ARES: An Adaptive, Resilient, Estimation Scheme for Enforcing Bandwidth Allocation in XG-PON Systems

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Abstract. Passive Optical Networks (PONs) constitute the dominant architecture in the last mile that effectively realize the Fiber To The Home/Building/Curve (FTTH/B/C) paradigm. It combines a cost-effective infrastructure with an effective data delivering, where multiple users are able to use high-quality services. The latest new generation PON (NG-PON) standard, known as 10-gigabit-capable passive optical network (XG-PON), stands a very promising framework that incorporates 10 Gbps nominal speed in the downstream direction. In the opposite, all users have to share the upstream channel, where multiple upstream traffic flows are delivered to the Central Office (CO), using a channel of 2.5 Gbps rate. Having in mind that in dense, urban areas the number of users is quite large, an efficient Dynamic Bandwidth Allocation (DBA) scheme is mandatory to guarantee unhindered high-quality service delivery. In this work, a resilient coordination scheme is presented that intends to ensure high-efficient traffic delivery under pressing traffic conditions. In order to achieve that, a sophisticated machine learning model is proposed that coordinates the Optical Networks Units (ONUs) based on their traffic profile. The proposed, Adaptive Resilient Estimation Scheme (ARES), contributes in a twofold way. First, it succeeds to provide balanced resource allocation, under heavy traffic circumstances, by isolating idle ONUs. Second, it manages to effectively adjust the amount of fixed bandwidth allocated to Alloc-IDs based on their traffic behavior. Simulation results demonstrate that ARES offers considerable improvements in terms of average upstream packet delay and traffic received, while the estimation accuracy attains at high levels.

M.S. Obaidat and A. Holzinger (Eds.): ICETE 2014, CCIS 554, pp. 131–151, 2015.
DOI: 10.1007/978-3-319-25915-4_8

Keywords: Dynamic bandwidth allocation · Machine learning · Passive optical networks · XG-PON.

1 Introduction

Optical fiber came to access networking scenario to stay. Nowadays, it constitutes the dominant technology in the last mile [15]. Optical technology penetration is considered as an end game scenario. The most promising architecture that realizes optical technology in the access playground is Passive Optical Network (PON). The low cost infrastructure in conjunction with the cost efficient maintenance emerges is a very attractive set of features that allows the fast grow of PON installations in access networks, especially in dense, urban areas. PONs enable an all-optical path between the Internet gateway and end-users. This allows the delivery of demanding and diverse services and applications to users as well as the function of Quality of Service (QoS) subscriber contracts. In essence, PONs realize an all-optical path, creating a transparent point to multi-point interconnection, offering high data rates for both upstream and downstream direction. Nevertheless, the coordination of multiple users in a common network infrastructure is not a straightforward task, since the traffic diversity in access networks is high. In addition, the bursty nature of traffic requests makes the coordination more complicated. Thus, many efforts are still needed to fully leverage the very promising potential of PON architecture.

Access networks entail a high-competitive playground. The 4G wireless networks, the old, yet cheap, copper-based infrastructure and the ambitious optical technology compete for the same subscribers. In order to be viable, PONs have to be as much attractive as possible. Thus, they have to support QoS provisioning, efficient data delivery, and the lowest possible subscriber cost. Given that the subscriber cost depends on the number of subscribers a PON connects, it is obvious that the resource allocation should be effective enough. By incorporating an effective DBA scheme, 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.

International Telecommunication Union (ITU-T) suggests dynamic resource allocation using polling mechanisms. The allocation should be efficient enough to adequately adapt to heterogeneous traffic conditions, without yet inducing QoS violating. The design of intelligent DBA algorithms becomes necessary to address the diverse traffic user demands, especially in the upstream direction.

Enhanced cryptography, energy-efficient management, strong cross-layer mechanisms, and high transmission rates are a few of the powerful features that the 10-gigabit-capable passive optical network (XG-PON) supports. End users (subscribers) are connected to Optical Network Units (ONUs) using copper-based connections (Ethernet). Optical fibers connect ONUs with the Optical Line Terminal (OLT) using two channels; one channel is utilized to forward data packets from OLT, which is located into the Central Office (CO), to ONUs, realizing thus the downstream direction, while a second channel is employed to upload data streams from ONUs to the OLT. A passive splitter/combiner splits the optical fiber, stemming from the OLT, to multiple (a typical value is 32) optical fibers that are connected to each ONU. On the opposite side, different signals from multiple ONUs are multiplexed into a single signal towards the OLT. Thus, a two-way communication is realized.

The downstream direction is implemented in a straightforward way. OLT is responsible to broadcast data packets stemming from the Internet to the ONUs. This task is easy to design since ONUs receive all downstream data traffic and select accordingly. On the other hand, upstream coordination seems demanding. A upstream transmission schedule is mandatory to avoid collisions in the shared fiber part located between the passive optical splitter/combiner and the OLT. The schedule design engages sophisticated allocation algorithms. In order to fully leverage the bandwidth potential of the optical fiber, the transmission schedule should be dynamic, efficient, and flexible. Given that such a schedule takes into account the traffic requests of each ONU, the ONU distance from the OLT, and the channel availability, it is clear that advanced techniques should be developed to address the demanding subscriber requests [4].

A dynamic, traffic-aware DBA scheme is proposed in this work to address the aforementioned challenges. A two-level, learning from experience framework is designed, motivated by the machine learning field, called Adaptive Resilient Estimation Scheme (ARES). First, ARES adopts the isolation mechanism of HYbrid Reporting Allocation (HYRA) [12], where underutilized ONUs are isolated, for a specific time period, from traffic distribution in order to re-distribute the surplus bandwidth to other bandwidth-hungry ONUs. The isolation period is extracted by a learning automaton, as a result of a well-defined learning process. Second, ARES extends our prior work, by estimating the fixed bandwidth which is allocated to each ONU. According to the standard, a fixed, guaranteed bandwidth is allocated to each ONU regardless of the ONU traffic request. However, the amount of this rate is not specified. ARES monitors ONU's traffic activity and applies an estimation technique in order to adequately make this decision. Once more, the surplus bandwidth, gained from ONUs that are inactive, is distributed to the ONUs that still have unmet traffic demands. This technique, as applied in a periodic fashion, ensures that the bandwidth wastage, due to ONUs that remain idle or underutilized, is minimized, while the bandwidth savings are re-distributed to cover other needs. In this way, the potential of the optical fiber is better exploited. The network capacity is getting higher, while the operations costs of the XG-PON are reduced.

