DBA Algorithm with Prioritized Services for 10G-EPON with Multi-ONU Customers

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***Abstract*—Passive optical networks (PONs) provide high access capacity to multiple services and applications. However, the deployment of PONs involves significant costs. On the other hand, infrastructure provider (InP) can lease their PONs to several customers. In this paper, we introduce a novel dynamic bandwidth allocation (DBA) algorithm for 10G-EPON called *subMOS-IPACT* which assures bandwidth at different granularity: individual ONUs, multi-ONU customer, and ONU subgroups. A subgroup is a set of optical network units (ONUs) belonging to the same multi-ONU customer. *subMOS-IPACT* also prioritized bandwidth distribution among subgroups of the same multi-ONU customer. Simulation results show that the proposed mechanism improves the network performance of multi-ONU customers supporting different services.**

Keywords—Dynamic Bandwidth Allocation, Passive Optical Networks, Mobile Backhauling/Fronthauling, Network Virtualization, Quality of Service, multi-ONU Customer.

I. Introduction

The capital expenditure (CAPEX) for the deployment of passive optical networks (PONs) can be an obstacle for new enterprises to go into network access business. On the other hand, infrastructure provider (InP) can lease their PONs to service providers (*customers/tenants*) [1] making possible their introduction into the market [2]. Virtual network operator, hereafter called also customer, can offer diverse type of services or even a single service to its clients. For example, a customer can lease optical network units (ONUs) from an InP to build its cellular backhaul network while other customers can lease ONUs to offer enterprise and residential services to its client. In the former, the leased set of ONUs is used by a single type of service while in the latter the set of ONUs is used by different services with diverse quality of service requirements.

Moreover, network as a service should provide customer isolation, customization, and efficient utilization of resources. Different schemes have been proposed to address these issues [1] [2] [3] and [4]. The work in [5] proposes the concept of a customer owning a group of ONUs (multi-ONU customer) which has assured bandwidth in gigabit-capable PON (GPON). The work in [6] provides bandwidth guarantees per-flow. The work in [7] proposes an architecture to support PON multi-tenant/customer, and [8] introduces an incentive mechanism for bandwidth sharing among customers.

In our previous work [9], we introduced a dynamic bandwidth allocation (DBA) algorithm for Ethernet PONs (EPONs) called IPACT with multi-ONU SLAs support (MOS-IPACT), which aggregates individual service level agreements (SLAs) of a group of ONUs belonging to the same customer as a single SLA. The *MOS-IPACT* algorithm allows to share the unused guaranteed bandwidth of an ONU with the other ONUs of a group while maintaining isolation from other customer's ONUs. Thus, bandwidth is assured at the ONU level, as well as, at the ONU group level.

The above presented algorithms do not, however, provide assured bandwidth for subgroups of ONUs (*e.g.,* ONUs/eNBs, enterprise ONUs and residential ONUs) in the multi-ONU customers. Therefore, subgroups of ONUs in a multi-ONU customer can suffer bandwidth starvation, even when the aggregate guaranteed bandwidth of the subgroup is sufficient to support the aggregate load.

In this paper, we introduce a DBA algorithm called *subMOS-IPACT* that provides bandwidth guarantee at different granularity: individual ONUs, multi-ONU customer, subgroups of ONUs as illustrated in Figure 1. A subgroup is a set of ONUs that belong to the same multi-ONU customer. *subMOS-IPACT* assures bandwidth to conventional customers with a single ONU, customers owning multiple ONUs but with a single service (i.e, Multiple ONUs/eNB) and customer with multiple ONUs serving diverse type of services. Moreover, *subMOS-IPACT* provides isolation at customer, subgroup and individual ONU level. Thus, various customers can coexist in a PON without affecting the bandwidth guarantee to other customers. *subMOS-IPACT* also allows multi-ONU customer to support a priority bandwidth allocation in the subgroups.

Simulation results show that *subMOS-IPACT* provides effective bandwidth isolation and efficient channel utilization. Furthermore, it reduces the delay and packet loss ratio (PLR) of overloaded high priority subgroups, and yet does not cause bandwidth starvation to low priority subgroups. The remaining of this paper is organized as follows. Section II and Section III discuss related work. Section IV describes the proposed DBA mechanism. Section V analyzes the results derived via simulations. Finally, Section VI concludes the paper.

