Dynamic bandwidth and wavelength allocation with coexisting transceiver technology in WDM/TDM PONs☆

Anna Buttaboni [a,*], Marilet De Andrade [a,b], Massimo Tornatore [a], Achille Pattavina [a]

[a] Politecnico di Milano, Department of Electronics, Information, and Bioengineering, Italy
[b] American University of Culture and Education, Department of Computer Science, Beirut, Lebanon

Passive Optical Networks (PONs) are continuously evolving. One important requirement of these systems is the possibility to smoothly upgrade the network infrastructure as technologies evolve. During the process of network upgrade, a coexistence of new and old end-users, i.e., Optical Network Units (ONU), with diverse transceiver technologies, is expected. In this work, we focus on a scenario where the network is upgraded from a TDM PON to a hybrid WDM/TDM PON (both short-reach and long-reach), and where the transceivers used in the old TDM PON can coexist with the new transceivers adopted in the hybrid WDM/TDM PON. Therefore, we consider that three different types of transceivers can be installed at the ONUs: single fixed tuned lasers, array of fixed tuned lasers, and tunable lasers. In particular, we propose new Dynamic Bandwidth and Wavelength Allocation (DBWA) algorithms which solve the problem of managing the traffic originated by end-users equipped with transceivers with different characteristics. In this paper we focus on the case of transceivers characterized by different tuning times. To investigate the importance of a DBWA able to manage transceivers with dif-ferent tuning times, we also compare them to DBWAs which are not aware that different transmission technologies coexist in the network. Then, we test these DBWAs in different network scenarios, and discuss what are the network parameters that mostly affect the algo-rithms performance. After showing the importance of having a DBWA that supports trans-ceivers characterized by different values of TTs, we investigate also the practical case of tunable lasers that have different values of TT depending on the wavelength they have to retune to (i.e., higher distances between two wavelengths require higher TTs). Finally, we evaluate the per-formance of the previously proposed DBWAs when the arrays of fixed tuned lasers can transmit over a limited number of wavelengths, i.e., the number of lasers of the array is limited.

1. Introduction

In a Passive Optical Network (PON), the possibility of upgrading the network infrastructure smoothly is an important requirement for network providers as it allows to minimize initial investment for network deployment [1,2]. An important aspect during the process of capacity upgrade is to avoid replacing the existing equipment without disrupting current services. For this reason, it is

Article history:
Received 25 June 2015
Received in revised form 27 October 2015
Accepted 7 December 2015
Available online 7 January 2016

Keywords:
Fixed mobile converged networks
Optical access networks
LR TDM/WDM PON
TT-aware DBWA

☆ The work presented is an extension of the previously published: A. Buttaboni, M. De Andrade, and M. Tornatore, “Dynamic bandwidth and wavelength allocation with coexistence of transmission technologies in TWDM PONs”, in: Proceedings of NETWORKS14, 17–19 September 2014, Funchal, Madeira Island, Portugal.

n Corresponding author.E-mail addresses: anna.buttaboni@polimi.it (A. Buttaboni),
marilet@auce.edu.lb (M. De Andrade),
massimo.tornatore@polimi.it (M. Tornatore),
achille.pattavina@polimi.it (A. Pattavina).

Published Journal Article available at: http://dx.doi.org/10.1016/j.osn.2015.12.001

expected that different transmission technologies (e.g., new and old technologies) may coexist over the same access network infrastructure, especially during upgrade periods.

Another scenario of technology coexistence over PON and long-reach PON (LR-PON) [3] is the recent paradigm of fixed and mobile converged (FMC) access/aggregation network, where both fixed and mobile traffic are backhauled through a common network infrastructure. In this scenario, different transceivers could be used to transmit the traffic originated by mobile and fixed access points due to the different performance requirements of the two types of services. Therefore, also in the FMC scenario different transmission technologies might need to coexist.

A possible solution to provide a scalable capacity upgrade in the access network is to use Passive Optical Networks (PONs) employing hybrid WDM/TDM technology. These networks, called TWDM PONs, were selected by the Full Service Access Network (FSAN) forum as a primary solution for Next-Generation PON Stage 2 (NG-PON2) [4]. Even if the solution in [4] for next generation access network is designed for GPONs, we believe that a similar design can apply to Ethernet-based PONs (EPONs). In this work, we focus on WDM/TDM PON (both short-reach and long-reach[1]) based on EPON.

WDM/TDM PONs have other positive features. First, they support a pay-as-you-grow provisioning, i.e., a WDM/TDM PON could be deployed starting with a single wavelength pair and then it could be upgraded adding more wavelength pairs, if a higher capacity is required. Also, WDM/TDM PON is useful for local loop unbundling (LLU) by installing different OLTs that support different sets of wavelengths for each vendor, and using a wavelength-selective device to multiplex the OLT ports over a single fiber [4].

In WDM/TDM PON two main bandwidth allocation problems must be addressed: (i) how to allocate the transmissions over multiple wavelengths, (ii) how to efficiently exploit the bandwidth in presence of very different propagation delays within the same network (especially in the case of LR-PON).

In our scenario, the transceivers of the ONUs differ according to: (i) their capacity to retune their lasers to different wavelengths (i.e., tunable or not tunable) and (ii) the time needed for tunable transceivers to retune its laser to a different wavelength. We refer to this time interval as Tuning Time (TT) of a laser. In our work, we identify three families of transceivers: (i) *single fixed tuned lasers* which cannot retune; (ii) *array of fixed tuned lasers* [5] which can immediately tune their laser to another wavelength ($TT = 0$ s); (iii) *Tunable lasers* [6] which are characterized by a given tuning time ($TT > 0$ s). In this scenario, we have to manage the traffic transmitted by different types of transceivers coexisting on the same network infrastructure, without deteriorating the performance (mainly in terms of average packet delay) of any particular technology.

The rest of the paper is organized as follows. In Section 2, we present related works on existing DBWAs and we detail the contributions provided by our work. Section 3 introduces our proposed TT-aware DBWAs. In Section 3.1, we propose methods that can be used by the OLT to retrieve the exact value of the TT of each transceiver of the network. Section 4 presents the new DBWA that takes into account the fact that real tunable lasers have different values of TT depending on the wavelength that they have to retune. In Section 5, we introduce the simulative scenario and we discuss some numerical results. In Section 6, we draw the main conclusions of this work.

