IGFS: A New MAC Protocol Exploiting Heterogeneous Propagation Delays in the Dynamic Bandwidth Allocation on WDM-EPON

Panagiotis G. Sarigiannidis, *Member, IEEE*, Sophia G. Petridou, *Member, IEEE*,
Georgios I. Papadimitriou, *Senior Member, IEEE*, and Mohammad S. Obaidat, *Fellow, IEEE*

***Abstract*—One of the most challenging issues of the Ethernet passive optical networks' (EPONs) architecture is the bandwidth allocation problem. Various dynamic allocation schemes have been proposed to schedule the subscribers' demands. However, the performance of all these schemes is significantly degraded when the round-trip times (RTTs) of the optical network units (ONUs) are dissimilar, due to the large number of gaps in the transmission schedule. Unfortunately, in real networks, RTTs are usually dissimilar. In this paper a new medium access control (MAC) protocol for multichannel EPONs, namely the Intelligent Gap Filling Strategy (IGFS) is proposed. The IGFS employs two algorithms: the** DissimilarityExploitation **algorithm, which exploits the RTTs' dissimilarities, and the** MinimumLatencyScheduling **algorithm, which rearranges the ONUs' service order in order to favor the requests that cause the minimum scheduling latency.**

***Index Terms*—Passive optical networks, reservation, scheduling, WDM-EPONs.**

I. Introduction

PASSIVE optical networks (PONs) seem to be the most promising technology to cover the bandwidth needs of access networks [1]–[7]. Although PONs are considered mature due to their longevity, low cost, and huge bandwidth [8], they need a more multiuser environment along with high bandwidth support. Wavelength division multiplexing (WDM) technique addresses this issue by deploying multiple wavelength channels into a single fiber [9]–[14]. This leads to the access path upgrade and offers higher levels of bandwidth to the subscribers. Since current ethernet passive optical networks (EPONs) are not longer adequate to fulfill the uprising challenges of access networks, because of utilizing a single-channel system, WDM-EPONs provide promising solution by increasing the transmission capacity of access networks [15], [16]. Beyond the bandwidth increase, WDM-EPONs are able to cope with the current single-channel PONs by converging the low-cost equipment and simplicity of Ethernet protocol and the low-cost fiber infrastructure of PONs. In this manner, w-channel WDM-EPONs, in which each channel is operating at a line rate equal to 1 Gbps, support a total bandwidth of w Gbps.

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P. G. Sarigiannidis, S. G. Petridou, and G. I. Papadimitriou are with the Department of Informatics, Aristotle University, 54124 Thessaloniki, Greece.

M. S. Obaidat is with the Department of Computer Science, Monmouth University, West Long Branch, NJ 07764 USA (e-mail: obaidat@monmouth.edu).

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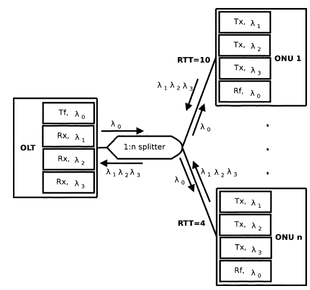

Fig. 1. Typical WDM-EPON architecture.

Typically, EPONs consist of an optical line terminal called OLT and a set of optical network units called ONUs [15]. The OLT is located at the central office of the service provider, while an ONU may connect to a single or more subscribers. Subscribers transmit their data to the OLT and the latter forwards data to the backbone network to reach the Internet. On the contrary, OLT broadcasts the incoming data from backbone to the connecting subscribers. EPONS have a physical tree topology with the central office located at the root of the tree and the subscribers connected to the leaf nodes of the tree, as illustrated in Fig. 1. The OLT is connected to multiple, e.g., n, ONUs through an $1 : n$ optical splitter/combiner. The most important factor of this topology has to do with the distance among the ONUs and the OLT. The round-trip time (RTT) between OLT and each ONU, which denotes the amount of time required by a bit to travel from OLT to ONU and return, affects seriously the network response time.

The downstream direction is utilized in a straightforward way, since the OLT is able to broadcast data to all ONUs. In the upstream direction the connection may be viewed as a multipoint-to-point network. This fact leads to a challenge, in sense of bandwidth scheduling. In other words, a WDM medium access control (MAC) protocol is needed in order to support multiuser functionality without collisions. In this paper, a MAC protocol for WDM-EPONs is proposed, namely the Intelligent Gap Filling Strategy (IGFS) scheme.

The core idea of the proposed scheme is to exploit the different RTTs. Since, RTTs are different for each ONU, some ONUs may experience different delays than others. The proposed IGFS scheme tries to schedule the subscribers' transmissions, by taking into account the various RTTs. The novel framework favors the transmissions of the ONUs which are located near the OLT, by giving them the opportunity to complete their transmission before the beginning of the transmission of the ONUs with higher RTTs. For this reason, the IGFS scheme employs a new algorithm,

TABLE I
NETWORK SYMBOLS' NOTATION

Symbol	Description
OLT	Optical line terminal
ONU	Optical line unit
RTT	Round-trip time
n, w	Number of ONUs and channels
k	Traffic load
W_{max}	The size of the transmission window

namely the DISSIMILARITYEXPLOITATION algorithm. Furthermore, the proposed scheme favors the requests that cause the minimum scheduling latency by adopting the MINIMUMLATENCYSCHEDULING algorithm. This algorithm rearranges the ONUs' service order in such a way that ONUs' requests that infer lower latency are prioritized over the requests that infer great transmission delays. This policy offers more available accommodation space for the forthcoming ONUs requests. Combining the DISSIMILARITYEXPLOITATION and MINIMUMLATENCYSCHEDULING algorithms in each transmission frame, the IGFS scheme provides a more efficient schedule compared to the conventional methods, inferring lower packet delays and better network throughput.