The remainder of the paper is organized as follows. Section 2 introduces the XG-PON standard as well as its main sub-layers. In Sect. 3 existing research efforts towards resource allocation in XG-PON are outlined. A detailed description of the proposed scheme is provided in Sect. 4. Section 5 illustrates the obtained results, followed by detailed reports. Finally, conclusions are given in Sect. 6.

2 Background

Undoubtedly, G-PON and EPON systems are currently the dominant deployed optical access architectures. The consideration of deployment NG-PONs has begun in 2007 having in mind that the major step was the establishment of 10 Gbps in at least one direction [1]. XG-PON comes as a product of this endeavor, supporting 10 Gbps in downstream and 2.5 Gbps in upstream. In addition, the XG-PON transmission convergence (XGTC) layer engages functional protocols and procedures, including resource allocation and QoS provisioning between the upper layers and the physical (PHY) layer [7]. XGTC layer is subdivided into three sub-layers: (a) the service adaptation sub-layer, where service data unit (SDU) encapsulation and multiplexing takes place, creating XG-PON encapsulation method (XGEM) frames, (b) the framing sub-layer, where the constructed XGEM frame is received and the downstream XGTC frame is formed, and (c) the PHY sub-layer, where bit error correction algorithms, content scrambling, and frame synchronization are performed. It is important to note that the downstream frame encloses multiple XGTC payloads which are distinguished based on their Allocation ID (Alloc-ID). The Alloc-ID field identifies the recipient of the allocation within the ONU.

The downstream direction supports transmission rate of 9.95328 Gbps. A downstream frame is periodically transmitted, forwarding data frames to the connected ONUs, every 125 μsec. Given this rate, the capacity of the downstream directions yields 155520 bytes. A downstream frame includes the physical synchronization block field 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. This information map is used by the OLT to broadcast to the ONUs their corresponding upstream, granted transmission opportunities. In other words, the ONUs are informed about the start time of the upstream transmission opportunity and the grant size per Alloc-ID for each ONU.

According to the standard, a maximum differential fibre distance up to 40 Km is allowed. This result to high propagation delays for the ONUs located far from the OLT. Hence, a robust synchronization framework is needed to adequately address the heterogeneity of the ONUs Round Trip Times (RTTs). According to the specifications, the 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 long propagation time. Thus, the allocation information included in the i-th downstream frame corresponds to the i-th upstream frame.

Given that (a) the upstream rate is 2.48832 Gbps and (b) the upstream frame is 125 μsec, it yields 38880 bytes per upstream direction. This capacity is shared to all ONUs. The PSB of the upstream frame (PSBu) contains the preamble and the delimiter fields and comes first within the upstream frame. 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 utilized 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.

The presence of the DBRu is controlled by the OLT with the DBRu flag of the corresponding allocation structure within the BWmap. The 4-byte DBRu structure carries a buffer status report which is associated with a specific Alloc-ID. The Buffer Occupancy (BufOcc) field is used by the Alloc-IDs to report their buffer occupancy at the moment that the upstream frame is transmitted. In other words, the BufOcc is quite important since it expresses the bandwidth request of an Alloc-ID, and therefore, the bandwidth request of an ONU.

As previously mentioned, the recipient entity of the upstream bandwidth allocation is represented by an Alloc-ID. In the context of upstream bandwidth allocation, each Alloc-ID is granted guaranteed and non-guaranteed bandwidth. The amount of guaranteed bandwidth includes the (a) fixed bandwidth, denoted by R_F, and (b) the assured bandwidth, denoted by R_A. In addition, there is an upper threshold in granting guaranteed bandwidth to Alloc-IDs. The parameter R_M implies the maximum bandwidth an Alloc-ID is granted in each upstream allocation opportunity. The amount of R_F is granted regardless of the BufOcc value; thus, all Alloc-IDs receive a portion of bandwidth irregardless of their bandwidth needs. Nevertheless, the amount of R_F is not specified in the standard guidelines.

3 Related Work

References [6,10] are a strong indication that the area of PONs constitutes a very challenging and compelling topic. Substantial research has already been conducted in the area of DBA development. A multitude of access schemes, allocations algorithms, and bandwidth distribution mechanisms have been implemented. However, the majority of these solutions refer to the Ethernet PONs (EPONs), where the Multi-Point Control Protocol (MPCP) is the main access mechanism of the underlying polling scheme. Though interesting the aforementioned solutions are, they are not directly applicable to XG-PONs, since the polling mechanism of XG-PON is totally different than that of EPON systems.

On the other hand, the conducted research towards XG-PON access solutions is limited, even though solid XG-PON testbeds have been demonstrated [3]. A few only solutions have been proposed for gigabit PONs (GPONs). For example, the authors in [5] introduced the offset-based scheduling with flexible intervals concept for gigabit GPONs. The rationale behind this concept stands on applying flexible scheduling intervals. Lower scheduling intervals are applied for message delivering between the ONUs and the OLT. The scheme presents improvements in terms of network throughput and average packet delay. One drawback of this approach is the the reporting method remains intact. Hence, noticeable bandwidth is wasted, especially under dynamic traffic circumstances.

In the context of bandwidth re-distribution, an interesting approach was presented in [2]. The access scheme aims at utilizing a common available byte counter and a common down counter for multiple queues of a service class. Thus, the surplus bandwidth is shared to demanding users. However, this approach seems to violate the standard definitions, by inducing extra control messages.

Flexible rates and upgrades are investigated in [16]. The objective of this work was to explore cost and performance issues when different rates and speeds are applied in Next Generation PONs (NG-PONs). Nonetheless, this approach stands beyond bandwidth allocation issues.