2. Related works and contributions

In this section, we provide an overview of existing DBWAs for WDM/TDM PONs and we detail the contributions provided by our work. In general, we can classify the DBWAs in two classes: (i) TT-aware and (ii) without TT. The *TT-aware DBWAs* are the algorithms which are optimized for taking advantage of the presence of the TT delay of the transceivers. The *DBWAs without TT* do not consider any TT. These solutions are designed for scenarios where the transceivers can immediately retune, i.e., they have a $TT = 0$. In order to schedule the transmissions of the ONUs there exist three main scheduling frameworks [7]: (i) offline scheduling, (ii) just-in-time scheduling, and (iii) online scheduling. In offline scheduling the transmission times of all the ONUs are calculated and allocated at the same time at the end of a polling cycle. This solution adds delays for the ONUs that need to wait one entire polling cycle to receive a scheduling for their transmissions. In the just-in-time scheduling the OLT postpones the decision-making time until one channel is about to become idle. Online scheduling enables ONUs to get an immediate allocation of their transmission. Over these scheduling frameworks several DBWAs can be designed.

Considering DBWAs without TT, a certain number of DBWA has been presented in the last years, some of which are architecture dependent [8]. Some of the recently proposed DBWA for LR WDM/TDM PONs are designed for particular network solutions. The first of these is specifically designed for the STARGATE EPON [9] which is a very particular network architecture based on Resilient Packet Ring (RPR). Another architecture dependent DBWA is Slotted Medium Access Control (SMAC), designed for SPON [10]. In this algorithm the OLT partitions the bandwidth on each upstream data wavelength into contiguous scheduling frames. Among these time slots, the first one in the bandwidth reservation slot. Finally the Optical Burst Switching DBA (OBS-DBA) is specifically designed for SARDANA architecture [11]. In our work, we propose DBWAs that are not architecture dependent but that are designed for generic WDM/TDM EPON-based networks.

---

[1] Long reach (LR) WDM/TDM PONs serve a large number of Optical Network Units (ONU), connected to a single Optical Line Terminal (OLT), over a larger geographical area, by extending the reach of PONs from 10–20 km up to 80–100 km. These network solutions will led towards higher integration of the metro and access network segments and are expected to reduce the Capital Expenditure (CapEx) and Operational Expenditure (OpEx) by decreasing the equipment interfaces, network elements, and active node locations.

In [12] different DBWAs are proposed for two different scenarios called Static Wavelength Dynamic Time (SWDT) and Dynamic Wavelength Dynamic Time (DWDT). In the SWDT scenario, the OLT allocates wavelengths in a static manner while the upstream transmissions are assigned dynamically in time domain depending on the request of the ONUs. In the DWDT scenario, both the wavelength and the upstream time slot are dynamically allocated by the OLT. Within this scenario, the OLT maintains a variable for every channel that record the time when the next transmission is possible on a particular channel. According to this main allocation policy, three algorithms are defined: (i) DWBA-1 allocates ONUs transmissions in an offline manner [7], (ii) DWBA-2 allocates lightly loaded ONUs in an online manner and highly loaded ONUs in an offline manner, (iii) DWBA-3 allocates all the transmissions of the ONUs in an online manner. In all these three DBWAs, the unused bandwidth of the lightly loaded ONUs is reassigned to the highly loaded ONUs. In our work, all the ONUs are scheduled in an online manner and in each polling cycle the bandwidth is assigned to the ONUs according to the limited grant sizing policy [13].

The Earliest Finish Time (EFT) algorithm [14] is a very simple but effective DBWA: the transmission of the ONUs is scheduled on the wavelength that is available first. We use this DBWA as a benchmark in our work and we extend it in order to make it a TT-aware DBWA.

The Latest-Finish Time with Void Filling (LFT-VF), Distanced Based Grouping (DBG) and Earliest-Finish Time with Void Filling (EFT-VF) algorithms [14] try to take advantage from the distribution of the distances from the OLT to the ONUs and try to remedy the inefficiencies in the utilization of the upstream channel given by this distribution. In the DBG algorithm ONUs are grouped according to the distance from the OLT. In each group the ONUs have similar distances from the OLT and use the same wavelength to transmit. Each group of ONUs use a different wavelength. The idea of this algorithm is to avoid the formation of voids (i.e., periods of time between two subsequent transmissions where there is no scheduled transmission on the channel) in the upstream channel. 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 rationale behind LFT-VF is that voids left before a scheduled upstream transmission are less likely to be used in the future, for this reason they should be minimized as much as possible. The void filling part keeps track and tries to fill the voids left on the upstream channel. The same objective is at the base of the EFT-VF algorithm which chooses the channel where the previously scheduled transmission will end first. In our work we extend the EFT-VF algorithm in order to make it a TT-aware DBWA. Basically these last three algorithms try to solve, using different strategies, the same problem solved by the multi-thread algorithm [15] which aims to reduce the waste of bandwidth in each polling cycle. The basic idea of the multi-thread algorithm is to run multiple polling processes (i.e., threads) between OLT and ONUs simultaneously. Instead, the DBWAs that we design in our work use a single thread.

TT-aware DBWAs have been proposed in [16,17]. In [16] the authors proposed a scheduling policy to exploit the benefit introduced by the laser tunability for both upstream and downstream transmissions. This work focused on offline scheduling and just-in-time scheduling [7], while in our work we study and propose DBWA with online scheduling. In [17] the authors extended the Interleaved Polling with Adaptive Cycle Time (IPACT) scheme with additional TT considerations and investigated the effect of the laser TT on the network performance. However, this work does not cover long reach access network or mixed transmission technologies. In [18], an automatic load-balancing DBWA algorithm for WDM/TDM PONs is presented. In this solution a tunable device (with very long TT, i.e., 10 ms or more) is tuned to a different wavelength when load-balancing is needed due to high load conditions. In our work, we focus on scenarios with mixed transmission technologies having different values of TTs, and with small TT (i.e., smaller than 1 ms).

To the best of our knowledge, our proposed TT-aware DBWA is the first that performs online bandwidth allocation, considers also a long reach scenario, and is designed to be applied in a scenario where the coexistence of several transmission technologies has to be managed. In [19], we firstly introduced the concept of DBWA able to support transceivers with different values of TTs. In this work, we extend the algorithms proposed in [19] considering also the case where tunable lasers have a variable TT depending on the distance of the wavelength to be retuned, and the case where array of fixed tuned lasers has a limited number of lasers (i.e., smaller than the number of wavelengths in the network).

The investigation in this paper has multiple objectives:

1. We propose new Dynamic Bandwidth and Wavelength Allocation (DBWA) algorithms (based on the functionalities of some existing non TT-aware DBWA) which support transceivers characterized by different values of TTs. We remark that studies of DBWAs dealing with transceivers with not negligible TTs already exist but not for the case that we are studying, i.e., DBWAs for transceivers with different TTs. The proposed DBWAs are able to jointly manage transmissions of fixed tuned lasers, array of fixed tuned lasers (i.e., with a $TT = 0$), and tunable transceivers with $TT > 0$ (i.e., the DBWA is *TT-aware*).
2. We evaluate the importance, in terms of performance (i.e., average packet delay), of having DBWAs that support transceivers with different values of TTs. Therefore, as comparison term we use DBWAs that are blind to the fact that different transceivers can have different values of TT.
3. We propose some method that can be used by the OLT to obtain the exact value of the TT of each transceiver of the network, in case tunable lasers at the ONUs have different TT values (and not one single TT for all ONUs, as typically assumed).
4. We propose a new DBWA that takes into account the fact that real tunable lasers have different values of TT depending on the wavelength they have to retune to (i.e., higher distance between wavelengths requires

higher TTs). To the best of our knowledge this is the first time that such a DBWA is proposed and analyzed.