The remainder of this paper is organized as follows. Section II provides the network structure, while Section III presents a related packet scheduling algorithm, namely the WDM-IPACT designed for WDM-EPONs. The proposed IGFS scheme is introduced in Section IV, while Section V discusses the simulation results. Finally, conclusions are given in Section VI.

II. NETWORK ARCHITECTURE

The network considered in this paper is a typical WDM-EPON with tree topology. As depicted in Fig. 1 the OLT is located at the root of the tree, while the n ONUs are connected to the leaf nodes of the tree. Thus, the illustrated network has a split ratio (OLT:ONU) of $1 : n$. The bandwidth in each direction is subdivided into w data wavelengths $\{\lambda_1, \ldots, \lambda_w\}$ ($w = 3$ in Fig. 1). The network also utilizes a control channel λ_0 in order to exchange control data, i.e., the GATE and REPORTS messages, described in Section III. Regarding the transmitting and receiving parts of the above network, each ONU may transmit packets on different wavelengths using a tunable transmitter Tx, while it receives GATE messages in the control channel using a fixed receiver Rf. On the other hand, the OLT transmits the GATE messages using a fixed transmitter Tf, while it receives data packets using a tunable receiver Rx.

The amount of bandwidth that OLT allocates to ONUs is denoted as transmission window. The length of transmission window can be defined according to one of the Fixed, Limited, or Gated assignment schemes [17]. In the Fixed assignment scheme, the OLT will allocate each ONU a fixed length of transmission window $W_{\max}$, while in the Gated scheme, each ONU will be granted transmission window whatever size it requests. In this paper, the Limited assignment scheme is adopted in order to provide fair coordination to the subscribers. According to [5] the Limited scheme prevents any ONU from monopolizing the shared link. More specifically, according to this scheme, the OLT will allocate ONU the amount of bandwidth it is requested if the request is smaller than the upper bound limitation $W_{\max}$, otherwise $W_{\max}$ is assigned. A summary of notation and basic abbreviations is given in Table I.

III. RELATED SCHEDULING ALGORITHMS

There are two broad approaches concerning dynamic scheduling, the offline and the online scheduling [8], [15], [18]. In the offline scheduling, the OLT collects the requests via REPORT messages from all ONUs and then produces the schedule, while in the online scheduling each new schedule comes upon the reception of each REPORT message from ONU. In this manner the OLT accommodates each ONU's request without global information of the current requests of the other ONUs. The online scheduling has the advantage of being direct, supporting instant scheduling decisions, while the offline fashion allows the OLT to make effective decisions, by taking into account the whole ONUs' requests.

Interleaved Polling with Adaptive Cycle Time (IPACT) is the main representative scheme regarding dynamic bandwidth allocation in Ethernet passive optical networks [17]. The role of IPACT is to produce a dynamic transmission schedule for the various connected ONUs in order to communicate with the OLT. The produced schedule is calculated having no collisions and this is achieved by exchanging control information between the OLT and the ONUs. In the case of WDM-EPONs, the system supports multiple channels for the upstream fiber media. The single channel IPACT algorithm has been expanded in order to support WDM-EPONs. Hence, the WDM-IPACT is a modification of IPACT algorithm and it operates in a similar way [15].

WDM-IPACT works as follows: initially the OLT gathers information about the transmitter and receiver devices of the ONUs as well as about the distance between the OLT and the ONUs, which is denoted by their RTTs. The control information for the arbitration is exchanged between the OLT and the ONUs with two special packet messages, namely the GATE and the REPORT messages. The GATE message is used by the ONU to give transmission grants to ONUs. On the other hand, each ONU transmits a REPORT message to announce the transmission request or equivalently its queue demand to the OLT. Upon receiving a REPORT message from an ONU, the OLT accommodates the ONU's next transmission grant. Eventually, the OLT has to take two different decisions regarding the schedule. The first one is the time that an ONU will be scheduled and then be announced with a GATE message to the ONU and the second one is the choice of the wavelength channel.

The proposed IGFS is based on the offline scheduling and thus it is compared to the offline WDM-IPACT i.e., the WDM-IPACT protocol that adopts offline scheduling [15].

IV. PROPOSED IGFS SCHEME

A. The Dissimilarity Exploitation Algorithm

Upon the reception of the whole GATE messages, the DISSIMILARITYEXPLOITATION algorithm is activated. This algorithm tries to find accommodation spaces between the transmissions of ONUs with different RTTs. The main feature that is being exploited is the following: if a certain bandwidth request (i.e., the information of the REPORT message), that is able to be scheduled before the beginning of another ONU, is found then this ONU is favored amongst the other ONUs. In other words, the algorithm attempts to look for ONUs that their transmission ends before the beginning of another ONUs transmission, due to dissimilar RTTs. In that case, the early transmission could be scheduled firstly, without shifting the rest of the transmissions. This altered accommodation technique allows the exploitation of time spaces that could be entitled as unavailable if the service order is random. In this way, short messages in conjunction with short RTTs are favored, without sacrificing scheduling time gaps.

Algorithm 1 Initialization algorithm.