II. DBA concepts for Ethernet PONs

EPONs employ time division multiple access (TDMA) for the uplink channel. The optical line terminator (OLT) grants transmission windows to the ONUs using a DBA algorithm which usually employs the multipoint control protocol (MPCP) for signaling. The MPCP defines the Gate and Report messages for bandwidth allocation. The Report message is sent by the ONUs to the OLT to request bandwidth. The Gate message is

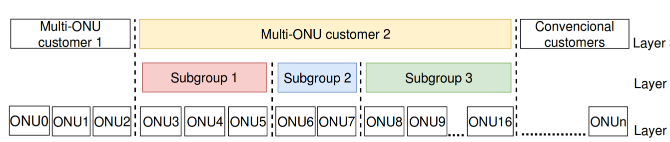

Figure 1: Granularity of Bandwidth Guarantees in *subMOS-IPACT*

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sent to the ONUs on the downlink by the OLT to inform the size and the start time of its next transmissions windows. DBA algorithms for EPONs involves a grant scheduling framework (GSF), a grant windows-size policy (GWP), an excess distribution policy (EDP), a grant scheduling policy (GSP) and a thread scheduling framework (TSF) [10].

A GSF defines the events triggering a scheduling decision which can be triggered by the arrival of a Report message (online) from a group of ONUs (offline).

A GWP defines the transmission window allocated per cycle to each ONU (W_i^G). The Limited policy defines a maximum windows size (W_i^{max}) equivalent to the guaranteed bit rate and Limited with Excess Distributions allocates the unused bandwidth from the underloaded ONUs to overloaded ones. Thus, the granted window for an overloaded ONU_i is equal to ($W_i^G = W_i^{max} + E_i$), being E_i the portion of the excess bandwidth calculated as explained next.

An EDP defines the distribution of unused bandwidth by the underloaded ONUs ($\mathcal{U}$) to the overloaded ONUs ($\mathcal{O}$). The Fair Excess policy (FE-DBA) [11] calculates the portion of the total excess bandwidth (E_i) to be allocated to each overloaded ONU according to the required bandwidth ($R_i - W_i^{max}$).

A GSP determines the order in which the ONUs are served by the Grant sizing policy in a granting cycle. A default policy is the round robin service one [12].

A TSF defines the number of scheduled Reports in a cycle. In the single thread polling (STP) framework there is only one Report message per ONU and per cycle. The delay is bounded since the ONU needs to wait one cycle to send the data. In the multi-thread polling (MTP) framework two or more Report message can be scheduled for the same ONU per cycle. The MTP frameworks are suitable to reduce the delay values. However, it introduces additional complexity to coordinate the threads and the extra guard times.

III. QoS differentiation in Ethernet PONs

For the Broadband Forum (BBF), there are two important issues to be addressed in the current PON networks: the provisioning of sustainable broadband services for residential customers by the InP, and the provisioning of a large variety of services on access networks, such as broadband service for business customers and fronthauling/backhauling services for the fifth generation 5G cellular network [13]. This is a new business opportunity for the InPs to increase revenues by offering a variety of services for multi-ONU customers.

A variety of DBA algorithms have been proposed in the literature to address the quality of service (QoS) support of diverse services; the most relevant are described next. Interleaved polling with adaptive cycle time (IPACT) algorithm [3] provides assured bandwidth to ONUs according to pre-defined SLAs. Bandwidth guaranteed polling (BGP) algorithm [4] provides guaranteed bandwidth for premium subscribers. Fair sharing with dual SLAs (FSD-SLA) algorithm [14] employs two SLAs to provide fairness for both priority and no priority services. A primary SLA describes the high priority service requirements and a secondary SLA the requirements of the lower priority service. A first upstream transmission allocates the priority services, meanwhile, the next upstream transmission is employed to accommodate the secondary SLA services. The two-layer bandwidth allocation (TLBA) algorithm [15] provides differentiated services. The TLBA propose a two-layer bandwidth allocation scheme that implements weight-based priority scheduling. In the first layer, part of transmission cycle is allocated among differentiated service. In the second layer, the allocated bandwidth to each service is distributed to all ONUs based on a max–min fairness policy.

The previous DBA algorithm provides QoS support to deliver differentiated services, however, does not consider multi-ONU customers coexisting in the same PON. Therefore, those algorithms does not provide bandwidth guarantee for multi-ONU customer. The *MOS-IPACT* algorithm provides bandwidth guarantees for customers owning multiples ONUs, however it does not differentiate services (*e.g.,* enterprise and residential services). Thus, time-critical services covering low-latency (such as mobile backhauling service) are not prioritized in multi-ONU customer schemes. The next section introduces the *subMOS-IPACT*, which provide bandwidth guarantees at a finer granularity including at subgroup/service level.

