HYRA: An Efficient Hybrid Reporting Method for XG-PON Upstream Resource Allocation

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Abstract: The dynamic bandwidth allocation (DBA) process in the modern passive optical networks (PONs) is crucial since it greatly influences the whole network performance. Recently, the latest new generation PON (NG-PON) standard, known as 10-gigabit-capable passive optical network (XG-PON), standardized by the international telecommunication union telecommunication standardization sector (ITU-T), emerges as one of the most efficient access networking framework to cope with the demanding needs of the fiber to the x (FTTX) paradigm, where x stands for home (FTTH), bulding (FTTB), or curve (FTTC). Motivated by the fact that the ITU-T specifications leave the bandwidth allocation process open for development by both industry and academia, we propose a novel DBA scheme for effectively delivering data in the upstream direction. Our idea is based on a subtle suggestion induced by the XG-PON specifications; each developed DBA method should combine both status reporting (SR) and traffic monitoring (TM) techniques. This means that a XG-PON framework should be cognitive enough in order to be able either to request bandwidth reporting from the connected users or estimate users' bandwidth demands or both. In this article we cover this gap by proposing a robust learning from experience method by utilizing a powerful yet simple tool, the learning automata (LAs). By combining SR and TM methods, the proposed hybrid scheme, called hybrid reporting allocation (HYRA), is capable of taking efficient decisions on deciding when SR or TM method should be employed so as to maximize the efficacy of the bandwidth allocation process. Simulation results reveal the superiority of our scheme in terms of average packet delay offering up to 33% improvement.

1 INTRODUCTION

The penetration of optical technology in the access network domain is rapidly gaining ground. Passive optical networks (PONs) are currently the most effective player of optical technology in the last mile playground, since they offer a complete, efficient, all-optical, and cost-effective solution to cope with modern, demanding, and diverse services and applications. In essence, PONs interconnects users to the backbone interface by means of optical fiber providing a full-optical path without the need of optical-to-electrical conversion. This all-optical path creates a transparent point to multi-point interconnection, offering high data rates for both upstream and downstream direction. Nonetheless, the great potential of PONs in terms of huge bandwidth provisioning has not yet fully utilized due to diverse of users behaviors and requirements.

In order to meet users requirements, quality of service (QoS) guarantees should be ensured in PON operation. However, static bandwidth allocations induce low channel utilization and therefore limited service provisioning. Having this in mind, the telecommunication standardization sector of the international telecommunication union (ITU-T) dictates the usage of dynamic bandwidth allocation (DBA) schemes. By applying dynamic bandwidth distribution methods the bursty user traffic demands are effectively addressed. The design of intelligent DBA algorithms advances in a crucial challenge, especially in the upstream direction where multiple users traffic streams have to share common optical paths without negatively affecting the network performance or violating QoS agreements. By incorporating an effective DBA algorithm, and therefore achieving a good network performance, more subscribers could potentially join the network, thus decreasing the network operations costs, and even more standards could be reached on providing cutting-edge applications to users.

The 10-gigabit-capable passive optical network (XG-PON) is one of the most promising standards of the next-generation PONs (NG-PONs). It comes with several powerful assets such as enhanced cryptography, compliance with older standards, higher data rates for both directions, clear QoS-aware bandwidth allocation processes, and energy-efficient support.

In this work, an adaptive, learning from experience, robust resource allocation scheme is proposed in order to alleviate the impact of time-varying traffic changes in the XG-PON systems. The so-called hybrid reporting allocation (HYRA) utilizes a combination of different, heterogeneous, yet allowed by the standard, allocation policies in order to provide a fully standard-compliant, efficient allocation method. HYRA exploits the capabilities of traffic monitoring technique so as to effectively re-distributes the surplus bandwidth gained by isolating the underutilized ONUs. Demanding users are favored and therefore more bandwidth is allocated to active users without overshadowing the network operation. The suggested scheme seems to be capable of adapting to various network changes offering thus notable improvements, in terms of upstream packet delay, as indicated by several simulation results based on real multimedia traffic traces.