Get the current time, $TIME = current\ time$
Define the collection set of ONUs, $S = \{all\ ONUs\}$
Define the collection set of data channels, $C = \{all\ data\ channels\}$
Get the round trip time of each ONU, denoted by RTT array
Get the report messages and store them to the REPORT array
$CAT[x] = TIME,\ x \in C$ (initialization of the CAT array)

For example, consider two ONUs, ONU_1 and ONU_2 with 110 μs and 190 μs RTT, respectively. Let us also assume that ONU_1 requests the transmission of 100 bytes, while the ONU_2 wish to send 1500 bytes. The DISSIMILARITYEXPLOITATION algorithm controls the starting and ending time of each ONU's transmission and decides to prioritize the ONU_1, since this transmission ends before the beginning of the ONU_2 transmission. More precisely, assuming that both ONUs have just received the GATE message from OLT. The ONU_1 needs $110/2 = 55$ μs, due to RTT, and 0.8 μs, due to data transmission, i.e., 55.8 μs in total to deliver its transmission to OLT. Given that the first bit of ONU_2 needs $190/2 = 95$ μs to reach the OLT, we can conclude that the ONU_1 transmission does not collide the ONU_2 transmission and the ONU_1 could be scheduled before ONU_2, without any harm. Yet, assuming that the guard time is less than 34.2 μs, it is possible to accommodate both of them in the same channel, giving to the scheduling algorithm flexibility for making decisions. Hence, the proposed scheme tackles to exploit the RTT dissimilarities between the connected ONUs in order to increase the system performance.

Algorithm 2 The DISSIMILARITYEXPLOITATION algorithm.

1: Choose the channel h with minimum CAT, $h \in C$ */*Calculate the beginning time of each ONU, denoted by the BT array and the ending time of each ONU, denoted by the ET array*/*
2: **for** $i := 1$ to ONU **do**
3:   **if** $(RTT[i] + TIME > CAT[h])$ **then**
4:     $BT[i] = RTT[i] + TIME, i \in S$
5:   **else**
6:     $BT[i] = CAT[h], h \in C$
7:   **end if**
8:   $ET[i] = BT[i] + REPORT[i]$
9: **end for**
10: Find the ONU y having the maximum $ET, y \in S$
11: **while** (FLAG_exploitable_RTT=TRUE) **do**
12:   Find the ONU z having the minimum BT, $z \in S$
13:   **if** $(ET[y] < BT[z])$ **then**
14:     FLAG_exploitable_RTT=TRUE
15:     choose ONU_z for the next accommodation, $y, z \in S, y \neq z$
16:     Schedule ONU_z and remove ONU_z from the set S
17:     Update the CAT value of the channel h, $CAT[h] = ET[z] + guard\_time$
18:   **else**
19:     FLAG_exploitable_RTT=FALSE
20:   **end if**
21: **end while**
22: DISSIMILARITYEXPLOITATION mechanism ends

More specifically, once the Initialization algorithm (Algorithm 1) is competed, the DISSIMILARITYEXPLOITATION mechanism, described by Algorithm 2, takes place. The Initialization algorithm gets the appropriate info, i.e., the current system time, the ONUs identities, the RTTs and the request of each ONU for the current frame (REPORT message). Then, Algorithm 2 selects the channel that is sooner available for the next accommodation. In lines 3–7, the Algorithm 2 calculates the beginning time for each ONU in line with the current info, i.e., the current RTT and CAT values, while in line 8 the ending time of each ONU is computed. Finally, the while structure looks for a certain ONU that can be scheduled prior other ONU, without inferring extra scheduling delay, until the set of unscheduled ONUs remains empty or there are not exist RTT dissimilarities.

The DISSIMILARITYEXPLOITATION algorithm terminates if no more ONUs could be found that have exploitable RTT dissimilarities. Then the MINIMUMLATENCYSCHEDULING algorithm takes place.

The above algorithms need the following computational time for their executions.

- The Algorithm 1 needs $O(1)$ time to run.
- The finding of the minimum CAT (Algorithm 2) has $O(w)$ computational cost, where w denotes the number of available data channels.
- Lines 2–8 of the Algorithm 2 need $O(n)$ time to calculate BT and ET arrays, where n denotes the number of the ONUs in the network.
- Line 9 needs $O(n)$ time to find the ONU with the maximum ET.
- The while loop (lines 11–21) runs in $O(n^2)$ in the worst case, since for each iteration the algorithm searches the ONU having the minimum BT. However this case is extremely rare.
- Overall, the initialization and the Algorithm 2 run in $O(n^2 + w)$ time in the worst rare scenario.

B. *The Minimum Latency Scheduling Algorithm*

The proposed scheme employs the MINIMUMLATENCYSCHEDULING algorithm, once the Algorithm 2 has been completed. According to this new algorithm, each ONU is examined in terms of its REPORT message in conjunction with its RTT. Then, the ONU with the minimum latency is chosen. The minimum latency is defined as the end time of the ONU transmission to the OLT side.

For instance, consider the ONU_1 and ONU_2 which requests 1500 bytes and 300 bytes, respectively. Furthermore, assume that the ONU_1 has 120 μs RTT, while ONU_2 is located in a greater distance and it has 150 μs RTT. If both ONUs begin the transmission simultaneously, ONU_1 will experience 12 μs, due to data transmission, and $120/2 = 60$ μs, due to RTT, which means 72 μs in total. On the other hand, the transmitted data of ONU_2 will be completely received by the OLT after $2.4 + 150/2 = 77.4$ μs. At this case, the transmission of ONU_1 will be favored, even though its bandwidth request is larger, since ONU_2 causes shorter latency compared to ONU_1. Eventually, this policy offers more available accommodation space for the forthcoming ONUs requests.

The MINIMUMLATENCYSCHEDULING is analyzed into steps by Algorithm 3. After receiving the appropriate info from Algorithm 2 (set of unscheduled ONUs, ,RTTs, REPORT messages, BT and ET arrays, etc.), Algorithm 3 selects the ONU with the minimum scheduling latency, i.e., the minimum ET array. Then

TABLE II
AN EXAMPLE OF DIFFERENT RTTS AND BANDWIDTH REQUESTS IN A WDM-EPON CONSISTING OF AN OLT AND FOUR ONUS

ONUs	RTT	Bandwidth request
ONU_1	190 $\mu secs$	7000 $bytes$
ONU_2	160 $\mu secs$	4500 $bytes$
ONU_3	110 $\mu secs$	3000 $bytes$
ONU_4	150 $\mu secs$	6000 $bytes$

the CAT, BT, and ET arrays are updated. Finally, Algorithm 3 runs until the set of unscheduled ONUs becomes empty.