IV. DBA Scheme for Supporting Multi-ONU Customers with Prioritized Services

This section describes the proposed DBA that assures bandwidth at three different levels of granularity: individual ONUs, customer and subgroups of ONUs. The proposed DBA allows bandwidth sharing to three types of customers: *i*) conventional customer having a single SLA per ONU, *ii*) Multi-ONU customer with no service differentiation and *iii*) Multi-ONU customer with service differentiation.

The proposed DBA algorithm is called *MOS-IPACT* with prioritized ONU subgroup support (*subMOS-IPACT*). Furthermore, a high priority subgroup, related to sensitive services (i.e., ONUs/eNBs for mobile backhauling/fronthauling), receives more bandwidth when overloaded. *subMOS-IPACT* allows bandwidth management at different levels of granularity with effective isolation.

subMOS-IPACT calculates the windows transmission size and the next transmission time ($t_{txStart}$) at each cycle. When a Report message arrives at the OLT, *subMOS-IPACT* verifies if the message coming from a conventional customer, a multi-ONU customer with no subgroups or a multi-ONU customer with subgroups.

When the Report message comes from a conventional customer, the OLT calculate the start time of the next transmission ($t_{txStart}$) and the windows size employing the Limited policy. The OLT then sends a Gate message to the corresponding ONU (online GSF).

If the Report message comes from a multi-ONU customer with a single service (without subgroups), the OLT waits for Report messages from all ONUs belonging to the same multi-ONU customer before sending the Gate messages to these ONUs (offline GSF). The windows transmission size is calculated employing the Limited with Excess policy to assure bandwidth at customer level.

If the Report message comes from a multi-ONU customer with subgroups, the OLT waits for the arrival each Report coming from a subgroup of ONUs before sending the Gate messages to those ONUs of that subgroup (offline GSF). The OLT then calculates the windows transmission size employing the Limited with Excess policy to assures bandwidth for the subgroup. The subMOS-IPACT scheme also assures the bandwidth at the customer level. When the Report message from all ONUs that belong to the same multi-ONU customer arrive at the OLT, a second Gate message is sent to the overloaded ONUs in that multi-ONU customer (MTP). The second Gate message informs the portion of the customer total excess bandwidth allocated to the overloaded ONUs. However, this

Algorithm 1: subMOS-IPACT DBA Algorithm

1 $\mathcal{R}'_k \leftarrow \emptyset, \forall k \in \mathcal{G}$
2 $\mathcal{R}_{k,s} \leftarrow \emptyset, \forall k \in \mathcal{G}, \forall s \in \mathcal{S}$
3 **for** *each received report R from ONU i in cycle j* **do**
4   Calculate $W_i^{limited}$ according to the limited policy
5   **if** *ONU* $i \in \mathcal{O}_C$ **then**
6   Calculate $t_{txStart}$
7   Gate$_i^j \leftarrow (W_i^{limited}, t_{txStart})$
8   Send $Gate_i^j$
9   **else**
10         $\mathcal{R}_{k,s} = \mathcal{R}_{k,s} \cup \{R\}$
11   **if** $|\mathcal{R}_{k,s}| = |\mathcal{O}_{k,s}|$ **then**
12   BulkGrantGenerator()
13   **if** $|\mathcal{R}'_k| = |\mathcal{O}_k|$ **then**
14   MultiThreadGrantGenerator()
15 $\mathrm{R}_{k,s} \leftarrow \emptyset$
16 **Function** `BulkGrantGenerator()`
17   **for** *each report* $R \in \mathcal{R}_{k,s}$ **do**
18   Calculate $t_{txStart}$
19   Calculate $W_i^{granted}$
20   **if** $R_i > W_i^{granted}$ **then**
21             $\mathcal{R}'_k = \mathcal{R} \cup (i, R_i - W_i^{granted})$
22   Gate$_i^j \leftarrow (W_i^{granted}, t_{txStart})$
23   Send $Gate_i^j$
24 **Function** `MultiThreadGrantGenerator()`
25     $\mathcal{R}'_k \leftarrow sort(\mathcal{R}'_k)$ by HPS policy
26   **for** *each report* $R \in \mathcal{R}'_k$ **do**
27   Calculate $W_i^{grantedThread}$
28   **if** $W_i^{grantedThread} != \emptyset$ **then**
29   Calculate $t_{txStart}$
30   Gate$_i^j \leftarrow (W_i^{grantedThread}, t_{txStart})$
31   Send $Gate_i^j$
32   **else**
33             $\mathcal{R}'_k \leftarrow \emptyset$

thread of messages consumes bandwidth due to the necessary guard time between messages. In order to reduce this waste of bandwidth and prioritize sensitive services, a new policy called High Priority Subgroup First (HPS) is proposed. HPS distributes the total customer excess bandwidth only between the overloaded ONUs of the high priority subgroup. If there is remaining bandwidth available, it is distributed between the next highest priority subgroup, until all subgroups are satisfied or all excess bandwidth is distributed.