The authors in [9] presented the impact of using wavelength blocking filters in networks where GPON and XG-PON infrastructures co-exist. The target of this effort lies in reducing the undesirable interference. Once more, this work neglects the resource allocation protocol.

Our previous efforts in [11] and in [13] deal 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.

In addition, our prior work in [12], introduced Hybrid Reporting Allocation (HYRA), which proved that the bandwidth allocation in XG-PON systems can be further improved. HYRA inaugurates the concept of isolating ONUs when they are idle. The surplus bandwidth is shared among the ONUs that really need it having unsatisfied traffic requests. In this way, the bandwidth allocation becomes more efficient than allocating statically.

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, excepting HYRA, assume the SR method as the core scheduling policy. In this article, we step beyond the pure usage of the SR method by extending our prior work. In particular, we examine how efficient is to estimate the amount of fixed bandwidth guaranteed an Alloc-ID receives based on its traffic pattern.

4 ARES

4.1 Objectives

Modern NG-PONs should be efficient enough to cope with demanding applications and services. Bandwidth allocation, as an inner, focal, component of PONs, is responsible of applying an efficient transmission schedule to the connected ONUs. One of the most serious cause that induce bandwidth wastage is when an ONU is idle or underutilized. The underlying bandwidth allocation scheme has to be able to perceive an idle or underutilized ONU, and accordingly, to re-distribute the bandwidth, that would be lost, to other ONUs that need more resources. An empty XGEM frame is an indication of idleness that should be taken into account on designing DBA schemes. Moreover, the allocation of guaranteed bandwidth has to be dynamic. According to the standard, all ONUs, and so all Alloc-IDs, are granted a portion of guaranteed bandwidth, irregardless of their needs. Nonetheless, according to the standard specifications bandwidth weights are allowed. Thus, each Alloc-ID could receive different guaranteed bandwidth according to a set of rules. Given that the fixed guaranteed bandwidth, R_F, is assigned to each Alloc-ID even when the specific Alloc-ID has no data no send, the selection of efficient weights would be helpful. In the light of the aforementioned remarks, the following two objectives are defined. First, a sophisticated monitoring mechanism is needed to identify ONUs and Alloc-IDs that remain idle or underutilized, based on what they are granted and what they send afterwards. Second, an adaptive method is required to determine the optimal fixed guaranteed bandwidth that is allocated in each Alloc-ID. This bandwidth amount could be different for each Alloc-ID, based on their traffic records. For the purposed of this work, a novel, traffic-aware, dynamic DBA is proposed to efficiently distribute bandwidth among ONUs.

4.2 Machine Learning

Machine learning studies automatic techniques for learning to make accurate predictions based on past observations [14]. Learning techniques are often applied to solve integration and optimization problems in large dimensional spaces or in environments with many unknown variables. These two types of problem (integration and optimization) play a fundamental role in machine learning, physics, statistics, econometrics and decision analysis.

Learning Automata (LAs) constitute a powerful, yet simple, tool towards accurate predictions. Its simplicity lies in the fact that they only need a feedback from the environment. They could operate under unknown environments, where there are with unknown and time-varying features. Furthermore, groups of LAs forming teams and feedforward networks have been shown to converge to desired solutions under appropriate learning algorithms.

In the context of this paper, we focus on access networks where 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.

In enforcing the decision process, LAs are employed a an dynamic, efficient, and flexible mechanism to steer the decisions made by the OLT. As artificial intelligence tools that can provide adaptation to systems operating in changing and/or unknown environments [8], LAs define 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.

A two-level learning automaton is proposed in this work. The OLT is encompassed with this automaton to interact with its environment, which in the context of this work includes the PON architecture as well as its features, such as the reporting of the ONUs 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.

The set of possible decisions an OLT could make constitutes the action poll of the automaton. In the case of a two-level automaton, the decision is twofold and affect two variables. Furthermore, the feedback, generated by the environment, is twofold. For example, an idle XGEM frame forms a feedback, while the percentage of the fixed bandwidth (R_F) consumed by an Alloc-ID may form another feedback. The automaton receives feedback, processes its data forms, and finally select the best possible action from a pool of possible ones.

4.3 DBA Structure

Figure 1 depicts the ARES structure in a state machine. The machine consists of four states, namely (a) the *traffic monitoring*, which is the initial state of the model, (b) the *status reporting*, (c) the *R_F adjustment*, and (d) the *isolation period*. This state machine takes place in the OLT side, since the OLT is the sole responsible of making decision regarding bandwidth allocation. Initially, the OLT monitors the traffic records of each ONU when receiving traffic from the them in the upstream direction. When an empty XGEM is received then the isolation mechanism, as proposed in HYRA, is triggered. Just after an ONU sends an empty XGEM, the OLT assumes that this ONU experiences a period of inactivity, hence it isolates it from the forthcoming bandwidth distribution for a period equal to *isolation period*. This ONU enters into traffic monitoring session, where neither upstream opportunities are included to the forthcoming downstream frame(s) to this ONU nor upstream bursts are accepted from this ONU. The bandwidth portion to be given in that ONU will be distributed among the other active ONUs. In applying the isolation mechanism bandwidth savings are gained, hence the upstream allocation process becomes flexible and efficient. A learning automaton is engaged to compute the duration of the *isolation period*. Upon the completion of the *isolation period*, this ONU returns to the *traffic monitoring* state. The OLT includes this ONU to the upstream bandwidth allocation to check whether the received XGEM (from this ONU) will be empty. In the case that an empty XGEM is received again, this ONU re-enters into the *isolation period* again, while the automaton calculates the duration of the new *isolation period*. On the other hand, upon receiving an active XGEM, this ONU enters into the *status reporting* state. Here, the ONU participates in the upstream bandwidth distribution normally. At the same time, the *R_F adjustment* takes place. The OLT decides on the amount of R_F, based on a second automaton. In essence, the OLT will determine a fixed bandwidth allocation value for each Alloc-ID. The decision depends on the feedback received from each Alloc-ID. The automaton will receive the amount of R_F bandwidth granted to an Alloc-ID and the corresponding bandwidth consumed by this Alloc-ID. The automaton will

