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Fair Bandwidth Allocation Algorithm for PONs Based on Network Utility Maximization

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***Abstract*—Network Utility Maximization Models (NUM) have been successfully applied to address multiple resource allocation problems in communication networks. This paper explores for the first time its application to model the bandwidth allocation problem in PONs and Long-Reach PONs. Using the NUM model, we propose the FEx-DBA (Fair Excess-DBA) algorithm a new Dynamic Bandwidth Allocation (DBA) scheme to allow a fair and efficient allocation of the upstream channel capacity. The NUM framework provides the mathematical support to formally define the fairness concept in the resource allocation, and the guidelines to devise FEx-DBA. A simulation study is conducted, so that FEx-DBA is compared to a state-of-the-art proposal. We show that FEx-DBA: (i) provides bandwidth guarantees to the users according to the Service Level Agreement (SLA) contracted, and fairly distributes the excess bandwidths among them, (ii) has a stable response and fast convergence when traffic or SLAs change, avoiding the oscillations appearing in other proposals, (iii) improves average delay and jitter measures and (iv) only depends on a reduced set of parameters, which can be easily tuned.**

***Index Terms*—Dynamic Bandwidth Allocation (DBA); Network Utility Maximization (NUM); Passive Optical Network (PON); Service Level Agreement (SLA).**

I. Introduction

Network Utility Maximization (NUM) models have received in the last years a significant attention from the scientific community in communication networks. In these models, each user or entity is associated with a utility function that can be viewed as a measurement of its satisfaction with the granted resources to comply with its QoS (Quality of Service) constraints [1-3]. Then, when some mathematical conditions are met, it is possible to show that the optimum solution of the NUM model is also the solution that more fairly distributes the resources among the competing users, according to a formal definition of fairness. Therefore, by creating an algorithm that solves the NUM problem, we are producing an algorithm that fairly allocates resources to the competing users.

NUM models have been the mathematical support for multiple allocation problems in communication networks like congestion control [4], adaptive routing [5], or for wireless networks-oriented contexts like transmission power allocation [6] in cell networks, persistence probability optimization in Aloha-type MAC protocols [7], coordinated transmission in vehicular networks [8], or data collection optimization in sensor networks [9]. NUM models have been also successfully used to guide the development of cross-layer algorithms with convergence guarantees, and to give insights in the interactions among algorithms at different layers [10]. In its turn, to the best of the authors' knowledge, the NUM methodology has not been yet applied in resource allocation problems in Passive Optical Access Networks. This paper is an attempt in this line, as we present a Dynamic Bandwidth Allocation (DBA) algorithm targeted to produce a fair assignment to the users of a Long Reach Passive Optical Network (LR-PON), using a NUM model of the underlying allocation problem.

PONs and LR-PONs are considered the future-proof infrastructure for the last mile network. It is expected that FTTH/B comprises more than half of the broadband accounts by 2018 (in 2014 was around 34%) [11]. In the European Union [12], about 22 million homes are predicted to be connected by the end of 2018, amounting to 10.6% of all homes.

PONs and LR-PONs are Point to MultiPoint (P2MP) networks and there are two principal PON standards: are EPON and GPON. Both are based on a passive tree topology between the Optical Line Terminal (OLT) and the user units called Optical Network Units (ONUs) or ONTs (Optical Network Terminals). Given its passive nature, PONs rely on bandwidth allocation schemes to coordinate the upstream transmission, from the ONUs (or ONTs) to the OLT, where the users share a common channel. These are the so-called Dynamic Bandwidth Allocation (DBA) algorithms [13-14]. To avoid packet collisions, DBAs are

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traditionally based on the TDMA (Time Division Multiple Access) concept, so that each ONU (or ONT) accesses the upstream link at different times controlled by the DBA implemented inside the OLT. In its operation, DBAs should grant time slots to the ONUs (or ONTs) taking into account not only the current user bandwidth demand, but also the QoS requirements contracted in the Service Level Agreement (SLA) with the network provider. The two principal PON standards are EPON and GPON and the way to deal with the bandwidth allocation process is different between them. The EPON standard uses the MPCP (Multi-Point Control Protocol) protocol to communicate the OLT with the ONUs [13-14]. ONUs report their demanded bandwidth for the next cycle using the so-called Report control message, whereas the OLT informs ONUs of their allocated bandwidth for the next cycle time using Gate control messages. The cycle time is the total time in which all ONUs transmit in a round robin discipline. In contrast, the bandwidth allocation process in GPON is based on T-CONTs. A T-CONT is a traffic container within an ONU that in the upstream channel is used to bear service traffic, so, each T-CONT corresponds to a specific type of service traffic. The OLT sends Bandwidth Map (BWmap) messages in the downstream channel to assign turns (or tickets) to each T-CONT of one ONU to extract its data in the upstream direction. Besides, ONUs use the DBRu (Dynamic Bandwidth Report upstream) field in the upstream frame to report their demanded bandwidth for the next cycles [15].

A relevant contribution of this paper is the modeling for the first time of the upstream allocation problem in PONs as a NUM problem. By doing so, we also formally define the concept of a fair allocation of the excess bandwidth in a DBA, and connect it with the optimum solution of the NUM model. A key advantage of this method over other existing algorithms is the robust mathematical model it relies on. Then, we propose FEx-DBA (Fair Excess DBA based on utility maximization) algorithm, to be implemented in the OLT. This algorithm finds the optimal solution of the NUM problem, and thus produces an optimally fair allocation. This is done applying the Karush-Kuhn-Tucker (KKT) optimality conditions to the problem, and devising an efficient scheme for finding its solution, amenable to real-time implementations in the OLT. In this way, another important advantage of NUM models over other existing alternatives is that all parameters to control the fairness can be set in advance. Then, we show how this algorithm not only produces a fair distribution of the bandwidth among the sources, but makes so improving (i) the delay, (ii) jitter, and (iii) fast response to SLA changes, in contrast to other alternatives. In this paper the EPON standard (Ethernet PON) has been selected to carry out the research. However, this DBA algorithm can be easily adapted to other PON technologies such as GPON.

The rest of the paper is organized as follows. Section II describes some notions regarding network utility and fairness. Sections III shows the description of the DBA algorithm based on a NUM model and fairness. In section IV it is presented the simulation scenario and the results of the simulation study. Finally, Section V summarizes the main conclusions achieved in the study research.

II. Network Utility and Fairness

A. NUM (Network Utility Maximization) models

Many network design problems are different versions of allocation problems, in which resources have to be assigned to different entities, under several constraints. The NUM (Network Utility Maximization) model is a way to deal with these problems.

Let A be a set of users to whom we have to allocate resources, and x_a the amount of resources (e.g. bandwidth) to assign to each user $a \in A$. We define the utility function of user a, $U_a(x_a)$, that returns the utility (as a reward) that a perceives depending on the amount of granted resources. Utility functions are always non-decreasing, meaning that assigning more resources to user a (x_a) is perceived as better (higher $U_a(x_a)$).

The general form of the NUM problem Eq. (1) finds the resource allocation $\left(x = \{x_a, a \in A\}\right)$ that maximizes the sum of the utilities perceived by all users, subject to a set of constraints, represented by the expression $x \in \chi$.

$$\max_x \sum\nolimits_a U_a(x_a), subject \quad to: x \in \chi \tag{1}$$

Different shapes of the utility function (U_a) result in different allocation schemes when the NUM model is applied.

In the next subsections, we sketch the connection between the particular utility function in Eq. (1) and the fairness among users in the optimal allocation.

B. Fairness in Resource Allocation

Intuitively, fairness in resource allocation means avoiding situations where some users are granted a high amount of resources (high x_a) while comparatively other users suffer starvation (low x_a).