Algorithm 1 summarizes the *subMOS-IPACT* algorithm. Let $\mathcal{G}$ be the set of multi-ONU customers and $\mathcal{S}$ the set of subgroups of a multi-ONU customer; $\mathcal{O}$ is the set of ONUs in the PON; $\mathcal{O}_C$ the set of individual ONUs that do not belong to any *multi-ONU customer*; and $\mathcal{O}_{k,s}$ the set of active ONUs which belong to the s-th subgroup of the k-th multi-ONU customer. $\mathcal{O}_k$ is the set of overloaded ONUs belonging to the k-th customer.

A transmission window $W_i^{limited}$ is calculated for each Report message R received by the OLT (Line 3) using the IPACT limited policy (Line 4), and defined as $W_i^{limited} = minimum(R_i, W_i^{max})$. In this policy, the ONUs have a maximum windows size (W_i^{max}) equivalent to the guaranteed bit rate. For message sent by conventional ONUs (Line 5), the start time $txStart$ for the next cycle is calculated, and a Gate message is sent to the ONU_i (Line 6 and 8).

If the Report message comes from an ONU belonging to a multi-ONU customer with subgroups, the Report message is added to the set of Report messages of the subgroup s that belongs to multi-ONU customer k ($\mathcal{R}_{k,s}$) (Lines 9 and 10). If the OLT has already received all the Report messages from the ONUs in that subgroup, the $BulkGrantGenetrator$ function is applied (Lines 11 and 12) for assuring bandwidth to the subgroups, using the same mechanism proposed in the *MOS-IPACT* scheme. When all Report messages from a multi-ONU customer with subgroups are received, a function called $MultiThreadGrantGenerator$ is applied for distributing the excess bandwidth of the multi-ONU customer among the subgroups in a second scheduling thread (Lines 13 and 14).

When the Report message comes from an ONU belonging to a multi-ONU customer with no subgroups, only the $BulkGrantGenetrator$ is applied since this multi-ONU customer has only one subgroup. The bandwidth is assured just for the customer and the individual ONUs.

In the $BulkGrantGenerator$ function, the OLT sends a Gate message for each Report message received from the ONUs belonging to the subgroup s and multi-ONU customer k. Each ONU is classified either as *underloaded* (if $R_i \leq W_i^{limited}$) or *overloaded* (if $R_i > W_i^{limited}$). The granted window size ($W_i^{granted}$) is calculated by executing the limited policy with excess bandwidth distribution (Line 19). The FE-DBA with excess control (EC) technique [16] is used to distribute the excess bandwidth among the overloaded ONUs in a subgroup.$W_i^{granted}$ is defined as

$$W_i^{granted} = \begin{cases} R_i & if \quad R_i \leq W_i^{max} + E_i \\ W_i^{max} + E_i & if \quad R_i > W_i^{max} + E_i \end{cases}, \tag{1}$$

where E_i is the excess bandwidth assigned to the overloaded ONU_i, calculated as

$$E_i = \frac{R_i - W_i^{max}}{\Sigma_{j \in O}(R_j - W_j^{max})} \cdot E_s^{total}; \tag{2}$$

O is the set of *overloaded* ONUs and E_s^{total} is the total excess bandwidth of *underloaded* ONUs in the same subgroup s in a given cycle. For an *underloaded* ONU, the allocated excess bandwidth E_i is zero and the granted window size is equal to the requested windows size ($W_i^{granted} = R_i$).

The OLT then sends a Gate message with the next start time and the size of the granted transition windows for the next cycle (Lines 22 and 23). In this way, E_s^{total} is distributed among the *overloaded ONUs* belonging to the same subgroup in a per cycle basis.

However, if the ONU continues to be overloaded after the excess distribution process (Line 20), the Report message is added to the set of Report messages of overloaded ONUs ($\mathcal{R}'_k$) that belongs to the multi-ONU customer k. In this case, the request windows size in each Report messages in R'_k is equal to the required window size ($W_i^{req} = R_i - W_i^{granted}$) (Lines 21). The set of Report R'_k will be scheduled when executing the $MultiThreadGrantGenerator$ function, after all Reports message arrived at the OLT from the ONUs of a multi-ONU customer k (Lines 13).

