses TDMA whereas Next-Generation EPONs (IEEE 802.3ca) employ TWDMA to achieve higher capacity (25 Gb/s, 50 Gb/s, and 100 Gb/s), reusing the already deployed fibres [5]. TDMA-PON customers share a single wavelength dividing the channel into periods of time (time slots), however it does not exploit interchannel statistical multiplexing. Unlike the previous access approach, the TWDMA-PON customers share multiple wavelength in both frequency and time domains by dynamic allocation of wavelength (DWBA).

The DWBA problem of TWDMA-PONs can be divided into two sub-problems; bandwidth allocation and wavelength allocation. Thus, the conventional DBA algorithms of the single-channel TDMA-PONs can be expanded to the transmissions on multiple channels. We focus on DBA algorithms for EPONs.

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In EPONs, a DBA algorithm at the OLT allocates bandwidth for upstream transmissions of each ONU by using the multipoint control protocol (MPCP) for signaling. This protocol employs two messages for scheduling; the Gate and Report messages, which are used, respectively, to request upstream resources and to inform the ONUs about the amount of bandwidth granted and the time transmission should start. Dynamic bandwidth allocation protocols have received considerable attention since QoS provisioning and the efficient resource utilization depend on the DBA algorithm employed.

Several DBA algorithms for PONs have been proposed in the literature and they comprise three design dimensions: grant scheduling framework, grant sizing policy and grant scheduling policy [6]. The grant scheduling framework defines the event triggering a scheduling decision. It can be triggered by the arrival of a Report message (online), or upon the arrival of Report messages from all ONUs (offline). The grant sizing policy defines the transmission window allocated to each ONU whereas the grant scheduling policy determines the scheduling order when the distribution of excess bandwidth is done.

The most popular DBA algorithm for EPONs is the interleaved polling with adaptive cycle time (IPACT) algorithm [7], which defines an online grant scheduling framework. The majority of existing algorithms proposed so far are variation of IPACT. To achieve multiplexing gain, IPACT gives transmission opportunities to each ONU using a round robin mechanism. IPACT defines four grant sizing policies called fixed, limited, closed, and excess, being limited the most widely used. With the limited policy, each ONU i has a maximum window size W_i^{max}, which is determined by the guaranteed bandwidth specified in the *individual SLA*.

When the OLT receives a Report message R_i, a Gate message G_i is sent to the ONU containing the granted transmission window $W_{limited}$, which is calculated as the minimum between the requested window (R_i) and the maximum allowed window size (W_i^{max}). Upon the arrival of a Gate message, the ONU starts an inter-ONU scheduler to distribute the received grant among the packets enqueued. When QoS differentiation is required, strict priority scheduling is typically used by the ONU.

Statistical multiplexing gain of the limited policy can be further improved by using excess bandwidth distribution. Based on the Report messages and the guaranteed bandwidth for each ONU. These algorithms divide the ONUs into *underloaded ONUs* and *overloaded ONUs* at every polling cycle. The former are those requesting at most the maximum transmission window (*i.e.*, $R_i \leq W_i^{max}$), whereas the latter are those with $R_i > W_i^{max}$. The excess bandwidth distribution algorithms distribute the unused resources of *underloaded ONUs* among *overloaded ONUs*, improving the network throughput.

The DBA1 policy [8] was the first proposed grant sizing policy with excess bandwidth distribution. This policy allocates the excess bandwidth according to the total demand of the *overloaded ONUs*. However, this policy does not give equal portions of the excess bandwidth to the *overloaded ONUs* because the bandwidth allocated depends on the individual requested bandwidth, and not on the guaranteed bandwidth. To overcome this problem, the Fair Excess DBA (FE-DBA) policy aims at distributing fairly the excess bandwidth [9]. It uses the guaranteed bandwidth value to calculate the requested bandwidth $(B_i^{req} = R_i - W_i^{max})$ instead of just using the Report value R_i.