The remainder of the paper is organized as follows. Section 2 introduces several features of the underlying allocation policies in order to provide a better understanding of the XG-PON sub-layers. In Section 3 existing research efforts towards resource allocation in XG-PON are outlined. A detailed description of the proposed scheme is provided in Section 4. Section 5 illustrates the obtained results, followed by detailed reports. Finally, conclusions are given in Section 6.

2 BACKGROUND

The XG-PON framework defines a point-to-multipoint optical access infrastructure providing (nominal) 10 Gbps data rate in at least one direction. One of its most determinant layers is the XG-PON transmission convergence (XGTC) layer, in which the functional protocols and procedures including the way of performing resource allocation and provisioning QoS between the upper layers and the physical layer, are thoroughly described. According to the standard specifications, 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 encloses multiple XGTC payloads which are distinguished based on their Alloc-ID. The Alloc-ID field identifies the recipient of the allocation within the ONU. Lastly, the PHY sub-layer applies bit error correction algorithms, it performs scrambling to the content, and it synchronizes the frames. It is worth mentioning that the XGTC layer holds for both upstream and downstream directions, hence the aforementioned procedures reversely hold in the upstream direction.

In the downstream direction the XGTC layer is responsible of receiving SDUs from the upper layers and producing an uninterrupted bitstream at the nominal interface, which in the downstream direction supports 9.95328 Gbps divided into 125 μsec downstream frames. The duration of the downstream frame, in accordance with the given downstream rate, corresponds to 155520 Bytes. However, this size includes coding and control information. The physical synchronization block field comes first in downstream flow (PSBd), which includes a synchronization bitstream, the PON identification number, counters, and other control information. An important control field, known as BWmap, which is associated with the bandwidth allocation process, is enclosed in the XGTC header. It is used by the OLT to inform the ONUs about the granted transmission opportunities; it defines the start time of the transmission opportunity and the grant size per Alloc-ID for each ONU. In essence, the OLT continuously broadcasts data to ONUs, including requested data delivery, messages, and bandwidth allocation information.

The XG-PON standard implicitly assumes synchronization between downstream and upstream frames. This means that the i-th downstream frame is associated to the i-th upstream frame, even though the i-th upstream frame could reach the OLT late due to propagation time. Nonetheless, the allocation information included in the i-th downstream frame corresponds to the i-th upstream frame. To be synchronized, both frames have the same length, thus the duration of the upstream frame is 125 μsec. However, it accounts for 38880 Bytes due to the fact that the (nominal) upstream data rate is 2.48832 Gbps. The

PSB of the upstream frame (PSBu) contains 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). The existence of the inner header, which is called dynamic bandwidth report (DBRu), determines the adopted resource allocation method. Two options are allowed by the standard, namely a) the *status reporting (SR) method*, in which each allocation encloses the DBRu header and reports the OLT its buffer status, and b) the *traffic monitoring (TR)*, in which the OLT monitors the idle upstream frames to perceive the bandwidth pattern of each Alloc-ID. According to the specifications, the XG-PON OLT should support both techniques in a separate way or even combined. More information about XG-PON could be found in (Effenberger, 2010).

The resource allocation obeys to specific downstream and upstream principles. Each ONU receives a guaranteed bandwidth portion including three allocation parameters: a) the fixed bandwidth, R_f, is given regardless of 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.

3 RELATED WORK

In general, the development of novel, efficient, and effective DBA schemes in PONs have received a lot of attention. The authors in (Kanonakis and Tomkos, 2009) introduced the offset-based scheduling with flexible intervals concept for gigabit PONs (GPONs). The rationale behind this concept stands on applying flexible scheduling intervals. In essence, the authors proposed lower scheduling intervals regarding the polling policy between the ONUs and the OLT; however they keep the SR method as the main reporting method. The scheme presents improvements in terms of network throughput and average packet delay. In (Han, 2014) a high-utilization scheme was presented. A common available byte counter and a common down counter for multiple queues of a service class are utilized in order to effectively share the surplus bandwidth to demanding users. Our previous efforts in (Sarigiannidis et al., 2013b) deals with the fairness provisioning, by intending to resolve unequal resource allocation in the downstream data delivery. In particular, a fair bandwidth assignment scheme is devised and evaluated. The Max-Min fairness concept is applied in order to ensure a fair downstream broadcast schedule between multiple ONUs.