5. Finally, in all the previous evaluations we assume the number of fixed tuned lasers installed in the array is equal to the number of wavelengths in the network. However, to have a cheap device, the number of fixed tuned lasers in an array has to be limited. For this reason, we also evaluate the performance of the previously proposed TT-aware DBWAs when the arrays of fixed tuned lasers can transmit over a limited number of wavelengths.

We compare the performance of our proposed solutions in both short-reach (up to 20 km of network span) and long-reach scenarios (up to 100 km of network span) when various types of transceiver coexist over the same network infrastructure.

3. TT-aware DBWAs with coexistence of transceivers

In this section, we describe the main functionalities of the proposed DBWAs that solve the problem of allocating the transmissions originated by transceivers with different TTs.

Background. All the proposed DBWAs are based on the Multi-Point Control Protocol (MPCP) [20]. MPCP employs two main messages in its normal operation: Report and Gate. The Gate message is sent from the OLT (where the DBWA is executed) to the ONUs and contains information on the assigned transmission timeslot. The Report message is transmitted by the ONUs at the end of each transmission and serves to notify the OLT about their transmission requests. In particular, in this work we adopt the MPCP extension for WDM PONs proposed in [21] where in the Gate message is added a field indicating the channel number assigned by the OLT to the ONU. Note that, a DBWA, like a generic DBA, can be viewed as consisting of grant sizing and grant scheduling problems [22]. 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 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 is calculated. In particular, we use as a grant sizing policy the limited sizing [13].

Without loss of generality, we consider here three different families of transceivers as described in Section 1. We refer to $N1$ as the set of ONUs that use tunable lasers to transmit and therefore they can tune to any wavelength in the network with a $\mathrm{TT} > 0$. $N2$ is the set of ONUs using array of lasers, which can transmit over each wavelength in the network with a $\mathrm{TT} = 0$. Finally, $N3$ are the ONUs that use a single fixed tuned laser, and so they can only transmit over their nominal wavelength. The definition of these ONU groups is presented in Table 1.

Our algorithms are developed extending the Earliest Finish Time (EFT) and the Earliest Finish Time with Void Filling (EFT-VF) [14]. EFT algorithm schedules ONU's transmission on the first wavelength that becomes available. In particular, wavelength assignment and the scheduling, according to EFT algorithm, are calculated as:

Table 1
Definition of variables.

t_i	Time when the report from ONU$_i$ arrives at the OLT
t_{guard}	Guard band time between two subsequent transmissions of different ONUs
t_{rx}	Time when the Gate message is received at the ONU
R_i	Round-trip propagation time between OLT and ONU$_i$
t_c	Time needed for the transmission of report or gate frame
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
$t_{g,i}$	Time needed to transmit the length of data which ONU$_i$ asks to transmit 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
t'_{eft}	Transmission start time within the w'_{eft} which could be chosen by the EFT algorithm
t'_{vf}	Transmission start time within the w'_{vf} wavelengths, which could be chosen by the Void Filling algorithms
w	Chosen upstream wavelength
t	Transmission start time within the w wavelength
$N1$	Set of ONUs that transmit using tunable lasers
$N2$	Set of ONUs that transmit using array of fixed-tuned lasers
$N3$	Set of ONUs that transmit using fixed-tuned lasers
TT	Tuning time of a tunable transmitter, which is the time needed to retune its laser to a different wavelength

$$w'_{eft} = \arg\min_{h}(L_h), \quad h \in W_i \tag{1}$$

$$t'_{eft} = \arg\max_{j}(F_{w,j}) + t_{guard} \tag{2}$$

The EFT-VF algorithm, which is an enhancement of the EFT algorithm, is based on the observation that in WDM/TDM PONs and in LR WDM/TDM PONs different distances between OLT and ONUs may lead to very diverse propagation delays creating *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. An *eligible void* is defined according to Eq. (3), 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:

$$V_i = \{F_{h,j} | S_{h,j+1} - \max(F_{h,j}, t_i + R_i + t_c) \geq t_{g,i} + t_c\}, \quad h \in W_i \tag{3}$$

The EFT-VF algorithm adds to the functionalities of the EFT defined in Eqs. (1) and (2), the Void Filling procedure that is defined in the following equations:

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

$$t'_{vf} = \arg\min_j (F_{w,j} | F_{w,j} \in V_i) + t_{guard} \tag{5}$$

Then, the wavelength and time scheduling for EFT-VF algorithm are finally assigned according to the equation:

$$w = \min(w'_{eft}, w'_{vf}), \quad t = \min(t'_{eft}, t'_{vf}) \tag{6}$$

Proposed TT-aware DBWAs. Since we apply all the studied DBWAs in a scenario where different technologies have different tuning times we first modify the previous algorithms to take into account the laser TT delay. Particularly, for the ONUs in $N1$, the modified algorithms calculate the interval between the instant when the Gate message is received at the ONU and the start time of the transmission at the same ONU.

During this interval the ONU can retune its laser, if needed. If this interval is shorter than the laser TT, the algorithm adds an additional delay (δ). In particular, δ is added if $t - t_{rx} < \text{TT}$ where t is the start time computed with the algorithm (EFT or EFT-VF), and the value assigned to δ is:

$$\delta = \text{TT} - (t - t_{rx}) \tag{7}$$

Therefore, in this case the EFT algorithm adds the computed δ to the start time computed in Eq. (2), and the EFT-VF algorithm adds δ to the start time computed in Eq. (6). The transmission start time of EFT+TT is calculated as shown in Eq. (8) while for the EFT-VF+TT algorithm the start time is computed according to the following equations:

$$t'_{eft+TT} = \arg\max_j (F_{w,j}) + t_{guard} + \delta \tag{8}$$

$$t'_{vf+TT} = \arg\min_j (F_{w,j} | F_{w,j} \in V_i) + t_{guard} + \delta \tag{9}$$

$$t = \min(t'_{eft+TT}, t'_{vf+TT}) \tag{10}$$

For the ONUs in $N2$ the original versions of EFT and EFT-VF are directly applied. ONUs in $N3$ transmit in the first available start time (considering also voids when it is applied the EFT-VF algorithm) over a fixed pre-assigned wavelength (and, since TT=0, there is no need to add TT-related delays). These new algorithms are referred here as *EFT+TT* and *EFT-VF+TT*, where TT indicates that these DBWAs take into account the TT delay, when needed.