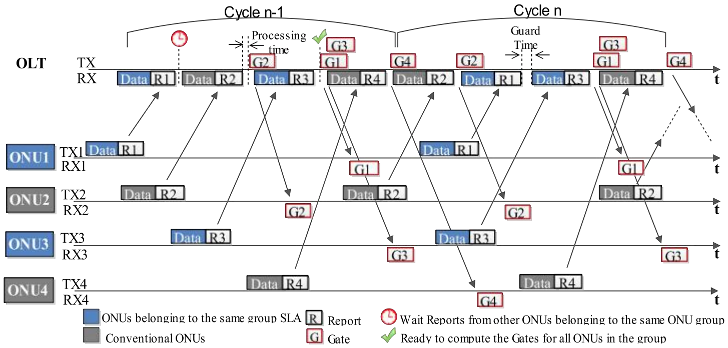

Figure 1. *MOS-IPACT* DBA scheme

Other DBA algorithms based on interleaved polling (IP) with fixed scheduling frame size were also proposed in the EPON literature (*e.g.*, [10] and [11]). They facilitate the implementation of differentiated services supporting SLA for individual ONUs. For instance, [11] proposes a DBA algorithms based on hierarchical two-layer allocation for differentiated services that meets the individual SLA requirements. The top layer dynamically allocates the bandwidth according to the SLA parameters, whereas the bottom layer allocates bandwidth for the instantaneous demand of each ONU. This proposal divides the ONUs in groups based on the SLA parameters such as delay, packet loss ratio (PLR), or traffic type. Thus, the group of ONUs are composed by ONU belonging to different customers. Therefore, it does not support multi-ONU customers.

A well known DBA algorithm for GPON called GigaPON Access Network (GIANT) defines four type of bandwidth guarantees: fixed, assured, non-assured and best-effort [12]. Alvarez *et. al* [13] [2] extended this algorithm to XGPON-based backhauling scenarios by proposing the group-GIANT (gGIANT) algorithm, which adds a fifth type of bandwidth called group assured. This algorithm shares the group assured bandwidth among multiple ONUs which host base stations of a mobile network operator. The authors showed the benefits of sharing the assured bandwidth of a group of ONUs.

Indeed, no EPON DBA scheme supports multi-ONU SLAs. Even though an XGPON DBA algorithm supports a similar concept (group assured bandwidth), the algorithm cannot be employed by EPONs due to fundamental differences between these two technologies. First, GPON has a maximum cycle length of 125 μs, whereas EPON has a typical maximum cycle length between 1 ms and 10 ms. Second, the gGIANT algorithm is based on centralized QoS intelligence [14], being the OLT responsible for the QoS provisioning of individual queues at the ONU. This scheme is attractive for small business or residential customers but not for multi-ONU customers with multiple connections at each ONU. Finally, GPON establishes logical connections called GPON encapsulation mode (XGEM) ports between the OLT and the ONUs, and generates groups of XGEMs called transmission containers (T-CONTs) for each type of service offered whereas EPON uses a native media access control layer to support any type of IP-based services (i.e. voice, video and data) over Ethernet without using logical connections for different type of services.

III. DBA SCHEME FOR SUPPORTING MULTI-ONU SLAS

This section introduces the proposed DBA scheme for supporting *multi-ONU SLAs* in EPON, called IPACT with multi-ONU SLAs support (*MOS-IPACT*). *MOS-IPACT* allows service providers to offer not only bandwidth guarantees for individual ONUs but also for groups of ONUs.

Currently, EPON DBA algorithms do not allow customers with more than one ONU in a PON to take advantage of the statistical multiplexing among their own ONUs. Traditionally, each ONU has an *individual SLA* specifying its guaranteed bandwidth. Conversely, in *MOS-IPACT* DBA scheme, a single SLA, called *multi-ONU SLA*, can be defined for a whole group of ONUs that belong to the same customer. This *multi-ONU SLA* defines a guaranteed bandwidth per ONU, which can be aggregated with the guaranteed bandwidth of the other ONUs in the group, composing the bandwidth of the group of ONUs. This aggregated bandwidth is shared among all ONUs in the same group in a granting cycle basis. In this way, the unused bandwidth from underloaded ONUs can be redistributed among overloaded ONUs belonging to the same group by using an excess bandwidth distribution algorithm, leading to increase network utilization.