Beyond bandwidth allocation development, in (Yoshimoto et al., 2013), flexible speed upgrades for NG-PONs, such as the XG-PON, are discussed. The authors investigate performance and cost issues while they face reach extensions matters. Efforts in (Mullerova et al., 2012) focus on the usage of specific wavelength blocking filters so as to restrain the undesirable interference when GPONs and XG-PONs coexist. In (Lee et al., 2013) an ONU fast management that reduces the time required to update a remotely-located user terminal's software was inaugurated. Finally, features of the first XG-PON testbed could be found in (Jain et al., 2011).

By examining the efforts presented in the literature we can easily infer that a) the research field of providing effective bandwidth allocation in XG-PON remains open and challenging and b) all DBA schemes presented in literature assume the SR method as the core scheduling policy. In this article, we step beyond the pure usage of the SR method by inaugurating a hybrid reporting method that takes into account the existing bandwidth pattern revealed by functioning the TR method.

4 HYRA

The proposed hybrid reporting allocation scheme is described in detail in this Section.

4.1 Problem Definition

The transmission of an idle XGEM by an ONU signals either upstream traffic absence or transmission restrictions, e.g., fragmentation violations. In any case, the OLT perceives that an ONU has no traffic to send when an idle XGEM frame is received by this ONU. This phenomenon could induce bandwidth wastage if the OLT neglects the reception of idle XGEM(s) by a single or more ONUs. For example, the OLT is responsible of distributing a minimum bandwidth fraction to all ONUs in accordance to ITU-T specifications. As in Section 2 mentioned, a fixed bandwidth rate, equal to R_f is given to all ONUs independently of their bandwidth reports. To this end, bandwidth losses are caused when the OLT shares bandwidth to ONUs that consecutively or sporadically return idle XGEM frames back to the OLT. Accordingly, bandwidth opportunities that remain underutilized overshadow the packet delivery quality of demanding ONUs in terms of data packet delay. This problem could be addressed by applying a more sophisticated method to effectively offer bandwidth to the connected ONUs. Nevertheless, the ITU-T specifications clearly allows the usage of monitoring techniques in order to deal with underutilized ONUs. This gap is efficiently faced in this article by proposing a robust, hybrid scheduling policy that effectively combines both reporting methods. To this purpose, a simple yet powerful adaptive mechanism is employed; the learning automata (LAs).

4.2 Learning Automata

In general, many networks operate in environments with unknown and time-varying features. In access networks especially the time-varying parameters are often quite radical and might dramatically affect the network performance. Examples of such parameters are the burstiness, the traffic heterogeneity, and the user traffic activity. The changing nature of such characteristics entails careful and sophisticated design of efficient networking protocols and as a consequence, adaptivity arises as one of the most important properties of such protocols.

In order to meet the aforementioned requirements, LAs are adopted as an enhancing, adaptive mechanism to the OLT's decision process. LAs are artificial intelligence tools that can provide adaptation to systems operating in changing and/or unknown environments (Misra et al., 2013). A LA is a finite state machine that interacts with a stochastic environment and tries to learn the optimal action offered by the environment via a learning process. In this work, a LA is encompassed in the OLT to interact with the environment. The environment included the ONUs, the network characteristics, such as the ONUs' requests, and the network configuration, e.g., bandwidth allocation rules and restrictions. Being the thinking tank, the OLT, enhanced with the LA, exchanges information with the environment. For example, the OLT decides about the schedule and informs the ONUs about it. On the contrary, each ONU reports to the OLT by sending bandwidth requests with regard to users needs. In accordance to the bandwidth allocation specifications, the OLT is able to make specific decisions. The set of possible decisions an OLT could make constitutes the action poll of the LA. Moreover, a feedback is generated each time the OLT, by the aim of the LA, makes a decision. The feedback is originated by the environment, e.g., an idle XGEM frame is a feedback, and the LA receives it, updates the significance of each action in its pool, and prepares the next action. The process is repeated and finally leads the LA to select the best possible action from the pool of possible ones.

