IFAISTOS: A Fair and Flexible Resource Allocation Policy for Next-Generation Passive Optical Networks

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***Abstract*—In modern, competitive, and dynamic access networks the underlying bandwidth distribution mechanism has to be capable of understanding user requirements, meeting stringent quality of service (QoS) demands, and satisfying a broad spectrum of user traffic dynamics. Undoubtedly, optical fiber is the dominant transmission medium enabling practical and cost-effective optical infrastructures in the last mile. Passive optical networks (PONs) represent one of the most promising player towards the fiber to the home (FTTH) vision allowing users to experience high quality, demanding multimedia services and applications. The 10-gigabit-capable passive optical network (XG-PON), one of the latest PON standard, incorporates a set of profound conditions a contemporary PON should ensure. Fairness provisioning constitutes one of the most critical features a PON should provide. However, ensuring fairness in an access network with numerous different users, requesting multiple traffic flows in any time, is not a straightforward task. In this work, we focus on the fairness issue by devising an adaptive, efficient, and fair dynamic bandwidth allocation (DBA) scheme called Insistent FAIr STrategy prOcesS (IFAISTOS). IFAISTOS investigates and maintains user traffic profiles. Overloaded users are carefully treated by gaining greater granting windows than other users; however bandwidth monopolization is prevented. Fairness is ensured for all users in terms of traffic load and average delay. A steering, adaptive mechanism records user traffic profiles by changing and defining bandwidth weights proportional to individual traffic needs. Extensive simulation results reveal the efficacy of the proposed DBA in terms of fairness and average packet delay.**

***Index Terms*—Dynamic bandwidth allocation, fairness, learning automata, passive optical networks, XG-PON.**

I. INTRODUCTION

Passive optical networks (PONs) architecture is the focal representer of optical technology in the last mile [1]. They present numerous influential assets: a) a cost-effective, optical-based solution, without needing regenerators, amplifiers, or active converters, b) a flexible infrastructure allowing scaling up at low cost, c) broad deployment which means that a PON could cover over 60 Km distance between the central office (CO) and the most distant user, and d) various, concurrent service level agreements (SLAs) enclosing heterogeneous quality of service (QoS) guarantees among numerous users withing the network. Indeed, there is a growing interest on optimizing the performance of many inner components and processes of the PON [2].

Next generation PONs (NG-PONs) have been recently inaugurated in order to further empower the network capabilities [3]. By delivering shared Internet access up to 10 Gbps, the latest standard of the telecommunication standardization sector of the international telecommunication union (ITU-T), called 10-gigabit-capable passive optical network (XG-PON), is envisioned to provide even more applications to even more users [4]. Nevertheless, having in mind that the number of users potentially connected to a PON is growing, the responsibility of delivering data following multiple user traffic requirements becomes more pressing. Data delivery should be carried out without violating QoS agreements, while user requests should be met in time according to their SLAs. Accordingly, users that share the same SLA should experience the same level of services. This implies that the network performance is efficient enough to provide good and fair data delivery to all users.

An adaptive, efficient, and fair bandwidth distribution scheme is proposed in this paper. The scheme is called Insistent FAIr STrategy prOcesS (IFAISTOS) and endeavors to address stability issues in XG-PON systems in terms of throughout and delay. In particular, IFAISTOS incorporates a traffic monitoring mechanism recording over-loaded traffic requests. It proportionally assigns weights in each user and it tries to satisfy insistent bandwidth requests without overshadowing other contending users. Bandwidth monopolizing is prevented and the bandwidth distribution becomes fair, satisfying all user requests even when they intensively press for more bandwidth. To this end, the bandwidth distribution is efficient and more fair compared to conventional schemes that apply a common, traffic-unaware, stringent sharing policy. Wide-ranging simulation results demonstrate the efficacy of the proposed scheme in terms of throughout, fairness provisioning, and average delay by employing real multimedia traffic traces.

The remainder of the paper is organized as follows. Section II introduces several features of the underlying allocation policies in order to provide a better understanding of the XG-PON sub-layers. In Section III existing research efforts towards resource allocation in XG-PON are outlined. A detailed description of the proposed scheme is provided in Section IV. Section V illustrates the obtained results, followed by detailed reports. Finally, conclusions are given in Section VI.

II. BACKGROUND

The XG-PON [4] emerges as the evolutionary standard from the previous gigabit PON (GPON) [5], offering a downstream capacity of 2.488 Gbps and an upstream capacity of 1.244 Gbps, to the NG-PON epoch [6], where it constitutes the main representative providing 9.953 Gbps in the downstream and 2.488 Gbps in the upstream direction. As its predecessors, assuming a tree topology, it consists of two main, active components, i.e., the optical line termination (OLT) in the CO and multiple optical network units (ONUs) in the user side, and a single passive one, i.e., the passive splitter/combiner which splits a single feeding fiber from the CO to the ONUs and combines multiple fiber lines stemming from the ONUs destined to the OLT. Accordingly, two directions are defined: the downstream flow, from the OLT to the multiple ONUs, and the upstream flow, from the ONUs to the OLT. Obviously, the downstream flow engages a broadcast transmission nature, while the upstream flow entails coordination communication between the OLT and the ONUs.