MOS-IPACT combines the online and offline grant scheduling frameworks. The former is used for scheduling *conventional ONUs*[1] whereas the latter is used for ONUs belonging to a *multi-ONU SLAs*. We called this framework Hybrid Polling (HP). *MOS-IPACT* also defines the grant sizing policy depending on the ONU type. The limited and limited with excess bandwidth distribution grant sizing policies are used, respectively, for conventional ONUs and ONUs belonging to *multi-ONU SLAs*. Finally, the shortest propagation delay first (SPD) grant scheduling policy is used by the ONUs belonging to *multi-ONU SLAs*.

The interleaved polling proposed in the IPACT scheme is modified to wait for Report messages from all active ONUs belonging to the same *multi-ONU SLA* before sending the Gate messages to those ONUs, as illustrated in Fig. 1. This modifies the sequence of control messages, which traditionally were organized by the Round Trip Time (RTT), in such a way that Report messages from ONUs belonging to the same customer, arrive one after the other.

Algorithm 1 summarizes the *MOS-IPACT* scheme residing at the OLT. Let $\mathcal{G}$ be the set of *multi-ONU SLAs* specified for a given EPON; $\mathcal{O}$ the set of ONUs in the EPON; $\mathcal{O}_C$ the set of ONUs that do not belong to any *multi-ONU SLA*; and $\mathcal{O}_k$ the sorted list of active ONUs belonging to the k-th *multi-ONU SLA* in increasing order of RTT value (which define the order of the Report message arrivals). $\mathcal{T}_k$ the ordered list of expected arrival times of Report messages from active ONUs in $\mathcal{O}_k$ in increasing order of RTT values.

For each Report message R received by the OLT, it is verified whether this message comes from an ONU in $\mathcal{O}_C$ (Lines 2 and 3). If it comes from a conventional ONU, the start time $txStart$ and the transmission window $W_{limited}$ are calculated by using the legacy IPACT limited policy (Lines 4 and 5). After that, the Gate message is issued and sent to the ONU (Line 6 and 7).

Algorithm 1 GS-IPACT DBA Algorithm

```
    $\mathbf{R}_k :\leftarrow \emptyset, \forall k \in \mathcal{G}$
1   for each received report R from ONU i in cycle j do
2       Let $\tau$ be the arrival time of report $R$ at OLT
3       if ONU $i \in \mathcal{O}_C$ then
4           Calculate $t_{txStart}$
5           Calculate $W_i^{limited}$ according to the limited policy
6           Gate$_i^j \leftarrow \left(W_i^{limited}, t_{txStart}\right)$
7           Send $Gate_i^j$
8       else
9           $\mathcal{R}_k = \mathcal{R}_k \cup \{R\}$
10          T$_i \leftarrow (\tau + \text{maximumCycleLength})$
11          if $|\mathcal{R}_k| = |\mathcal{O}_k|$ then
12              BulkGrantGenerator()
13          end
14      end
15      if ONU $i-1 \notin \mathcal{O}_c$ and $\tau > T_{i-1}$ then
16          $\mathcal{O}_k = \mathcal{O}_k - \{ONU_{i-1}\}$
17          $\mathcal{T}_k = \mathcal{T}_k - \{T_{i-1}\}$
18          if (ONU $i \in \mathcal{O}_c$) then
19              BulkGrantGenerator()
20          end
21      end
22  end
    function BULKGRANTGENERATOR
23  for each report $R \in \mathcal{R}_k$ do
24      Calculate $t_{txStart}$
25      Calculate $W_i^{granted}$ according to grant sizing policy
26      Gate$_i^j \leftarrow \left(W_i^{granted}, t_{txStart}\right)$
27      Send $Gate_i^j$
28      T$_i \leftarrow \left(t_{txStart} + W_i^{granted} + RTT_i/2\right)$
    end
30  R$_k \leftarrow \emptyset$
    end function
```