Different notions of fairness have been presented, the user is referred to [3] for further references, but one of the most common fairness methods is the max-min fairness. An allocation is max-min fair when a user a_1 cannot increase its allocation without decreasing the allocation of other user a_2 that now receives less resources than a_1. By doing so, this policy maximizes the allocation of the user with less allocation (and this motivates the name max-min fairness). In [16], the concept of proportional fairness was proposed. A vector x^* is said to be proportionally fair if the proportions of increases/decreases of any other feasible allocations $x \in \chi$ should sum negative, as it is shown in Eq. (2):

$$\sum_a \frac{x_a - x_a^*}{x_a^*} \le 0, \quad \forall x \in \chi \tag{2}$$

In this paper, we make use of the generalization of fairness, so-called $(w,\alpha)-$proportional fairness, presented in [17]. Given a vector of weights $w = \{w_a, a \in A\}$

measuring the importance of each user, and a factor $\alpha \geq 0$, we say that an allocation x^* is $(w,\alpha)-$proportionally fair if (Eq. (3)):

$$\sum_a w_a \frac{x_a - x_a^*}{x_a^{*\alpha}} \leq 0, \quad \forall x \in \chi \tag{3}$$

It is easy to see that when $w_a = 1, \forall a$, the $\alpha = 0$ case provides the solution which maximizes the total amount of resources allocated $\left(\Sigma_a x_a\right)$, $\alpha = 1$ is equivalent to proportional fairness, and $\alpha \rightarrow \infty$ approximates max-min fairness [17]. Therefore, the α parameter helps to tune the "fairness" of the scheduler.

C. Fairness and utility functions

The relevance of $(w,\alpha)-$proportional fairness in Eq. (3) is given by its connection with the NUM model of Eq. (1). As shown in [3], as a generalization of the result in [17], if utility functions have the form Eq. (4):

$$U_a(x_a) = \begin{cases} w_a \log x_a & if \quad \alpha = 1 \\ w_a \dfrac{x_a^{1-\alpha}}{1-\alpha} & if \quad \alpha \geq 0, \alpha \neq 1 \end{cases} \tag{4}$$

and χ is a convex set, then the optimum solution of Eq. (1), is an allocation that is $(w,\alpha)-$proportionally fair, and it is unique if $\alpha > 0$. Then, optimally solving a particular NUM problem is the door to produce fair allocations.

III. Related work in DBA algorithms

DBA algorithms have to take into account not only the updated bandwidth demand of users, but also the QoS requirements contracted with any service provider. Then, these QoS requirements are reflected in a Service Level Agreement (SLA), typically related with a guaranteed bandwidth level to be satisfied. One extended policy to provide bandwidth guarantees is setting weighted factors to each ONU (according to its SLA) that complies with their QoS bandwidth requirements. Although this technique is quite easy to implement, it lacks of flexibility and adaptability, especially when bandwidth requirements are changed by service providers in a real time network scenario. Other algorithms, such as the one proposed in [18], divide the ONUs into two groups, the bandwidth guaranteed ONUs and best effort ONUs. Every ONU of the first group (high priority ONUs) receives the demanded bandwidth and the remaining bandwidth is distributed among the best effort ONUs (low priority ONUs). Other DBA algorithms are based on a guaranteed bandwidth associated with the highest priority classes of service [19-20], but they do not distinguish that different ONUs show different SLA profiles. Other recent proposals focus on providing SLA awareness considering that users with different delay bounds (specially for high sensitive traffic) are not treated identically, so the DBA algorithm controls the delay-bound requirements. In [21] authors propose that users with a more stringed delay-bound condition are polled more frequently. Authors in [22] implement a P (Proportional) control strategy to control the delay threshold of high priority classes of services. However, neither [21] nor [22] guarantee minimum bandwidth levels to the users.

Some recent DBA algorithms have proposed the integration of Proportional-Integral-Derivative (PID) control strategies to control different QoS restrictions in PONs and LR-PONs networks. PID techniques are very popular as they offer a high robustness and good performance in many fields (control process, motor drives, flight control, instrumentation) [23-24]. The algorithm proposed in [25] implements a PID controller to manage bandwidth resources to provide bandwidth guarantees to different priority profiles (SLAs). This novel strategy has shown good results in PONs, and the main challenge is the integration of efficient tuning techniques: PID controllers are defined by a set tuning parameters that depends on the particular system under control. There are different tuning techniques to implement in PIDs. On the one hand, analytical methods calculate the tuning parameters from analytical or mathematical descriptions. Heuristic techniques (such as Ziegler-Nichols) manually tune the PID from a set of experiments [23-24]. These methods may become laborious and time-consuming. On the other hand, there are optimization methods, such as genetic algorithms [26] or online tuning techniques, as those based on Neural Networks [27] that produce good results at a cost of increasing the complexity of the DBA algorithm.

In this context, we present the design and implementation of a novel DBA algorithm based on a Network Utilization Maximization model to provide QoS bandwidth requirements in a multi-profile scenario (SLA). The new algorithm dynamically assigns bandwidth to each ONU complying with the stipulated guaranteed bandwidth levels contracted. To the best of our knowledge this is the first time to apply a NUM approach in PONs infrastructures to guarantee QoS requirements, enjoying the support of this robust mathematical model.

IV. Description of the algorithm

In this section, we describe the DBA algorithm developed, called FEx-DBA (*Fair Excess DBA based on utility maximization*), and its integration in the operation cycle of the PON.

A. The DBA allocation cycle in EPON

As the FEx-DBA algorithm is based on EPON, it uses the MPCP Protocol to deal with the bandwidth allocation process between the OLT and the ONUs by means of the Report and the Gate control messages. Then, FEx-DBA implements a polling (online) policy [28], where the OLT allocates bandwidth to each ONU just after receiving its updated demand, independently of the status of the remaining ONUs, and thus long packet delays are avoided [28]. We use subindex m=0,1,…,M-1 to denote the M ONUs in the tree, as we justified in Section I that PONs follow a tree topology between the OLT and the ONUs/ONTs. Report, messages are periodically sent by the ONUs in a round-robin fashion once each ONU ends its transmission time at each cycle. In the Report message of ONU m, the ONU sends the requested bandwidth (in bytes) for the next cycle, which we denote as B_m^{req}. Immediately after the Report message is received, the OLT sends back a Gate message with the granted bandwidth for that next cycle B_m^{grant} according to the Eq. (5):

$$B_m^{grant} = \min\left\{B_m^{req}, B_m^{\max}\right\} \tag{5}$$

In Eq. (5), $B_m^{\max}$ is the maximum permitted bandwidth to each ONU at each cycle that depends on the QoS requirements associated with its contracted SLA. The cycle time, is the total time in which all ONUs transmit in a round robin discipline, limited to a maximum of 2 ms in the EPON standard [29].

The maximum allocated bandwidths $B_m^{\max}$ to each ONU are precisely the output of the DBA algorithm: FEx-DBA is periodically modifying the $B_m^{\max}$ term of each ONU (every T_{update} seconds) with the aim of producing a fair distribution of the excess bandwidth, i.e., the surplus bandwidth after the minimum requirements are met for all ONUs. Such minimum requirements are given by $B_m^{\min}$ input values: the minimum amount of bytes that each ONU m=0,1,…,M-1 should be granted in each round-robin cycle, determined by its SLA. Other possible input parameters to the algorithm are the $W_m^{sla\,j}$ values, a factor that weights the importance of the ONU (it will depend on the conditions of the SLA j contracted) in the utility function associated with it (this will be seen later). Higher $W_m^{sla\,j}$ values are translated into higher assignments of the excess bandwidth in the cycles. As an example, Fig. 1 shows the complete allocation process done by the overall algorithm in some consecutive cycles, considering that every ONU is located at the same distance to the OLT (to simplify the visualization).

