A New Approach to the Design of MAC protocols for WDM-EPONs

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***Abstract*—Medium Access Control (MAC) protocols for WDM Ethernet passive optical networks (WDM-EPONs) suffer from low performance when the users' round trip times are different. In this paper a new MAC protocol for WDM-EPONs is introduced which overcomes the above limitation by filling the gaps in the scheduling program. Moreover, the proposed scheme favors the requests that present a burst-like behavior, by altering the nodes' service order in such a way that further eliminating the aforementioned gaps. The performance of the proposed scheme is being studied via simulation results which indicate that it achieves a significantly lower delay and packet loss ratio in relation to the well-known WDM IPACT protocol.**

I. Introduction

Nowadays, the ever-growing number of Internet users in conjunction with the wide-spreading use of bandwidth-demanding applications, e.g. triple play, video on demand, video conference and voice over IP, raise both difficulties and challenges for designing high efficient access networks. Passive Optical Networks (PONs) seem to be the most promising technology to cover the bandwidth needs of access networks [1], [2], [3]. Although PONs are considered mature due to their longevity, low cost and huge bandwidth [4], they need a more multi-user environment along with high bandwidth support. Wavelength Division Multiplexing (WDM) technique comes to address this issue, by deploying multiple wavelength channels into a single fiber [5], [6], [7], [8]. 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 [9], [10]. 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.

Typically, EPONs (and PONs in general) consist of an optical line terminal called OLT and a set of optical network units called ONUs [9]. The OLT is located at the central office (CO) 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 CO 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 multi-user 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 IGFS is to exploit the different RTTs of ONUs. Since RTTs are different for each ONU, some ONUs may experience different delays than others. The proposed 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. Furthermore, the new scheme favors the low-delay transmissions, by altering the ONUs' service order. In this way, ONUs' requests that infer lower delay, denoted in channel occupancy, are prioritized over the requests that infer

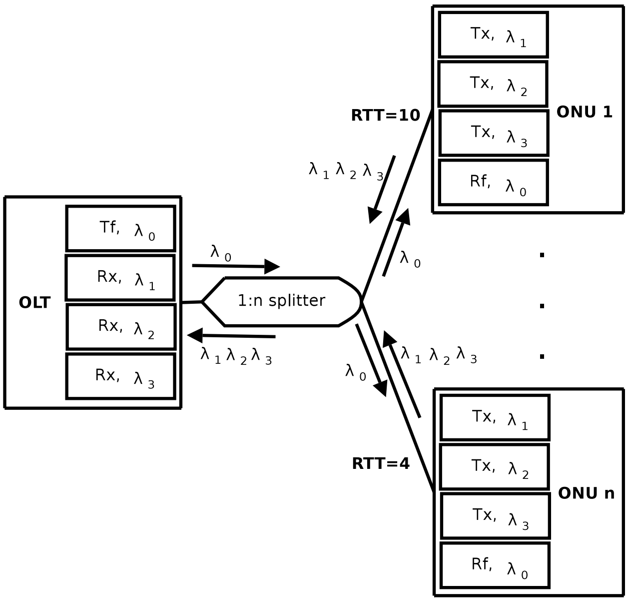

Fig. 1. A typical WDM-EPON architecture

great transmission delays.

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 $\{\lambda_1, \dots, \lambda_w\}$ ($w = 3$ 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 WDM-EPON, 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 [11]. 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. 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 is given in Table I.

TABLE I
Network symbols' notation

Symbol	Description
n, w	Number of ONUs and channels
k	Traffic load
W_{max}	The size of the transmission window
RTT	Round trip time

III. Related Scheduling Algorithms

IPACT is the main representative scheme regarding dynamic bandwidth allocation for EPONs [11]. 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 [9].

WDM IPACT works as follows: initially the OLT gathers information about the transmitter and receiver devices of the ONUs as long 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 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, in a WDM-EPON system the ONU 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.

At this point a critical differentiation must be underlined. There are two broad paradigms concerning dynamic scheduling, the offline and the online scheduling [4], [9], [12]. 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 info 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. 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 [9].

IV. The Proposed Algorithm

The WDM IPACT algorithm, as it was previously presented, has two basic weaknesses:

1) It follows the round robin service order used by the IPACT scheme. This static way of servicing may lead to low performance, since the algorithm does not consider the bandwidth request of each ONU separately. Furthermore, according to the WDM IPACT scheme, the selection of the data channel may cause a high scheduling latency (where the channel scheduling latency is defined as the time difference between the beginning of the transmission in the channel and the time that the channel becomes available at the OLT's side). This is due to the fact that the algorithm always chooses the earliest available data channel without taking into account the OLT's availability. This could lead to a significant degradation of the channel utilization. Hence, if the first ONU registered to the OLT database requests the maximum bandwidth GRANT and the last ONU requests the minimum bandwidth GRANT, then the algorithm is not able to accommodate the high length GRANT first. Eventually, this limitation leads to a lengthy schedule which in turn results in an increase of the mean packet delay.
2) Given that the various ONUs have diverse RTTs, it is important to exploit this information, by examining if a packet can be scheduled in the gap created because of the different RTTs. For example, if an ONU is close to the OLT then the GRANT message from OLT arrives to the ONU in a short time. On the other hand, a long-distance ONU experiences a longer delay until the arrival of its GRANT message. This information is not utilized by the WDM IPACT, since the service order is static and follows a round robin approach.