However, if the Report message comes from an ONU belonging to a *multi-ONU SLA*, the Report message is added to the set of Report messages of its group k (Line 10). To cope with ONU failures, the OLT stores the expected arrival time (T) of the upcoming Report message for every active ONU in a multi-ONU SLA. The corresponding T_i value is initially updated with a value larger than the next Report message arrival time (Line 11). The maximum cycle length is used to ensure $T_i > T_{i+1}$ in any traffic condition and configuration scenario.

If the OLT has already received all the Report messages from the ONUs in that group, a grant for each ONU in $\mathcal{O}_k$ is issued (Lines 12, 14 and 24 to 27). Based on the Report messages, each ONU is classified either as *underloaded*, if the requested value (R) is less than or equal to its maximum window size ($R \leq W_{max}$), or as *overloaded* in the opposite case ($R > W_{max}$). The granted window size ($W_{granted}$) is calculated by executing a limited policy with excess bandwidth distribution (*e.g.*, DBA1 and FE-DBA). For an *overloaded ONU*, it is first calculated the portion of the total excess bandwidth that will be allocated to the ONU, called excess bandwidth (W_{excess}). Then, the final granted window size to be attached to the Gate message of an *overloaded ONU* is calculated as $W_{granted} = W_{max} + W_{excess}$. In this way, the total excess bandwidth from *underloaded ONUs* belonging to a given *multi-ONU SLA* is distributed among the *overloaded*

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[1] These are ONUs that do not belong to any *multi-ONU SLA*

ONUs belonging to the same customer in a per granting cycle basis. In the case of an *underloaded* ONU, W_{excess} is zero and the granted window size is equal to the requested value R ($W_{granted} = R$). Finally, the OLT sends the Gate messages to the ONU (Line 28). In this fashion, all Gate messages intended to the ONUs in the same group are sent in sequence. After sending the Gate message, the corresponding T_i value for the ONU is updated with the actual Report arrival time (Line 29).

On every Report message arrival, if the previous expected Report message belongs to an ONU in a multi-ONU SLA and this message did not arrive (Line 16), the ONU is considered to be out of reach. This ONU is excluded from the active ONUs of the multi-ONU SLA (Line 17) and its corresponding expected Report arrival time is also removed from $\mathcal{T}_k$ (Line 18). Furthermore, if the received Report message comes from a conventional ONU and the expected Report has not arrived, the OLT inferred that the last ONUs belonging to the group are down. Then, the OLT proceeds to send the Gate messages to the remaining active ONUs in the group (Lines 19 and 20).

The complexity of the proposed algorithm is analyzed as follows. With the IPACT scheme, each Report is considered once per cycle, thus the allocation is performed with a time complexity of $O(n)$, where n is the number of ONUs in the PON. On the other hand, *MOS-IPACT* scheme applies the normal procedure of IPACT to receive the Reports and the excess bandwidth allocation is calculated once for every active ONUs in the groups. Thus, time complexity in the worst case is $O(n+l)$, where l is the total number of ONUs in the groups ($l = \sum_{i=1}^{k} l_i$).

IV. PERFORMANCE EVALUATION

In this section, we assess the performance of the proposed *MOS-IPACT* DBA scheme by using an EPON simulator (EPON-Sim), developed in Java and previously validated in [1], [15] and [16]. EPON-Sim implements the IPACT DBA algorithm together with the limited discipline introduced by Kramer *et. al* in [7]. The *MOS-IPACT* scheme with the FE-DBA policy was introduced in the EPON-Sim simulator and the new version of the simulator was validated extensively.