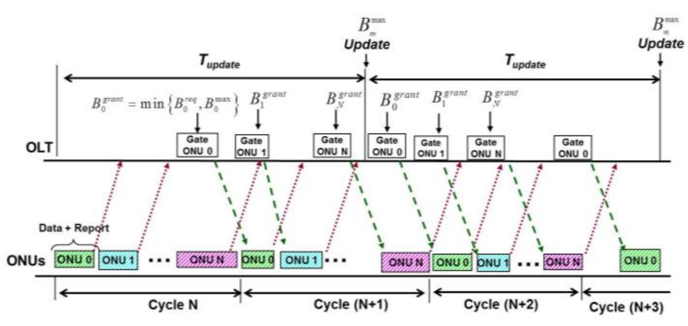


Fig. 1. Example of the allocation process of the overall DBA algorithm.

B. *Fair $B_m^{\max}$ update algorithm*

FEx-DBA algorithm periodically updates the $B_m^{\max}$ values to apply in Eq. (5). The update period is supposed to be higher than the cycle period, and actually updates can occur asynchronously to the cycle.

The inputs to the algorithm are:

- The average required bandwidth of each ONU for the next cycle $\overline{B_m^{req}}$, taken as the average of the last values appearing in the Report messages, contained in a fixed window time.
- The values $B_m^{\min}$ that correspond with the associated guaranteed bandwidth per cycle, coming from the SLAs of the ONUs.
- The values $W_m^{sla\,j}$ that can tune the preference in the fairness allocation for each ONU, depending on its contracted SLA. Initially, we consider $W_m^{sla\,j} = 1,\ \forall m, j$.
- The value $\alpha \geq 0$, that controls the fairness notion for allocating bandwidth.

The objective of our proposal is to distribute the excess bandwidth among the ONUs (users) in a fair manner. So first, the algorithm starts assigning the minimum bandwidth to the ONUs, following the next scheme:

1. We compute B_m^{init} (Eq. (6)), the initial amount of bandwidth assigned to each ONU, which is the minimum between the average requested bandwidth in the last cycles (contained in a fixed window time), and the guaranteed bandwidth by its contract:

$$B_m^{init} = \min\left\{\overline{B_m^{req}}, B_m^{\min}\right\} \tag{6}$$

2. Compute the excess bandwidth B' if this initial quantity was assigned to each ONU (Eq. (7)):

$$B' = B - \sum_m B_m^{init} \tag{7}$$

   If $B' = 0$, the algorithm ends and $B_m^{\max} = B_m^{init}$. This happens only when $\sum_m B_m^{\min} = B$, i.e., the sum of the guaranteed bandwidths equals the total bandwidth B, and also all ONUs request at least this quantity.

3. If not, for each ONU, it computes the excess demanded bandwidth $B_m = \overline{B_m^{req}} - B_m^{init}$. For all ONUs which do not request an extra bandwidth ($B_m = 0$), we have $B_m^{\max} = B_m^{init}$.

The rest of the algorithm is applied to the rest of the ONUs (which we denote as set M') for which $B_m > 0$. That is, those which require more bandwidth (up to B_m) than the one granted, and among which we should distribute the excess bandwidth.

FEx-DBA allocates this excess bandwidth among the ONUs in set M' in a fair manner, by finding the allocation that solves the following NUM shown in Eq. (8):

$$\max_x \sum_{m \in M'} U_m(x_m) \tag{8a}$$

$$\sum_{m \in M'} x_m \leq B^{'} \tag{8b}$$

$$x_m \leq B_m \quad \forall m \in M' \tag{8c}$$

$$x_m \geq 0 \quad \forall m \in M'^{'} \tag{8d}$$

where x_m denotes the amount of excess bandwidth assigned to ONU m, and U_m is the utility function associated with the contract (SLA profile) of ONU m, to enforce a $(w,\alpha)-$proportionally fair allocation (Eq. (9)):

$$U_m(x_m) = \begin{cases} W_m^{sla_j} \log x_m & if \quad \alpha = 1 \\ W_m^{sla_j} \dfrac{x_m^{1-\alpha}}{1-\alpha} & if \quad \alpha \geq 0, \alpha \neq 1 \end{cases} \tag{9}$$

Recall that α is a fixed factor that determines the type of fairness enforced in the excess bandwidth assignment. Value $\alpha = 0$ can be arbitrarily unfair, while, as predicted by theory [16-17] and shown later in the results, low values of α tend to provide high allocation differences between users (more "unfairness"), whereas high α values tend to reduce the differences between them. The impact and selection of this parameter will be analyzed in the simulation study.

Utility functions are concave, and thus problem of Eq. (9) involves the maximization of a concave function subject to linear constraints and, therefore, it enjoys the strong duality property [3]. Then, an allocation optimally solves Eq. (8) if and only if satisfies the KKT (*Karush–Kuhn–Tucker*) optimality conditions. If we denote π as to the multiplier of Eq. (8b), V_m the multipliers for Eq. (8c) and v_m the multipliers for Eq. (8d) we obtain that the Lagrange function (in a minimization problem version) follows the expression Eq. (10):

$$L(x,\pi,V,v) = -\sum_{m \in M^{'}} U_m(x_m) + \pi\left(\sum_{m \in M^{'}} x_m - B^{'}\right) + \sum_{m \in M^{'}} V_m(x_m - B_m) - \sum_{m \in M^{'}} v_m x_m \tag{10}$$

The Lagrange minimization conditions are shown in Eq. (11):

$$\begin{aligned} &\frac{\partial L}{\partial x_m} = -W_m^{sla_j} x_m^{-\alpha} + \pi + V_m - v_m, \qquad \forall m \in M^{'} \\ &\Rightarrow x_m = \left(\frac{W_m^{sla_j}}{\pi + V_m - v_m}\right)^{1/\alpha} \end{aligned} \tag{11}$$

From the dual feasibility conditions, it also holds that $V_m \geq 0, v_m \geq 0, \pi \geq 0$, and from complementary slackness KKT conditions we know that if an inequality is not tight (is satisfied as an strict inequality), then its associated multiplier is zero, and equivalently, if the multiplier is not zero, the inequality is tight (is satisfied as an equality).

To get the optimum allocation, we make use of all the previous conditions. Rearranging terms in Eq. (11), we have Eq. (12):

$$\pi = v_m - V_m + W_m^{sla_j} x_m^{-\alpha} \tag{12}$$

Then, for any $\alpha > 0$ (we do not pursue the case $\alpha = 0$ in the paper, since it allows arbitrarily unfair allocations) it holds that $x_m > 0$ since if not $\pi \to \infty$. Then, applying complementary slackness optimality conditions, we have that $v_m = 0, \forall m$.

Now, we study the case when $\pi = 0$. In this case, $V_m = W_m^{sla_j} x_m^{-\alpha} > 0$ and then $x_m = B_m$. Then, $\pi = 0$ is only possible when the sum of the excess requirements is below or equal to $B^{'}$, and then each ONU receives everything it requests.

If $\pi > 0$, we have that $\sum_m x_m = B^{'}$, since the constraint of Eq. (8b) should be tight. From this we have Eq. (13):

$$B^{'} = \sum_m \left(\frac{W_m^{sla_j}}{\pi + V_m}\right)^{1/\alpha} \tag{13}$$

Then, if the optimum π was known, the optimum x_m allocations for all ONUs would be known, and given by Eq. (14):

$$x_m(\pi) = \begin{cases} \left(\dfrac{W_m^{sla_j}}{\pi + V_m}\right)^{1/\alpha} & if \quad \left(\dfrac{W_m^{sla_j}}{\pi + V_m}\right)^{1/\alpha} \leq B_m \\ B_m & Otherwise \end{cases} \tag{14}$$

Note that every allocation x_m is non-increasing with π, which means that higher values of π always mean less or equal assignments to all. A way form to find the optimum π would be starting from a low value, and then increase it until $\sum_m x_m = B$. However, there is a way of doing this in an exact number of iterations with the following sequence of steps:

Compute the value $\pi_m = \dfrac{W_m^{sla\,j}}{B_m^{\alpha}}$ for each m. π_m is the value that makes the ONU receive all its requested bandwidth (also, for every $\pi < \pi_m, x_m = B_m$). That is, π_m comes from Eq. (15):

$$B_m = \left(\frac{W_m^{sla_j}}{\pi_m}\right)^{1/\alpha} \tag{15}$$

Order the π_m values in ascending order (from lower to higher). Take them in order. In the iteration i, we denote as $m(i)$ to the ONU associated with that iteration.