XG-PON transmission convergence (XGTC) layer is the core mechanism of the system. It involves several protocols, processes, and procedures that define and incorporate functional tasks such as a) executing resource allocation in both directions, b) ensuring QoS guarantees, and c) interconnecting the upper layers with the physical layer. According to the ITU-T, the XGTC layer is structured in three sub-layers, namely the service adaptation, the framing, and the physical (PHY) sub-layer. The service adaptation sub-layer performs service data unit (SDU) encapsulation and multiplexing and creates XG-PON encapsulation method XGEM frames. The framing sub-layer receives the constructed XGEM frame and forms the downstream XGTC frame. The downstream frame is formed by multiplexing XGTC payloads based on their Alloc-ID. The Alloc-ID identifies the recipient of the allocation within the ONU. Lastly, the PHY sub-layer applies error coding bits, performs scrambling to the content, and synchronizes the frames.

The downstream direction is utilized in order to deliver traffic flow from the OLT to the ONUs. The OLT is responsible of creating a downstream frame, which is periodically broadcast to ONUs every 125 μsec, including the data packets destined to ONUs together with control and coordination information. The duration of the downstream frame, in accordance with the given downstream rate, corresponds to 155520 Bytes. Downstream and upstream flows are associated via a coordination information field, called bandwidth map (BWmap). This field is used by the OLT in order to inform the ONUs about the allocated transmission opportunities. It informs them about the start time of the transmission opportunity and the grant size per Alloc-ID for each ONU.

The upstream flow entails more complex issues. First, a coordination policy is mandatory since the optical fiber which connects the OLT with the passive splitter/combiner is shared among all ONUs. Having in mind that signal collisions are not allowed in this part of fiber, the OLT is solely responsible to devise a transmission schedule and distribute it to all ONUs. As previously mentioned, this schedule is delivered to each ONU via the BWmap control information, hence each ONU is aware of the transmission schedule. The upstream bandwidth accounts for 38880 Bytes due to the fact that the (nominal) upstream data rate is 2.488 Gbps. The upstream burst is constructed by the ONU enclosing the physical synchronization block upstream (PSBu) in the beginning of the burst, containing the preamble and the delimiter fields. Then the XGTC burst follows which includes a control field in the front (XGTC header) and a trailer (XGTC trailer). After XGTC header the allocations per Alloc-ID of the ONU follows. An inner control information called dynamic bandwidth report (DBRu) carries out critical bandwidth information form the corresponding ONU to the OLT. In particular, the buffer occupancy (BufOcc) field contains the total amount of SDU traffic, expressed in units of 4-byte words, aggregated across all the buffers associated with the Alloc-ID. In other words, the OLT informs the ONU using the BWmap field and each ONU responds, with its traffic requests, using the BufOcc field.

Nevertheless, a specific bandwidth allocation policy is needed in order to serve the multiple ONUs. According to the XG-PON specifications, each ONU is granted a portion of guaranteed bandwidth and a portion of best effort traffic. In particular, each ONU is granted a guaranteed bandwidth portion including three allocation parameters: a) the fixed bandwidth, R_f, is given regardless of the ONU's traffic demands, b) the assured bandwidth, R_a, is given as long as the ONU has unsatisfied traffic demands, and c) the maximum bandwidth, R_m, represents the upper limit on the total (guaranteed) bandwidth. Beyond the guaranteed bandwidth, the surplus bandwidth is shared to ONUs still having unmet bandwidth requests. Nonetheless, the exact way of defining the bandwidth allocation process has been left open for designing and optimization.

III. RELATED WORK

Despite several research efforts towards the development of DBA schemes, mostly for the upstream direction, for GPONs or XG-PONs, the trade-off between efficiency and fairness has not been extensively addressed. For example, bandwidth distribution effectiveness is the main objective in [7], where a high-utilization policy was introduced in order to effectively share the surplus bandwidth to users. However, the fairness issue was not examined. Another effort in [8] presented a different approach on delivering data traffic to end user in XG-PON systems. The authors designed an integrating XG-PON architecture and an end-to-end generalized multi-protocol label switching (GMPLS) environment. By using labels instead of other addressing systems, the work applies a flexible multi-layer network supporting multiple configurations. Nonetheless, the bandwidth distribution neglects the fairness feature.

On the other hand, recent studies in examining potential deficiencies in downstream direction indicated that considerable insufficiency in terms of fair bandwidth distribution may be induced when a simple policy like first come first served (FCFS) is applied [9] [10]. This pitfall was addressed by proposing fair solutions for distributing the available bandwidth to the downstream traffic rows, utilizing efficient techniques such as the Max-Min method and the weighted shortest processing time (WSPT) first rule.