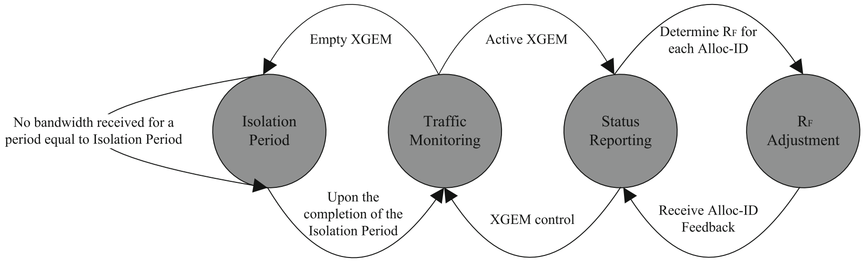

Fig. 1. ARES structure in a state machine in the OLT side.

increase the fixed guaranteed bandwidth for an Alloc-ID that really needs it, while it will decrease it for an Alloc-ID that remains idle or underutilized.

4.4 Isolation Automaton

A learning automaton, called *isolation automaton*, is employed to estimate the duration of the *isolation period*. The automaton makes decisions based on the ONU traffic behavior. To this end, a pool of actions is defined, where each action corresponds to a state. The set of actions A is defined:

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

Figure 2 illustrates the states and the corresponding actions of the automaton. Each action is associated with an *isolation period* duration in terms of 125 μsec multiples. Hence, the first action implies no isolation, the second action implies an *isolation period* of 125 μsec, the third action denotes an *isolation period* of 250 μsec and so on. The last action corresponds to a period of 50 msec. The rationale behind this selection is attached to the fact that a maximum limitation on setting an ONU in idle/sleep condition is specified by ITU-T; this is equal to 50 msec. So, larger isolation periods are not allowed. Thus, a maximum of $50000/125 = 400$ possible isolation periods are defined plus the one corresponding to no isolation.

Let N denote the set of ONUs. The action probability vector of the *isolation automaton* at the downstream frame f is defined as follows:

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

Each probability implies how possible is the state to be the optimal one. Obviously, it holds that:

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

Initially, all probabilities are equally set:

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

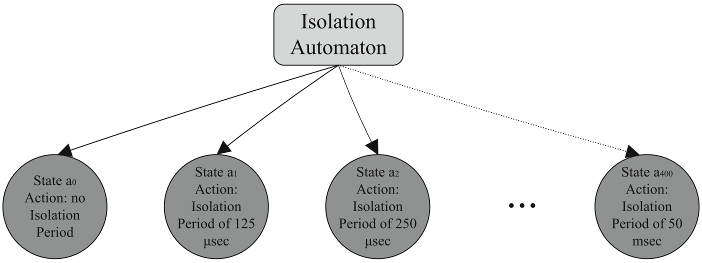

Fig. 2. The states and the corresponding actions of the *Isolation Automaton*. It aims at estimating the *Isolation Period*.

Action probabilities are updated based on a feedback that received by each ONU. When the OLT receives an empty XGEM from an ONU, it records the elapsed time passed since this ONU remained idle, i.e., between this instance and the reception of an active XGEM. This time period signals the *isolation automaton* feedback. The feedback, which is denoted by the state a_k, is modeled as follows, where t_1 is the time instance the OLT receives an empty XGEM and t_2 stands for the time an active XGEM received by the OLT:

$$a_k = \lfloor \frac{t2 - t1}{125} \rfloor, 0 \leq k \leq 401 \tag{5}$$

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 $a_4 = 3 \cdot 125\,\mu\text{sec}$.

Upon receiving a feedback at frame f for ONU i, the automaton updates the action probability distribution of ONU i. First, the action corresponding to the feedback is awarded:

$$p_k^i(f+1) = p_k^i(f) + \sum_{j=0, j \neq k}^{400} L(p_j^i(f) - a), \forall i \in N \tag{6}$$

In the above equation, 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:

$$p_j^i(f+1) = p_j^i(f) - L(p_j^i(f) - a), \forall j \neq k, 0 \leq j \leq 400, \forall i \in N \tag{7}$$

In a nutshell, the *isolation automaton* selects the most probable action to adjust the *isolation period* for each ONU that presents underutilized behavior. Hence, given that the feedback receptions increase the probability of the action that appears most, known as optimal action, the automaton is able to determine the traffic pattern of each ONU.

4.5 Fixed Bandwidth Adjustment Automaton

In order to adequately adjust the amount of the fixed bandwidth guaranteed, R_F, of each Alloc-ID, when the ONU that owns this Alloc-ID, operates normally, i.e., being in the *status reporting* state, we employ a second learning automaton called *Fixed Bandwidth Adjustment (FBA) automaton*. The automaton is used to estimate the amount of R_F for each Alloc-ID, for each downstream period, given that the corresponding ONU is active. Again, a set of action pool is defined:

$$B = \{b_0, b_1, b_2\} \tag{8}$$

$$B = \{b_0, b_1, b_2\}$$

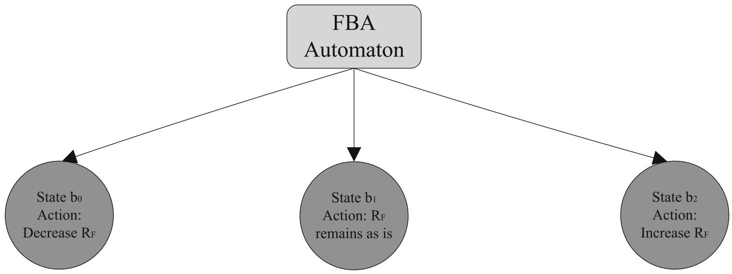

Fig. 3. The states and the corresponding actions of the *FBA Automaton*. It aims at estimating the amount of fixed bandwidth guaranteed of each Alloc-ID.

