A Multi-Threaded Dynamic Bandwidth and Wavelength Allocation Scheme With Void Filling for Long Reach WDM/TDM PONs

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***Abstract*—Dynamic Bandwidth Allocation (DBA) is a major research challenge in the migration of Passive Optical Networks (PON) systems towards Long Reach PON, especially when hybrid WDM/TDM is used (LR WDM/TDM PON). New solutions for Dynamic Bandwidth and Wavelength Assignment (DBWA) are sought to address two main critical issues of such PON systems: how to schedule the transmissions over multiple wavelengths and how to efficiently exploit the bandwidth in presence of long propagation delays of long reach scenarios. In this work, for the first time, we investigate the Multi-thread polling in a LR WDM/TDM PON. Then, we propose a new DBWA scheme, called EFT-partial-VF Multi-threaded, which effectively combines some of the features of, the Earliest Finish Time with Void Filling (EFT-VF) algorithm, with the Multi-thread algorithm. The two proposed solutions, namely the MT algorithm and the EFT-partial-VF Multi-threaded algorithm, provide significant improvement in terms of average delay, if compared with existing algorithms such as the EFT and the EFT-VF. Besides this, we extend the definition of polling cycle to hybrid WDM/TDM PON and we provide a method to calculate it.**

***Index Terms*—Cycle time, dynamic bandwidth allocation, hybrid WDM/TDM PON, long-reach PON.**

I. Introduction

PASSIVE Optical Networks (PONs) are considered a promising next-generation access technologies to address the increasing demands of traffic. A PON is composed of an Optical Line Termination (OLT) located at the Central Office (CO) and several Optical Network Units (ONUs). A common feeder fiber connects the OLT to a passive optical splitter/combiner through which the signal is conveyed to each ONU in the network. The ONUs share the upstream channel in the time domain, with Time Division Multiple Access techniques (TDMA) whereas the downstream channel is broadcasted to all ONUs. This basic implementation of PON can be also referred to as TDM-PON.

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Recently, several solutions using WDM (called WDM-PON) have been presented [2]. A simple version of WDM-PON, where a pair of wavelengths is assigned to each ONU, can provide a large amount of bandwidth to final users. However, this approach can lead to inefficiencies in the use of the available capacity because ONUs do not always transmit or use the entire channel capacity. This is why it is important to combine WDM with TDM in order to increase the channel utilization by sharing wavelengths among more than one ONU.

Long Reach Passive Optical Networks (LR-PONs) [1], an evolution of PONs where the reach of the optical segments is significantly extended, are expected to relevantly simplify the metro-access network architecture, by reducing the number of network elements, and, in turn, to reduce the network's Capital Expenditure (Capex) and Operational Expenditure (Opex).

The evolution from LR TDM PON towards LR TDM/WDM PON is a quite recent research topic motivated by the need of such network architectures to support higher capacity.

The development of LR WDM/TDM PON architectures [3]–[5] poses new research challenges in terms of transmission technologies and control protocols. In fact, the introduction of the long reach leads to an increase of the propagation delay which affects the duration of the polling process with a consequent degradation of DBA performance. Therefore, it is important to design new DBAs for LR-PONs instead of directly reusing the already existing DBAs implemented for traditional PONs (EPONs or GPONs) [6].

New algorithms, designed for LR WDM/TDM PONs, can provide an effective utilization of the upstream channels and aim at minimizing the average packet delay between the OLT and ONUs.

Among the proposed DBWA algorithms, one of most promising is the Earliest Finish Time with void filling (EFT-VF) algorithm for LR WDM/TDM EPON (Ethernet-based PON) [7]. In this work we evaluate only DBAs for EPON [8]. The possible extension of these ideas to GPON has not been investigated and is out of the scope and objectives of this research. The contribution of this work is threefold: i) we investigate the behaviour of the Multi-thread polling algorithm, by extending in the case of a LR WDM/TDM PON. To the best of our knowledge, the Multi-thread polling has never been applied to a hybrid WDM/TDM access network. ii) We propose a new algorithm based on the idea of EFT-VF and Multi-thread schemes, designed to improve the performance of these two allocation solutions. iii) We extend the definition of polling cycle to a hybrid WDM/TDM PON and we define an equation to calculate the maximum amount of bytes that each ONU can transmit in a cycle time, given the cycle time length. It is important to be able to calculate this maximum amount of traffic per cycle to guarantee a certain bandwidth to each ONU.

The algorithms proposed in this work use as a signalling protocol the Multi-Point Control Protocol (MPCP) [8] in which the two major control frames are REPORT and GATE messages. In particular the REPORT message is used by the ONU to inform the OLT the status of the queue. The GATE instead is used by the OLT for granting the upstream timeslot to each ONU.

The rest of the paper is organized as follows: in Section II we present a quick survey of existing DBWA solutions. In Section III we present the EFT-VF algorithm. Section IV briefly describes the Multi-thread polling and its implementation in a LR WDM/TDM PON. In Section V, we introduce our proposed algorithm. In Section VI, we extend the definition of polling cycle to a hybrid WDM/TDM network and we propose an equation to calculate the cycle time, given the network parameters. In Section VII, we provide a simulation analysis and illustrative results of the previously presented algorithm implementations, over different network scenarios. Finally, in Section VIII, we give concluding remarks on the performance of the different scheduling disciplines.