The possible cases of the allocation procedure for an ONU in $N1$ are shown in Figs. 1–4. In Fig. 1, the first available wavelength to allocate a transmission is W_2. In this case, ONU$_i$ does not need to retune its laser since also its previous transmission was allocated on W_2, and consequently its laser was already tuned on that wavelength. In Fig. 2, the first available wavelength to allocate a transmission is W_3, so ONU$_i$ needs to retune its laser. In this case the algorithm calculates the interval between the instant when the Gate message is received at the ONU (t_{rx}) and the start time of the transmission (t_{eft}), and then it adds a delay in order to give time to the laser of ONU$_i$ to retune. Therefore, the transmission start time will be delayed ($t_{eft} + \delta$). In Fig. 3, the first available wavelength to allocate a transmission is again W_3. In this case, the laser of ONU$_i$ has enough time between the reception of the Gate message and assigned start time to retune its laser. In this case there is no need to add a delay to the start time. Fig. 4 shows the case where the first available transmission

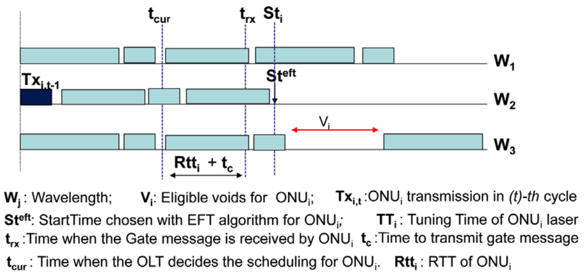

Fig. 1. Example of the transmission allocation of an ONU in $N1$ with no retuning (hence no need to add delay to retune the laser).

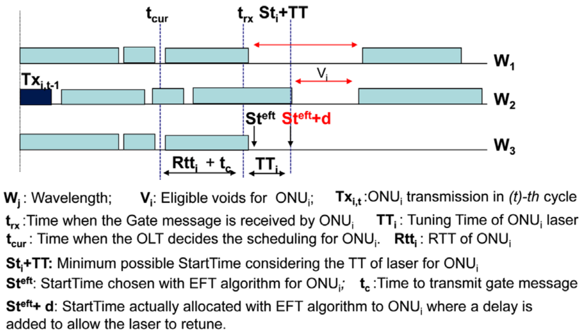

Fig. 2. Example of the transmission allocation of an ONU in $N1$ with retuning (hence there is a need to add delay to retune the laser).

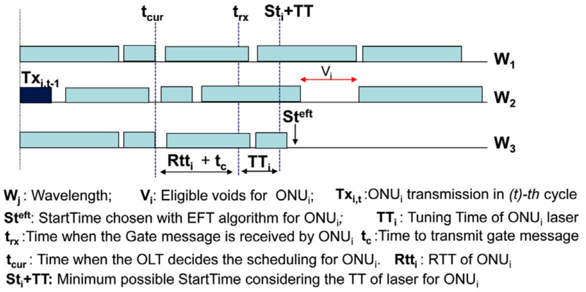

Fig. 3. Example of the transmission allocation of an ONU in $N1$ with retuning, but the interval between the instant when the Gate message is received at the ONU (t_{rx}), and the start time of the transmission (St^{eft}) is long enough to allow the laser to retune, hence there is no need to add any delay.

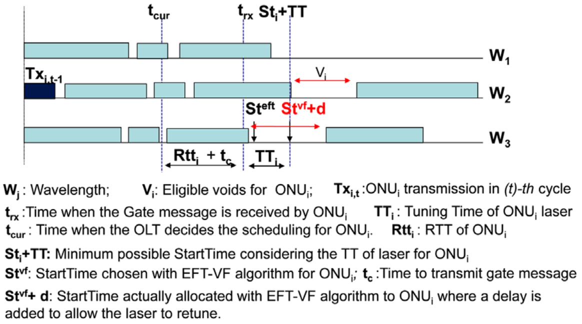

Fig. 4. Example of the transmission allocation of an ONU in $N1$ in a void with retuning (hence there is a need to add delay to retune the laser).

opportunity is in a void over wavelength W_3 (i.e., EFT-VF+TT algorithm is applied). In this case, ONU$_i$ needs to retune its laser. Also in this case the algorithm calculates the interval between the instant when the Gate message is received at the ONU (t_{rx}) and the start time of the transmission (t_{eft}), and then it adds a delay in order to give time to the laser of ONU$_i$ to retune. Since the transmission needs to be delayed, the length of the transmission that can be allocated in the void is shorter than in the case where the transmission is not retuned. For this reason, the EFT-VF+TT algorithm is less effective in filling voids compared to the basic EFT-VF algorithm.

Simplified version of TT-aware DBWAs. For the sake of comparison, we considered also simplified versions of EFT and EFT-VF where the OLT does not know the exact value of the TT of each ONU, but it only knows if a particular transceiver is able to retune or not, referred as *Simple EFT+TT* and *Simple EFT-VF+TT*. We implemented these versions to evaluate the importance of having a DBWA which is aware of the exact values of TT and is able to add different delays to different transmissions (i.e., like EFT+TT and EFT-VF+TT do). For this reason, Simple EFT+TT and Simple EFT-VF+TT add a delay to all the transmissions of the ONUs which have to retune (i.e., $N1$ and $N2$) considering a maximum value of TT (the same for all the ONUs). We expect that both the EFT+TT and the EFT-VF+TT provide a lower average packet delay with respect to the simple versions of the same algorithms. Our aim is to evaluate the gain in terms of average packet delay using EFT+TT or EFT-VF+TT instead of Simple EFT+TT or Simple EFT-VF+TT, and then understand the importance of a DBWA that is aware of the type of transceivers used by each ONU.

3.1. Discovering methods of the TT values

For the previous algorithms, except the simplified versions, we assume that OLT knows the exact value of the TT of all the transceivers in the network. Three methods can be implemented to inform the OLT about the TT values: (i) through an initial setting provided by the network operator and (ii) with a calculation during the ranging phase, when the round-trip-time between the ONUs and the OLTs can be calculated using the packet delay of the ONUs. Once the round-trip-time is estimated, the OLT can run the ranging mechanism another time over a different wavelength, and then it will be able to compute also the value of the TT of each ONU. (iii) Each TT value can be transmitted within the Report message which is sent by each ONU.

3.2. Array of fixed tuned lasers with limited tunability

We also evaluate the performance of some of the previously studied DBWAs (i.e., EFT+TT and EFT-VF+TT) when the arrays of fixed tuned lasers can transmit over a limited number of wavelengths. In fact, in all the previous evaluation we assumed that the array of tunable lasers is able to tune to every wavelength of the network, i.e., the number of lasers in an array is equal to the number of wavelengths. However, we know that to have a cheap device the number of fixed tuned lasers in the array has to be limited.