By examining the efforts presented in the literature, we can infer that a) the playground of developing fair and efficient DBA algorithms for both directions in XG-PON systems remains open and compelling and b) the trade-off between efficient and fair bandwidth distribution has not been adequately investigated. This work endeavors to cover this gap by developing a fair, efficient, and adaptive DBA scheme for upstream bandwidth allocation in XG-PON systems.

IV. IFAISTOS

This Section outlines the proposed upstream DBA strategy.

A. Objectives

Solving the trade-off between fairness and efficiency regarding the performance of upstream bandwidth distribution remains an open and compelling challenge. This work endeavors to provide a balanced upstream bandwidth allocation in terms of fairness and efficiency. In particular, the following objectives are set as the aim of this work:

- Bandwidth monopolization prevention. Overloaded ONUs should be not permitted to monopolize the upstream capacity. However, they are allowed to receive special treatment as long as they do not harm the rest ONUs.
- Traffic-aware scheduling. The bandwidth allocation policy should be capable of perceiving the individual traffic needs of the ONUs, supporting a dynamic, balanced, and fair upstream schedule.
- Fairness should be ensured for all users based on their SLAs. The way of guaranteeing fair bandwidth distribution should be adequate in such a way that all ONUs receive proportionally equal bandwidth in proportionally equal waiting time (delay).
- The network performance should be attained in the same good level, yet it could be improved, if possible.

It is obvious that a sophisticated method is required to provide both fairness and efficiency in the upstream flow of the XG-PON system. The method should be adaptive, capable of detecting the special traffic requirements of each ONU, flexible, able to readjust the allocation schedule based on the traffic observations, and rigorous, entailing concrete and effective rules to prevent negative phenomena (traffic monopolization). To this purpose, a traffic-aware, adaptive, and fair strategy based on learning automata (LAs) is employed.

TABLE I
IFAISTOS NOTATIONS

C	Upstream Capacity
N	Number of ONUs
$R^i(y)$	Requested Bandwidth of ONU i at Cycle y
$R^i_g(y)$	The Non Guaranteed Bandwidth Granted to ONU i at Cycle y
R_f	Fixed (granted) Guaranteed Bandwidth
R_a	Assured (granted) Guaranteed Bandwidth
R_m	Maximum (upper bound) Guaranteed Bandwidth
$C_f(y)$	Residual Bandwidth After Allocating Fixed Guaranteed Bandwidth at Cycle y
$C_a(y)$	Residual Bandwidth After Allocating Assured Guaranteed Bandwidth at Cycle y
$C_m(y)$	Residual Bandwidth After Allocating Guaranteed Bandwidth at Cycle y
$BUP^i(y)$	Bandwidth Utilization Profile of ONU i at Cycle y
R^i	Accumulated Requested Bandwidth of ONU i
A^i	Accumulated Allocated Bandwidth for ONU i
ABU	Average Bandwidth Utilization
$U(y)$	Group of Underloaded ONUs at Cycle y
$O(y)$	Group of Overloaded ONUs at Cycle y
$W(y)$	Allocation Weights at Cycle y
L	Updating Impact
a	Zero Protection Parameter
$SW(y)$	Portion of Weight Obtained by the Underloaded ONUs and Granted to OverLoaded ONUs at Cycle y
$q^i(y)$	Normalized Factor of ONU i at Cycle y

B. Traffic-aware Enhancement

LAs play an important role as adaptive enhancement in a broad range of communication schemes, algorithms, and protocols. They are flexible enough to adapt in all networking layers. In this work, the logic of LAs is adopted in order to provide the OLT with intelligence on deciding the upstream schedule.

Each OLT is enhanced with a learning from experience component. LAs are artificial intelligence tools that can provide adaptation to systems operating in changing and/or unknown environments [11]. An automaton interacts with its surrounding environment and aims at learning the optimal action subject to a complete set of possible decisions. The environment feeds the automaton with a feedback as a result of its decision. In other words, the automaton decides, the environment reacts and generates a feedback, and then this feedback is received by the automaton. As an inner process of the automaton, there is a learning mechanism which compiles the feedback and readjusts its decision logic. In our case, the environment includes the traffic activity of the ONUs and the network configuration, e.g., bandwidth allocation rules and restrictions.