II. Related Works

A number of DBWA for both online and offline scheduling has been presented in the last years, some of which are architecture dependent [9], i.e., they are designed for particular network solutions. The first of these is specifically designed for the STARGATE EPON [10]. Another existent architecture dependent DBWA is designed for SPON [11]. In [12] is presented a DBA for the SARDANA network. Other proposed solutions can be used for generic network architectures. Among them, there is GATE Driven DBA (GD-DBA) [13].

The Latest-Finish Time with Void Filling (LFT-VF), Distanced Based Grouping (DBG) and Earliest-Finish Time with Void Filling (EFT-VF) algorithms [7] take advantage of the distribution of the distances from the OLT to the ONUs, trying to remedy the inefficiencies in the utilization of the upstream channel given by this distribution. Even if the DBG algorithm gives satisfactory performance, this solution has the drawback of reducing the WDM multiplexing gain within each group of ONUs due to the lower amount of wavelengths assigned to each of these groups. LFT-VF algorithm, instead, chooses the channel with the latest horizon. In particular the selected wavelength must have the latest finish time among all channels. The void filling part keeps track and tries to fill the voids left on the upstream channel. The EFT-VF algorithm chooses the channel where the previously scheduled transmission will end first. Both the LFT-VF and the EFT-VF algorithms, having a similar performance, give a large improvement in the average transmission delay, if compared with the EFT scheme, only when they are used in a network where the distances between OLT and ONUs have a very large distribution, e.g., between 500 m and 100 km. Instead, when LFT-VF and EFT-VF are applied in a network where the ONUs-OLT distances are not so spread, the improvement provided by these two algorithms is limited, like shown later in this paper. Basically, these last three algorithms try to solve the same problem addressed by the Multi-thread algorithm [14], using different strategies. Multi-thread algorithm aims at reducing the waste of bandwidth in each polling cycle adding two or more threads in the middle of the first polling cycle. Essentially, multiple transmission threads are maintained between each ONU and the OLT.

DBWA in LR WDM/TDM PONs, like a generic DBA, can be viewed as consisting of grant sizing and grant scheduling problems [15]. In this work we focus on the decision of when to schedule the transmission of ONUs with the aim of reducing the average packet delay. We assume that the grant sizing has already been solved during a preprocessing phase where it is calculated the maximum amount of data that can be transmitted by each ONU in each cycle time in order to guarantee certain bandwidth to each ONU.

III. EFT-VF Basic Functionalities

The EFT-VF algorithm, which is an enhancement of the EFT algorithm [7], is based on the observation that in a PON and in LR-PONs different distances between OLT and ONUs may lead to very diverse propagation delays creating what authors define as scheduling voids. A scheduling void is a period of time between two subsequent transmissions where there is no scheduled transmissions on the channel. The Void Filling part of the EFT-VF algorithm aims at filling these voids by scheduling other transmissions during the time when the channel is unused. A void must be long enough to enable transmissions; a time period with this feature is called *eligible void* and its length in bytes is equal to the length of data requested by the ONU plus the REPORT message. Instead the EFT algorithm schedules the transmission on the wavelength that becomes available first. It has been proven that the EFT-VF algorithm yields better performance than EFT. In our work, we use some features of EFT-VF to design a scheduling strategy which improves the network performance delay in LR-PON.

IV. Multi-Thread Polling Algorithm

A. Multi-Thread Polling in LR TDM PONs

Multi-thread (MT) algorithm [14] has been proposed as a solution to overcome the problem of the increased RTT in a LR TDM PON, with respect to TDM PONs, which leads in general to an increased average packet delay. Therefore, to achieve better performance in terms of packet delay in a LR-PON, the basic idea of the Multi-thread algorithm is to allow an ONU to send its REPORT before the previous GATE message is received. Practically, this allocation scheme exploits the benefits of having multiple polling processes running simultaneously. In such way, the ONUs do not have to wait until the end of data transmission of the previous thread to send a new REPORT message asking for a new transmission opportunity. With this strategy, the overall average packet delay of the LR-PON can then be lowered.

B. Multi-Thread Implementation in LR WDM/TDM PONs

In this section, we introduce our proposed extension of the Multi-thread algorithm over LR WDM/TDM PONs to which we refer as WDM-MT. To the best of our knowledge, this is the first time that the Multi-thread is applied in LR WDM/TDM PONs. When MT is implemented in a WDM/TDM network, the basic idea of having multiple polling processes running simultaneously remains the same and furthermore the benefits of having more wavelengths are exploited. However, the transmission of the a generic thread t, for ONU_i must be scheduled after the end of the transmission of thread $t-1$, because a single ONU can only send one transmission at a time. As a consequence, it may happen that on a particular wavelength a transmission is not scheduled at the earliest available time of the channel, but it is forced to wait till the end of the previously granted transmission for the same ONU. We refer to this scheduling constraint as *thread coordination*. This constraint introduces an additional delay and it may lead to inefficiencies in the utilization of the channel. By using multiple wavelengths, the average time between two subsequent transmissions of the same ONU_i is significantly decreased. However, note that, the greater the number of wavelengths used, the more the thread coordination constraint affects the algorithm performance. The fact of having more wavelengths gives a higher possibility to allocate more transmissions at the same time. Unfortunately, the thread coordination constraint limits this possibility avoiding that different transmissions of the same ONU are allocated during the same period. If two different transmissions of the same ONUs can not be scheduled during the same time period, may happens that one of these two transmissions will be delayed until the end of the previous one. In such way, more voids are created in the channel. In the following section we present an allocation strategy which combines the positive features of the EFT-VF and Multi-thread algorithms, to improve the overall performance of the allocation scheme.