Make $\pi = \pi_{m(i)}$, and compute all the x_m values for all the ONUs using Eq. (14) (the values of $x_{m(k)}$ for $k > i$ will have $x_m = B_m$). If $\sum_m x_m > B^{'}$, the π value is still small, go to next iteration i. If not, we have increased π too much, and the optimal value is between $\pi_{m(i)}$ and $\pi_{m(i-1)}$. We can compute the exact optimum value of π in one shot following Eq. (16).

$$\sum_m x_m = B' \Rightarrow$$
$$\sum_{k\le i}\left(\frac{W_{m(k)}^{sla_j}}{\pi}\right)^{1/\alpha} + \sum_{k>i} B_{m(k)} = B' \Rightarrow \qquad (16)$$
$$\pi = \left(\frac{\sum_{k\le i}\left(W_{m(k)}^{sla_j}\right)^{1/\alpha}}{B' - \sum_{k>i} B_{m(k)}}\right)$$

Then, from the optimum π we compute the excess bandwidth x_m of the ONUs using Eq. (14), and the algorithm ends. As summary, Fig. 2 shows a flow diagram of the algorithm.

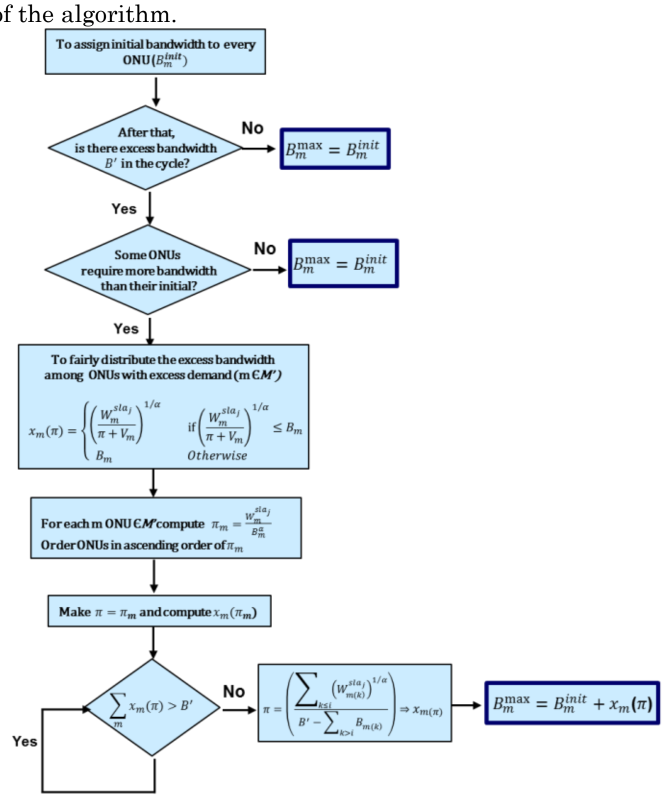


Fig. 2. Flow diagram of the algorithm to fairly update B_m^{max}.

C. Algorithm complexity

The complexity of the FEx-DBA algorithm is dominated by the procedure where the π_m values should be ordered. The ordering problem can be solved in $O(M \log M)$ worst-case complexity using standard sorting algorithms, where M is the number of ONUs. This is perfectly within the capabilities of standard general purpose processors, but it could be also implemented in FPGAs with moderate efforts. Note that the algorithm should produce an allocation every B_m^{max} update period, which is expected to be larger than the cycle duration, thus relaxing the real-time constraints.

V. Results

A. Simulation scenario

This section describes the simulation tests performed to validate and study the performance of the FEx-DBA algorithm. Simulations were implemented using OMNET++ [30] framework, for a LR-EPON with 16 ONUs and one user connected to each ONU. The transmission rate of the upstream link (between ONUs and the OLT) is 1 Gbit/s and the link from the user to its ONU is of 100 Mbit/s [29]. This is a standard Fiber To The Home setup (FTTH).

Every ONU contributes in the same proportion to the total network load, using a symmetric model as occurs in the majority of studies in PONs and Long-Reach PONs ([13-14] [31-33]). The distance between ONUs and the OLT is set to 100 km, a realistic LR-PON setup [31-33]. The simulated traffic exhibits the properties of self-similarity using the traffic generator provided by Kramer in [34] (packets between 84 and 1538 bytes following the Ethernet standard). In order to store the packets and schedule their transmission, ONUs are equipped with a 10 Mbytes buffer using the strict priority queue policy [35]. The maximum cycle time is set to 2 ms following the EPON standard restrictions [29].

The main characteristics of this scenario are summarized in Table I. We consider three SLAs: SLA_0 for the highest priority service level (1 ONU associated), SLA_1 for the medium one (5 ONUs contracted) and SLA_2 for the lowest priority profile (10 ONUs contracted), similarly to other the tests in other works like [25, 31]. The guaranteed bandwidth of each SLA is set to different QoS bandwidth levels following Table I. Recall that each ONU must receive at least this bandwidth when requested, even if the upstream channel is temporarily congested.

TABLE I
GUARANTEED BANDWIDTH LEVELS FOR EVERY SLA PROFILE FOR DIFFERENT SCENARIOS

Scenario	Guaranteed Bandwidth SLA_0	Guaranteed Bandwidth SLA_1	Guaranteed Bandwidth SLA_2
Scenario 1	80 Mbps	60 Mbps	40 Mbps
Scenario 2	70 Mbps	50 Mbps	30 Mbps

For the FEx-DBA algorithm, we consider that the weights associated with every profile in the utility function are set to 1, W_m=1; $\forall\, m$. The impact of this parameter will be analysed in the simulation study. The value of the parameter α is initially set to 1, but its impact will be also analysed in the next sections. We have selected a value of 1 second for the window time that stores the mean demanded bandwidth used by the algorithm to update the maximum permitted bandwidth to every ONU.

We compare the performance of FEx-DBA with that of SPID (Service level agreement PID) algorithm [25]. Both schemes follow a polling policy to allocate bandwidth and they dynamically enforce QoS guaranteed bandwidth in a multi-profile scenario (different SLA profiles). SPID allocates bandwidth without considering fairness in the process, making use of a robust PID controller based on the committed error when ensuring the stipulated bandwidth requirements. The characteristics of this algorithm are summarized in the next section. Finally, to periodically update the maximum permitted bandwidth we have chosen for both algorithms the time used by SPID in [25], three seconds.