Algorithm 3 The MINIMUMLATENCYSCHEDULING algorithm.

1: Define the collection set of the remaining ONUs, $S' = \{remaining\ ONUs\}$
2: Define the collection set of data channels, denoted as $C = \{all\ data\ channels\}$
3: Get the RTT of each ONU, denoted by RTT array
4: Get the REPORT messages and store them to the REPORT array
5: Get the CAT, BT and ET arrays from Algorithm 2
6: Choose the channel h with minimum CAT, $h \in C$
7: **while** $(S' \neq \emptyset)$ **do**
8: Choose the ONU_i with the minimum ET, $i \in S'$
9: Schedule ONU_i and remove ONU_i from the set S'
10: Update the CAT value of the channel h, $CAT[h] = ET[i] + guard\_time$, $h \in C, i \in S'$
11: Update BT and ET arrays
12: **end while**
13: Set the current time equal to the $ET[latest]$, where latest denotes the ONU with the maximum ET values
14: MINIMUMLATENCYSCHEDULING mechanism ends

The calculation process of the Algorithm 3 depends on the following procedures.

- Line 6 runs in $O(w)$, where w denotes the number of the available data channels.
- The while loop (lines 7–12) needs at most $O(n^2)$ time to schedule the remaining ONUs of the S' set, since for each iteration the algorithm has to find the minimum ET. Hence in the worst case the algorithm runs in $O(n^2)$, if none of the ONUs has been scheduled during the Algorithm 2.
- Overall the computational complexity of the Algorithm 3 is $O(n^2 + w)$.

C. Indicative Example

In this section, an illustrative example of the proposed IGFS scheme is presented. Consider 4 ONUs that are connected to OLT. ONUs are located in various distances, hence they experience dissimilar RTTs, which are given in Table II.

For this example, it is supposed that the system supports one control channel, denoted by λ_0, and two data channels, denoted by λ_1 and λ_2, respectively. It is also assumed that the common system clock has just started. The line rate of each channel is equal to 1 Gbps. OLT has collected all ONUs' REPORT messages and the IGFS begins constructing the schedule for the current frame. During the previous frame (that is not illustrated in the following figures), the ONUs requested 7000, 4500, 3000, and 6000 bytes, respectively, while it is considered a guard time between the bandwidth allocations, equal to 5 μs. Initially, Algorithm 2 takes place and it looks for ONUs requests that can be fitted before the beginning of at least one other ONU transmission. The search is successful, indicating ONU_3, since ONU_3's transmission ends after 139 μs (including the guard time), while considering the best case ONU_4's data will reach OLT after 150 μs. Hence, ONU_3 is preferred to be scheduled at this moment and the schedule so far is depicted in Fig. 2.

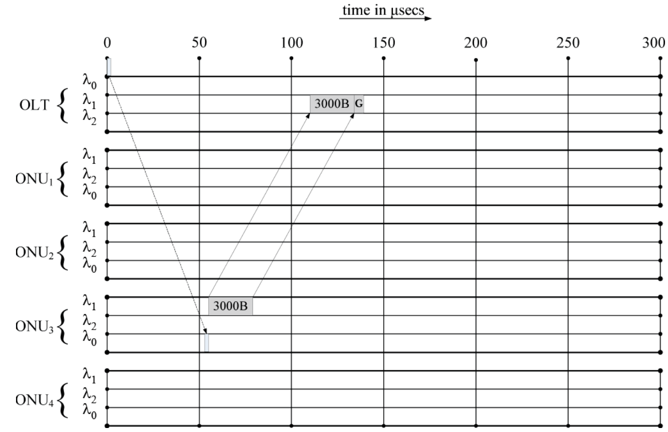

Fig. 2. Formed transmission schedule by the IGFS after the accommodation of ONU_3 REPORT message.

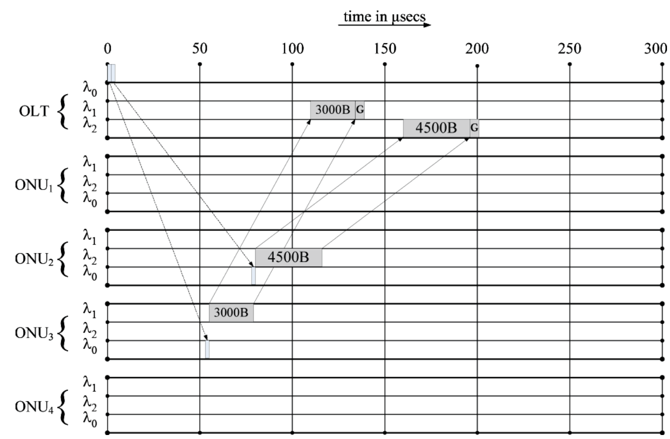

Fig. 3. Formed transmission schedule by the IGFS after the accommodation of ONU_3 and ONU_2 REPORT messages.

Channel λ_1 is selected for the above accommodation, since it is the first available (and it has the lowest index number). Then, Algorithm 2 looks again for an ONU with applicable RTT, though the search is empty. At this moment Algorithm 3 is applied. It examines the latency scheduling time of the rest ONUs and it decides to schedule ONU_2, since it has the minimum latency time. Hence, ONU_2 is scheduled in channel λ_2, because λ_2 has the minimum channel available time. The schedule so far is illustrated in Fig. 3.

In the same manner, ONU_4 is chosen (due to minimum latency), since its transmission ends at 204 μs, contrary to ONU_1's transmission ending time, that is at 255 μs. The first data channel is selected for this schedule, due to its minimum available time. Fig. 4 shows the formed schedule at this stage.