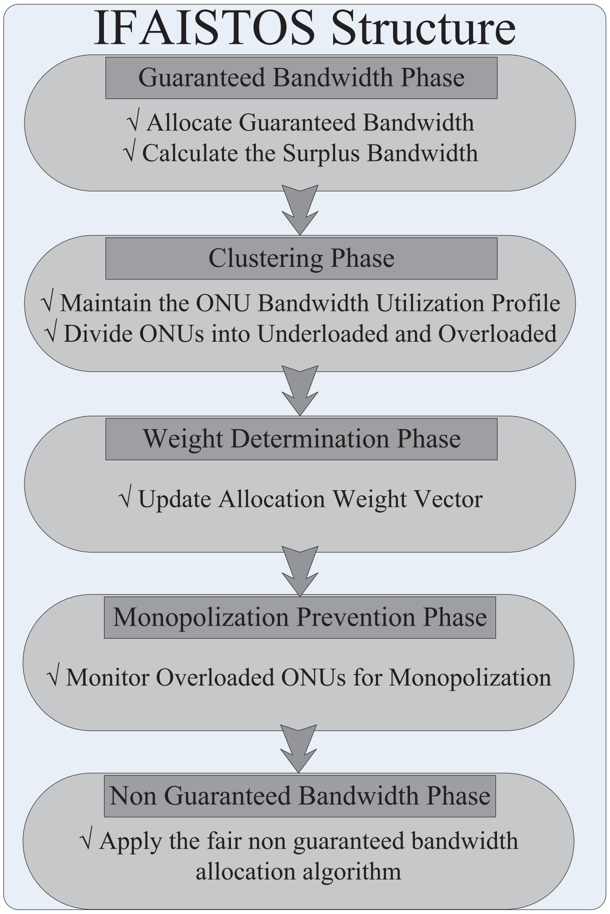

Fig. 1. IFAISTOS phases.

C. Building Blocks

The operation of the proposed scheme is illustrated in Figure 1, while Table I outlines the main notations of the proposed scheme. The operation of IFAISTOS contains five phases, namely a) the *guaranteed bandwidth phase*, b) the *clustering phase*, c) *weight determination phase*, d) the *monopolization prevention phase*, and e) the *non guaranteed bandwidth phase*. The operation of IFAISTOS is periodically repeated each 125μsec. This period defines a cycle, denoted by y.

D. Guaranteed Bandwidth Phase

Given that the portion of guaranteed bandwidth is enough for all ONUs, i.e., $C > \sum_{i=1}^{N} R_m$, where C denotes the available upstream bandwidth, R_m the upper bound of the guaranteed bandwidth, and N the number of the ONUs in the XG-PON, IFAISTOS first allocates the fixed bandwidth, R_f, to all ONUs initialing thus the first phase (*guaranteed bandwidth phase*) of the allocation policy. As a result, the residual bandwidth after allocating the fixed rate, $C_f(y) = C - \sum_{i=1}^{N} R_f$, where $C_f(y) > 0$, is now available to distribute the assured bit rate, R_a, to the ONUs still having unsatisfied bandwidth requests. Accordingly, the algorithm allocates the assured bandwidth to ONUs needing more bandwidth, hence the residual bandwidth after allocating the assured rate, $C_a(y) = C_f(y) - \sum_{i=1}^{N} R_a$, where $C_a(y) > 0$, is now available to meet the bandwidth requirements of the ONUs that remain unsatisfied. Lastly, IFAISTOS finalizes the first phase of the allocation process by completing the distribution of the guaranteed bandwidth to all ONUs. The surplus bandwidth allocation is defined as follows:

$$C_m(y) = C_a(y) - \sum_{i=1}^{N}(R_m - R_a - R_f), \text{ where } C_m \geq 0 \quad (1)$$

Next, the algorithm examines whether the surplus bandwidth ($C_m(y)$) is sufficient to meet the non guaranteed ONU demands. In the optimal case holding $C_m(y) > \sum_{i=1}^{N}(R^i(y) - R_m)$, where $R^i(y)$ stands for the requested bandwidth of ONU i, the allocation process of this cycle comes to an end. Otherwise, the algorithm moves to the *clustering phase*. In the following, each phase is described in detail.

E. Clustering Phase

IFAISTOS is responsible of ensuring a fair and efficient bandwidth distribution of non guaranteed bandwidth to ONUs that contend access to satisfy their best effort traffic requirements. In this case, it holds:

$$\sum_{i=1}^{N}(R^i(y) - R_m) > C_m(y) \quad (2)$$

The bandwidth utilization profile ($BUP^i(y)$) is introduced in each cycle y to record the traffic profile of each ONU i:

$$BUP^i(y) = \frac{R^i}{A^i} \quad (3)$$

The parameters R^i and A^i denote the accumulated requested and allocated bandwidth of each ONU i respectively. Furthermore, the average bandwidth utilization (ABU) is calculated in order to be used as a balanced factor:

$$ABU(y) = \frac{\sum_{i=1}^{N} BUP^i(y)}{N} \quad (4)$$

Consequently, IFAISTOS divides the group of ONUs, having non guaranteed requests, into two groups; the group of overloaded ONUs, $O(y) = \{ONU_1, ONU_2, ..., ONU_j\}$, and the group of underloaded ONUs, $U(y) = \{ONU_1, ONU_2, ..., ONU_k\}$, where $j + k = N$. ONUs experience $BUP^i(y)$ lower than the balanced factor ABU are deemed as overloaded and inserted to $O(y)$ list, whereas ONUs having utilization larger than ABU are added to the $U(y)$ list. The third phase inaugurates the *weight determination phase*.