LAs are widely used in networking involving all layers. In the physical layer, LAs provide adaptive behavior towards channel characteristics (Nicopolitidis et al., 2011), framing determination (Sarigiannidis et al., 2011), and signal processing (Huang, 2008). In the data link layer, medium access decisions are governed by LAs towards transmission power determination (Joshi et al., 2008), packet collision avoidance (Eraghi et al., 2011), and spectrum sensing in cognitive networks (Sarigiannidis et al., 2013a). Routing enhancement is provided by LAs in (Economides and Silvester, 1988), while efforts in (Navid, 2010) support energy-aware adaptive LAs-based protocols. In transport layer, the congestion control mechanism is empowered with a LA to adapt to network changes (Venkata Ramana et al., 2005). Lastly, LAs play a critical role to provide reliable data transmission vehicular ad hoc networks (VANETs) (Kumar et al., 2013) considering the application layer, while the authors in (Bozicevic et al., 2004) demonstrated how modern applications can become more efficient using LAs.

The rationale behind the adoption of LAs as the core learning from experience mechanism in this work can be summarized as follows:

1. Low complexity; the calculations the LA engages are linear and quite simple.
2. Rapid convergence; the convergence speed is controlled by specific parameters, hence LA are capable of rapidly converging under normal conditions.
3. Flexibility; a LA is able to cooperate with any thinking module, so the enhancement of the OLT with a LA is a straightforward and cost-effective task.
4. Efficiency; LAs are proved to be efficient and widely utilized due their ability to support accurate estimations.

4.3 Formulation

Figure 1 illustrates how HYRA operates to provide an efficient solution to the upstream bandwidth allocation. This state diagram holds in the OLT side. It determines how the OLT behaves depending on each ONU reaction/feedback. The upper rectangular encloses the SR operation, denoted by the *Status Reporting* state, where the OLT includes an ONU in the upstream bandwidth allocation process as long as the ONU reports an active XGEM. Upon the reception of an empty XGEM by an ONU, the OLT assumes that this ONU experiences a period of inactivity, hence it isolates it from bandwidth distribution.

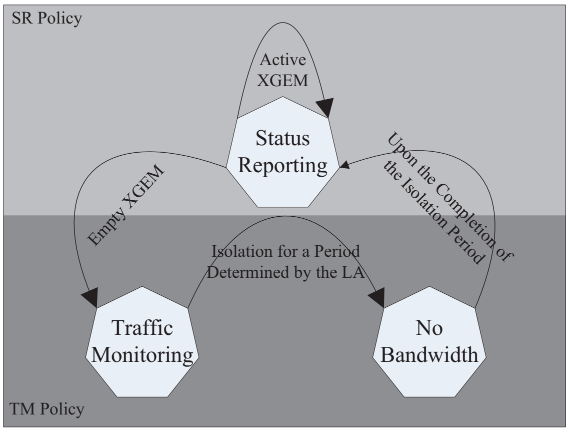

Figure 1: HYRA structure.

Thus, this ONU enters to TM session, where neither upstream opportunities are included to the forthcoming downstream frame(s) to this ONU nor upstream bursts are accepted from this ONU. In other words, the assigned guaranteed bandwidth destined to this ONU is shared among the active ONUs. In such a way, upstream bandwidth is saved in favor of the demanding users. Moreover, active users can effectively experience even high degrees of QoS. Yet, the connectivity ratio of the PON can be expanded including more users and ONUs. The isolation period is determined by the automaton.

The duration of the isolation period is determined by the LA. Setting an ONU in TM status, the OLT makes a decision about the isolation interval based on the past traffic activity of this ONU. To this end, the automaton maintains a pool of actions where each action denotes a specific isolation interval. Of course, due to the periodicity of the downstream transmission, each action is expressed as a multiple of 125 μsec. Furthermore, according to the ITU-T there is a maximum limitation on setting an ONU in idle condition, that is 50 $msec$. Thus, a maximum of $50000/125 = 400$ possible isolation periods are defined. Bearing these in mind, the action pool is defined as follows:

$$A = a_0, a_1, a_2, ..., a_{400} \tag{1}$$

The state a_0 means no isolation, i.e., the ONU returns to SR status. The automaton maintains a probability for each action. This probability is determined based on the past traffic pattern of each ONU and it dictates how possible is the state to be the optimal one. The (action) probability vector at downstream frame f is given below:

$$P^i(f) = p^i_0(f), p^i_1(f), p^i_2(f), ..., p^i_{400}(f) \tag{2}$$

where i stands for the ONU identity. Obviously, it holds that:

$$\sum_{j=0}^{400} p^i_j(f) = 1 \; \forall \; i \tag{3}$$

Initially, all probabilities are equally set:

$$p^i_j(f) = 1/401, 0 \leq j \leq 400, \forall \; i \tag{4}$$

The feedback received by each ONU is translated based on Eq. (1). When the OLT receives an empty XGEM from an ONU, it records the elapsed time passed this ONU remained idle, i.e., between this instance and the reception of an active XGEM. This time period signals the LA's feedback. If T_1 stands for the time instance the OLT received an empty XGEM and T_2 denotes the time an active XGEM received by the OLT, the time period is transformed to an action:

$$a_k = \lfloor \frac{T2 - T1}{125} \rfloor \; 0 \leq k \leq 401 \tag{5}$$

In essence, the automaton takes this time period and associates it with an action from the pool. For example, let $T_1 = 1200$ and $T_2 = 1633$. The associated action is $a_4 = 3 \cdot 125 \mu sec$.

The adaptivity of the present model lies in the incorporated learning mechanism, which enables the adjustment of the action probability vector based on past experience. Upon the reception of the feedback, at frame f, the automaton updates its action probability distribution. First, the action corresponding to the feedback is awarded:

$$p^i_k(f+1) = p^i_k(f) + \sum_{j=0, j \neq k}^{400} L(p^i_j(f) - a) \tag{6}$$

In the above equation, i denotes the ONU, k denotes the feedback action, L stands for the convergence speed (the larger L the faster convergence), and a symbolizes a quite small number used for avoiding the probabilities taking zero values. Of course, the award given to the actual action k stems from summarizing a small fraction from all others $j \neq k$ probabilities. Accordingly, the probability of all other actions is slightly reduced:

$$p^i_j(f+1) = p^i_j(f) - L(p^i_j(f) - a) \; \forall \; j \neq k, 0 \leq j \leq 400 \tag{7}$$

In the light of the aforementioned aspects, the operation of the LA lies in the *Traffic Monitoring* state of Figure 1. In order to decide about the duration of the isolation period the LA selects the most probable action. Hence, given that the feedback receptions increase the probability of the action that appears most, known as optimal action, the LA is able to determine the traffic pattern of each ONU. In this way, the OLT effectively exploits the combination of SR and TM policies in order to provide adequate upstream scheduling.

Finally, the isolated ONU returns to SR state. This triggers the OLT to include this ONU to the next downstream frame. If its traffic inactivity sustains, i.e., it sends an empty XGEM again, the operation of the ONU is switched to the *Traffic Monitoring* state. Otherwise, it normally continues using the SR policy.

4.4 Operation

The complete operation of the enhanced OLT is described in Algorithm1. The update procedure is shown in Algorithm2. It is worth mentioning that a probability vector update holds when a newer feedback is received by the OLT. This fact appears when the propagation delay of an ONU is large, hence upstream bursts of this ONU arrive at OLT late, i.e., after the transmission of the next downstream frame. In this case, the isolation of the ONU is canceled, if the previous upstream burst was an empty XGEM. In addition, the feedback is equal to a_0, meaning that the received actual idle time of this ONU was less than 125 μsec.

5 PERFORMANCE EVALUATION

This section is devoted in presenting the evaluation results of the proposed scheme.

Algorithm 1 : Bandwidth allocation process

```
Initialize the probability vector
for each 125 $\mu sec$ do
    for each ONU do
        if ONU is isolated then
            Exclude the ONU from the downstream frame
        end if
        if ONU sent empty XGEM then
            The LA decide about the isolation period calculated in terms of 125 $\mu sec$; let it be $T$
            Exclude the ONU from the downstream frame for the next $T$ frames
        end if
        if ONU sent active XGEM then
            Apply SR policy to grant bandwidth
        end if
    end for
end for
```

Algorithm 2 : Update procedure

```
Initialize the probability vector
for each received upstream burst by ONU $j$ do
    Calculate the feedback
    Associate the feedback to an action from the pool
    Update the ONU's probability vector
    if a newer upstream burst received then
        if the burst included empty XGEM then
            Set the feedback equal to $a_0$
            Update the ONU's probability vector
            Cancel the isolation of the ONU (if any)
        end if
    end if
end for
```