In this case, the algorithm allocates the transmissions of the ONUs through Eqs. (1)–(6), where for Eq. (1) W_i is not equal to the entire set of wavelengths of the network.

4. TT-aware DBWAs with wavelength dependent tuning times

In the previous sections, we considered that the tunable lasers of ONUs in $N1$ can retune from a wavelength to each other wavelength with the same TT. In this section we introduce our proposed TT-aware DBWAs for the case when tunable lasers have different TTs according to the wavelength they have to retune (i.e., the higher the spectral distance between two wavelengths, the higher the TT). In this scenario, the lasers of the ONUs in $N1$ have a different value of TT according to the spectral distance between the wavelength i where they currently transmit and the wavelength j they have to retune to. We refer to this distance as *wavelength gap*, w_{ij}. The wavelength gap is computed through Eq. (11) as the difference in terms of number of wavelengths between the wavelength where an ONU is currently transmitting (w_i) and the wavelength the ONU has to retune to transmit (w_j):

$$w_{ij} = |w_i - w_j|, \quad i \neq j \tag{11}$$

The TT of ONUs lasers in $N1$ is proportional to the wavelength gap, and it is computed through Eq. (12) where TT_{base} is the TT needed to retune between two adjacent wavelengths (i.e., when $w_{ij} = 1$). TT_{ij} is the time needed to retune from a wavelength to any other wavelength in the network. This $\mathrm{TT}_{\mathrm{ij}}$ is proportional to w_{ij}:

$$\mathrm{TT}_{ij} = w_{ij} * \mathrm{TT}_{base}, \quad i \neq j \tag{12}$$

We first tested the EFT-VF+TT algorithm proposed in Section 3 in this scenario where the tunable lasers of ONUs in $N1$ have different TTs according to the number of wavelengths they have to retune. In this scenario, the EFT-VF+TT algorithm has the same functionalities explained in Section 3, but for the ONUs in $N1$ the considered TT is computed through Eq. (12). We refer to this variation of the EFT-VF+TT algorithm as EFT-VF+TT$_{ij}$, where "+TT$_{ij}$" refers to the fact that the TT of the tunable lasers changes according to the distance between two wavelengths.

Then, we propose a new DBWA technique specifically designed for this scenario where the tunable lasers of ONUs in $N1$ have different TTs according to the number of wavelengths they have to retune.

We refer to this new proposed DBWA as *Earliest start-time with Void Filling* $+\mathrm{TT}_{ij}$ (EsT-VF$+\mathrm{TT}_{ij}$), where "$+\mathrm{TT}_{ij}$" refers to the fact that the TT of the tunable lasers changes according to the distance between two wavelengths. Also the new proposed DBWA is based on the functionalities of EFT-VF but the policy used to allocate the transmissions of ONUs in $N1$ is designed to minimize the effect of the different TT_{ij} on the packet delay. For ONUs in $N2$ and $N3$ this algorithm use the same allocation procedure defined for EFT-VF+TT. For the ONUs in $N1$, this algorithm first computes for each wavelength and for each void the start time, as defined in Eqs. (2) and (5), adding when it is needed the delay (δ_{ij}) to allow the lasers to retune. In particular, if $t-t_{rx}<\mathrm{TT}_{ij}$, the δ_{ij} is computed according to the following equation:

$$\delta_{ij}=\mathrm{TT}_{ij}-(t-t_{rx}) \tag{13}$$

When all the possible transmission start times are computed, the Est-VF$+\mathrm{TT}_{ij}$ chooses the minimum start time and it assigns this start time and the corresponding wavelength to the ONU. This strategy reduces the average delay introduced by the ONUs in $N1$, but it also indirectly reduces (i) the amount of retunings of the tunable lasers and (ii) the average wavelength gap (i.e., the average distance between two wavelengths between which a laser has to retune). This algorithm differs from the EFT-VF$+\mathrm{TT}_{ij}$ because the EFT-VF$+\mathrm{TT}_{ij}$ first chooses the minimum start time and then it adds, when needed, the delay to allow the lasers to retune.

5. Results and discussion

In this section, we compare the performance in terms of average delay of all the proposed DBWAs. In particular, in Section 5.1 we present the simulative scenarios in which we tested our algorithms. In Section 5.2 we present the comparison between the proposed TT-aware DBWAs and their simple version. In Section 5.3 we evaluate the performance of EFT+TT and EFT-VF+TT when the arrays of fixed tuned lasers can transmit over a limited number of wavelengths. Finally, in Section 5.4 we present the results of our proposed EsT-VF$+\mathrm{TT}_{ij}$ compared with EFT-VF$+\mathrm{TT}_{ij}$.

5.1. Simulative scenario

The proposed algorithms are evaluated and compared through simulation. For this purpose, we implemented the DBWA algorithms in a network simulator based on the Discrete Event Simulation Library (DESL) [24], which we modified to model a WDM/TDM PON (both short-reach and long-reach). This simulation tool only implements 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 is set to 10 Mbytes. The maximum polling cycle time is 2 ms, and accordingly the $B_{max,i}$ is calculated with the same equation that we previously proposed in [23]. We assume the same $B_{max,i}$ for every ONU. The guard band time between two subsequent transmissions is 1 µs. The TT value for ONUs in $N1$ is 100 µs. Our tree topology includes 24 wavelengths (W) and 192 ONUs divided into three groups, depending on their transmission technology. We tested all the DBWAs in three scenarios where we changed the capacity of the wavelengths and the distribution of the transmission technology (i.e., number of ONUs using a particular transmission technology in each group). Then, for each scenario we varied the OLT–ONU distance distribution. The parameters of the 9 scenarios are shown in Table 2, where C_w refers to the capacity of the wavelengths. Note that we assume that the network is properly designed to support increased losses due to high splitting ratios and long fiber lengths.

Table 2
Network parameters for different network scenarios.

	Scenario 1	Scenario 2	Scenario 3
C_w	1 Gbit/s	10 Gbit/s	1 Gbit/s
Transmission technologies distribution	$N1=1/3$	$N1=1/3$	$N1=2/3$
	$N2=1/3$ $N3=1/3$	$N2=1/3$ $N3=1/3$	$N2=1/6$ $N3=1/6$
OLT–ONUs distances distributions	(a) 1–20 km	(a) 1–20 km	(a) 1–20 km
	(b) 80–100 km (c) 500 m–100 km	(b) 80–100 km (c) 500 m–100 km	(b) 80–100 km (c) 500 m–100 km

5.2. TT-aware DBWAs vs. simple DBWAs

In this section, we compare EFT+TT, EFT-VF+TT, Simple EFT+TT, and Simple EFT-VF+TT algorithms in Scenario 1 where three different transmission technologies operate in the PON, and the OLT–ONUs distances distribution is between 500 m and 100 km. Note that, even if the EFT+TT and the EFT-VF+TT algorithms are designed to manage several different values of TT of the transceivers, in this simulations we test the DBWAs using only two different values of TT: TT=0 and TT = 100 µs.