Finally, ONU_1 is serviced, the set of unscheduled ONUs becomes empty and the final schedule is depicted in Fig. 5. It is obvious that the schedule length for the current frame is equal to 255 μs.

It is really interesting to compare both offline WDM-IPACT and IGFS schemes for the aforesaid example. In accordance with the process of the offline WDM-IPACT the service order is

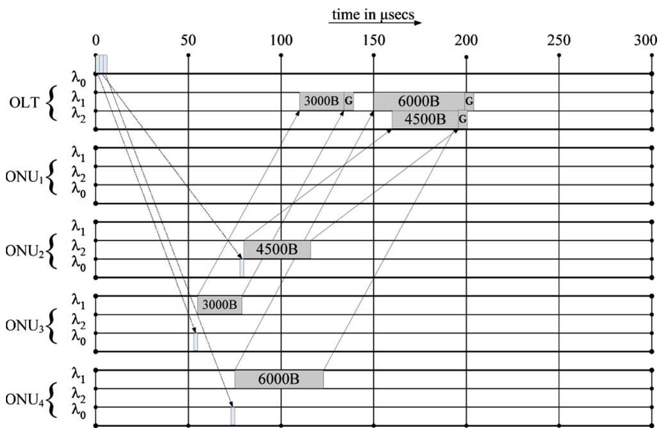

Fig. 4. The formed transmission schedule by the IGFS after the accommodation of ONU_3, ONU_2 and ONU_4 REPORT messages.

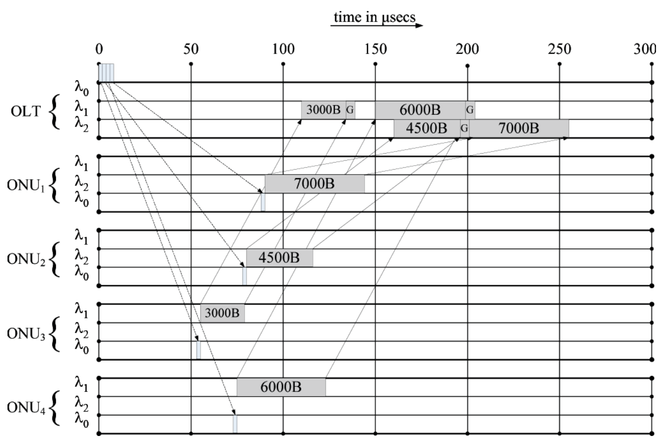

Fig. 5. Final transmission schedule by the IGFS.

stated as follows: ONU_1, ONU_2, ONU_3, and ONU_4. Accordingly, the constructed schedule by the offline WDM-IPACT algorithm is shown in Fig. 6.

Comparing the two formed schedules, it is clear the IGFS is more efficient than the offline WDM-IPACT scheme, in terms of schedule length and delay. The schedule length that IGFS produces lasts $279 - 255 = 24$ μs less than that of offline WDM-IPACT. Moreover, the mean packet delay that the IGFS scheme infers is lower than that of offline WDM-IPACT. More specifically, the calculated mean packet delay that IGFS infers for the current frame is stated as shown in the first equation at the bottom of the page (drt stands for data reception time).

Respectively, the mean packet delay for the offline WDM-IPACT scheme is shown in the second equation at the bottom of the page.

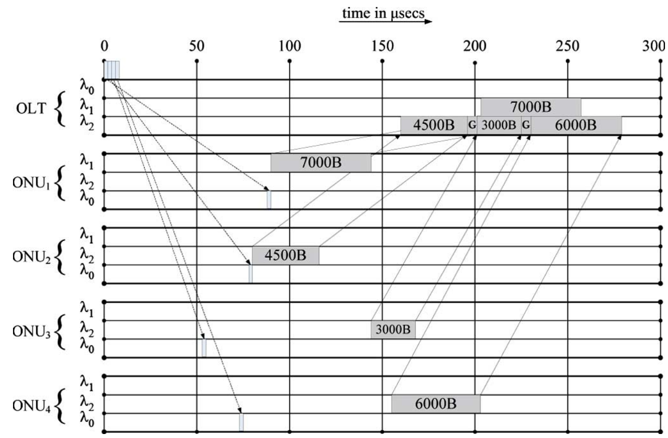

Fig. 6. Transmission schedule for same example constructed by the offline WDM-IPACT.

In conclusion, the reduction of the mean packet delay for the above example is $239 - 196 = 43$ μs.

V. Simulation Results

In this section, the performance of the proposed IGFS scheme is evaluated given a WDM-EPON consisting of an OLT and n ONUs. As mentioned in Section I, the core idea of IGFS is to exploit the different RTTs of ONUs. Actually, every ONU is assigned a downstream propagation delay, i.e., the amount of time required by a bit to travel from the OLT to the ONU, and an upstream propagation delay, i.e., the amount of time required by a bit to travel from the ONU back to the OLT. The RTT between OLT and each ONU is defined to be the sum of downstream and upstream propagation delays and affects seriously the network response time. In this study, it is assumed independent RTTs which are randomly generated according to a uniform distribution $U[100\ \mu\mathrm{s},\ 200\ \mu\mathrm{s}]$ and correspond to 15–30 km distances between ONUs and OLT [15].