F. Weight Determination Phase

In this stage, IFAISTOS makes use of the enhanced automaton operation. The OLT combines the acquired information by checking ONUs' traffic profiles and the output of the automaton in order to form the upstream bandwidth allocation. This process is periodically repeated each 125 μsec.

First, a weight vector is maintained for each ONU. The weight vector is called *allocation weight* and denotes the priority of each ONU on receiving non guaranteed bandwidth. The higher the weight of an ONU is, the more bandwidth is granted to this ONU. The *allocation weight* vector is defined as follows:

$$W(y) = \{w_1(y), w_2(y), ..., w_N(y)\} \tag{5}$$

The summation of all *allocation weights* yields unit:

$$\sum_{i=1}^{N} w_i(y) = 1 \tag{6}$$

Initially, all weights are equally set:

$$w_i(1) = 1/N,\, 1 \leq i \leq N \tag{7}$$

The weights attached to the ONUs are dynamic subject to the traffic profile of each ONU. Overloaded ONUs are associated with higher weights then underloaded ONUs. Hence, the BUP parameter determines the *allocation weight* vector. Motivated by the award/penalty probability update of learning automata [12], the *allocation weight* vector is dynamically updated based on the *clustering phase* result. Those ONUs belong to the group of overloaded ONUs ($O(y)$) are slightly favored, whereas ONUs that belong to the group of underloaded ONUs ($U(y)$) are slightly penalized. The updating process at cycle $y+1$ holds as follows:

$$w_i(y+1) = w_i(y) - L(w_i(y) - a),\, \forall ONU_i \in U(y) \tag{8}$$

According to Eq. (8) the weight of all underloaded ONUs is slightly reduced by $L(w_i(y) - a)$, where L stands for the updating impact and a is a very small number that keeps each weight larger than zero. The updating impact parameter defines the impact of the weight updating process. The larger the L, the larger the impact. Normally, the parameter a receives a minimal number, i.e., 10^{-5}. The summation of the amount of weight obtained of each underloaded ONU, denoted as $SW(y)$, is given below:

$$SW(y) = \sum_{k=1, ONU_k \in U(y)}^{N} L(w_k(y) - a) \tag{9}$$

In the following, the amount of $SW(y)$ is divided into the overloaded ONUs proportionally to their weights:

$$w_i(y+1) = w_i(y) + SW(y) \cdot q_i(y),\, \forall ONU_i \in O(y) \tag{10}$$

The parameter $q_i(y)$ expresses the normalized factor which is obtained in accordance with the ONUs' weights:

$$q_i(y) = \frac{w_i(y)}{\sum_{k=1, ONU_k \in O(y)}^{N} w_k(y)} \tag{11}$$

G. Monopolization Prevention Phase

Upon updating the *allocation weight* vector, the *monopolization prevention phase* takes place. Undoubtedly, a bandwidth monopolization can occur if the *allocation weight* of an ONU continuously increases. To this end, IFAISTOS applies a prevention mechanism to each ONU that belongs to the overloaded group. In particular, a probability equal to $w_i(y)$ is defined for each overloaded ONU ($ONU_i \in O(y)$), at cycle y, that enforces this ONU to return to the initial state, where the initial state entails that $w_i(y) = 1/N$. Hence, the larger the $w_i(y)$, the more probable for the ONU_i of transitioning to the initial state. If this happens, the residual amount of weight ($Residual$) of this ONU is divided into the rest ONUs.

$$Residual = w_i(y+1) - 1/N \tag{12}$$

$$w_i(y+1) = 1/N \tag{13}$$

$$\text{with probability } w_i(y+1)\ \forall ONU_i \in O(y)$$

$$w_j(y+1) = w_j(y+1) + \frac{Residual}{N-1},\, \forall ONU_j,\, j \neq i \tag{14}$$

H. Non Guaranteed Bandwidth Phase

Algorithm 1: Fair non guaranteed bandwidth allocation

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INPUT: The allocation weights, the surplus bandwidth $C_m(y)$, the requested bandwidth of each ONU, $R^i(y)$ $(1 \leq i \leq N)$
OUTPUT: The non guaranteed bandwidth granted to each ONU, $R^i_g(y)$
for each cycle $y$ do
   Set $R^i_g(y) = w_i(y) \cdot C_m(y)$
   for i=1:N-1 (each $ONU_i$) do
      if $R^i_g(y) > R^i(y) - R_m$ then
         for j=i+1:N do
            $R^j_g(y) = R^j_g(y) + \frac{R^i_g(y)-(R^i(y)-R_m)}{N-i}$
         end for
      end if
   end for
end for
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The final phase (*non guaranteed bandwidth*) incorporates the final bandwidth allocation process. Non guaranteed bandwidth is granted to ONUs that still have non guaranteed requests based on their *allocation weights.* Motivated by the fact that the max-min policy can ensure optimal schedule, a modified max-min non guaranteed bandwidth allocation policy