B. Description of the SPID Algorithm

In SPID [25] the maximum permitted bandwidth $B_m^{\max}$ to each ONU $m=0,1,\ldots,M$ is controlled by a PID, that updates this value according to the present, the past and the future prediction of the errors $e[n]$, following Eq. (17). In that equation, the committed error $e[n]$ is the difference between the mean allocated bandwidth to one m ONU $\left(\overline{B_{alloc}^{onu_m}}\right)$ and its stipulated minimum guaranteed bandwidth $\left(B_{guarantee}^{sla\in onu_m}\right)$, that is, $e[n]=B_{guarantee}^{sla\in onu_m}-\overline{B_{alloc}^{onu_m}}$.

$$
\begin{aligned}
&B_m^{\max}=B_m^{\max}+u[n]\\
&u[n]=K_p\left(e[n]+\frac{T}{T_i}\sum_{m=0}^{n}e[n]+\frac{T_d}{T}\left(e[n]-e[n-1]\right)\right)
\end{aligned}
\tag{17}
$$

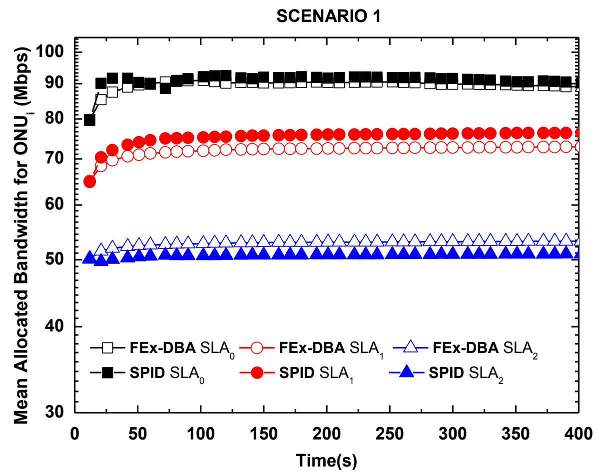
The terms K_p, T_i and T_d are the tuning parameters that have to be carefully initialized so that the control system is stable and converges to the objective it was designed for. This tuning process is a challenge in PID operation, and different tuning techniques have been proposed for them (e.g. see [23-24]). On one hand, well-known and extended manual techniques (such as the Ziegler-Nichols method) may consume a lot of time and become laborious. In contrast, other automatic and auto-adaptive tuning techniques exist, such as based on Genetic algorithms and Neural Networks, that have shown good results, at a cost of increasing the DBA complexity.

The difficulties of such tuning process are a drawback compared to FEx-DBA scheme, which does not require of a previous parameter tuning phase to guarantee convergence and a stable operation. SPID results in this paper have been obtained after a Ziegler-Nichols tuning phase, with the parameters set to: $K_p=0.66$, $T_i=11s$ and $T_d=2.75s$ (selected as the best in the simulation study done in [25]).

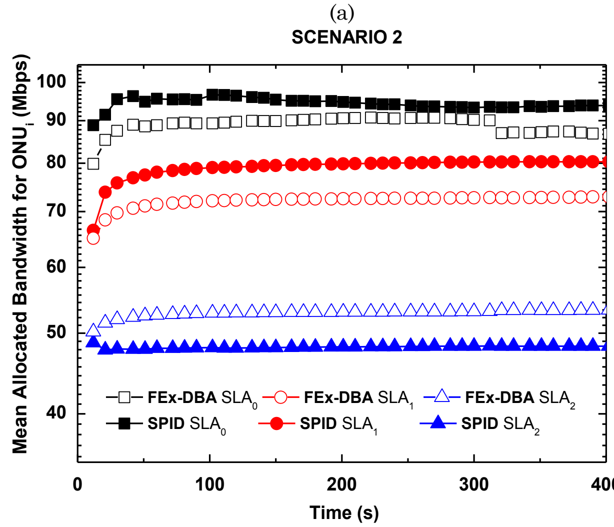
C. Comparison of FEx-DBA vs SPID

Fig. 3 (a) and (b) show the real time evolution of the allocated bandwidth (in Mbps) made by FEx-DBA and SPID algorithms for each SLA when considering the QoS levels of Scenario 1 and Scenario 2, respectively. Only one ONU of each SLA is represented, to simplify the graphs. In our tests, all ONUs behaved equally.

Firstly, it can be observed that both algorithms comply with the QoS bandwidth restrictions, 80/60/40 Mbps ($SLA_0/SLA_1/SLA_2$) for Scenario 1 and 70/50/30 Mbps ($SLA_0/SLA_1/SLA_2$) for Scenario 2. However, it can be noticed for both scenarios that FEx-DBA distributes the bandwidth with a notion of fairness which prefers giving more resources to users of the lowest priority profile (SLA_2), instead of SLA_0 and SLA_1 users. As will be seen later we can control the fairness notion with the α parameter. In contrast, SPID always benefits to the highest priority profiles.



(a)



(b)

Fig. 3. Instant variation of the mean allocated bandwidth of one ONU every profile for SPID and FEx-DBA when considering different guaranteed bandwidth levels (a) Scenario 1 (b) Scenario 2.

Fig. 4 shows the evolution of the maximum permitted bandwidth, B^{max}, in both DBAs. As it can be observed, while FEx-DBA provides a stable response from the very beginning of the simulation, SPID needs around a minute to adjust the PID according to the committed errors.

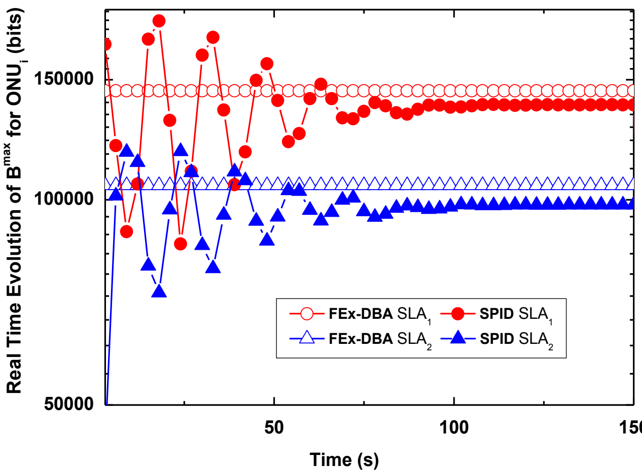


Fig. 4. Variation of the maximum permitted bandwidth for every profile.

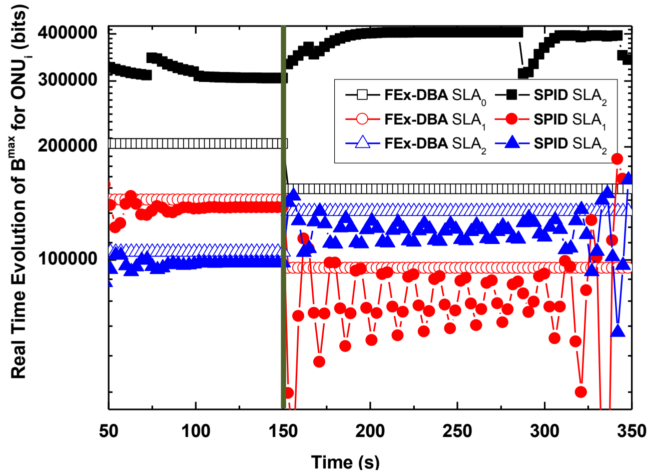


Fig. 5. Variation of the maximum permitted bandwidth for every profile when the guaranteed bandwidth changes along the time.

This oscillating performance is a relevant degradation in DBAs operation. In [36], the ability of a DBA to readjust the allocated bandwidths to the current traffic demands (mainly when a change in the traffic demand happens) is defined as a key performance indicator, since there is a delay between the moment that the traffic demand increases, to the moment that the DBA algorithm reacts to the increase. For instance, the XG-PON recommendations [36] define this time as the Assured Bandwidth Restoration Time (ABRT) with a target value of 2 ms.

To compare the performance of both algorithms (FEx-DBA, SPID) under this situation, we have modified the guaranteed bandwidth levels at 150 seconds, following values collected in Table II. Fig. 5 depicts the algorithms' evolution. As it can be observed, both algorithms dynamically adapt the allocated bandwidth attempting to converge to the new guaranteed bandwidth levels. However, FEx-DBA exhibits a fast and stable response while SPID needs more time and oscillations to adjust. Specially, large differences can be observed for the two lowest priority profiles (SLA_1 and SLA_2).

TABLE II
DIFFERENT GUARANTEED BANDWIDTH LEVELS FOR EVERY PROFILE ALONG THE TIME

Time (s)	Guaranteed Bandwidth SLA_0	Guaranteed Bandwidth SLA_1	Guaranteed Bandwidth SLA_2
0-150 s	100 Mbit/s	70 Mbit/s	50 Mbit/s
> 150 s	70 Mbit/s	50 Mbit/s	30 Mbit/s

D. Impact of FEx-DBA parameters

In this subsection, we will illustrate with some examples how the $W_m^{sla_j}$ weights and the α parameter can affect the allocations resulting in FEx-DBA algorithm. As we will show, its effect is small, and the trends predictable according to the theory. As a result, they can be safely set in advance. In particular, note that both settings will just affect how the excess bandwidth is distributed among competing source, after the guaranteed bandwidth is allocated, and thus the guaranteed bandwidths will be met in any setting.