In the $MultiThreadGrantGenerator$ function, the total excess bandwidth of multi-ONU customer (E_k^{total}) is distributed among the ONU subgroups, beginning with the highest priority subgroup ($s1$). This is achieved by generating a list of the set R'_k sorted by their priorities (from the highest to lowest priority) (Lines 25 and 26). Moreover, E_k^{total} is normalized considering the total bandwidth required by the given subgroup. In order to avoid affecting the guaranteed bandwidth to others, an additional guard period (TG) used for the new thread is taken into account as a part of the required windows size by overloaded ONUs as show in Equation 3.

$$E_i = \frac{W_i^{req} + TG}{\Sigma_{j \in C}(W_j^{req} + TG)} * E_k^{total} \tag{3}$$

C is the set of *overloaded* ONUs in the subgroup. The granted window size of the Gate message for the second thread ($W_i^{grantedThread}$) (Lines 32) is calculated as

$$W_i^{grantedThread} = \begin{cases} W_i^{req} & if \quad W_i^{req} + TG \leq +E_i \\ W_i^{req} - TG & if \quad W_i^{req} + TG > +E_i \\ \emptyset & if \quad TG \geq E_i \end{cases} \tag{4}$$

and subsequently the next start time is calculated and the Gate message is sent to the overloaded ONU_i (Lines 28-31).

After distributing the customer excess bandwidth among the overloaded ONUs of the high priority subgroup, the OLT subtracts the bandwidth used from the total excess bandwidth, as shown next

$$E_k^{total} = E_k^{total} - \Sigma_{j \in C}(W_j^{grantedThread} + TG) \tag{5}$$

Subsequently, the overloaded ONUs of the next high priority subgroup ($s2, ..., sn$) are processed to allocate the remaining bandwidth of the customer. When the total customer excess bandwidth is completely distributed or all overloaded ONUs in the customer receives the necessary bandwidth, the excess bandwidth allocation process is finished and the corresponding R'_k and $R_{k,s}$ are emptied (Lines 15 and 33).

V. Performance Evaluation

In this section, we assess the performance of the proposed *subMOS-IPACT* DBA scheme by using an EPON simulator (EPON-Sim), developed in Java and previously validated in [17]. The EPON-Sim implements the IPACT DBA algorithm together with the limited discipline introduced by Kramer *et. al* in [3]. This simulation also implements the *MOS-IPACT* scheme with the FE-DBA policy. The *subMOS-IPACT* scheme was introduced in the EPON-Sim simulator and the new version of the simulator was validated extensively.

A. Simulation Model and Setup

A 10G-EPON network with a tree topology and 1 OLT that handles the upstream channel of a set of ONUs ($\mathcal{O}$), with $|\mathcal{O}| = 32$, was simulated. Three different traffic classes were configured for each ONU in $\mathcal{O}$. Voice and other delay-sensitive applications belong to the expedited forwarding (EF) traffic. A constant bit rate encoding with a fixed-size packet of 70 bytes and packet inter-arrival time (τ) that depends on the ONU offered load (λ) is employed. If (λ) is higher than 45 Mbps, τ is 12.5 μs, giving 44.8 Mbps. Otherwise, τ is 125 μs, which gives 4.48 Mbps. The remaining offered load is evenly divided among assured forwarding (AF) and best effort (BE) traffic. AF traffic represents host applications that require bounded delay and bandwidth guarantees, whereas BE traffic represents applications that have neither delay nor bandwidth requirement [3]. To reflect the property of those traffics, the generated traffic in the ONUs is self-similar with Pareto ON-OFF sources. Inter burst generation time is exponential distributed and the burst duration is Pareto distributed with a Hurst parameter of 0.8. The packet lengths are uniformly distributed between 64 and 1518 bytes. The guard time period used was 0.624 μs and the maximum cycle length 1 ms. At every polling cycle, each ONU received at least the grant required to send a Report message (the minimum Ethernet frame size is 64 bytes). Each simulation scenario lasted 50 s and it was replicated 50 times.