TABLE II
TRAFFIC PARAMETERS

Traffic Class	Average Rate	Total Number of Packets
VoIP	0.038 Mbps	300
Real Media Streaming	0.04 Mbps	1400
Live Stream	0.04 Mbps	1500

is proposed. Algorithm 1 describes this policy. It receives a) the ONU *allocation weights*, b) the surplus bandwidth $C_m(y)$ (available to serve non guaranteed bandwidth requests), and c) the requested bandwidth of each ONU $R^i(y)$ ($1 \leq i \leq N$), at cycle y. It calculates the non guaranteed bandwidth granted to each ONU, denote by $R^i_g(y)$. In essence, the algorithm calculates the granted bandwidth in accordance with the normalized weights of each ONU ($R^i_g(y) = w_i(y) \cdot C_m(y)$) and then each surplus bandwidth from ONUs that request less bandwidth than the granted ($R^i_g(y) > (R^i(y) - R_m)$) is shared among the rest ONUs ($R^j_g(y) = R^j_g(y) + \frac{R^i_g(y)-(R^i(y)-R_m)}{N-i}$). In this way, IFAISTOS ensures a fair and a traffic-aware bandwidth allocation policy.

V. PERFORMANCE EVALUATION

The performance of the proposed scheme is investigated in this Section in terms of efficiency and fairness.

A. *Environment*

The operation of a typical XG-PON in a tree topology was simulated in Matlab environment in order to assess the performance of IFAISTOS. The designed network consists of an OLT, which applied IFAISTOS on constructing the upstream bandwidth allocation schedule, and multiple ONUs. Each ONU produces upstream traffic which is divided into four categories: a) Voice over IP (VoIP) session using the user datagram protocol (UDP) and the Skype application, b) real media streaming application based on transmission control protocol (TCP), c) live stream session based on transmission control protocol (TCP), and d) constant bit rate (CBR) background (best effort) traffic. The first three traffic sessions were produced based on real traffic traces, obtained by real sessions, captured with the Wireshark tool. Table II summarizes the multimedia traffic parameters. The background traffic is dynamically configured in each ONU in order to keep heterogeneous traffic requests among the various ONUs. In this way, the rate of the applied background traffic alters in each ONU i according to the following formula:

$$\text{Background Rate } = \frac{0.1 \cdot i}{\textit{Background Load Parameter}} \text{ Mbps} \tag{15}$$

The *background load parameter* is introduced to express the rate of the background traffic requests of each ONU. The default value of this variable is 1.

The guaranteed bandwidth was configured according to the standard descriptors. To be more specific, the fixed bandwidth was set to 250 Bytes per ONU, the assured bandwidth was set to 500 Bytes per ONU, and the maximum bandwidth was set to 750 Bytes per ONU. The position of each ONU from the OLT was uniformly determined from 30 to 60 Km. Each ONU is equipped with a large enough buffer so as to prevent data packet losses, e.g., 100 MB. Considering the operation of the automaton, the updating impact was set to 0.1, since this value was the most effective one based on the conducted experiments. The value of the parameter a was set to 10^{-5}. For each experiment conducted the simulation time was set to 100 sec. To prevent upstream transmissions from colliding and jamming each other, the OLT keeps a guard time between upstream allocations equal to 64 bits. Table III summarizes the main simulation parameters.

TABLE III
SIMULATION PARAMETERS

Upstream Rate	2.488 Gbps
Downstream Rate	9.953 Gbps
ONU Buffer Size	100 MB
Fixed Guaranteed Bandwidth	250 Bytes
Assured Guaranteed Bandwidth	500 Bytes
Maximum Guaranteed Bandwidth	750 Bytes
Downstream Frame Period	125 μsec
Guard Time	64 bits
Updating Impact	0.1
Protection Parameter	10^{-5}
Simulation Time	100 sec
Background Load Parameter (default)	1

IFAISTOS is compared against the so called 'Fixed' scheme. The Fixed scheme differs from IFAISTOS on the way of processing the surplus bandwidth stemming after the guaranteed bandwidth allocation. Unlike IFAISTOS, it applies a 'blind' policy granting bandwidth to each ONUs still having unsatisfied (non guaranteed) traffic requests uniformly.

The following assessment examines three focal performance factors: a) the *delay fairness index*, b) the *load fairness index*, and c) the *average packet delay*. The *delay fairness index* revels how fair is the bandwidth allocation among the ONUs in terms of packet delay. It is based on the well known Jain's fairness index [13] and is defined as follows:

$$J_1(d_1, d_2, ..., d_N) = \frac{(\sum_{i=1}^{N} d_i)^2}{N \sum_{i=1}^{N} d_i^2} \tag{16}$$

In Eq. (16) the parameter d_i denotes the average (upstream) packet delay of each ONU i in terms of seconds. Accordingly, the *load fairness index* indicates how fair the bandwidth allocation is in terms of traffic load received (from ONUs). It is defined as follows:

$$J_2(l_1, l_2, ..., l_N) = \frac{(\sum_{i=1}^{N} l_i)^2}{N \sum_{i=1}^{N} l_i^2} \tag{17}$$