5.1 Environment

A simulation environment was implemented in Matlab in order to assess the proposed hybrid scheme. In particular, the upstream process of a XG-PON is examined in terms of average packet delay. The introduced scheme is compared with the pure SR policy keeping the same network features and parameters. The pure SR policy operates including all ONUs in the downstream frame interdependently of their traffic activity. Both schemes follow the same resource allocation and QoS provisioning guidelines as described in ITU-T G987.3 specifications.

Table 1: Simulation Parameters.

Upstream Rate	2.48832 Gbps
ONU Buffer Size	100 MB
Assured Bandwidth	500 Bytes
Maximum Bandwidth	750 Bytes
Downstream Frame Period	125 μsec
Learning Period	100 Downstream Frames
Guard Time	64 bits
L	0.1
a	10^{-5}
Number of actions	401
Simulation Time	100 sec

In order to provide realistic results, real multimedia packet traces have been used. The captured traffic corresponds to the upstream direction, i.e., it contains traffic flows from users to server (OLT). The captured traffic streams were obtained using the Wireshark tool. Three traffic streams have been utilized: 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), and c) live stream session. Furthermore, a constant bit rate (CBR) background traffic was assumed for each ONU.

Concerning the VoIP application, each ONU produces an average traffic of 0.038 *Mbps*, while the average packet size is equal to 1372 *Bytes*. The session includes a total number of 297 data packets. The real media streaming application generate an average traffic of 0.04 *Mbps* (per ONU) having an average packet size of 121 *Bytes*. The session engages 1277 data packets. The live stream (per ONU) contains 1458 data packets with average traffic equal to 0.05 *Mbps* and an average packet size of 1430 *Bytes*. The background traffic generates an average load of 0.01 *Mbps* for each individual ONU. The average summarized traffic load per ONU reaches 0.138 *Mbps*.

Considering the propagation differentiation of the ONUs the following formula was employed:

$$Distance_i = RTTfactor + i \tag{8}$$

The above formula expresses the distance of the i-th ONU ($Distance_i$) from the OLT in terms of Km. The default value of the $RTTfactor$ is 30. Thus, if 10 ONUs are assumed, the last, i.e., the 10-th, ONU is considered $40Km$ far from the OLT.

The (upstream) resource allocation incorporates a traffic descriptor in accordance to the standard specifications. To be more specific, the default values of each bandwidth flow were: a) the fixed bandwidth, R_f was set to 250 *Bytes*, b) the assured bandwidth, R_a, was set to 500 *Bytes*, and c) the maximum bandwidth, R_m, was set to 750 *Bytes*.

Each ONU possesses a large enough buffer so as to exclude packet drops, e.g., 100 *MBytes*. The average packet delay is defined as the time elapsed from the packet arrival to the final packet delivery to the OLT.

Considering the LA operation, the convergence speed parameter L was set to 0.1, since this value was the most effective one based on the conducted experiments. The value of protecting parameter a was set to 10^{-5}.

To prevent upstream transmissions from colliding and jamming each other, the OLT keeps a guard time between upstream allocations equal to 64 *bits*.

For each experiment conducted the simulation time was set to 100 *sec*. A learning initial period for the LA was considered where only the probability vector update takes place without engaging decisions. For this learning period, the OLT utilizes the pure SR policy. The duration of the learning period was 100 downstream frames, i.e., $100 \cdot 125\ \mu sec = 12.5\ msec$.

Table 1 summarizes the main simulation parameters.

5.2 Results and Discussion

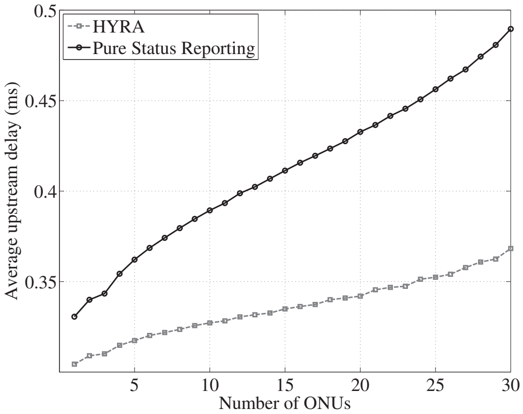

Figure 2: Average Upstream Delay vs. Number of ONUs.