A. Simulation Model and Setup

The simulation scenarios include a 10G-EPON network with 1 OLT serving a set of ONUs $\mathcal{O}$ on an optical distribution network in a tree topology, with $|\mathcal{O}| = 32$. Each ONU in $\mathcal{O}$ has three different traffic classes: expedited forwarding (EF), assured forwarding (AF), and best effort (BE). The EF traffic represents voice and other delay-sensitive applications that require low end-to-end delay, and it was modelled by using a constant bit rate encoding with a fixed-size packet of 70 bytes. The packet inter-arrival time (τ) depends on the ONU offered load (λ). If λ is less than 45 Mbps, τ is 125 μs, which gives 4.48 Mbps. Otherwise, τ is 12.5 μs, giving 44.8 Mbps [17]. The rest of the offered load is evenly distributed among AF and BE traffic, which typically host applications that require not only bounded delay but also bandwidth guarantees, and applications which do not have these requirements, respectively. Both AF and BE are self similar traffic simulated by using aggregation of ON-OFF sources. The ON period time and packet-burst size follow a Pareto and Bounded Pareto distributions with Hurst parameter equals 0.8, respectively [7]. The packet length follows a uniform distribution between 64 and 1518 bytes. Every ONU is assumed to receive, at least, the grant required to send a Report message (the minimum Ethernet frame size is 64 bytes) at every polling cycle [7]. The guard time period is 1 μs and the maximum cycle length is 1 ms. Each simulation scenario lasted 50 s and was replicated 10 times.

Table I. SIMULATION PARAMETERS

Parameter	Value
Optical speed	10 Gbps
Maximum cycle time	1 ms
Guard band	1 μs
Distance between OLT and ONUs	[10,20] km
Propagation delay in fiber	5 μs/km
OLT-ONU RTT	[100,200] μs
ONU buffer size	10 MB
Number of ONUs	32
Number of ONUs in the group	2,3,8
Aggregated guaranteed bandwidth	$N_{group} \times 300$ Mbps
Guaranteed BW of target ONU	300 Mbps
Offered load of target ONU	[0,600] Mbps
Guaranteed BW for ONUs in the group (excluding the target ONU)	[150,450] Mbps
Offered load for group of ONUs (excluding the target ONU)	[0, $(N_{group} - 1) \times 300$] Mbps
Offered load for ONUs in the group (excluding the target ONU)	[0,600] Mbps
Guaranteed BW for conventional ONUs	300 Mbps
Offered load for conventional ONUs	300 Mbps
Inter-ONU scheduler	IPACT (limited policy) GS-IPACT (limited with FE-DBA excess distribution policy)
Intra-ONU scheduler	strict priority

We assume that there is one costumer with multi-ONU SLA S assigned to the group of customer's ONUs $\mathcal{O}_S \subset \mathcal{O}$; $|\mathcal{O}_S| = N_{group}$ varies in the set {2,3,8}. Among the ONUs in $\mathcal{O}_S$, there is a target ONU (ONU_{target}) with guaranteed bandwidth $B_{ONU_{target}}$ of 300 Mbps. The other $N_{group} - 1$ ONUs belonging to S have guaranteed bandwidth B_i, $i \in \mathcal{O}_S \backslash \{ONU_{target}\}$, between 150 Mbps and 450 Mbps, provided that $\sum_{i \in \mathcal{O}_S \backslash \{ONU_{target}\}} B_i = (N_{group}-1) \times 300$ Mbps. which is the effective aggregated guaranteed bandwidth of the ONU group excluding the target ONU ($A_{\mathcal{O}_S \backslash \{ONU_{target}\}}$). On the other hand, there is a set of conventional ONUs $\mathcal{O}_C \subset \mathcal{O}$, with $\mathcal{O}_C \cup \mathcal{O}_S = \mathcal{O}$ and $\mathcal{O}_C \cap \mathcal{O}_S = \emptyset$. Each ONU belonging to $\mathcal{O}_C$ has a guaranteed bandwidth B_j, $j \in \mathcal{O}_C$, equals 300 Mbps. The offered load of the target ONU ($\lambda_{ONU_{target}}$) is varied from 0 to 200 % of the $B_{ONU_{target}}$ value, corresponding to up to 600 Mbps, whereas the aggregated offered load of the ONUs in S excluding the target ONU ($\lambda_{\mathcal{O}_S \backslash \{ONU_{target}\}}$) varies from 0 to 100 % of the $A_{\mathcal{O}_S \backslash \{ONU_{target}\}}$ value. In this latter case, the individual offered load (λ_i) varies randomly between 0 and 600 Mbps. To properly assess the proposed scheme, the offered load of conventional ONUs (λ_j) equals their guaranteed bandwidth ($\lambda_j = B_j$), which is an overloaded condition for ONUs in $\mathcal{O}_C$. Table I summarizes the main configuration parameters used in the simulation.