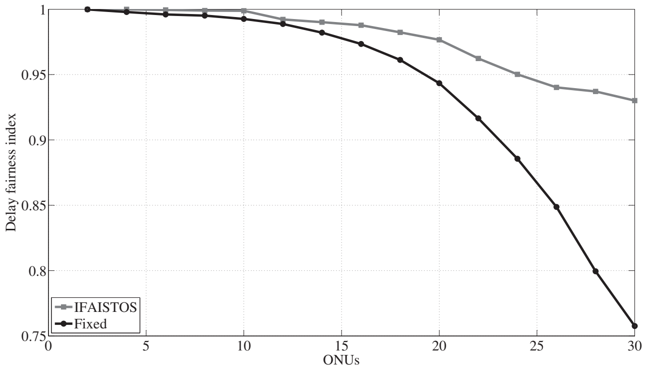

Fig. 2. Delay fairness index as the number of ONUs changes.

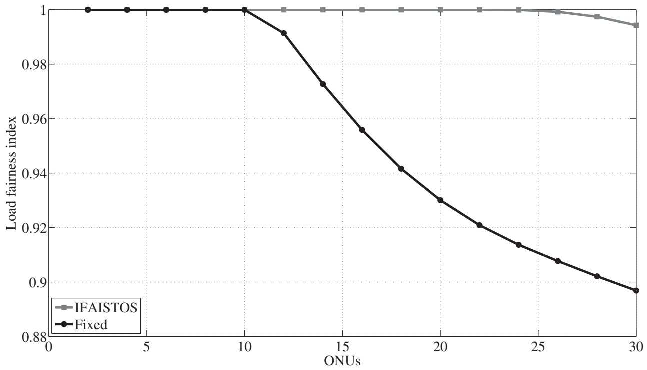

Fig. 3. Load fairness index as the number of ONUs changes.

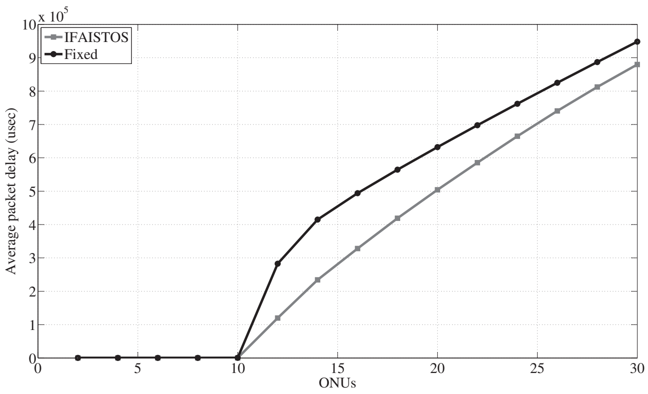

Fig. 4. Average (upstream) packet delay as the number of ONUs changes.

In Eq. (17) the parameter l_i expresses the BUP_i of each ONU i. In other words, it indicates how fair is the ONU satisfaction on addressing its traffic requests. Lastly, the *average packet delay* is defined as the time elapsed from the packet arrival to the final packet delivery to the OLT.

B. Results and Discussion

The impact of population is examined first by increasing the number of ONUs from 2 to 30. Figure 2 and Figure 3 show the *delay fairness index* and the *load fairness index* respectively. Based on the observed results, we can deduce the following remarks:

1) As the number of ONUs increases, the bandwidth distribution becomes more unfair. This is attached to the fact that the (upstream) traffic produced from the ONUs become more heterogeneous. This means that the differentiation between underloaded and overloaded ONUs becomes even larger.
2) By observing the *delay fairness index*, it is obvious that IFAISTOS provide a more fair upstream bandwidth allocation than the Fixed scheme. When the number of ONUs becomes 10, both schemes present losses in terms of delay fairness. However, the proposed allocation policy attains a quite fair performance by reducing this index not less that 0.93 when 30 ONUs are connected to the network. On the other hand, the Fixed scheme collapses by presenting an index of 0.755 for the same number of ONUs. Thus, the level of improvements in terms of *delay fairness index* reaches 25%.
3) The investigation of the *load fairness index* impact reveals even more interesting aspects. The Fixed scheme collapses earlier than in *delay fairness index* performance, after the number of ONUs in the network becomes 10. On the other hand, IFAISTOS succeeds to keep the index more than 0.9 even when the ONUs are 30. The rationale behind this aspect lies in the traffic-aware bandwidth policy. IFAISTOS grants more (non guaranteed) bandwidth to overloaded ONUs in order to address their pressing needs for bandwidth. Concurrently, it prevents traffic monopolization phenomena, and so the bandwidth allocation process of the rest ONUs is not disorientated.