Figure 3 depicts the states and the corresponding actions of the automaton. Three states are distinguished. First, the R_F is increased in state b_0. In the following analysis, we consider that $R_F(f)$ denotes the amount of fixed bandwidth guaranteed allocated at frame f in terms of bytes. In addition, assuming that R_F^U and R_F^L denote the upper and the lower threshold of the R_F, based on the configuration parameters, the R_F is increased as follows:

$$R_F(f) = \begin{cases} 2 \cdot R_F(f-1) & \text{if } 2 \cdot R_F(f-1) \leq R_F^U \\ R_F(f-1) + 1 & \text{else} \end{cases} \tag{9}$$

Second, the R_F remains the same in the state b_1:

$$R_F(f) = R_F(f-1) \tag{10}$$

Lastly, the R_F is decreased in the state b_2:

$$R_F(f) = \begin{cases} \frac{R_F(f-1)}{2} & \text{if } \frac{R_F(f-1)}{2} \geq R_F^L \\ R_F(f-1) - 1 & \text{else} \end{cases} \tag{11}$$

Let O denote the set of Alloc-IDs. The action probability vector of the *FBA Automaton* at the downstream frame f is defined as follows:

$$G^q(f) = \{g_0^q(f), g_1^q(f), g_2^q(f)\}, \forall q \in O \tag{12}$$

Clearly, it holds that:

$$\sum_{j=0}^{2} g_j^q(f) = 1, \forall q \in O \tag{13}$$

Initially, all probabilities are equally set:

$$g_j^q(f) = 1/3, 0 \leq j \leq 2, \forall q \in O \tag{14}$$

On the contrary to the *isolation automaton*, in the case of *FBA Automaton* the feedback is acquired by the Alloc-IDs. It depends on the reported bandwidth each Alloc-ID made in the previous frames. Note, that this information is included in the BufOcc field within the upstream frame. Hence, the feedback is the result of comparing what an Alloc-ID requested in conjunction with what it consumed. Considering that $E(f)$ stands for the Alloc-ID reported at frame f, the feedback is defined as follows:

$$b_k = \begin{cases} b_0 & \text{if } E(f) < R_F(f) \\ b_1 & \text{if } E(f) = R_F(f) \\ b_2 & \text{else} \end{cases} \tag{15}$$

Upon receiving a feedback at frame f for Alloc-ID q, the automaton updates the related action probability distribution, considering that b_k is the correct state according to the feedback:

$$g_k^q(f+1) = g_k^q(f) + \sum_{j=0, j \neq k}^{2} L(g_j^q(f) - a), \forall q \in O \tag{16}$$

Moreover, the probability of all other actions is accordingly reduced:

$$g_j^q(f+1) = g_j^q(f) - L(g_j^q(f) - a), \forall j \neq k, 0 \leq j \leq 2, \forall q \in O \tag{17}$$

In the light of the aforementioned analysis, *FBA automaton* aims at estimating the fixed bandwidth allocated in the forthcoming frame for each Alloc-ID that belong to an active ONU. The adjustment of the R_F seriously depends on the Alloc-ID traffic behavior. The automaton is able to identify an Alloc-ID that remains idle for a period of time resulting in progressively reducing its R_F, until it will become active again.

4.6 Operation

Algorithm 1. Bandwidth Allocation Process

```
Initialize the probability vectors
For each 125 microseconds
     For each ONU
          If an ONU is isolated
               Exclude the ONU from the downstream frame
          EndIf
```

```
        If an ONU sent empty XGEM
            The duration of the Isolation period is estimated
            by the Isolation Automaton calculated in terms
            of 125 microseconds; let it be T
            Exclude the ONU from the downstream frame for the next T frames
        EndIf
        If an ONU sent active XGEM
            The amount of fixed bandwidth guaranteed is estimated for all
            Alloc-IDs (of this ONU) by the FBA Automaton
        EndIf
    EndFor
EndFor
```

Algorithm 1 describes the OLT operation. The operation is periodically repeated each 125 μsec, i.e., for each downstream frame. First, the OLT checks all ONUs. The ONUs that have been isolated are excluded from the bandwidth distribution. For the rest ONUs, the OLT examines whether they sent an empty XGEM. If so, these ONUs are entered into an *isolation period*, where the *isolation automaton* estimates its duration. On the contrary, the fixed bandwidth allocated for each Alloc-ID for an ONU that remains active is computed by the *FBA automaton*.

Algorithm 2 depicts the update process when an ONU upstream frame arrives at the OLT. For each ONU the feedback a_k is acquired, while the feedback b_k is calculated for each Alloc-ID of this ONU. Then the probability vectors are updated according to equations Eqs. (6), (7), (16), and (17).

Algorithm 2. Update Process

```
Initialize the probability vectors
For each received upstream burst by ONU j
    Calculate the feedback ak
    Associate the feedback to an action from the pool A
    Update the ONU j probability vector
    For each Alloc-ID of ONU j
        Calculate the feedback bk
        Associate the feedback to an action from the pool B
        Update the Alloc-ID probability vector
    EndIf
    If a newer upstream burst received (due to long propagation delay)
        If the burst included an empty XGEM
            Set the feedback equal to a0
            Update the ONU's probability vector
            Cancel the isolation period (if the ONU is isolated)
        EndIf
    EndIf
EndFor
```

5 Performance Evaluation

5.1 Environment

The performance of the proposed scheme is assessed in the section. A simulation environment in Matlab has been modeled in accordance to the XG-PON specifications. The XG-PON upstream process is especially investigated when applying different DBA schemes. In particular, three DBA schemes are examined: (a) the *pure status reporting scheme*, (b) *HYRA*, and (c) the proposed *ARES*. The *pure status reporting scheme* includes all ONUs to the upstream bandwidth distribution, while allocates fixed bandwidth to all Alloc-IDs equally without examining their traffic background. *HYRA* applies the isolation method to ONUs that report empty XGEMs. *ARES* extends the operation of *HYRA* by enhancing it with the fixed bandwidth estimation. The downstream process of the protocol remains intact for all schemes.