Fig. 5 reports the comparison in the average packet delay of all ONUs in the PON vs. offered load among EFT+TT, EFT-VF+TT, Simple EFT+TT, and Simple EFT-VF+TT algorithms, when the TT of the tunable lasers is 100 µs. We can state that, with our settings, the coexistence of different transmission technologies over the same WDM/TDM PON is possible since all the evaluated DBWAs can still provide a low average delay (less than 1.5 ms), except for very high load (over 80%–90%), as shown in Fig. 5. In Fig. 5 we notice that Simple EFT+TT has a higher average delay with respect to EFT+TT, and Simple EFT-VF+TT has a higher average delay compared to EFT-VF+TT. This is due to the fact that in the Simple EFT+TT a delay is added to all the ONUs that have to retune while in EFT+TT the retuning delay is added only for the ONUs that really have a TT > 0. We can also notice that the Simple feature has a higher impact in the case of the EFT-VF+TT algorithm than in the case of EFT+TT. Since the EFT-VF+TT has a better usage of the voids compared to Simple EFT-VF+TT, the gap between the average delay of EFT-VF+TT and Simple EFT-VF+TT is higher compared to the gap between EFT+TT and Simple EFT+TT.

In the following, we compare the relative gain of EFT-VF+TT and Simple EFT-VF+TT respect to EFT+TT. In Figs. 6 and 7, we show the average delay reduction of EFT-VF+TT and Simple EFT-VF+TT with respect to EFT+TT in different scenarios where we vary: (i) the OLT–ONUs distances (Fig. 6), (ii) the percentage of tunable transceivers within the network (Fig. 6 vs. Fig. 7). Particularly, in Fig. 6 we show the results obtained in Scenario 1 and in Fig. 7 we report the results obtained in Scenario 3. We can notice that EFT-VF+TT always reduces the average delay compared to Simple EFT-VF+TT, in all the investigated scenarios. Moreover, when the load increases, the difference between Simple EFT-VF+TT and EFT-VF+TT increases, since the average delay reduction of Simple EFT-VF+TT decreases. This is due to the fact that at high loads the number of voids in the network decreases and the behavior of Simple EFT-VF+TT becomes closer to the behavior of EFT+TT. This is true for all the scenarios, but is much more evident in the short-reach cases (i.e., OLT–ONUs distances between 1 and 20 km), as shown in Figs. 6 and 7 where the distance between the curves of EFT-VF+TT (1–20 km) and Simple EFT-VF+TT (1–20 km) is much higher than in all the others cases.

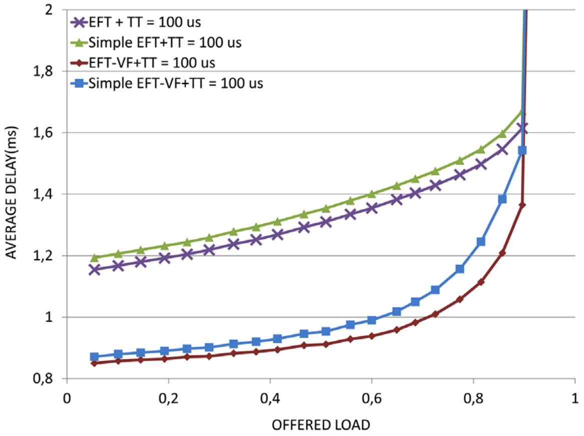

Fig. 5. Average packet delay comparison among EFT+TT, EFT-VF+TT, and Simple EFT-VF+TT in Scenario 1 where the ONUs in $N1$ have a TT = 100 μs. The ONUs–OLT distance distribution is between 500 m and 100 km.

Variation of the OLT–ONUs distances. The curves of EFT-VF+TT (80–100 km) and Simple EFT-VF+TT (80–100 km) in Figs. 6 and 7 refer to a long reach scenario and show that the average delay reduction of both Simple EFT-VF+TT and EFT-VF+TT with respect to EFT+TT is very limited (less than 5%). This is due to the fact that in a long-reach scenario, where there is low distribution of the distances between OLT and ONUs (i.e., between 80 and 100 km), the number of voids decreases and then the performance of EFT+TT and EFT-VF+TT (both simple and not simple versions) are very close. Comparing the short-reach cases with the long-reach cases (i.e., OLT–ONUs

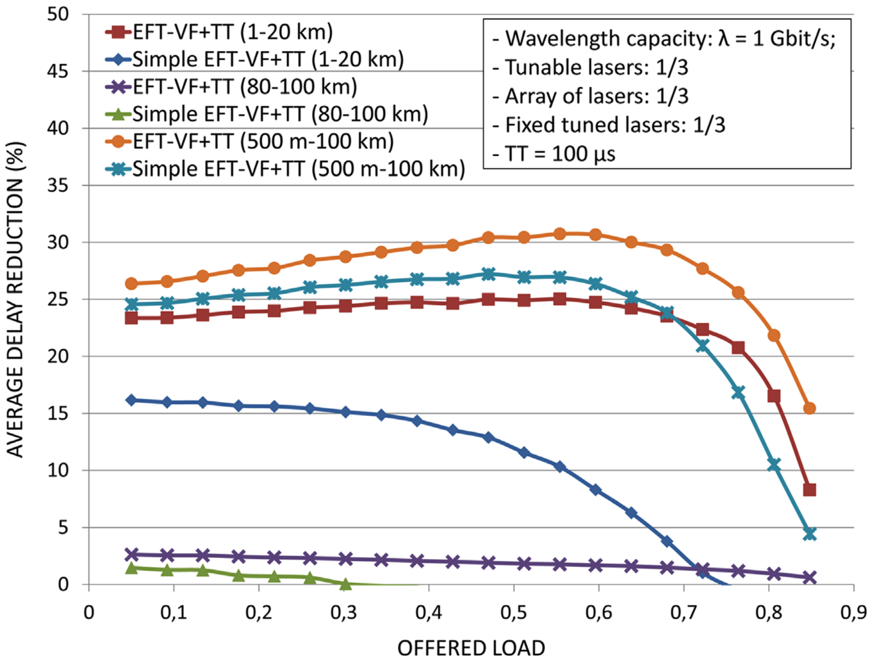

Fig. 6. Average delay reduction of the Simple EFT-VF+TT and the EFT-VF+TT algorithms compared to EFT+TT scheme, where the ONUs in $N1$ have a TT = 100 μs, in Scenario 1.