In simulations carried out, the IGFS scheme is compared to the well-known WDM-IPACT protocol presented in Section III, as WDM-IPACT is the main offline scheduling paradigm [19], [20]. The traffic traces used are synthetic exhibiting the properties of self-similarity and long-range dependence (LRD). More specifically, the self-similar traffic used is an aggregation of multiple sources each consisting of alternating Pareto-distributed ON/OFF periods with shape parameter $\alpha = 1.6$ [17], [19], [20]. The proposed scheme is evaluated under different traffic load k, number of channels w and ONUs n. Each channel operating in the section between OLT and ONUs supports 1 Gbps, while the line rate of the distributed section from ONU to individual end-user is assumed to be 100 Mbps. The load is measured with respect to this rate which means that a load of

$$\frac{\mathrm{ONU}_1(\mathrm{drt}) + \mathrm{ONU}_2(\mathrm{drt}) + \mathrm{ONU}_3(\mathrm{drt}) + \mathrm{ONU}_4(\mathrm{drt})}{\mathrm{ONUs}} = \frac{255 + 195 + 134 + 199}{4} = 196\ \mu\mathrm{s}.$$

$$\frac{\mathrm{ONU}_1(\mathrm{drt}) + \mathrm{ONU}_2(\mathrm{drt}) + \mathrm{ONU}_3(\mathrm{drt}) + \mathrm{ONU}_4(\mathrm{drt})}{\mathrm{ONUs}} = \frac{257 + 196 + 225 + 279}{4} = 239\ \mu\mathrm{s}.$$

TABLE III
IGFS VERSUS WDM-IPACT: THE VALUES OF NETWORK THROUGHPUT, DROP RATIO AND MEAN PACKET DELAY AND THE % REDUCTION OF DROPPED PACKETS AND MEAN PACKET DELAY AS A FUNCTION OF NETWORK LOAD FOR $n = 32$ ONUs AND $w = 3$ CHANNELS

load (k)	Network throughput		Drop ratio		Mean packet delay (sec)		% reduction of dropped packets	% reduction of mean packet delay
	IGFS	WDM-IPACT	IGFS	WDM-IPACT	IGFS	WDM-IPACT		
0.1	0.1	0.1	0%	0%	0.49×10^{-3}	0.59×10^{-3}	-	16.91%
0.2	0.2	0.2	0%	0%	0.53×10^{-3}	0.69×10^{-3}	-	21.78%
0.3	0.3	0.3	0%	0%	0.59×10^{-3}	0.82×10^{-3}	-	27.51%
0.4	0.4	0.4	0%	0%	0.68×10^{-3}	0.94×10^{-3}	-	27.51%
0.5	0.5	0.5	0%	0%	0.83×10^{-3}	1.08×10^{-3}	-	23.42%
0.6	0.6	0.6	0%	0%	1.24×10^{-3}	1.52×10^{-3}	-	18.77%
0.7	0.696	0.694	0.6%	0.9%	1.65×10^{-3}	2.00×10^{-3}	29.70%	17.40%
0.8	0.790	0.787	1.3%	1.6%	2.87×10^{-3}	3.11×10^{-3}	20.98%	7.79%
0.9	0.811	0.805	9.9%	10.6%	4.02×10^{-3}	4.16×10^{-3}	6.97%	3.41%
1	0.857	0.847	14.3%	15.3%	4.83×10^{-3}	4.95×10^{-3}	6.23%	2.41%

e.g., 0.7 represents a traffic load of 70 Mbps per ONU. Queue size of each ONU is 100 Kbytes and $W_{\max} = 11000$ bytes. The performance of the compared protocols is measured in terms of network throughput, mean packet delay and packet drop ratio.

In the first part of simulation, the aforementioned network metrics are evaluated under different network load for $k = [0.1, 0.2, \ldots, 1.0]$, while the number of ONUs is $n = 32$ and the number of channels is set to $w = 3$. The results are presented in Table III, which illustrates the network throughput, the drop ratio as well as the mean packet delay as a function of network load. More specifically, the network throughput increases along with the network load for $k = [0.1, 0.2, \ldots, 0.6]$. This is due to the fact that there are no dropped packets for the above values of k, as it is shown in drop ratio column of Table III. On the other hand, as the network load exceeds the medium values, i.e., $k = [0.7,\ 0.8,\ 0.9,\ 1.0]$, the dropped packets increase leading to decreased network throughput.

Although the same in trend, the two schemes are different in performance. It is apparent from Table III that for the same levels of network throughput, the proposed IGFS scheme keeps the mean packet delay lower than the WDM-IPACT from 2.41% up to 27.51% for all values of k. Fig. 7 depicts the % reduction of mean packet delay as a function of network load presented in the last column of Table III. High levels of performance are observed for low-to-medium levels of network load, i.e., $k = [0.1, 0.2, \ldots, 0.7]$, while the highest ones are detected for medium network load, i.e., $k = [0.3,\ 0.4,\ 0.5]$, which derives from the IGFS's basic idea to fill the gaps based on RTTs. More specifically, when the traffic load is low there are not enough packets to fill the gaps in the schedule, while for high load there are no gaps to be filled. Thus, a medium load, which is also more representative for the network's load, can actually exploit the idea of changing the ONUs' service order when the one's request is lower than the other's RTT.

The superiority of IGFS is confirmed by the drop ratio column of Table III. It is clear that IGFS and WDM-IPACT exhibit the same performance for $k = [0.1, \ldots, 0.6]$, since for these levels of network's load there are no dropped packets. For high levels of network load packets' drops are occurred, but IGFS is steadily superior to WDM-IPACT from 6.23% up to 29.70% for $k = [0.7, \ldots, 1.0]$ (the "% reduction of dropped packets" column of Table III).