V. EFT-Partial-VF Multi-Threaded

In this section, we try to exploit the positive features of Multi-thread and EFT-VF algorithms, by combining them appropriately. Therefore, in this section we present our proposed allocation scheme called EFT-Partial-VF Multi-threaded (EFT-partial-VF MT). In Table I, we define the notation used hereafter.

TABLE I
Definition of Variables

t_i	Time when the REPORT from ONU_i arrives at the OLT.
R_i	Round-trip propagation time between OLT and ONU_i.
t_c	Time needed for the transmission of REPORT or GATE frame.
$T_{i,j}$	Start Time for the *j-th* transmission of the ONU_i which is the time when an ONU can start its transmission according to its R_i.
W_i	Set of wavelength supported by ONU_i.
$S_{h,j}$	Arrival time at the OLT of the first bit of the *j-th* scheduled transmission on the *h-th* wavelength.
$F_{h,j}$	Finish time of the *j-th* transmission on the *h-th* wavelength corresponding to the reception of the last bit of the control frames which is piggy-backed to the data packets.
L_h	Finish time of the last transmission scheduled on the *h-th* wavelength.
$B_{max,i}$	Maximum length for a transmission of ONU_i, in each cycle time, in order to ensure fairness among the ONUs and grant the maximum capacity achievable from each of them.
V_i	Set of eligible voids for ONU_i calculated according to its R_i and its requested length of data, which must be granted.
G_i	Length of data, in bytes, requested by an ONU_i.
$t_{g,i}$	Time needed to transmit the length of data which ONU_i asks to transmit.
P	Maximum number of portions in which a transmission can be partitioned.
w'_{eft}	Upstream wavelength which could be chosen by the EFT algorithm.
w'_{vf}	Upstream wavelength which could be chosen by the Void Filling algorithm
n'_{eft}	Transmission turn within the w'_{eft} which could be chosen by the EFT algorithm.
n'_{vf}	Transmission turn within the w'_{vf} wavelengths, which could be chosen by the Void Filling algorithms
w	Chosen upstream wavelength.
n	Transmission turn within the w wavelength.

We assume that the laser tuning time is negligible in considered architecture. Note that this assumption reasonably holds for advanced technologies such as fast tunable lasers and for the multi-wavelength lasers [16].

At a high level, this algorithm can work under two modes of operation namely the Single Thread (ST) operation and the Multi-thread (MT) operation. The algorithm stays in the ST operation if a transmission can be completed without partitioning, for example in a wavelength channel where the horizon is idle at the time when data are ready for transmission or a void large enough is found; instead the algorithm moves to the MT operation if the transmission needs to be partitioned into P trunks. Furthermore, an ONU returns in ST operation if the REPORT messages of at least $P-1$ trunks report an amount of data equal to zero as extensively explained in the following. The scheme switches from the ST operation to the MT operation independently for each ONU, according to the traffic load provided by each user. This means that at the same time some ONU can be in MT operation while some other ONU can be in ST operation. More specifically, in the ST operation the decision on where to schedule the transmission is made following the same strategy of the EFT-VF algorithm. Differently than EFT-VF, in the EFT-Partial-VF MT, an eligible void is defined, according to (1), as a time period between two already scheduled transmissions which is long enough to schedule at least a fraction P of the requested length of data.

$$V_i = \left\{ F_{h,j} \,|S_{h,j+1} - \max(F_{h,j}\,, t_i + R_i + t_c) \geq \frac{t_{g,i}}{P} + t_c \right\},\quad h \in W_i \tag{1}$$

Where $S_{h,j+1} - F_{h,j}$ is the time distance between the reception by the OLT of the first bit of the $(j+1)$-th transmission on the h-th wavelength, and the reception of the last bit of the j-th transmission on that same wavelength. $t_i + R_i + t_c$ is the minimum allocation time for ONU_i, depending on the round trip time and on the time needed to send the gate message to the ONU. $S_{h,j+1} - (t_i + R_i + t_c)$ is the time distance between the reception at the OLT of the first bit of the $(j+1)$-th transmission on the h-th wavelength, and the time when the first bit of the transmission of ONU_i can reach the OLT, according to its R_i. In such way, a transmission for a single ONU_i can be divided into multiple blocks of data, each of which having a different $T_{i,j}$. These $T_{i,j}$ are all allocated through the equations listed below. If a transmission is partitioned in more portions, an additional constraint is needed in order to schedule the blocks of data following the first one. Such condition must guarantee that the different transmissions do not overlap since an ONU can not usually send multiple transmissions at the same time.