5.2 Traffic

In order to evaluate the performance of the three DBA schemes under realistic conditions real traffic traces has been captured. These traffic flows refer to upstream direction and include three types of traffic: (a) Voice over IP (VoIP) sessions using the User Datagram Protocol (UDP) and the Skype application, (b) real media streaming application using the Transmission Control Protocol (TCP), and (c) live stream session. The VoIP session engages an average traffic of around 0.04 Mbps, while the average packet size is equal to 1372 bytes. The real media streaming application generated a traffic flow of about 0.06 Mbps with an average packet size of 125 bytes. Lastly, the live stream session produced a rate of 0.05 Mbps with an average packet size of 1430 bytes. These traces have been utilized either solely, for example a user, realized by an Alloc-ID, utilizes a VoIP application, or in a combined way, i.e., a user utilizes a VoIP application and concurrently watches a real media streaming video.

5.3 Network Density

For each experiment conduced, the number of ONUs alters. We consider 2–32 ONUs, where each ONU owns 10 Alloc-IDs. For instance, there are 320 total Alloc-IDs in the network when the number of ONUs is 32. The number of ONUs was chosen in such a way so as to investigate the behavior of the applied DBA when the traffic scale is getting larger. In other words, it is interesting to explore how the different allocation algorithms perform when the traffic requests are getting more pressing. In addition, it is important to infer about the performance of the proposed scheme when traffic pressure is high. One of the most critical findings is its ability to cope with high traffic pressure, resulting in potentially serving more users.

5.4 Scenarios

For the purposes of the performance assessment, two main scenarios were executed. The first scenario, called *heavy-traffic scenario*, was developed so as to study the performance of each scheme under heavy traffic conditions. To be more specific, the following assumptions were set when the *heavy-traffic scenario* was conducted. Users (Alloc-IDs) are split in four groups. In the first group belong users that utilize a single application only. Hence, the first group consists of the following subsets: (a) 10 % of the Alloc-IDs use VoIP application solely, (b) 10 % of the Alloc-IDs use real media streaming application solely, and (c) 10 % of the Alloc-IDs use live stream application solely. The second group includes users that combine multiple services, so (a) 10 % of the Alloc-IDs use VoIP in conjunction with media streaming applications, (b) 10 % of the Alloc-IDs use VoIP in conjunction with live stream applications, and (c) 10 % of the Alloc-IDs use all available applications concurrently. The third group composes of users that are likely to utilize a service. Thus, 30 % of total Alloc-IDs have 50 % probability to use one of the available services with equal probabilities, i.e., 33 % for VoIP, 33 % for media streaming, and 33 % for live stream. Lastly, there is a group of 10 % of the Alloc-IDs that consists of users that remain idle during the whole experiment.

The second scenario, called *light-traffic scenario*, is engaged to indicate how the proposed scheme performs under lighter traffic conditions than those of *heavy-traffic scenario*. Here the first and the second groups remain the same. The third group, consisting of the total 30 % of the Alloc-IDs, includes users that have 10 % probability to use one of the available services equally. Finally, the last group involves users that remain idle during the experiment.

5.5 Simulation Parameters

The simulation environment was design in line with ITU-T G987.3 specifications. Table 1 summarizes the main simulation parameters. Specifically, the downstream rate is 9.95328 Gbps, while the upstream rate is 2.48832 Gbps. The downstream frame period was set 125 μsec. A guard time of 64 bits is interjected between upstream allocations. Each ONU possesses a buffer of size equal to 100 MB for each Alloc-ID. The default value of the fixed (guaranteed) bandwidth, R_F, was 75 bytes, per Alloc-ID, for all algorithms. The assured bandwidth, R_A, was set 25 bytes, while the maximum bandwidth, R_M was 150 bytes. The upper and lower thresholds were $R_F^U = 75$ and $R_F^L = 2$ respectively. The rationale behind the selection of the threshold values is given as follows. The upper threshold is equal to the default value of R_F, hence $R_F^U = 75$. In this way, an active Alloc-ID will receive at least 75 bytes per downstream frame. On the contrary, an idle Alloc-ID will be granted a minimum bandwidth of 2 bytes; this capacity results in $\frac{2 \cdot 8\,\text{bits}}{125\,\mu\text{sec}} \approx 128\,\text{Kbps}$, fully covering a high-quality VoIP session. Thus, this minimum fixed bandwidth is high enough to address a simple user call, until the bandwidth allocated to this user fully recovers. The learning period of the *isolation automaton*, which is the time period needed for the algorithm to learn, without estimating, regarding the isolation period of ONUs, the parameter L, which constitutes the learning speed of the automaton, and the parameter a, which is a zero probability protection value are adopted from *HYRA*.

Table 1. Simulation and algorithm parameters.

Upstream rate	2.48832 Gbps
Downstream rate	9.95328 Gbps
Alloc-IDs	10 per ONU
ONU buffer size	100 MB per Alloc-ID
Fixed bandwidth	75 bytes
Assured bandwidth	25 bytes
Maximum bandwidth	150 bytes
R_F^U	2 bytes
R_F^L	75 bytes
Downstream frame period	125 μsec
Guard time	64 bits
Simulation time	1 min
Learning period	100 Downstream Frames
L	0.1
a	10^{-5}

5.6 Results and Discussion

Figures 4 and 5 depict the average upstream delay in terms of msec for the *heavy-traffic* and the *light-traffic* scenarios respectively. The number of ONUs changes from 2 to 32 with a step of 2; hence the number of Alloc-IDs alters from 20 to 320 respectively. It is evident that *ARES* presents the lower delay compared to both schemes. Indeed, the *pure status reporting* collapses when the number of ONUs becomes 24 and 26, based on Figs. 4 and 5, respectively. *HYRA* degrades when the traffic pressure is higher (30 and 32 ONUs). On the contrary, the proposed scheme manages to reduce the delay under any traffic conditions. It is worth mentioning that the delay reduction is much better when the traffic becomes higher. Tables 2 and 3 show the delay reduction that *ARES* succeeds compared to the two other schemes in terms of msec for the *heavy-traffic* and the *light-traffic* scenarios respectively. The most significant feature of *ARES* that can be observed in both figures is its ability to enforce low-delay traffic provisioning under pressure. For example, in the *heavy-traffic* scenario, when the number of ONUs is 32, *ARES* manages to reduce the delay by 166.75 msec compared to the conventional report method. It is clear that such an improvement allows the network to scale up more in order to include more subscribers. Hence, high-quality traffic provisioning is guaranteed with the same infrastructure to more users, resulting in higher profit for the telecom company. Therefore, a strong motivation is created to spend and install optical access networks.