Table I: Simulation Parameters

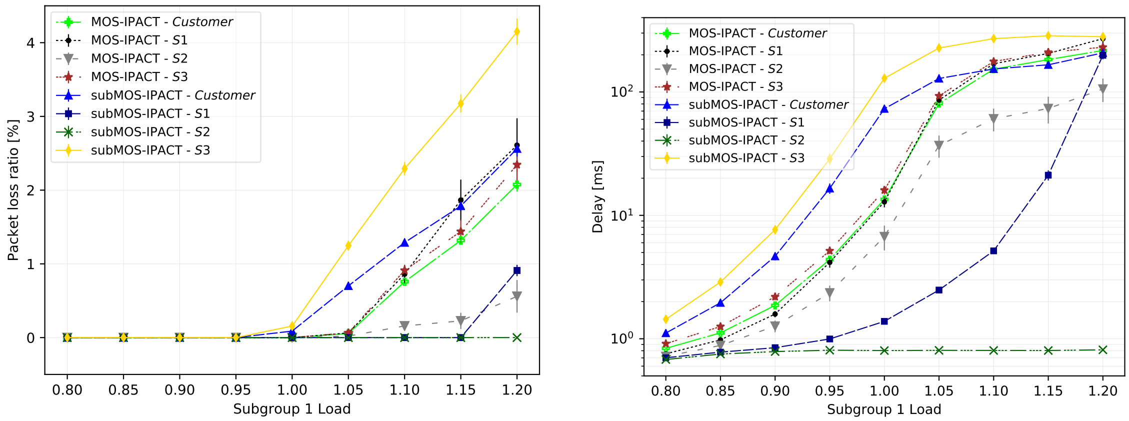
Parameter	Value		
Optical speed	10 Gbps		
Maximum cycle time	1 ms		
Guard band	0.624 μs		
Distance between OLT and ONUs	[10,20] km		
Propagation delay in fiber	5 μs/km		
OLT-ONU RTT	[100,200] μs		
ONU buffer size	10 MB		
Number of ONUs	32		
Number of ONUs in the group	16		
Aggregated guaranteed bandwidth in the group	$N_{group} \cdot 300$ Mbps		
Mean Guaranteed BW of ONUs in the group	300 Mbps		
Guaranteed BW for ONUs in the group	[150,450] Mbps		
Offered load for ONUs in the group	[0,600] Mbps		
Guaranteed BW for conventional ONUs	312.5 Mbps		
Offered load for conventional ONUs	312.5 Mbps		
Subgroups	$S1$	$S2$	$S3$
Number of ONUs	4	3	9
Aggregated offered load (Scenario 1)	[0.8,1.2]	0.7	1.05
Aggregated offered load (Scenario 2)	0.7	[0.8,1.2]	[0.8,1.2]
Inter-ONU scheduler	*MOS-IPACT* and *subMOS-IPACT*		
Intra-ONU scheduler	strict priority		

We assume one multi-ONU customer M with three ONU subgroups ($S_i, i \in \{1,2,3\}$). The multi-ONU customer has a group of ONUs $\mathcal{O}_M \subset \mathcal{O}$. The ONUs of subgroup i, $\mathcal{O}_{S_i} \subset \mathcal{O}_M$ and $\mathcal{O}_{S_i} \cap \mathcal{O}_{S_j} = \emptyset \mid i \neq j$ and $i, j \in \{1,2,3\}$. The S_1 subgroup has the highest priority, S_2 intermediate priority and S_3 the lowest priority. The number of ONUs in the group and subgroups is fixed; $|\mathcal{O}_M| = N_{group} = 16$, $|\mathcal{O}_{S_1}| = N_{S_1} = 4$, $|\mathcal{O}_{S_2}| = N_{S_2} = 3$ and $|\mathcal{O}_{S_3}| = N_{S_3} = 9$. Each ONU j in subgroup i has guaranteed bandwidth B_j between 150 Mbps and 450 Mbps, provided that $\sum_{j \in \mathcal{O}_{S_i}} B_j = N_{S_i} \cdot 300 \text{ Mbps} = A_{S_i}$, which is the effective aggregated guaranteed bandwidth in subgroup i. The ONUs of the multi-ONU customer can be either overloaded or underloaded since the offered load of ONU j (λ_j) varies randomly between 0 and 600 Mbps. The aggregate offered load in the subgroup i (λ_{S_i}) satisfied ($\sum_{j \in \mathcal{O}_{S_i}} \lambda_j = \lambda_{S_i}$). On the other hand, there is a set of conventional ONUs $\mathcal{O}_C \subset \mathcal{O}$, such that $\mathcal{O}_C \cup \mathcal{O}_M = \mathcal{O}$ and $\mathcal{O}_C \cap \mathcal{O}_M = \emptyset$. Each ONU k in $\mathcal{O}_C$ has a guaranteed bandwidth B_k equals 312.5 Mbps, which is the remaining bandwidth in the network evenly distributed. The offered load of a conventional ONU k (λ_k) is equal to its guaranteed bandwidth ($\lambda_k = B_k$), which is an overloaded condition. Table I summarizes the main configuration parameters used in the simulation.