The equations used to define the wavelength assignment and the scheduling, according to EFT algorithm, are:

$$w'_{eft} = \arg\min_h (L_h), \quad h \in W_i \tag{2}$$

$$n'_{eft} = \arg\max_j (F_{w,j}) + 1 \tag{3}$$

Whereas, for the Void Filling part of the algorithm the wavelength assignment and the scheduling are chosen according:

$$w'_{vf} = \arg\min_h (F_{h,j} \,|F_{h,j} \in V_i), \quad h \in W_i \tag{4}$$

$$n'_{vf} = \arg\min_j (F_{w,j} \,|F_{w,j} \in V_i) + 1 \tag{5}$$

Then, the wavelength and time scheduling finally assigned for a transmission are chosen according to the equation:

$$w = \min(w'_{eft}, w'_{vf}), \quad n = \min(n'_{eft}, n'_{vf}) \tag{6}$$

The additional constraint to schedule subsequent transmission blocks for ONU_i is defined by (7), using the notation:

$n_{i,p}$: Position index of the reservation within the wavelength w for the p-th block of data for the ONU_i, with $p \in [1, \mathrm{P}]$ integer.

t_p : Time needed by the ONU to transmit the length of data granted in the p-th transmission block.

$$n_{i,p} \geq n_{i,p-1} + t_{p-1}; \tag{7}$$

An example of the basic operation of this algorithm, where all the data are transmitted in a single block, is shown in Fig. 1. In Fig. 1 we show how the $T_{i,j}$ is assigned by choosing the earliest between the one chosen by Void Filling algorithm (case 1) and the one chosen by EFT algorithm (case 2). Examples of the EFT-Partial-VF MT operations, where the transmission is divided into different blocks, are shown in Figs. 2 and 3. Fig. 2 shows a situation where the partial void filling algorithm is applied for both first and second transmission. Conversely, Fig. 3 shows the case where the first transmission is scheduled through the partial void filling algorithm while the second transmission is assigned using EFT rule. In all these examples, we use $P = 2$, which means that at most a transmission will be split in two blocks of data. In ST operation, when the transmission for the ONU_i is divided into different portions of data, the algorithm switches to MT operation. The number of threads that are created for a particular ONU corresponds to the number of chunks in which a single transmission is partitioned. Therefore, at most P threads are assigned to this same ONU_i. The number of threads assigned to an ONU corresponds to the number of chunks in which its transmission is partitioned. The maximum

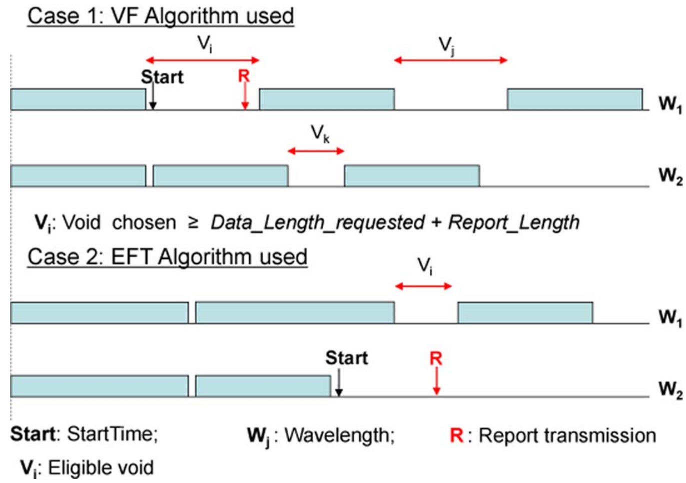

Fig. 1. Operation of the EFT-VF Algorithm with Partial Void Filling Multithreaded.

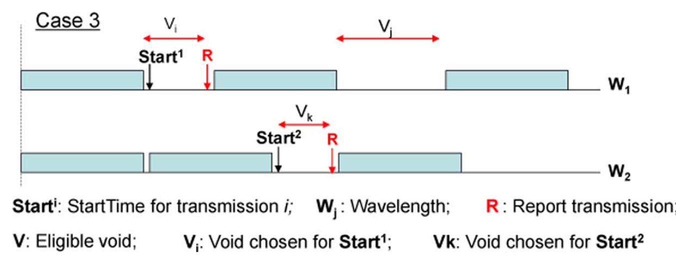

Fig. 2. Operation of the EFT-VF Algorithm with Partial Void Filling Multithreaded when the Void Filling solution is used to schedule both first and second transmission.

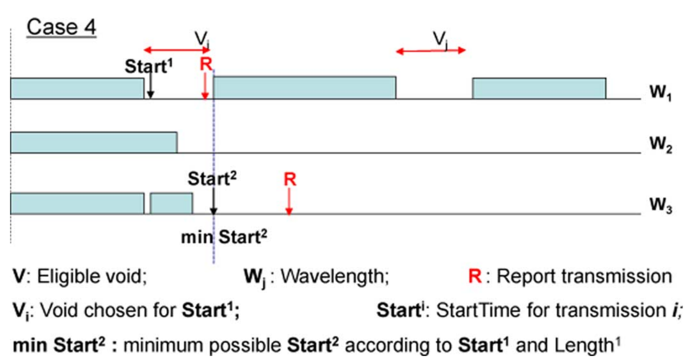

Fig. 3. Operation of the EFT-VF Algorithm with Partial Void Filling Multithreaded when the first part of the transmission is scheduled through the Void Filling algorithm, while for the second the EFT strategy is used.