First, we observe the effect of $W_m^{sla_j}$ weights. According to Eq. (14), two ONUs $m=1$ and $m=2$ with weights $W_1^{sla_1}$ and $W_2^{sla_2}$, which have a high amount of pending traffic and compete for excess bandwidth, will receive an allocation x_1 and x_2 that is related by Eq. (18):

$$\frac{x_1}{x_2} = \left(\frac{W_1^{sla_1}}{W_2^{sla_2}}\right)^{1/\alpha} \tag{18}$$

For instance, if $\alpha = 1$ this means that a double weight reflects in a double allocation. However, note that this allocation is only double for the excess bandwidth, and when both ONUs have pending traffic to transmit. In real operation, such situations quickly compensate in average. This is reflected in Fig. 4, which shows the real time evolution of the mean allocated bandwidth to one ONU of the three SLAs (SLA_0, SLA_1, SLA_2) when considering the three scenarios depicted in Table III, for the case $\alpha = 1$.

TABLE III
CONSIDERED WEIGHTS TO ESTABLISH DIFFERENT GUARANTEED BANDWIDTH LEVELS FOR SLA_0, SLA_1 AND SLA_2.

	$W_m^{sla_0}$	$W_m^{sla_1}$	$W_m^{sla_2}$
Scenario 1	1	1	1
Scenario 2	3	2	1
Scenario 3	1	2	3

Results from Fig. 6 show that the algorithm complies with the bandwidth guarantees for every SLA at every scenario. Actually, the differences between scenarios are not very significant and quite predictable. By comparing the scenarios 2 and 3 where some weights are different to one, respect to the baseline scenario 1, where all ONUs have weight one, we see that:

- In Scenario 2, where SLA_0 is preferred and SLA_2 has the lowest weight, SLA_0 has more bandwidth than in the baseline case, and SLA_2 less.
- Similarly, in Scenario 3, where SLA_2 is preferred and SLA_0 has the lowest weight, SLA_2 receives more bandwidth than in the baseline case, and SLA_0 less.

Then, we see that $W_m^{sla_j}$ weights are an effective form to control how the excess bandwidth is distributed.

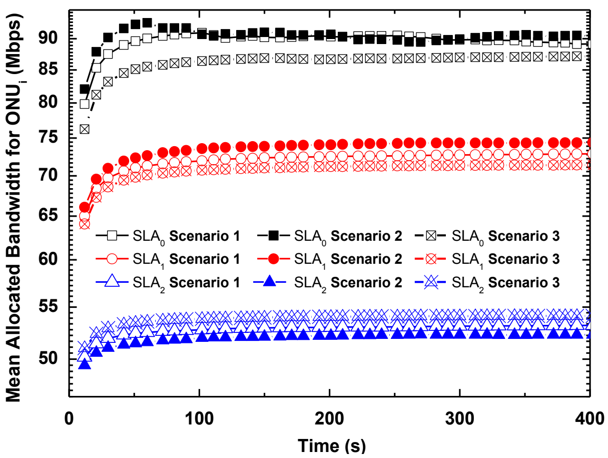


Fig. 6. Real time evolution of the mean allocated bandwidth for every profile considering scenarios with different weights.

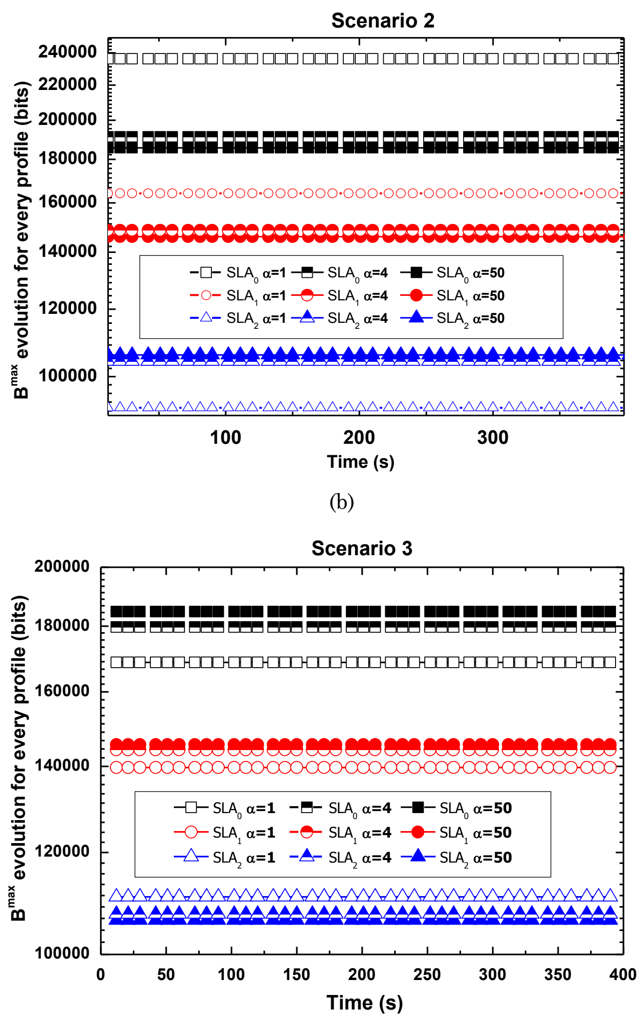
Table IV summarizes how the algorithm distributes the excess bandwidth among ONUs of the three SLAs. In that case, as we consider a guaranteed bandwidth for SLA_0, SLA_1, SLA_2 set to 80/60/40 Mbps (respectively), the remaining bandwidth is around 220 Mbps (over the upstream capacity of 1 Gpbps). Then, FEx-DBA distributes this bandwidth according to the weighted factors at each scenario. When weights are equal, FEx-DBA offers the same bandwidth to every ONU (Eq. (18)). For Scenario 2, the algorithm gives more bandwidth to ONUs of SLA_0 and SLA_1 as their associated weights are higher. Finally, in Scenario 3 the most benefited ONUs are those belonging to SLA_2 (with higher weights). For every scenario it can be observed in Table IV that the total sum of bandwidth of all ONUs corresponds with the total excess bandwidth, and FEx-DBA does not waste any excess bandwidth.

TABLE IV
EXCESS BANDWIDTH ASSOCIATED WITH EACH SLA PROFILE FOR DIFFERENT SCENARIOS

Scenario	Excess bw. SLA_0 (1 ONU)	Excess bw. SLA_1 (5 ONUs)	Excess bw. SLA_2 (10 ONUs)	Total Excess Bandwidth
Scenario 1	13,7 Mbps	13,7 Mbps	13,7 Mbps	220 Mbps
Scenario 2	28,70 Mbps	19,13Mbps	9,56 Mbps	220 Mbps
Scenario 3	5,23 Mbps	10,7 Mbps	16 Mbps	220 Mbps

The impact of α parameter is studied now. Results in Fig. 6 have been obtained for the case $\alpha = 1$. Observing Eq. (18), we can infer that when all the ONUs have the same weight $W_1^{sla_1} = W_2^{sla_2}$ like in Scenario 1 in Table IV, the α parameter makes no difference in the assignment. This was confirmed by our simulation tests. However, different α values can result in different allocations when this does not happen. This is illustrated in Fig. 7 (a) and (b) for conditions of Scenario 2 and 3 of Table IV. In these graphs we depict the real time evolution of the B_m^{max} values associated with every ONU of each SLA provided by the FEx-DBA when considering different α values ($\alpha = 1, 4, 50$). The effect observed is that higher a values reduce the preference that receives the ONUs with higher weight:

- In Fig. 7 (a) for Scenario 2, when lower weighted factor corresponds to SLA_2 profile, high α values provision more bandwidth to it in detriment to the others.
- In Fig. 7 (b) for Scenario 3, the lower weighted factor is SLA_0, that receives a lower share of excess bandwidth, but that improves for higher α values.