The proposed IGFS scheduling algorithm overcomes the above limitations of the WDM IPACT scheme by adopting a dynamic approach in defining the service order and exploiting the RTT of each ONU. In this way, the following advantages are achieved:

1) The scheduling latency is significantly reduced by selecting the available channel with a new criterion. While the WDM-IPACT scheme selects the earliest available channel (i.e. the channel that becomes available first), the proposed IGFS scheme selects the available channel optimally by taking into account the ONU availability. In other words, the algorithm selects the channel that sets the ONU available earlier. In this way, a shorter schedule is achieved leading to a lower packet delay.
2) A more compact schedule program is constructed by filling the gaps caused by the various RTTs. This information is revealed by examining the time gaps that are eventually appeared in the available channels. For each free time gap, the proposed algorithm accommodates packets that can fit into, if there so. Obviously, the higher differences in RTT values of ONUs lead to higher probability of finding out fitting time intervals. For this purpose, the ONUs' service order changes based on the availability of the time gaps. In this way, an efficient exploitation of the available bandwidth is achieved and the network performance is improved.

The algorithmic description of the proposed IGFS scheme is given by the Algorithm 1.

Algorithm 1 The algorithmic description of the IGFS.

1: Locate the time gaps between different RTTs
2: Find the REPORT that can be fitted in at least one time gap. If two or more REPORTS may fit to the available time gaps select that which can be transmitted earlier
3: If no more REPORTS can be fitted or no more time gaps are exist find the REPORT with the minimum scheduling latency
4: If there no more REPORTS end the current transmission frame

V. Simulation Results

To evaluate the performance of the proposed IGFS scheme we carried out simulations where the IGFS is compared to the well-known WDM IPACT presented in Section III. 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 $\alpha = 1.6$ [11]. The proposed scheme is evaluated under different traffic load k, while the number of channels is $w = 3$. 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 e.g. 0.7 represents a traffic load of 70 Mbps per ONU. For our simulations the RTT was randomly generated according to a uniform distribution $U[100\mu sec, 200\mu sec]$, which corresponds to $15-30$ km distances between ONUs and OLT [9]. Queue size of each ONU is 100 Kbytes and $W_{max} = 11000$ bytes. The performance of the compared protocols is measured in terms of mean packet delay and packet loss ratio.

Fig. 2 illustrates the mean packet delay as a function of the 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 $w = 3$. It is clear that the IGFS keeps the mean packet delay lower than the WDM IPACT from 12% up to 74% for all values of k. However, the highest levels of performance are observed for $k = [0.5, 0.6, 0.7]$ which is expected, since it 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

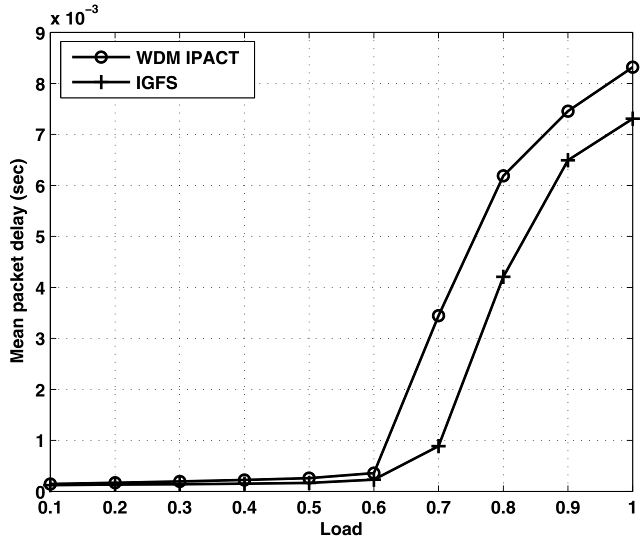

Fig. 2. Mean packet delay as a function of the network load for $n = 32$ and $w = 3$

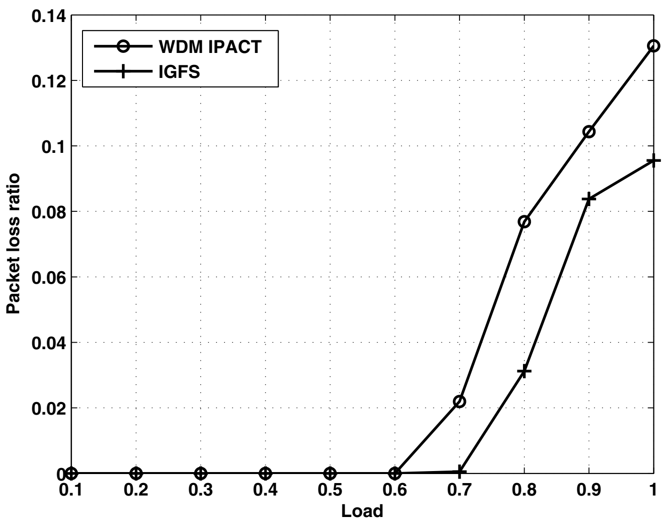

Fig. 3. Packet loss ratio as a function of the network load for $n = 32$ and $w = 3$

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 second system metric which is evaluated is the packet loss ratio. Fig. 3 depicts the packet loss ratio as a function of the network load for the aforementioned values of network's parameters. In this case, the IGFS and WDM IPACT exhibit the same performance for $k = [0.1, \ldots, 0.6]$, since for these, low-to-medium levels of network's load there are no dropped packets. But, as the load increases the drops also increase with IGFS being steadily superior to WDM IPACT for $k = [0.7, \ldots, 1.0]$.

VI. Conclusion

This paper introduces and evaluates a novel MAC protocol for WDM-EPONs. The proposed Intelligent Gap Filling Strategy (IGFS) rearranges the service order of ONUs based of the information of their RTTs. Thus, it prioritizes the ONUs whose requests are short enough so as to be scheduled before the RTTs of others ONUs past. The proposed scheme has been evaluated under self-similar traffic for different loads and it has resulted in providing significant improvements in mean packet delay and packet loss ratio.

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