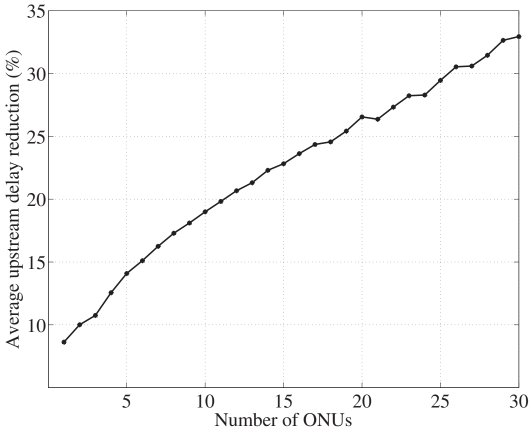

Figure 3: Average Percentage of Upstream Delay Reduction vs. Number of ONUs.

First, the impact of the proposed scheme pertinent to the population of the XG-PON is investigated. Figure 2 depicts the performance of both policies as the number of ONUs increases. Four remarks are raised by observing the results of this figure:

1. The average upstream delay increases; this is attached to the fact that the population growth induces more bandwidth requests for the upstream direction leading a considerable number of data packets to be delayed in the ONU queue due to resource constraints.
2. HYRA presents much lower average upstream delay; the superiority of the proposed scheme is undoubted. The suggested adaptive technique has managed to adequately reform the way of constructing the upstream schedule. Underutilized ONUs are temporarily isolated, giving the chance to demanding ONUs to faster forwarding their data to the OLT.

3. The operation of the LA is accurate; This is proved by the observation that the function of the learning from experience tool is beneficial to the network performance in terms of packet delay. If the LA process was inaccurate then the operation of HYRA would lead to higher upstream delays.
4. The extend of beneficial offering by HYRA is notable; According to Figure 3, the improvement offered by HYRA is at least 8% and at most 33.5%. The mean improvement advanced by HYRA reaches almost 22%, while it gains ground as the population of the XG-PON becomes dense.

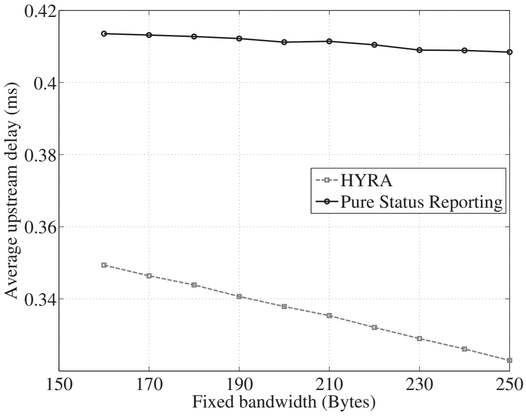

Figure 4: Average Upstream Delay vs. Fixed Bandwidth.

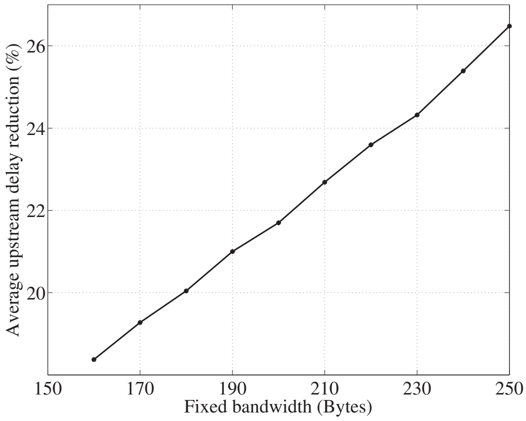

Figure 5: Average Percentage of Upstream Delay Reduction vs. Fixed Bandwidth.