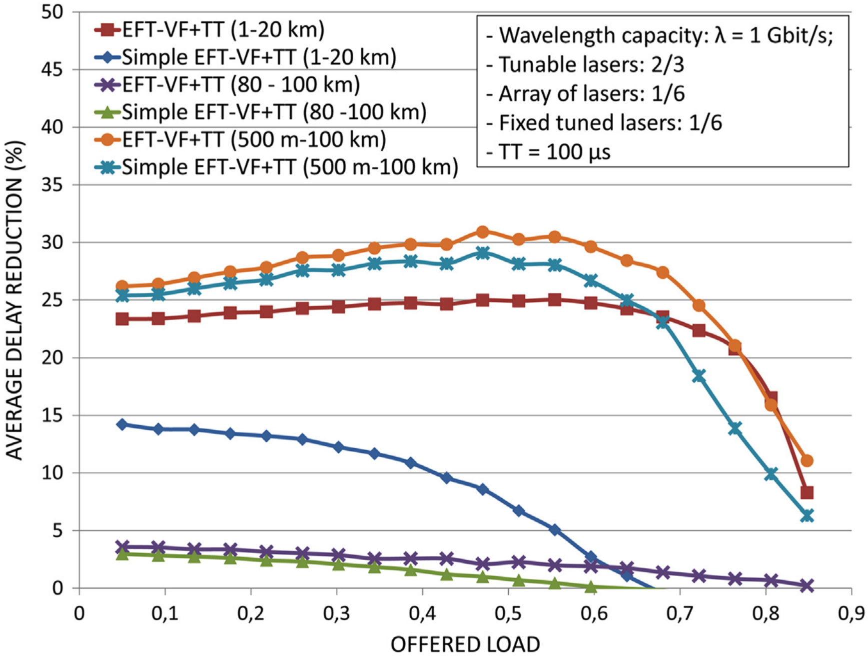

Fig. 7. Average delay reduction of the Simple EFT-VF+TT and the EFT-VF+TT algorithms compared to EFT+TT scheme, where the ONUs in $N1$ have a TT = 100 µs, in Scenario 3.

distances between 80–100 km and 500 m–100 km) shown in Figs. 6 and 7 we notice that the difference in the average delay reduction between Simple EFT-VF+TT and EFT-VF+TT is higher in the short-reach cases. Therefore, we can state that in short-reach scenarios it is more important to have a DBWA which is able to manage the TT in a smart manner.

Variation of the percentage of transceivers. Comparing Fig. 6 with Fig. 7, we can notice that in the case where the percentage of tunable transceivers increases (as in Scenario 3) the difference between the performance of Simple EFT-VF+TT and EFT-VF+TT slightly increases with respect to Scenario 1 (i.e., the transmission technologies are uniformly distributed). In Scenario 3, the average delay reduction of Simple EFT-VF+TT is lower than in Scenario 1. This happens because in Scenario 1 (Fig. 6), in Simple EFT-VF+TT, 2/3 of the transmissions are not delayed (i.e., from ONUs in $N2$ and $N3$) while in Scenario 3 (Fig. 7) only 1/3 of the transmissions are not delayed (i.e., from ONUs in $N2$ and $N3$).

Variation of the wavelength capacity. We also evaluated the differences in terms of average delay reduction between Simple EFT-VF+TT and EFT-VF+TT when the wavelengths have different capacities. The graph for Scenario 2 is not reported here since we noticed that a different capacity does not affect significantly the performance of the evaluated DBWAs. In the case where the capacity is 10 Gbit/s the average delay reduction of both Simple EFT-VF+TT and EFT-VF+TT are slightly higher (around 5% more) than in the case where the capacity of each wavelength is 1 Gbit/s.

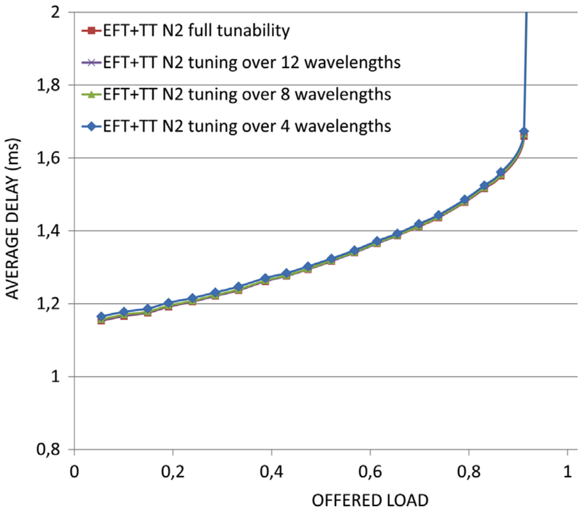

Fig. 8. Average delay of the EFT+TT when the ONUs in $N2$ have different limited tunability, compared to the case where the ONUs in $N2$ have full tunability. The ONUs in $N1$ have a TT = 100 µs.

5.3. *Average delay evaluation: array of fixed tuned lasers with limited tunability*

In this section, we evaluate the performance of some the previously studied DBWAs (i.e., EFT+TT and EFT-VF+TT) when the arrays of fixed tuned lasers can transmit over a limited number of wavelengths, as explained in Section 3.2. The simulation scenario used for this evaluation is Scenario 1c defined in Table 2. In this scenario, each

ONU in *N*2 can transmit over a limited set of contiguous wavelengths. These sets of wavelengths are assigned in a round robin manner to the ONUs in *N*2, this means that these ONUs do not transmit over the same limited number of wavelengths. For example, if in a network we have 3 ONUs with arrays of fixed tuned lasers and 4 wavelengths, and each ONUs can transmit only over 3 wavelengths. The sets of wavelengths are assigned as follows: ONU1 can transmit over wavelengths 1, 2, and 3. ONU2 can transmit over wavelengths 2, 3, and 4. ONU3 can transmit over wavelengths 3, 4, and 1. In this scenario, all the ONUs in *N*2 are equipped with the same arrays of fixed tuned lasers. In particular, we test three cases where the array of fixed tuned lasers is composed by 4, 8, or 12 lasers. We compare these three cases with the case where the number of lasers in the arrays of fixed tuned lasers is the same of the number of available wavelengths in the network (i.e., 24 wavelengths), we refer to this case as *full tunability*.

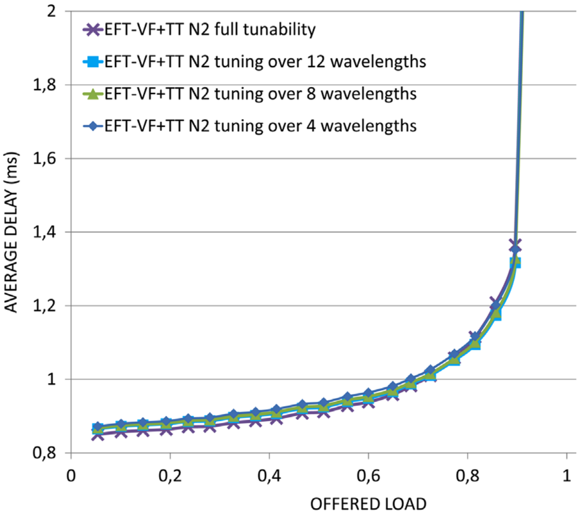

Fig. 9. Average delay of the EFT-VF+TT when the ONUs in *N*2 have different limited tunability, compared to the case where the ONUs in *N*2 have full tunability. The ONUs in *N*1 have a TT = 100 μs.