number in which a transmission can be partitioned (P) must be chosen considering that it exists a tradeoff between dividing a transmission in a large amount of small "sub-blocks" of data (large value of P) and dividing the same transmission in a small amount of large "sub-blocks" of data (small value of P). In fact, when the "sub-blocks" are small it is easier to fill also very small voids in the channel, but at the same time this condition leads to a proliferation of control messages which increases the total amount of transmission overhead, finally leading to a poor performance of the algorithm. Conversely, by partitioning the transmission in few "sub-blocks", we limit the total amount of transmission overhead due to control messages, but we also give less opportunities to the algorithm to find a void which can be filled with a longer "sub-block" of data. However, to guarantee a certain capacity to each ONU, in EFT-Partial-VF MT, the sum in bytes of all the chunks in which a transmission can be partitioned must be at most equal to $B_{\max,i}$. Switching from ST to MT operation is possible because, in EFT-Partial-VF MT algorithm, the ONU is allowed to send a REPORT message after each "sub-block" transmission. Each of these REPORT messages, when received by the OLT, initiates a new thread. In fact, for each REPORT received, the OLT sends a new GATE message to the ONU indicating when it can start the transmission for this new thread. As an example, when the *p-th* REPORT associated to the *p-th* "sub-block" ($p \in 1, 2, \ldots, P$) is received, the OLT generates a new scheduling for the length of data requested by the ONU_i. Then, the OLT sends the GATE message which starts the *p-th* thread of ONU_i. When an ONU is in MT operation, its transmissions are scheduled using the same strategies of the EFT-VF algorithm described by (2), (3), (4), and (5). This means that the scheduling for each thread is done choosing the $S_{h,j}$ between the earliest $S_{h,j}$ assigned using the EFT algorithm and the $S_{h,j}$ chosen by the VF rule. During the MT operation, an eligible void is defined through the following equation:

$$V_i = \{F_{h,j}\,|S_{h,j+1} - \max(F_{h,j}\,, t_i + R_i + t_c) \geq t_{g,i} + t_c\},\quad h \in W_i \tag{8}$$

Where $S_{h,j+1} - F_{h,j}$ is the time distance between the reception by the OLT of the first bit of the $(j+1)$-th transmission on the h-th wavelength, and the reception of the last bit of the j-th transmission on that same wavelength. $t_i + R_i + t_c$ is the minimum allocation time for ONU_i, depending on the time round trip time and on the time needed to send the gate message to the ONU. $S_{h,j+1} - (t_i + R_i + t_c)$ is the time distance between the reception at the OLT of the first bit of the $(j+1)$-th transmission on the h-th wavelength, and the time when the first bit of the transmission of ONU_i can reach the OLT, according to its R_i. As a result, the requested length of data for a single thread is not divided into multiple transmissions. This feature is motivated by the fact that it is necessary to prevent an uncontrolled proliferation of threads. Moreover it is expected that, since there are more threads, each REPORT of each thread requests to transmit a smaller length of data. This happens because, with more threads, data and REPORT packets are sent more often with respect to ST operation. Then the length of data in the ONU queue decreases faster. Consequently, this feature of having smaller REPORT requests allows the algorithm to fill also small voids without the need to cut the requested length G_i into multiple transmissions. When the traffic load of the ONU_i decreases, the ONU_i sends REPORT messages to the OLT stating that since the queue is becoming smaller, less data is required in the next cycle. Therefore, if the number of bytes required in a REPORT is zero this REPORT is ignored by the OLT. In this way, if the ONU was transmitting in P threads it now uses only $P-1$ threads. When the OLT receives $P-1$ REPORT messages reporting zero bytes in the ONU queue, the algorithm switches again to ST operation.

DEFINITION OF THE CYCLE TIME

The cycle time (T_{cycle}) is the time interval between successive requests from the same ONU, where every ONU transmits exactly once. For the Multi-thread algorithm the definition of T_{cycle} is slightly different and is the time interval between successive requests of the same thread from the same ONU, where every ONU sends one transmission for each thread. It is important to provide a new definition for T_{cycle} in order to guarantee a certain capacity to each ONU. In fact, when the duration of the T_{cycle} is defined, it is possible to calculate the $B_{\max,i}$ which is the maximum amount of bytes that each ONU can transmit in each T_{cycle}. Concerning TDM PONs, a definition of T_{cycle} is given in [17]. In this section we extend the definition of T_{cycle} to a hybrid WDM/TDM system and we propose an equation to calculate $B_{\max,i}$. In order to calculate the maximum T_{cycle}, we consider the network at high load, when all the ONUs are transmitting at their maximum capacity and there are no voids on the channel. We consider the average number of ONU transmitting on a wavelength in each T_{cycle}, N/W. We define the cycle time as the time period between two subsequent transmissions of the same ONU, where all ONUs transmit once, without regard to the wavelength they are transmitting on. According to this definition we identify an equation to calculate the value of $B_{\max,i}$:

$$B_{\max,i} = \left\lfloor \frac{\left(T_{cycle} - T * \left(\frac{N}{W}\right) * T_{guard}\right) * \phi_i * C_w}{8} \right\rfloor \tag{9}$$

In this equation ϕ_i is a weight, computed in (10), which represents the fraction of the total capacity of a wavelength required by ONU_i. T is the number of threads, where $T = 1$ corresponds to the single thread case. T_{guard} is the guard band time between two subsequent transmissions and C_w is the capacity of each wavelength. $(T_{cycle} - T * (N/W) * T_{guard})$ is the total duration of the cycle time where we substract all the T_{guard} of all the N/W ONUs which are transmitting, in average, over the same wavelength. This time period is the time dedicated to the transmission of the data of the ONUs. When this amount of time is multiplied by C_w we obtain the total amount of bits which can be transmitted in a cycle time. Finally, multiplying this value by ϕ_i we have the maximum amount of bits that ONU_i can transmit according to its transmission rate C_i.

$$\phi_i = \frac{C_i}{\sum\limits_{1 \leq k \leq N/W} C_k} = \frac{C_i}{C_w} \tag{10}$$

To compute the ϕ_i, we must consider a constraint on the capacity of the ONUs, shown in (11), which states that the sum of the capacity required by the different ONUs must be less or equal to the total capacity of the network, C_{pon}. The C_{pon} is basically the sum of the capacity of the single wavelengths.

$$\sum_{1 \leq k \leq N} C_k \leq C_{pon} \tag{11}$$

In such way, the previous equations guarantee that each ONU is able to transmit at its required transmission rate.