The previous results derived for fixed number of ONUs and for $w = 3$ channels. Simulations were also carried out under different number of ONUs, e.g., $n = 8,\ 16,\ 24,\ 32,\ 40$, while the number of channels was fixed at $w = 3$ and the network load was $k = 0.7$. As it was expected, the results were similar to that of Table III, since the number of ONUs is another way to vary the network load. This means that in a network with few $n = 8$ or many $n = 40$ ONUs proportionally to the number

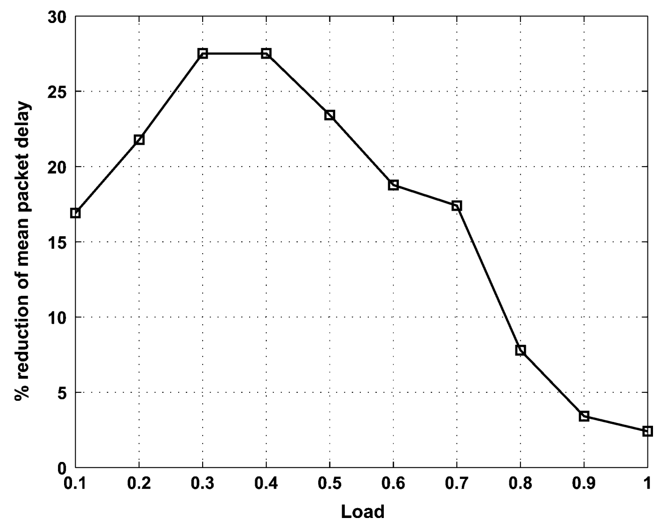

Fig. 7. IGFS versus WDM-IPACT: % reduction of mean packet delay as a function of network load.

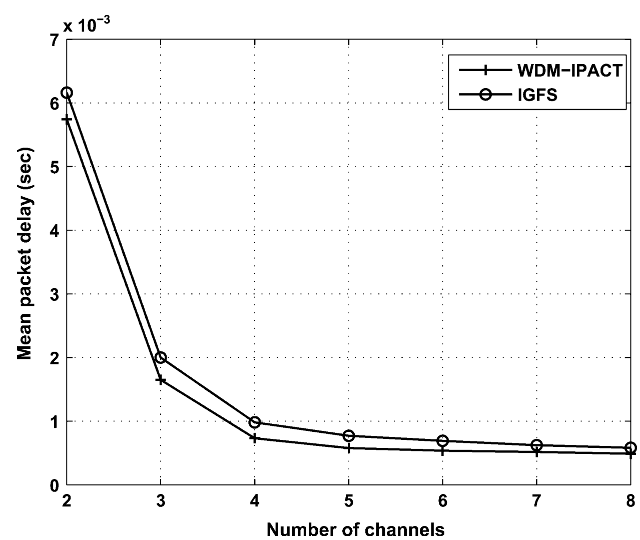

Fig. 8. Mean packet delay as a function of network channels for $n = 32$ ONUs and network load $k = 0.7$.

TABLE IV
IGFS VERSUS WDM-IPACT: THE VALUES OF NETWORK THROUGHPUT AND MEAN PACKET DELAY AND THE % REDUCTION OF MEAN PACKET DELAY AS A FUNCTION OF NETWORK CHANNELS FOR $n = 32$ ONUS AND NETWORK LOAD $k = 0.7$

channels (w)	Network throughput		Mean packet delay (sec)		% reduction of mean packet delay
	IGFS	WDM-IPACT	IGFS	WDM-IPACT	
2	0.587	0.570	5.74×10^{-3}	6.16×10^{-3}	6.81%
3	0.696	0.694	1.65×10^{-3}	2.00×10^{-3}	17.40%
4	0.7	0.7	0.73×10^{-3}	0.98×10^{-3}	25.44%
5	0.7	0.7	0.58×10^{-3}	0.77×10^{-3}	25.27%
6	0.7	0.7	0.54×10^{-3}	0.69×10^{-3}	22.48%
7	0.7	0.7	0.52×10^{-3}	0.62×10^{-3}	17.32%
8	0.7	0.7	0.49×10^{-3}	0.58×10^{-3}	15.90%

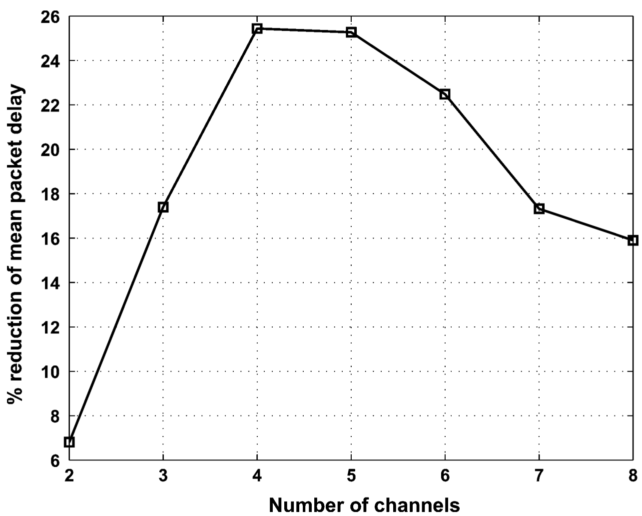

Fig. 9. IGFS versus WDM-IPACT: % reduction of mean packet delay as a function of network channels.

of channels, which corresponds to low- or high-load network, the proposed scheme is marginally superior to the WDM-IPACT protocol. But, for $n = 16,\ 24,\ 32$ the IGFS succeeds noticeable improvements, from 17.40% up to 25.21%, for the same reason as for $k = [0.3,\ 0.4,\ 0.5]$. As far as the packet drop ratio is concerned, it was found to be equal to 0% for $n = 8,\ 16,\ 24$ and increased with the number of ONUs. This observation is also in accordance with the results of Table III, since many ONUs means high-load network and this leads to packets' drops. However, the proposed scheme exhibits better performance, since results showed that IGFS succeeds up to 29.7% reduction of dropped packets compared to WDM-IPACT.