Second, the effect of the guaranteed bandwidth rate is examined. In particular, Figure 4 draws the performance of both schemes in terms of average upstream packet delay when the fixed bandwidth changes. By altering the level of guaranteed bandwidth we endeavor to demonstrate how the XG-PON operation is effected by applying an adaptive policy such as HYRA. The fixed bandwidth, R_f, alters from 150 to 250 Bytes. Concurrently, Figure 5 presents the percentage of improvements compared to pure SR. The observed aspects are summarized as follows:

1. The average upstream delay remains stable when the pure SR is applied; this is caused due to the fact that the SR policy provides the same fixed bandwidth to all ONUs irregularly to the traffic condition of each ONU.
2. HYRA performance excels; HYRA achieves not only to support faster upstream communication, yet it manages to accomplish even less upstream delay as the fixed bandwidth increases. This phenomenon is attached to the fact that the impact of idle ONUs is better exploited by re-distributing the bandwidth of inactive ONUs to the demanding ONUs. Hence, the more the surplus bandwidth the faster upstream data delivery.
3. The average improvements are guaranteed and considerable; The minimum observed improvement is achieved when the fixed bandwidth received its minimum value. The difference between pure SR and HYRA peaks when the guaranteed bandwidth takes its maximum value.

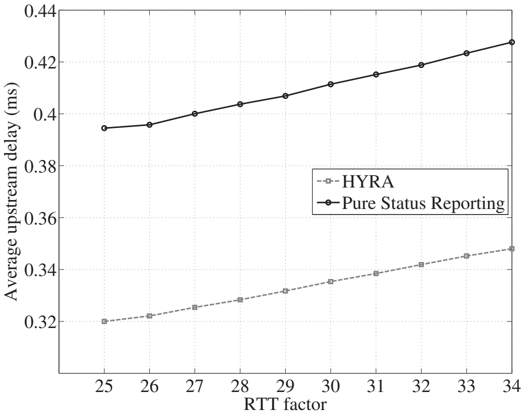

Figure 6: Average Upstream Delay vs. RTT Factor.

Third, the impact of the propagation delay is inspected in Figure 6. Once more, the superiority of the proposed scheme is revealed. The $RTT factor$ changes from 25 to 34 shedding light to the impact of the distance differentiation in the network performance. It is obvious that the distance change keeps the difference between the two schemes stable and equal to 22.5% approximately. As expected, the propagation impact induces a marginal effect to the performance of HYRA; however the average delay keeps increasing as the RTTs become larger. Nonetheless, HYRA has managed to offer lower delay yet in wider XG-PON systems.

Overall, the proposed scheme succeeds to offer

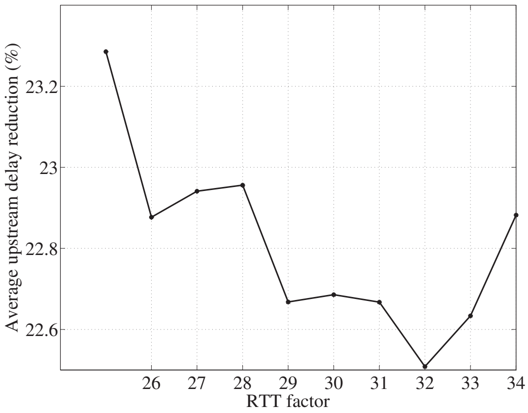

Figure 7: Average Percentage of Upstream Delay Reduction vs. RTT Factor.

considerable improvements to network performance in terms of average upstream packet delay. The role of LAs is deemed as quite beneficial providing accurate and efficient decisions to the OLT. The simulation results present a realistic picture since they based on real traffic sessions, yet incorporating multimedia traces.

6 CONCLUSIONS

An adaptive, efficient, and robust allocation scheme, known as HYRA, was presented in this paper for XG-PON systems. The scheme incorporates a LA to the OLT in order to strengthen the efficacy of the upstream resource allocation decisions. The learning from experience technique exploits both SR and TM policies in order to benefit the demanding ONUs. This is accomplished by re-distributing the surplus bandwidth portion, gained by the idle ONUs, to the users that really need more bandwidth. The re-distribution is signaled by the existence of empty XGEMs. Extensive simulation results using real multimedia packet traces indicate the superiority of the proposed scheme when compared to the pure SR policy. The improvements observed by the obtained results show that HYRA has managed an average improvement percentage of 22.5%, while it achieves to reduce the delay levels by 33% in high populated XG-PONs.

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