We compare the packet loss ratio (PLR) and the delay per subgroup of the *subMOS-IPACT* scheme with those produced by the *MOS-IPACT* algorithm. The load and number of ONUs in the subgroups, and the load in the conventional ONUs are the same for *MOS-IPACT* and *subMOS-IPACT* in order to make a fair comparison. The *MOS-IPACT* algorithm is used in this comparison since the other algorithms for EPON in the literature do not provide guarantee bandwidth for a group of ONUs of a multi-ONU customer. Therefore, those algorithms generate high packet loss and produce long delays in scenarios with highly unbalanced traffics [9], like the ones proposed for in this paper. Thus, this would be an unfair comparison.

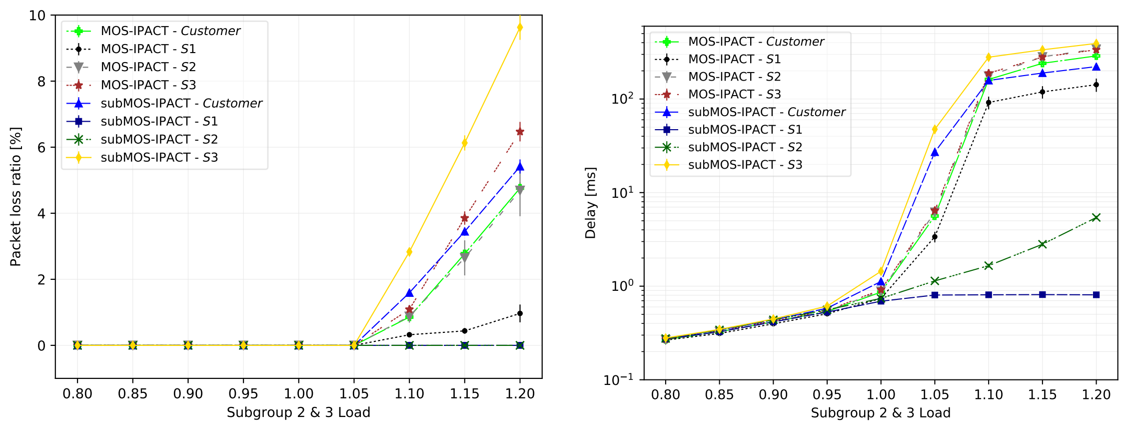
B. Scenario 1: Excess Bandwidth Distribution

In this scenario, the aim is to analyze how the excess bandwidth of the medium priority subgroup is distributed between the other two subgroups, when the high priority



(a) Packet Loss Ratio (b) Mean Delay

Figure 2: Scenario 1 network performance



(a) Packet Loss Ratio (b) Mean Delay

Figure 3: Scenario 2 network performance

subgroup moves from underloaded to overloaded state. Thus, the aggregated offered load of S_1 (λ_{S_1}) varies from $0.8 \cdot A_{S_1}$ to $1.2 \cdot A_{S_1}$ (herein after, A_{S_i} is omitted from the offered load values), whereas S_2 is underloaded with load 0.7 and S_3 is overloaded with load 1.05.

The PLR and average delay for the subgroups and the multi-ONU customer with *MOS-IPACT* and *subMOS-IPACT* schemes are shown in Figure 2. No packet loss occurs when the average offered load is lower than 1.0. Thus, each subgroup is fully served.

When *MOS-IPACT* is employed and the offered load on S_1 is equal to 1.2, the delay and PLR values of the subgroup S_2 are equal to 100 ms and 0.5%, respectively. Conversely, *subMOS-IPACT* scheme yields delay values smaller than 1 ms and no packet loss regardless the S_1 load. These results show that the failure to guaranteeing bandwidth at subgroup level by *MOS-IPACT* makes the overloaded ONU subgroups (S_1 and S_3) to decrease the allocated bandwidth to the underloaded ONU subgroup (S_2), even when the aggregated offered load is equal to 0.7.