In the last part of simulation, we keep the values of k and n parameters fixed and observe the mean packet delay corresponding to different number of network channels w. Figs. 8 and 9 depict the results obtained for $w = 2, 3, \ldots, 8$, while the number of ONUs is $n = 32$ and the network load is $k = 0.7$. Our observation about IGFS's superiority under medium levels of network load is confirmed by curves' trend of Fig. 8. It is clear that our scheme succeeds lower levels of mean packet delay for all values of w, however for $w = 4,\ 5,\ 6$ IGFS is better to WDM-IPACT from 22.48% up to 25.44%, while for the rest values of w the % reduction of mean packet delay observed by IGFS is from 6.81% up to 17.40% better than that of WDM-IPACT, as presented in Fig. 9.

Finally, according to the values of network throughput of Table IV the packet drop ratio is equal to 0% for $w = 4, 5, \ldots, 8$, which derives from the fact that a network with increased number of channels proportionally to the number of ONUs corresponds to a low-load network. For $w = 2,\ 3$, the proposed scheme performs better, since it succeeds up to 29.7% reduction of dropped packets compared to WDM-IPACT.

VI. CONCLUSION

This paper introduces and evaluates a novel MAC protocol for WDM-EPONs. The proposed IGFS employs two algorithms, namely the DISSIMILARITYEXPLOITATION algorithm, which exploits the different RTTs of ONUs in order to fill the gaps in the scheduling program, and the MINIMUMLATENCYSCHEDULING algorithm, which further eliminates the aforementioned gaps by prioritizing the requests that cause the minimum scheduling latency.

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Panagiotis G. Sarigiannidis (S’05–M’07) received the Diploma and Ph.D. degrees in computer science from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2001 and 2007, respectively.

He is currently an Adjunct Lecturer at the University of Western Macedonia, Macedonia, Greece. His research interests include optical networks and optical switching.

Sophia G. Petridou (M’08) received the Diploma and Ph.D. degrees in computer science from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2000 and 2008, respectively.

Her research interests include clustering, optical and wireless networks.

Georgios I. Papadimitriou (M’89–SM’02) received the Diploma and Ph.D. degrees in computer engineering from the University of Patras, Patras, Greece in 1989 and 1994, respectively.

In 1997, he joined the faculty of the Department of Informatics, Aristotle University of Thessaloniki, Aristotle,Greece, where he is currently an Associate Professor. His main research interests include optical networks and wireless networks. He is co-author of three books published by Wiley and is author or coauthor of 75 journal and 85 conference papers.

Dr. Papadimitriou is an Associate Editor for five IEEE journals.

Mohammad S. Obaidat (S’85–M’86–SM’91–F’05) received the M. S. and Ph.D. degrees in computer engineering (with a minor in computer science) from The Ohio State University, Columbus.

He is an internationally well known academic, researcher, and scientist and has made pioneering and lasting contributions to the multifaceted fields of computer science and engineering. He is currently a Full Professor of Computer Science at Monmouth University, Long Branch, NJ. Among his previous positions are Chair of the Department of Computer Science and Director of the Graduate Program at Monmouth University, and Faculty Member at the City University of New York. He also served as a Consultant for several corporations and organizations worldwide. He has received extensive research funding and has authored or co-authored ten books and over 425 refereed scholarly journal and conference articles. His research interests are: wireless communications and networks, modeling and simulation, performance evaluation of computer systems, and telecommunications systems, security of computer and network systems, high-performance computing/computers, applied neural networks and pattern recognition, security of e-based systems, and speech processing. During the 2004/2005 academic year, he was on sabbatical leave as the Fulbright Distinguished Professor and Advisor to the President of Philadelphia University (Dr. Adnan Badran, who became in April 2005 the Prime Minster of Jordan).

Dr. Obaidat is an Editor of many scholarly journals, including Editor-in-Chief of the *International Journal of Communication Systems* (Wiley) and Editor of *IEEE Wireless Communications*. He has Guest Edited numerous special issues of scholarly journals such as IEEE TRANSACTIONS ON SYSTEMS, MAN AND CYBERNETICS, *IEEE Wireless Communications*, IEEE SYSTEMS JOURNAL, *Performance Evaluation* (Elsevier), *SIMULATION: Transactions of SCS*, *Computer Communications Journal* (Elsevier), *Journal of C & EE*, and *Security and Communication Network Journal* and *International Journal of Communication Systems* (both Wiley), among others. He has served as a Steering Committee Chair, Advisory Committee Chair, Honorary Chair, and Program Chair of many international conferences. He is the Founder of the International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS) and has served as the General Chair of SPECTS since its inception. Between 1994–1997, he served as Distinguished Speaker/Visitor for the IEEE Computer Society. Since 1995, he has been serving as an ACM Distinguished Lecturer. He is also an SCS Distinguished Lecturer, Founder of the SCS Distinguished Lecturer Program (DLP), and its present Director. Between 1996 and 1999, he served as an IEEE/ACM Program Evaluator of the Computing Sciences Accreditation Board/Commission (CSAB/CSAC). Between 1995 and 2002, he served as a member of the Board of Directors of the Society for Computer Simulation International. In 2002, he was the Scientific Advisor for the World Bank/U.N. Workshop on Fostering Digital Inclusion. Between 2002 and 2004, he served as Vice President of Conferences of the Society for Modeling and Simulation International (SCS). Between 2004 and 2006, he served as Vice President of Membership of SCS. Between 2006–2009, he served as the Senior Vice President of SCS. He is currently the President of SCS. He is the recipient of the distinguished Nokia Research Fellowship and the Distinguished Fulbright Award, the Best Paper Award at the IEEE AICCSA 2009 International Conference, the Best Paper Award at the IEEE GLOBCOM 2009 Conference, and the prestigious SCS McLeod Founder’s Award in recognition of his outstanding technical and professional contributions to modeling and simulation. He has received a recognition certificate from the IEEE. He is a Fellow of SCS.