Figure 4 depicts the *average packet delay*. It is important to examine both fairness and efficiency issues so as to deduce about the performance of the two schemes. According to the obtained results, IFAISTOS is able to slightly reduce the average delay, meaning that it offers faster data delivery to the users even though it incorporates a fair bandwidth allocation policy. The difference between the two schemes is around 10% when the number of ONUs reaches its peak. This improvement stems from the fact that IFAISTOS provide more (upstream) traffic opportunities to the bandwidth-hungry ONUs without wasting resources or overshadowing those ONUs that are not so demanding.

In the following, the impact of the background load parameter is examined. Here, the number of ONUs remains stable and equal to 15. Figure 5 and Figure 6 demonstrate the *delay fairness index* and the *load fairness index* respectively, when the background load parameter changes. The obtained results are similar. When the background load parameter is low the traffic demands are high. The pressure for bandwidth becomes more loose when the background load parameter increases. Hence, the bandwidth distribution becomes more fair in general. Thus, it is important to notice the behavior of the two schemes when the background traffic is pressing. For both indexes IFAISTOS provide more fair schedule than the Fixed scheme. It offers about 27% and 10% improvements

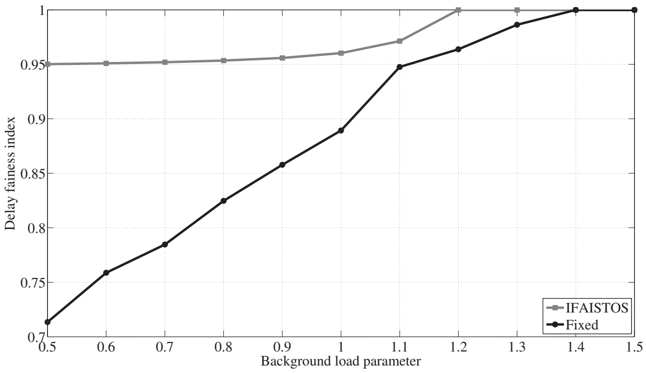

Fig. 5. Delay fairness index as the rate of the background traffic alters.

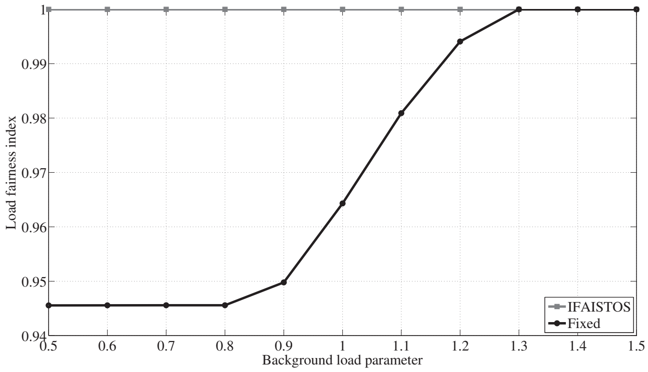

Fig. 6. Load fairness index as the rate of the background traffic alters.

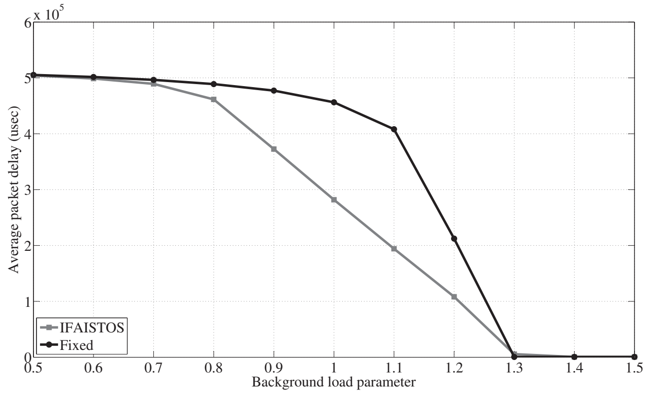

Fig. 7. Average (upstream) packet delay as the rate of the background traffic alters.

in terms of *delay fairness index* and the *load fairness index* respectively. Finally, Figure 7 illustrates the average packet delay as the background traffic requests change. Once more, the proposed scheme presents lower delay that the Fixed scheme due to its ability to serve the demanding ONUs much faster.

Overall, IFAISTOS accomplishes to provide the users of the XG-PON with a fair and effective bandwidth distribution in the upstream direction. The fairness issue is indicated by both the *delay fairness index* and *load fairness index*. At the same time, it ensures a faster data delivery in comparison with the fixed scheme.

VI. CONCLUSIONS

The trade-off between fairness and efficiency is addressed in this work for NG-PON systems. By applying an adaptive, fair, and traffic-aware bandwidth allocation policy the network performance is improved and the bandwidth distribution between the various, heterogeneous ONUs becomes more fair than functioning a uniform, 'blind' policy. The proposed bandwidth allocation policy succeeds to offer up to 27% improvements in terms of fairness index and 10% in terms of average packet delay. In this way, a modern XG-PON system can provide versatile services and application to more users in a fair fashion.

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