The high priority subgroup (S_1) delay and PLR values increase while those of low priority subgroup (S_3) decrease when *MOS-IPACT* is employed since subgroups S_1 and S_3 dispute the excess bandwidth of the underloaded ONUs in S_2. Conversely, when *subMOS-IPACT* is employed, the high priority subgroup (S_1) has no packet loss for all offered loads. This occurs because when the S_1 is overloaded, the remaining excess bandwidth of S_2 is prioritized for S_1 without affecting the performance of S_2. However, this increases the delay and PLR of S_3. Thus, there is a tradeoff between the performance of the high and low priority subgroups.

subMOS-IPACT produces around 0.5% more packet losses than does *MOS-IPACT* for the multi-ONU customer, in average. Moreover, *MOS-IPACT* produces lower delay values than those produced by *subMOS-IPACT*. This effect is the result of the extra thread scheduling in *subMOS-IPACT*, because even though it provides additional bandwidth in the same cycle to overloaded ONUs, this demands additional bandwidth for the guard periods. However, the average delay and PLR produced by *subMOS-IPACT* for S_1 are lower than those produced by *MOS-IPACT*. Thus, *subMOS-IPACT* provides traffic differentiation for high priority services.

This scenario showed that *subMOS-IPACT* distributes the excess bandwidth of the underloaded subgroups for the high priority subgroups without affecting the assured bandwidth of other subgroups. However, this implies a small loss of available resources for the multi-ONU customer due to the extra guard times used for the multi thread scheduling. Nevertheless, all subgroups have no packet losses until an aggregated load of 1.0.

C. Scenario 2: ONU subgroup isolation

In this scenario, the aim is to analyze the isolation, especially in the high priority subgroup, as well as, to evaluate the bandwidth distribution among the low-priority subgroups. In this case, we assume that the high priority subgroup is underloaded with aggregated load equals 0.7, and the other subgroups (medium and low priority subgroup) have an aggregated load varying from 0.8 to 1.2.

The average packet delay and the PLR of the multi-ONU customer and its subgroups with *MOS-IPACT* and *subMOS-IPACT* in Scenario 2 is shown in Figure 3. When the average offered load in S_2 and S_3 are lower than 1.0, both algorithms produce an average delay smaller than 1 ms and no packet loss occurs in all subgroups.

The delay of the underloaded subgroup S_1 reaches 150 ms when using *MOS-IPACT*, while it reaches only 0.8 ms when using the *subMOS-IPACT*. Moreover, *subMOS-IPACT* produces no packet loss for the subgroup S_1 whereas *MOS-IPACT* yields up to 1 %. This occurs because the excess bandwidth of underloaded ONUs in the customer is distributed among all overloaded ONUs of the same customer when *MOS-IPACT* is used. Conversely, *subMOS-IPACT* assures bandwidth at subgroup level under unbalancing load conditions.

Although the aggregated load of is smaller than that of S_2, the delay values of the medium priority subgroup (S_2) using *subMOS-IPACT* are lower than those produced by *MOS-IPACT* to the ONUs with high priority services (S_1). This occurs because the medium priority subgroup (S_2) receives the unused bandwidth of S_1 when *subMOS-IPACT* is employed. However, when *MOS-IPACT* is used, the subgroups S_2 and S_3 compete for the excess bandwidth of S_1, generating packets losses in the subgroup S_2 under high loads. For instance, when the aggregated load in S_2 and S_3 are 1.10, the subgroup S_2 and S_1 have average delay lower than 2 ms when using *subMOS-IPACT*, while the subgroup S_2 experience average delays of 200 ms and S_1 experience average delays of 90 ms when using *MOS-IPACT*.

Moreover, the bandwidth used to improve the performance of the S_1 and S_2 with *subMOS-IPACT* causes performance degradation under $S3$ in overloaded condition. However, S_3 has no packets loss and produces similar delay values than those produced by the *MOS-IPACT* until loads of 1.1. This means that S_3 (low priority subgroup) supports an offered loads greater than the aggregated guaranteed bandwidth due to the use of part of the excess bandwidth of the highest priority subgroups.

This scenario showed that *subMOS-IPACT* algorithms ensures effective isolation regardless of the subgroup priority. Furthermore, if there is excess bandwidth in the highest priority subgroups, the bandwidth can be used for the lowest priority subgroup.

VI. Conclusion

This paper introduced a novel DBA scheme that supports priority scheduling subgroups in multi-ONU customers in EPON networks. We compared the performance of our proposed scheme to that of the *MOS-IPACT* scheme, when varying the aggregated average load of subgroups. Simulation results show that the *subMOS-IPACT* provides effective isolation and guarantees aggregate bandwidth. Furthermore, high priority subgroups have a decrease likelihood of packet loss and reduced delay when compared to those produced by the *MOS-IPACT* scheme and yet guarantees bandwidth to low priority subgroups even under unbalanced traffic conditions. As future work, we plan to compare the impact of different excess bandwidth distribution policies in *subMOS-IPACT*. We also plan to integrate a buy/sell bandwidth engine combined with the multi-thread excess distribution framework to support cooperative customer in EPON.

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