B. Simulation Results

The figures presented in this section show the mean values derived from 10 independent replications. For the sake of clearness, confidence intervals are omitted. However, the upper bounds of the confidence intervals for the delay and PLR are 4.8% and 8% of the mean values, respectively. We compare the performance of the *MOS-IPACT* scheme with the excess bandwidth distribution policy proposed in Section III to that of the traditional IPACT algorithm with the limited policy in term of the PLR and delay observed at the target ONU. To do a fair comparison, when the IPACT algorithm is employed the load and settings of N_{group} ONUs are the same as the ones in the multi-ONU SLA in *MOS-IPACT*, including the target ONU. The rest of ONUs have the same settings as the conventional ONUs in the *MOS-IPACT*.

Simulation results show that the EF traffic experiences delay values less than 1 ms and no packet loss (figures not show in this paper) because the guaranteed bandwidth is enough to serve the high priority traffic, which is prioritized by the intra-ONU scheduler. Similar as the EF traffic, the AF traffic do not present packets loss, giving its priority over the BE traffic. Thus, in this section, we focus on the analysis of the PLR of the BE traffic (vulnerable to bandwidth starvation) and the average packet delay of AF traffic (delay-sensitive) in the target ONU when $\lambda_{ONU_{target}}$, $\lambda_{\mathcal{O}_S\setminus\{ONU_{target}\}}$ and N_{group} varies as explained previously.

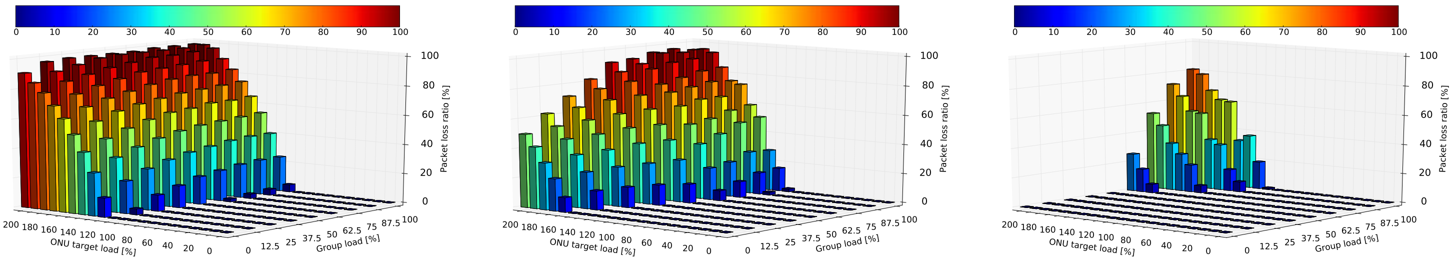
The PLR of the BE traffic in the target ONU for IPACT and *MOS-IPACT* schemes are shown in Fig. 2 and Fig. 3, respectively. When the IPACT scheme is employed and N_{group} equals two (Fig. 2(a)), the target ONU produces packet loss for loads greater than its guaranteed bandwidth ($\lambda_{ONU_{target}} \geq B_{ONU_{target}}$). As the N_{group} value increases (Fig. 2(b) and Fig. 2(c)), the number of ONUs with a load equal to the guaranteed bandwidth decreases. Thus, the cycle length is reduced, leaving more resources to be distributed in the system. This is the reason for the slightly decreasing in the PLR as the value of N_{group} increases, despite IPACT scheme provides only the individual guaranteed bandwidth. When an ONU does not use a portion of its guaranteed bandwidth, this excess bandwidth is distributed to the other 31 ONUs by the IPACT adaptive cycle technique.