TABLE II
NETWORK PARAMETERS FOR DIFFERENT NETWORK SCENARIOS

	W	N	N/W	Capacity per ONU	Capacity per λ
Case 1	8	1024 512 256 128	128 64 32 16	62,5 Mbit/s	8 Gbit/s 4 Gbit/s 2 Gbit/s 1 Gbit/s
Case 2	2 4 8 16	256	128 64 32 16	62,5 Mbit/s	8 Gbit/s 4 Gbit/s 2 Gbit/s 1 Gbit/s
Case 3	8	128	16	32 ONU@250 Mbit/s 96 ONU@62.5 Mbit/s	1 Gbit/s

VI. ILLUSTRATIVE NUMERICAL RESULTS

A. Generic Simulation Framework

To evaluate the performance of the proposed algorithms, we implemented a network simulator based on the Discrete Event Simulation Library (DESL) [18], modified to simulate a LR WDM/TDM PON. This simulation tool only implement the upstream transmissions. To reflect the property of the real Internet traffic, we generate self-similar traffic by aggregating multiple sub-streams, each consisting of alternating Pareto-distributed ON/OFF periods, with a Hurst Parameter of 0.8. The simulator generates Ethernet frames with a length distributed between 64 and 1518 bytes. The buffer size of each ONU has a length of 10 Mbytes. The polling cycle time is 2 ms, and accordingly the $B_{\max,i}$, calculated through (9), is 7687 bytes for Multi-thread and 15500 bytes for the other schemes, where the $B_{\max,i}$ is the same for each ONU. The guard band time between two subsequent transmissions is 1 μs. Our topology includes 128 ONUs all transmitting over all the 8 wavelengths. Each channel, consisting of a single wavelength, has a bit rate of 1 Gbit/s which gives a total capacity of 8 Gbit/s. As we simulate a Long-Reach scenario, the distances from the OLT to the ONUs are uniformly distributed between 80 km and 100 km. The load offered to the network by the ONUs varies during the simulation from 0.05 to 1. At load 1 the bit rate of each ONU is 62.5 Mbit/s. For the Multi-thread algorithm, we use $T = 2$, while for EFT-Partial-VF MT we use $P = 2$ that we consider a reasonable value in which to partition a transmission in order to fill also very small voids while avoiding a proliferation of control messages.

B. Simulation Framework Varying Network Parameters

In this section, we present different simulation scenarios, obtained varying network parameters, in which we evaluated the algorithms considered in our work. We consider that all the ONUs transmit over all the available wavelengths and then we consider that $W_i = W \forall i$, where W is the set of wavelengths of the network. We also define N to be the total number of ONUs of the LR WDM/TDM PON and N/W is the average number of ONUs per wavelength. C_i is capacity per ONU. We consider two different network scenarios where the parameters W, N and N/W have been varied as shown in Case 1 and Case 2 of Table II. Case 3 in Table II summarize the parameters used to simulate a scenario where different sets of ONUs transmit at a different rate.

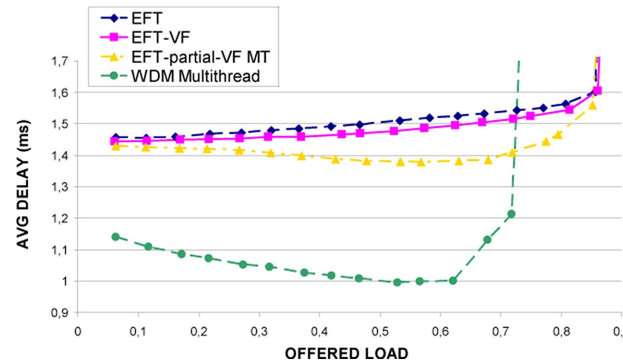

Fig. 4. Average packet delay comparison between EFT, EFT-VF, Multi-thread over LR WDM/TDM PON, and EFT-Partial-VF MT algorithms.

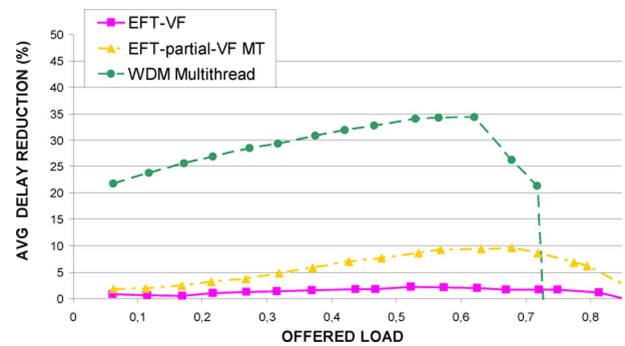

Fig. 5. Average delay reduction of EFT-VF, Multi-thread over LR WDM/TDM PON, and EFT-Partial-VF MT algorithms compared to EFT scheme.

C. Numerical Results and Discussion

1) Generic Simulation Framework: We first compare our results with pure EFT algorithm to see the improvement due to the implementation of the Multi-thread and to our proposed allocation scheme. Then we compare the results given by EFT-VF, Multi-thread over LR WDM/TDM PON, and EFT-Partial-VF MT.