(b)

(b)

Fig. 7. Real time evolution of the maximum permitted bandwidth considering a set of α and different weighted factors to each ONU (a) Scenario 2 (b) Scenario 3.

This performance is consistent with what is predicted by theory: that high α values tend to approach the max-min fairness allocation, so the algorithm distributes the excess bandwidth more uniformly among all ONUs, irrespective of its weight. In summary, low α values provide more differences in the allocation process between SLAs in contrast to high values of α that tend to the max-min approach.

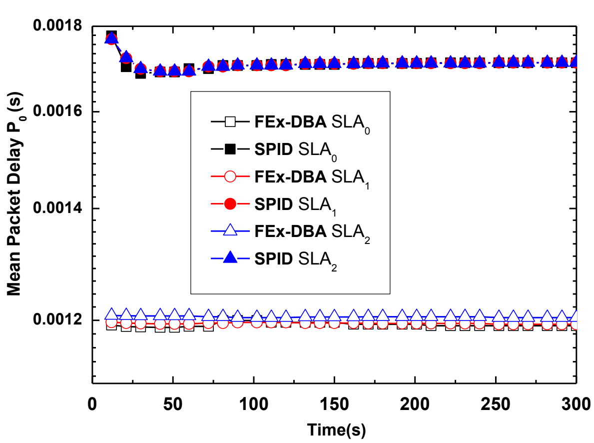
E. Analysis of other QoS parameters: Mean packet delay and Jitter

In order to extend the QoS analysis, we present in this subsection the mean packet delay and jitter performances of the algorithms. In this case, we assume that the EPON is fed with three classes of service. For this, ONUs are equipped with three queues of different priority (Table V), P_0 for the highest priority traffic (interactive), P_1 for the medium priority traffic (responsively) and P_2 for the non-critical traffic (best-effort). In order to store the packets and schedule their transmission the well-known strict priority queue method is used [4,31]. For this simulation scenario it is considered that every weight is set to 1 $\left(W_m^{sla_j}=1,\ \forall m, j\right)$ and $\alpha=1$.

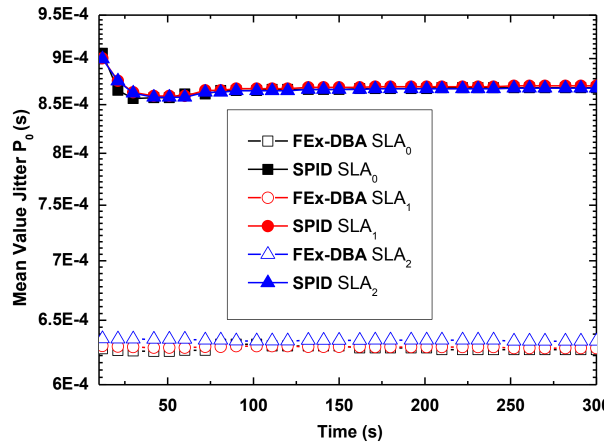
TABLE V
CLASSES OF SERVICES CONSIDERED IN THE EPON NETWORK

Classes of service	Applications
P_0 (Interactive)	VoIP, videoconference, interactive games, Telnet
P_1 (Responsively)	Voice Messaging, web-browsing HTML, E-mail, Transaction services
P_2 (Non-Critical)	Bulk Data

Results are plotted in Fig. 8 for P_0 traffic. Regarding the most sensitive traffic P_0, we observe that the mean packet delay, Fig. 8 (a), is fairly low for both algorithms, lower than 2 ms. However, FEx-DBA provides better performance than SPID for every profile, as it improves the mean packet delay up near 0.5 ms for every SLA. Fig. 8 (b) shows the jitter performance, where again FEx-DBA algorithm provides better results than SPID (note in this case that values are in the E-4 scale).



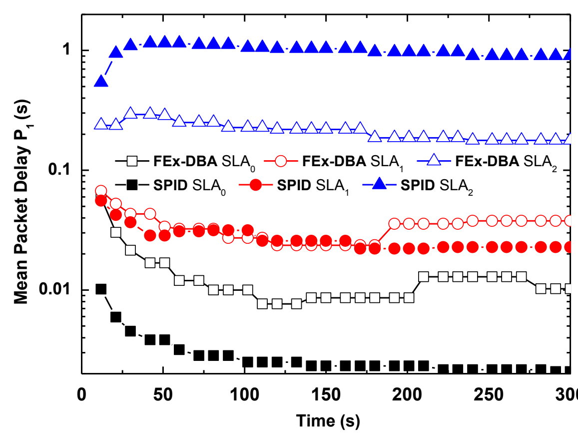
(a)



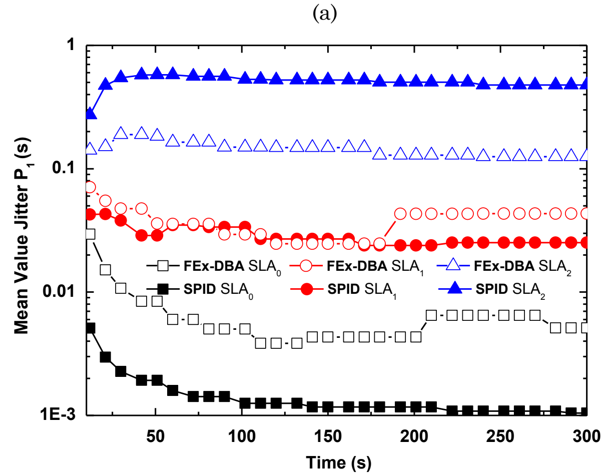
(b)

Fig. 8. Performance of the highest priority class of service P_0 (a) Mean packet delay (b) Mean jitter.

For the medium priority service P_1, Fig. 9 (a) shows that the mean packet delay higly depends on the contracted profile. In SLA_0 and SLA_1 both options provide fairly low delays (below 5 ms), and better for SPID. However, this advantage of SPID is made at a cost of strongly penalizing SLA_2 profile, with near one second of more average packet delay than FEx-DBA. This is an example of unfair behavior of SPID, that FEx-DBA avoids. Similar behavior is observed in the jitter (Fig.9 (b)).



(a)



(b)

Fig. 9. Performance of the medium priority class of service P_1 (a) Mean packet delay (b) Mean jitter.

VI. Conclusion

In this paper, we present FEx-DBA (*Fair Excess DBA based on utility maximization*), the first (to the best of the authors' knowledge) DBA algorithm based on a NUM modeling of the resource allocation process in the PONs. FEx-DBA pursues an optimally fair allocation of the upstream channel capacity, according to the formal definition of fairness enabled by the NUM model.

We have tested and validated FEx-DBA by means of simulation, comparing its performance with that of SPID, a state-of-the-art DBA proposed for LR-PONs. Our studies show that FEx-DBA effectively produces a fair distribution of the bandwidth among ONUs according to their associated QoS bandwidth conditions, guaranteeing the minimum bandwidth levels in the SLAs, and fairly distributing the excess bandwidth. Compared to SPID, we observe that FEx-DBA has a significantly better stability in the bandwidth allocation process. It avoids oscillations and fluctuations when guaranteeing the stipulated QoS bandwidth constraints, especially when real time changes in the SLAs happen. FEx-DBA also results in better delay and jitter performances. Finally, in contrast to SPID, the parameter tuning for FEx-DBA is much simpler, supported by the NUM framework guidelines, and all the parameters can be set in advance.