Conversely, when the *MOS-IPACT* algorithm is employed, unused resources of an ONU in the group are first distributed to the other ONUs belonging to the same group. When the other ONUs in the group have no load, the target ONU can handle a load of up to 200 % of the $B_{ONU_{target}}$ value with very low packet loss. When the group is 100 % loaded, the target ONU presents the same packet loss previously observed in the IPACT scheme since there is no excess bandwidth to be distributed. Furthermore, the increase in the number of ONUs in a group has a positive effect on packet loss (Fig. 3(b) and Fig. 3(c)). As the N_{group} value increases, the excess bandwidth can be further shared among the ONUs in the group, even under high offered load. Thereby, the target ONU can have 100 % more bandwidth than its individual guaranteed bandwidth with no packet loss until 75 % of the $A_{\mathcal{O}_S\setminus\{ONU_{target}\}}$ value.

The average packet delay of the target ONU AF traffic for the IPACT and *MOS-IPACT* schemes are shown in Fig. 4 and Fig. 5, respectively. Once again, a positive impact on the network performance is observed when the number of ONUs in the group increases since the extra available bandwidth also increases, allowing the ONUs to transmit a higher number of packets in shorter periods. Moreover, when the *MOS-IPACT* scheme is employed with group loads under 87.5 % and eight ONU in the group, the average packet delay is negligible. In the worst case, when the target ONU is under loads of 200 % and the offered group load is 100 %, the average packet delay is 5 ms with the *MOS-IPACT* scheme, whereas this value reaches 200 ms if IPACT is employed.

V. CONCLUSION

This paper has introduced a novel DBA scheme that enables multi-ONU service level agreement support in EPON networks. We compared the performance of our proposed

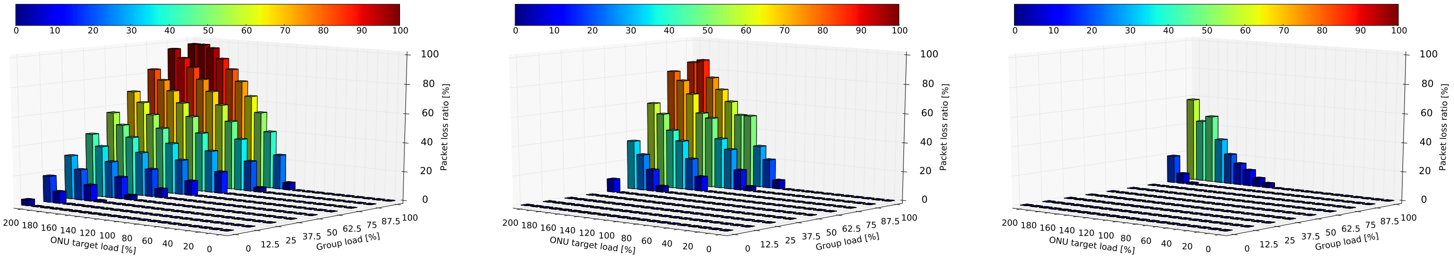


(a) $N_{group} = 2$

(b) $N_{group} = 3$

(c) $N_{group} = 8$

Figure 2. Impact of the number of ONUs in the group on the PLR of the BE traffic for the IPACT DBA algorithm