In Fig. 4 we plot the average packet delay versus the offered load. We can observe that the EFT-P-VF MT and the Multi-thread algorithms introduce a significant improvement regarding the packet delay, compared to EFT. Conversely the gain of the EFT-VF solution with respect to the EFT algorithm is limited (less than 5%). We can notice the same result also in Fig. 5 where we show the percentage of average delay reduction with respect to EFT algorithm. Besides this limited gain, we observe that the computational complexity of the EFT-VF is $\mathrm{O}(N(\mathrm{N+W}))$ while the complexity of the EFT is $\mathrm{O}(N * W)$. Since the value of $W \ll N$ we can consider that the complexity of the EFT-VF is $\mathrm{O}(N^2)$ and the complexity of EFT is $\mathrm{O}(N)$, so the first one is linear in N while the second is exponential in N, and the difference is not relevant if N is limited. Regarding the Multi-thread over LR WDM/TDM PON, this improvement is significantly relevant for low loads whereas for medium loads it starts to decrease. Unfortunately, for high loads the average delay provided by this scheme becomes very high. This behaviour is due to the thread coordination effect introduced in Section IV which does not allow to efficiently exploit multiple wavelengths. Note that, for low/medium loads, the average delay in the two MT-based solutions tends to become smaller for increasing traffic. This behaviour is counter-intuitive, but it can be reasonably explained considering the transmission of control messages. In fact, at low loads, the length (in byte) of the transmissions of the ONUs tends to be short, and so control messages are sent very often, negatively impacting algorithm performance. Conversely, when the load increases and the length of data packets becomes higher, the number of control messages is smaller, and less time is wasted in the control phase, allowing us to take more advantage from multiple and simultaneous polling processes.

The EFT-VF algorithm shows an average packet delay slightly lower with respect of the EFT scheme. Such difference strictly depends on the characteristics of the access network where this allocation is applied. In fact the authors in [7] apply their algorithm in a very particular architecture, similar to SARDANA and SUCCESS, where the distances from ONUs to the OLT are very diverse. Conversely, we tested the EFT-VF scheme in a LR WDM/TDM PON where all the ONUs are at a very large distance from the OLT. The solution which gives the best performance is the EFT-Partial-VF MT proposed in this work. At low loads, this scheme provides results similar to those provided by EFT-VF algorithm. This happens because, at these loads, the lengths of data requested by ONUs are small if compared to the length of voids and, for this reason, it is possible to fill the voids on the channel without slice transmissions. When the load increases, the EFT-Partial-VF algorithm makes better use of the voids formed on the channel as it is allowed to cut transmissions in more portions. In such way it is able to fill also smaller voids. Moreover, if an ONU requires to send a huge amount of data, it can switch to MT operation achieving a better performance. In contrast, when the load of an ONU in MT operation decreases, the ONU will enter again in ST operation. Through this strategy it possible to avoid the performance degradation, observed instead when Multi-thread is applied over LR WDM/TDM PONs, due to the constant presence of control messages to maintain the different threads for each ONU. This feature is very important to avoid unnecessary control messages especially given the bursty self-similar nature of Internet traffic. Finally, we can observe that the EFT-P-VF MT algorithm provide a higher gain in the average delay with respect to the EFT-VF, while both these two schemes have a computational complexity of $O(N^2)$. Also in this case we consider that the values of P and W are negligible with respect to N.

2) Performance Evaluation Varying Network Parameters: In this section we evaluate the performance of the algorithms in different simulation scenarios, defined in Table II, where different network parameters have been varied. Note that we show the performance only for our proposed EFT-P-VF MT algorithm, but the same considerations apply also for the other algorithms evaluated in this work. Moreover, all the considerations that we make in this section are valid when the C_i is maintained constant for each scenario. In the first scenario, we vary the number of ONUs N and we fix the number of wavelengths W. According to these parameters, the value of N/W changes. In this simulation scenario, we can notice that the performance given by each algorithm is the same for each value of N, for low and medium loads. Fig. 6 shows that, the more the value of N

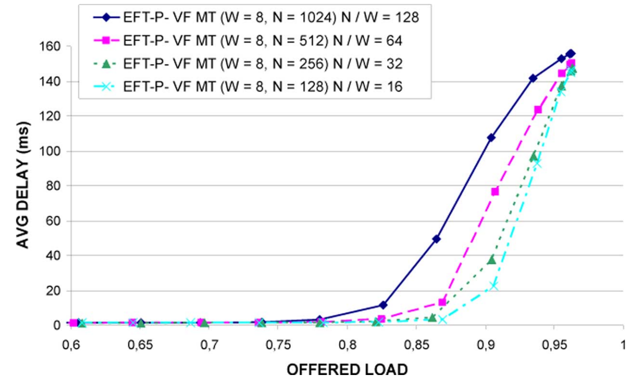

Fig. 6. Average packet delay comparison of EFT-Partial-VF MT algorithm varying the value of N.