Acknowledgment

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References

[1] S. Shakkottai, G. Shakkottai, and R. Srikant, *Network Optimization and Control*. Now Publishers Inc, 2008.
[2] R. Srikant and L. Ying, *Communication Networks: An Optimization, Control, and Stochastic Networks Perspective*. Cambridge University Press, 2013.
[3] P. Pavón Mariño, "Optimization of Computer Networks: Modeling and Algorithms. A Hands-On Approach", Wiley, 2016.
[4] S. Low, H. Steven and D. Lapsley, "Optimization flow control-I: basic algorithm and convergence," *IEEE/ACM Transactions on Networking (TON)*, vol. 7, pp. 861-874, December 1999.
[5] X. Lin and N. Shroff, "Joint rate control and scheduling in multihop wireless networks," *In Proc. of the 43rd IEEE Conference on Decision and Control*, 2004, Bahamas, pp.1484-1489.
[6] M. Chiang, "Balancing Transport and Physical Layers in Wireless Multihop Networks: Jointly Optimal Congestion Control and Power Control," *IEEE Journal on Selected Areas in Communications*, vol. 23, pp. 104-116, January 2005.
[7] J-W. Lee, M. Chiang, and A. Calderbank, "Utility-optimal random-access control," IEEE Transactions on Wireless Communications, vol. 6, pp. 2741-2751, July 2007.
[8] E. Egea-Lopez, P. Pavon-Marino, "Distributed and Fair Beaconing Rate Adaptation for Congestion Control in Vehicular Networks," to be published in *IEEE Transactions on Mobile Computing*.
[9] I. Ren and W. Liang, "The use of a mobile sink for quality data collection in energy harvesting sensor networks," *In Proc. of theIEEE Wireless Communications and Networking Conference (WCNC): networks*, 2013, Shanghai, China, pp. 1145-1150.
[10] M. Chiang, S.H. Low and J.C. Doyle, "Layering as optimization decomposition: A mathematical theory of network architectures," *In Proc. of the IEEE*, 2007, pp.255-312.
[11] O. Aytar and M. Rogers, "Pyramid Research's Insider Report", Technical Report, (2014, November). Available: www.pyramidresearch.com.
[12] G. Finnie, "Creating Connected Continents Bringing people together through FTTH", *The Light Age Communicating at the speed of light*. February 2015. Volume 6. Available: http://www.ftthcouncil.eu/documents/Publications/TLA6.pdf.
[13] Ö Can Turna, M. Al, A. Halim Zaim and T. Atmaca, "A new dynamic bandwidth allocation algorithm based on online–offline mode for EPON", *Optical Switching and Networking*, vol.15, pp. 29–43, January 2015.
[14] S. Herrería-Alonso, M. Rodriguez, M. Fernández and C. López, "On the Use of the Doze Mode to Reduce Power Consumption in EPON System," *IEEE/OSA Journal of Lightwave Technology*, vol. 32, pp. 285–292, January 2014.
[15] A. Walid and A Chen, "Efficient and dynamic bandwidth allocation for Non-Status Reporting Gigabit Passive Optical Networks (GPON)," *In Proc. of the 2015 IEEE International Conference on Communications (ICC)*, 2015, Kuala Lumpur, Malasia, pp. 1000-1005.
[16] F. Kelly, "Charging and rate control for elastic traffic," *European transactions on Telecommunications*, vol. 8, pp. 33–37, 1997.
[17] J. Mo and J. Walrand, "Fair end-to-end window-based congestion control," *IEEE/ACM Transactions on Networking (ToN)*, vol. 8, pp. 556–567, 2000.
[18] M. Ma, Y., Zhu and T-H. Cheng, "A bandwidth guaranteed polling MAC protocol for ethernet passive optical networks," *In Proceedings of the Twenty Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003)*, 2003, San Francisco, USA, pp. 22–31.
[19] H. Kim, H. Park, D-K. Kang, C. Kim and G-Y. Yoo, "Sliding Cycle Time-based MAC Protocol for Service Level Agreeable Ethernet Passive Optical Network," *In Proceedings of the IEEE Conference on Communications (ICC 2005)*, 2005, Seul, Korea, pp. 1848-1852.
[20] D. Nowak, P. Perry and J. Murphy, "A Novel Service Level Agreement Based Algorithm for Differentiated Services Enabled Ethernet PONs," *In Proceedings of the 3rd International Conference on Optical Internet (COIN 2004)*, 2004, Japan, pp. 598-599.
[21] A. Dixit, B. Lannoo, G. Das, D. Colle, M. Pickavet and P. Demeester, "Dynamic bandwidth allocation with SLA awareness for QoS in ethernet passive optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, pp. 240–253, March 2014.
[22] T. Jiménez, N. Merayo, P. Fernández. R.J. Durán, I. de Miguel, R.M. Lorenzo and E.J. Abril, A PID-based algorithm to guarantee QoS delay requirements in LR-PONs. *Optical Switching and Networking*, vol. 14, pp.78-92, August 2014.
[23] C. Knospe, "PID Control," *IEEE Control Systems Magazine*, vol. 26, pp. 30-31, February 2006.
[24] K.H. Ang, G. Chong and Y. Li, "PID Control System Analysis, Design and Technology," *IEEE Transactions on Control Systems Technology*, vol. 13, pp. 559-576, July 2005.
[25] T. Jiménez, N. Merayo, P. Fernández. R.J. Durán, I. de Miguel, R.M. Lorenzo and E.J. Abril, "Implementation of a PID Controller for the Bandwidth Assignment in Long-Reach PONs," *Journal of Optical Communications and Networking*, vol. 4, pp. 392-401, May 2012.
[26] K.M., Hussain, R. Allwyn, M. Shantha and M. Giriraj, "Comparison of PID Controller Tuning Methods with Genetic Algorithm for FOPTD System," *International Journal of Engineering Research and Applications*, vol. 4, pp. 1177-1180, March 2014.
[27] W. Lu, "The PID Controller Based on the Artificial Neural Network and the Differential Evolution Algorithm," *Journal of Computers*, vol. 7, pp. 2368-2375, October 2012.

[28] G. Kramer, B. Mukherjee, Y. Ye, S. Dixit and R. Hirth, "Supporting differentiated classes of service in Ethernet passive optical networks," Journal of Optical Networking, vol. 1, pp. 280–298, August & September 2002.
[29] IEEE 802.3ah Ethernet in the First File Task Force, IEEE 802.3ah Ethernet in the First File Task Force home page. Available: http://www.ieee802.org/3/efm/public/.
[30] Available: OMNeT++ Discrete Event Simulator-Home. (2015). http:// www.opnet.com, Accessed.
[31] C-H. Chang, N. Merayo, P. Kourtessis, R.M. Lorenzo and J.M. Senior, "Full-service MAC protocol for metro-reach GPONs," *IEEE/OSA Journal of Lightwave Technology*, vol. 28, pp. 1016 -1022, April 2010.
[32] H. Song, A. Banerjee, B.W. Kim and B. Mukherjee, "Multi-Thread Polling: A Dynamic Bandwidth Distribution Scheme in Long-Reach PON," *IEEE Journal on Selected Areas in Communications*, vol. 27, pp. 134-142, February 2009.
[33] B. Kantarci and H.T. Mouftah, "Delay-Constrained Admission and Bandwidth Allocation for Long-Reach EPON," *Journal of Networks*, vol.7, pp. 812-820, May 2012.
[34] Kramer G. (2001). Synthetic self-similar traffic generation, Available: http://glenkramer.com/ucdavis/trf_research.html.
[35] N. Merayo, P. Fernández. R.J. Durán, I. de Miguel, R.M. Lorenzo and E.J. Abril., "EPON bandwidth allocation algorithm based on automatic weight adaptation to provide client and service differentiation," *Photonic Network Communication*, vol. 17, pp. 119-128, April 2009.
[36] 10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification, ITU-T Recommendation G.987.3, ITU Standard, January 2014.

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