The effectiveness of the three schemes in terms of traffic received is investigated in Figs. 6 and 7 regarding the *heavyspstraffic* and the *light-traffic* scenarios respectively. In essence, this metric expresses the network goodput, i.e., the rate

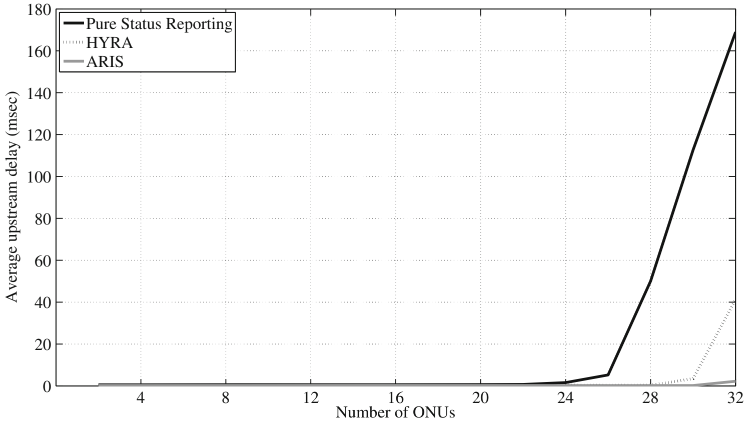

Fig. 4. Average delay in upstream direction in terms of msec. The results relate to the heavy traffic scenario.

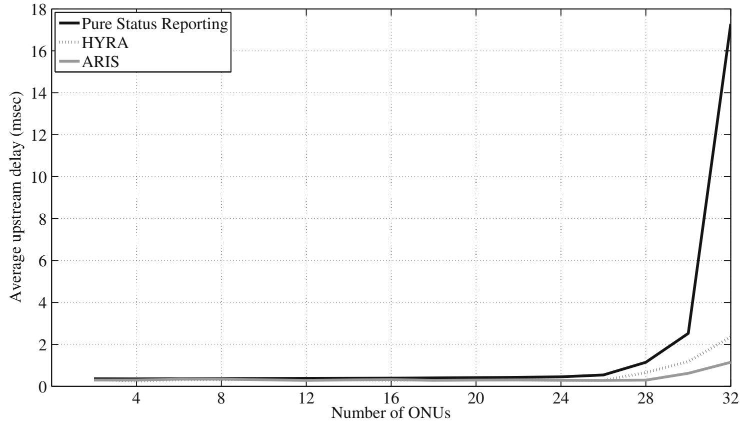

Fig. 5. Average delay in upstream direction in terms of msec. The results relate to the light traffic scenario

Table 2. Heavy Traffic Scenario. Upstream delay reduction.

# of ONUs	4	8	12	16	20	24	28	32
Reduction over Pure Status Reporting (msec)	0.36	0.34	0.36	0.39	0.43	1.39	49.87	166.75
Reduction over HYRA (msec)	0.14	0.16	0.14	0.13	0.14	0.13	0.14	39.09

the ONUs receive data using the upstream channel. *ARES* exhibits the higher rate in traffic receiving. Once more, the *pure status reporting* degrades when the number of ONUs is high, i.e., when the number of ONUs is 24 and 28 in the

Table 3. Light Traffic Scenario. Upstream delay reduction.

# of ONUs	4	8	12	16	20	24	28	32
Reduction over Pure Status Reporting (msec)	0.05	0.02	0.10	0.06	0.11	0.16	0.85	16.13
Reduction over HYRA (msec)	0.01	0.01	0.01	0	0.01	0.01	0.36	1.2

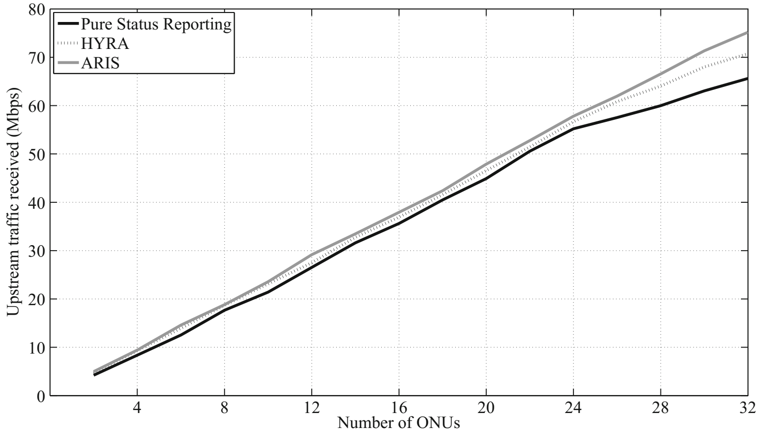

Fig. 6. Traffic received in upstream direction in terms of Mbps. The results relate to the heavy traffic scenario.