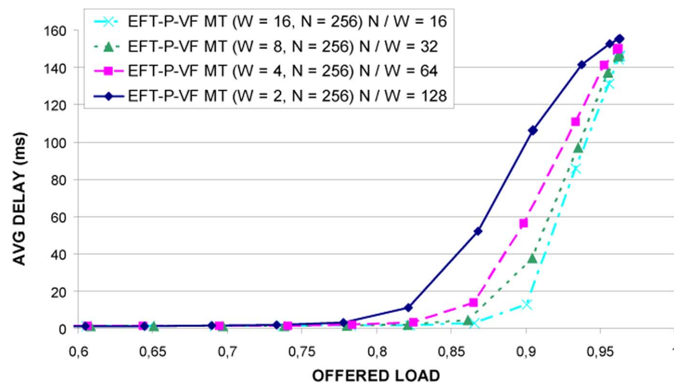

Fig. 7. Average packet delay comparison of EFT-Partial-VF MT algorithm varying the value of W.

increases and therefore increasing N/W, the more the average packet delay assumes very high values at a low value of traffic load. This counter intuitive behaviour will be explained later in this section. In the second simulation scenario, we vary the number of wavelengths W and we fix the number of ONUs N. Fig. 7 shows that, also in this second scenario, the performance of the algorithm is the same under all configurations for low and medium loads. For high loads, when the number of wavelengths W decreases and, consequently, N/W increases, the delay assumes very high values at a lower traffic loads. Having noticed that the performance depends on the value of N/W, we also tested our algorithm in a scenario where we vary both N and W in order to have always the same N/W. We can then affirm that, the performance variation highlighted in first and second scenarios it does not depend on the values of N and W but on the ratio N/W. In fact, we noticed that when the value of N/W remains the same, the algorithm has the same average delay for all loads, even if the values of N and W vary. In the third simulation scenario we compare the case where different set of ONUs transmit at a different rate, called unbalanced case, with the situation where all the ONUs transmit at the same rate, the balanced case. In Fig. 8 are shown the results of this comparison. In the unbalanced case we notice that, even if a set of ONUs is transmitting at a high rate, the performance of the ONUs transmitting at a lower rate is not affected to much. This means that our proposed algorithm is able to manage an unbalanced scenario providing a reasonable average delay to each set of ONUs. The

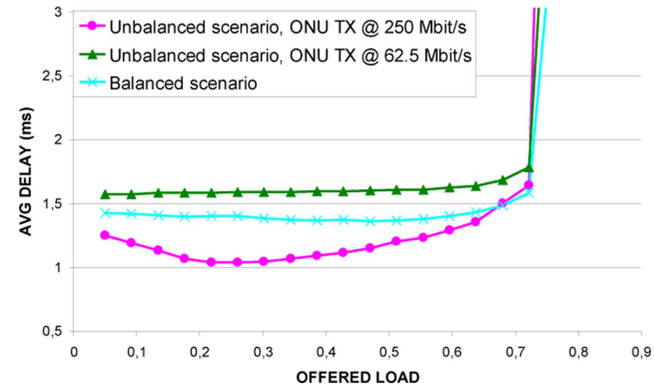

Fig. 8. Average packet delay of EFT-Partial-VF MT algorithm in a scenario with $\mathrm{W} = 8$, $\mathrm{N} = 128$ ONU, and where 32 ONUs are transmitting at 250 Mbit/s and 96 ONUs are transmitting at 62.5 Mbit/s. This scenario is compared to a scenario where all 128 ONUs are transmitting at 62.5 Mbit/s (Balanced scenario).

performance degradation noticed when the value of N/W increases is due to the T_{guard}. We can observe from (9) that, given a certain T_{cycle}, when the number of N/W increases, the impact of the guard band time in (9) increases, being it multiplied by N/W. Therefore, the percentage of guard band time with respect to the data transmission time increases when N/W increases. A solution to avoid the performance degradation which follows the increase of the value of N/W is to define a longer T_{cycle} for networks with a higher N/W. In such way, the percentage of guard band time remains constant. In fact, as the length of the T_{guard} depends on technological constraints which define a minimum value of this parameter [19], it is not possible to set a lower T_{guard} when N/W increases. There is a limit on the length of the T_{cycle}. The more the T_{cycle} become longer, the more the transmissions of the ONUs are delayed. Then the average cycle time increases. So, we can conclude that exists a trade off between having a small cycle time, which allow to reach small average packet delay, and having a long cycle time, that allows to have a small overhead due to the guard band time per T_{cycle}. Further study is needed to identify the right balance.

VII. Conclusion

In this work we have presented, analyzed and evaluated different strategies for LR WDM/TDM PON to perform upstream scheduling and wavelength assignment.

Regarding the implementation of a pure Multi-thread polling strategy in LR WDM/TDM PONs, our results show that, while at low/medium loads it achieves large improvement with respect to EFT algorithms, for medium/high loads it suffers from a sudden increase of delay. So, in a LR WDM/TDM PON, the pure application of Multi-thread algorithm replicates the same gain achieved in LR TDM PONs with respect to single thread polling, at least at low and medium loads. Therefore, in this work we found an effective solution to combine the positive features of the EFT-VF algorithm with the Multi-thread algorithm, in order to provide a new and efficient allocation scheme for LR WDM/TDM PON. In fact, simulation results show that the EFT-partial-VF Multi-threaded algorithm provides lower average packet delay, for a wide range of traffic load, compared to the other schemes. Simulation results underline that the performance of the algorithms depends on the average number of ONU transmitting on each wavelength in a cycle time (N/W). We also investigated the effect of the overhead due to guard band time on the performance of the algorithms. We can conclude that, for a fixed value of T_{cycle}, when the value of N/W increases, the overhead increases, and in turn the average packet delay becomes higher. Future works in the field of DBWA algorithm for hybrid WDM/TDM PON include the investigation of the impact of the lasers tuning time on the performance of such allocation schemes.

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