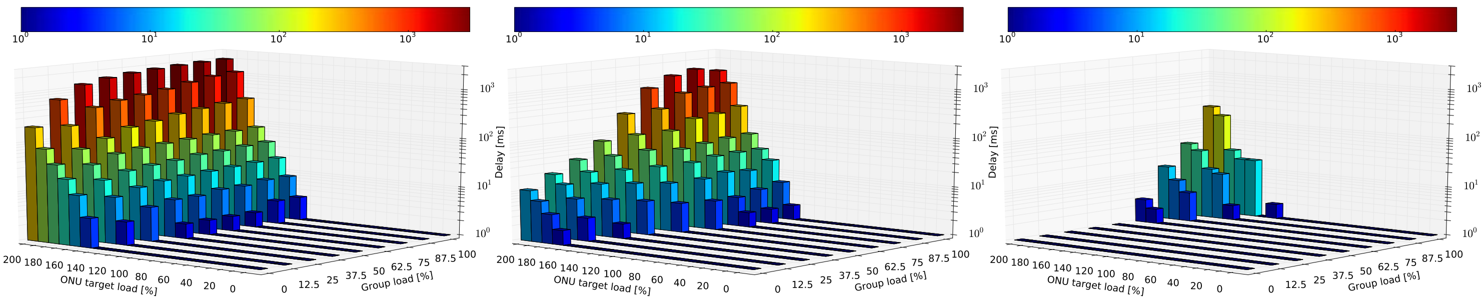


(a) $N_{group} = 2$

(b) $N_{group} = 3$

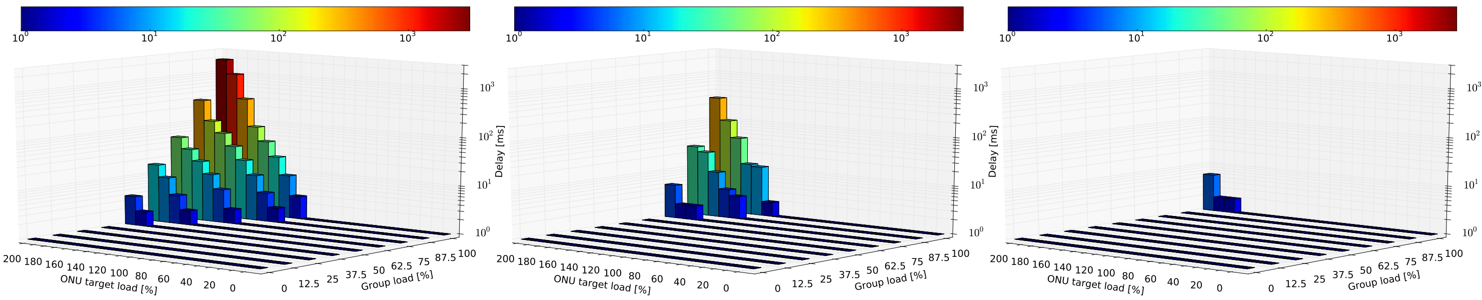
(c) $N_{group} = 8$

Figure 3. Impact of the number of ONUs in the group on the PLR of the BE traffic for the *MOS-IPACT* DBA algorithm



(a) $N_{group} = 2$ (b) $N_{group} = 3$ (c) $N_{group} = 8$

Figure 4. Impact of the number of ONUs in the group on the delay of the AF traffic for the IPACT DBA algorithm



(a) $N_{group} = 2$ (b) $N_{group} = 3$ (c) $N_{group} = 8$

Figure 5. Impact of the number of ONUs in the group on the delay of the AF traffic for the *MOS-IPACT* DBA algorithm

scheme to that of the IPACT algorithm, which does not support Multi-ONU SLAs, when varying the number of ONU in the group as well as the offered loads of the target ONU and the group. Simulation results show that the proposed scheme provides lower packet loss ratio and delay than does the IPACT algorithm for multi-ONU customers with unbalanced traffic. As future work, we plan to compare the performance of different excess bandwidth distribution policies. We also plan to integrate the *MOS-IPACT* scheme in an EPON-based mobile backhauling scenario such as that in [1] and [15], in which the base stations use an EPON backhaul link.

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