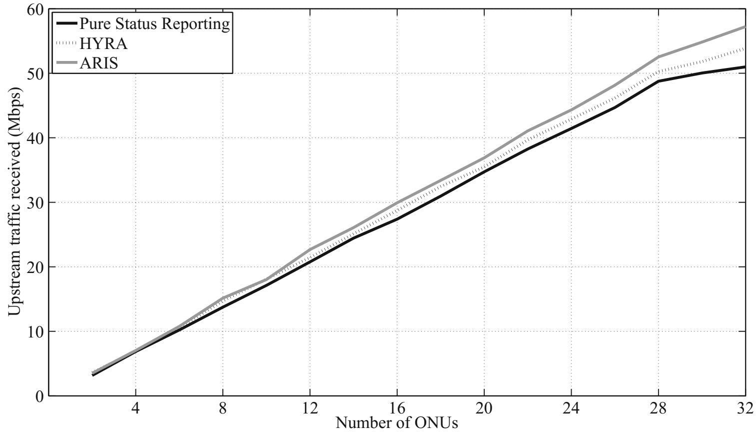

Fig. 7. Traffic received in upstream direction in terms of Mbps. The results relate to the light traffic scenario.

heavy-traffic and the *light-traffic* scenarios respectively. In essence, this degradation is caused by the inefficiency of *pure status reporting* to cope with demanding traffic requests. Hence, a portion of data that wait to the queues of ONUs to

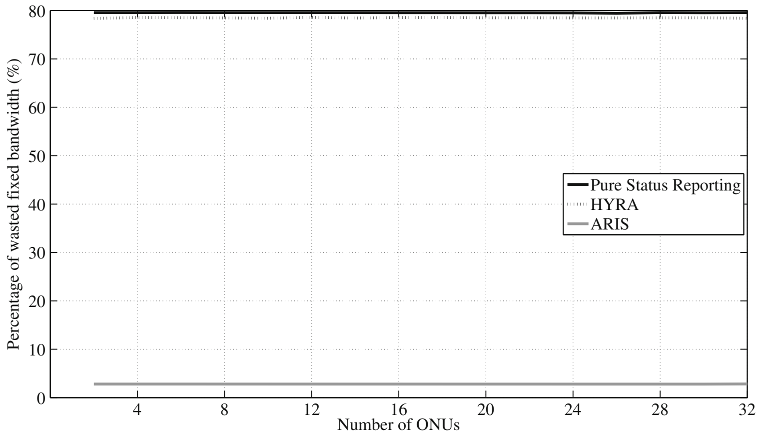

Fig. 8. Percentage of wasted bandwidth when allocating fixed rate. The results relate to the heavy traffic scenario.

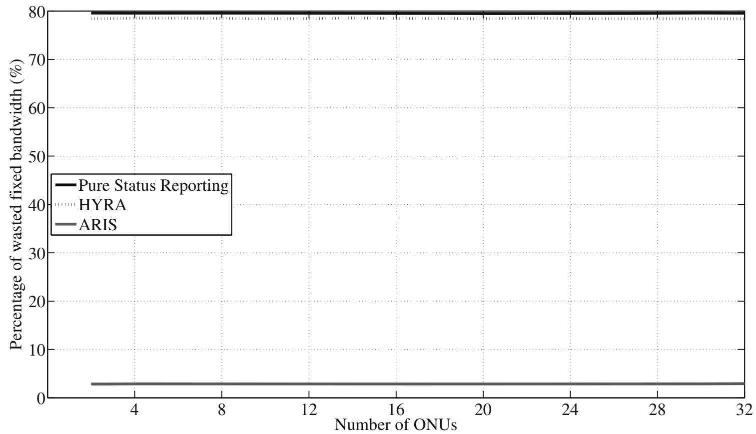

Fig. 9. Percentage of wasted bandwidth when allocating fixed rate. The results relate to the light traffic scenario.

be delivered to the OLT, stay at the queues more then a single (downstream) period. That is the reason behind this phenomenon. Note, that the use of *ARES* instead of *HYRA* results in slightly increased network goodput. This marginal improvement is attached to the efficacy of the *FBA automaton*, which is able to adjust the level of R_F offering more data (user data not control information) to be delivered in time.

It is interesting to explore the impact of the R_F estimation mechanism. To this end, Figs. 8 and 9 demonstrate the bandwidth wastage caused by the R_F allocation in the *heavy-traffic* and the *light-traffic* scenarios respectively. What this metric reveals has to do with the R_F utilization. For instance, a wastage of

30 % means that an Alloc-ID used 70 % of the fixed bandwidth granted by the OLT. Hence, the less the percentage of the wasted fixed bandwidth the more efficient bandwidth allocation. By observing both figures it is evident that the efficacy of the *FBA automaton* is quite influential. The acquired improvements in terms of bandwidth utilization reveal a difference of 75 % between *ARES* and *pure status reporting* in both scenarios. When comparing *ARES* and *HYRA* the difference is slighter. This is due to the fact that *HYRA* applies the isolation method - as *ARES* does - and it more likely to have some data to be delivered to the ONUs that experienced an isolation period. Thus, the amount of R_F is better utilized by these ONUs that recover from an isolation phase than other ONUs. In any case, the large impact of applying the fixed bandwidth adjustment method is deemed beneficial. Note, that obtained improvement remains stable as the number of ONUs increases. This happens due to the fact that the applied method is dynamic; hence it adequately adjust the level of R_F in a flexible way, independently of the traffic conditions.

6 Conclusions

A novel, dynamic, adaptive bandwidth allocation scheme was proposed in this work for XG-PON systems. The OLT is enhanced with a learning from experience mechanism in order to enforce its resource allocation decisions. A two-level learning automaton was designed to provide the OLT with a twofold estimation. First, underutilized ONUs are identified and in the next step are isolated from the bandwidth allocation process for a time period predicted by the automaton. Concurrently, the amount of fixed bandwidth allocated to the connected Alloc-IDs in each ONU is adjusted based on a second automaton. Both estimations intend to limit the bandwidth wasted to ONUs (or Alloc-IDs) that remain idle. Accordingly, the bandwidth savings are re-distributed to ONUs that are still request bandwidth. By applying the proposed two-level adaptive enhancement, the XG-PON systems presents notable improvements in terms of upstream delay and traffic received, while the estimation process is indicated quite accurate based on the provided simulation results.

Acknowledgements. This work has been funded by the NSRF (2007–2013) SynergasiaII/EPAN-II Program "Asymmetric Passive Optical Network for xDSL and FTTH Access," General Secretariat for Research and Technology, Ministry of Education, Religious Affairs, Culture and Sports (contract no. 09SYN-71-839).

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