Fig. 8 shows the average packet delay of the EFT+TT algorithm when the ONUs in *N*2 have different limited tunability (i.e., they can use only to 4, 8, or 12 wavelengths since the array of fixed tuned lasers are composed only of 4, 8, or 12 lasers), compared to the case where the ONUs in *N*2 have full tunability (i.e., they can tune to every wavelength of the network since these ONUs are equipped with large arrays of lasers). We can notice that the average delay of EFT+TT in the full tunability case and where the arrays of lasers can use only a limited number wavelengths has a very small variation, which is almost negligible. Lowering the number of available wavelengths for each array of fixed tuned lasers slightly increases the average delay, if compared with the case where the arrays of lasers can use all the wavelengths in the networks. However, this difference in terms of average packet delay is very limited, i.e., less than 2 μs.

Fig. 9 shows the average packet delay of the EFT-VF+TT algorithm when the ONUs in *N*2 have different limited tunability, compared to the case where the ONUs in *N*2 have full tunability. Similar considerations drawn for the EFT+TT algorithm apply in the case of EFT-VF+TT. With EFT-VF+TT the difference in terms of average delay is a little larger than in the EFT+TT case, but however it is very limited.

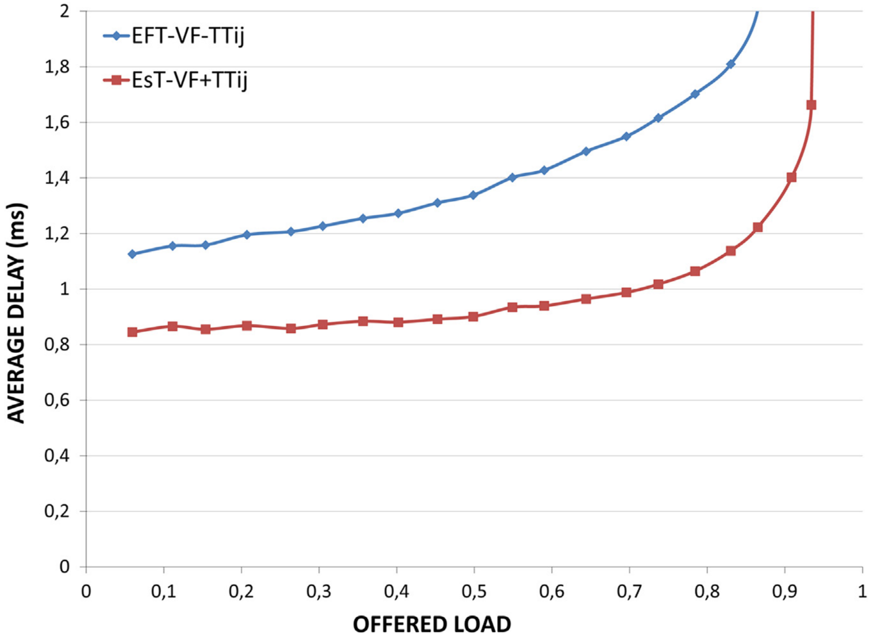

Fig. 10. Average delay of the EsT-VF+TT$_{ij}$ algorithm, compared to the EFT-VF+TT algorithm applied in the Scenario 1 where tunable lasers have different TTs according to the number of wavelengths they have to retune. The ONUs in *N*1 have a TT$_{base}$ = 100 μs.

5.4. TT-aware DBWAs with different wavelength TTs

Fig. 10 shows the results in the scenario where tunable lasers have different TTs according to the number of wavelengths they have to retune. To test this two algorithms we used Scenario 1 defined in Table 2 where the OLT–ONUs distances distribution is between 500 m and 100 km. We use a value of TT_{base} of 100 1 μs. In Fig. 10 we compare the EFT-VF+TT_{ij} and the EsT-VF+TT_{ij} in terms of average delay. First, we can notice that the EsT-VF+TT_{ij} algorithm has the lowest average delay. Moreover, the average delay provided is lower than the average delay usually required for an access network, i.e., 1.5 ms. Indeed, the EsT-VF+TT_{ij} is specifically designed for the case when tunable lasers have different TTs according to the number of wavelengths they have to retune, and we can prove that this allocation technique, minimizing the transmission start time of the ONUs in $N1$, is able to reduce the overall average packet delay of the network. In Fig. 10 we can notice that the average delay of the EFT-VF+TT_{ij} is much higher than the corresponding version of the algorithm (i.e., EFT-VF+TT) shown in Fig. 5, tested in the same scenario.

6. Conclusion

In this work we proposed DBWA algorithms that solve the problem of managing the traffic originated by transceivers with different characteristics (e.g., different tuning time). Starting from two existing algorithms (i.e., EFT and EFT-VF) we proposed two new DBWAs that take into account the laser TT considering that different transceivers at the ONU can have different values of TT. These DBWAs are able to manage at the same time transmissions of transceivers which cannot retune (e.g., fixed tuned lasers), transceivers with a $TT=0$ (e.g., array of fixed tuned lasers), and transceivers with $TT > 0$ (e.g., tunable lasers). We refer to these solutions as EFT+TT and EFT-VF+TT. We compared the performance of EFT+TT, EFT-VF+TT, and two simplified versions that are not aware that ONUs can have different TT values. Our results show that the EFT-VF+TT is the solution, among the three considered, that provides the lower average packet delay. Results show also that in the case of short-reach scenarios (about 20 km) it is more important to use a DBWA that is aware of the different values of TT in the network, while in a long reach-scenario (up to 100 km) Simple EFT-VF+TT can be used without having a significant loss in terms of average packet delay.

Then we proposed a new DBWA that we called EsT-VF+TT_{ij} that takes into account the fact that real tunable lasers have different values of TT depending on the wavelength that they have to retune to. Our results show that the proposed TT-aware DBWA is able to reduce the overall average packet delay of the network, compared to the case where a DBWA that is not specifically designed for this scenario is applied.

Finally, we considered the case where the arrays of fixed tuned lasers are equipped with a number of lasers which is lower than the total number of wavelengths available in the network. According to our results, we can conclude that lowering the number of lasers in the arrays of lasers of ONUs negligibly increases the average packet delay, this difference in terms of average packet delay is very limited (i.e., less than 2 μs).

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2013-2015 under Grant agreement no. 317762 COMBO project.

References

[1] Y.-L. Hsueh, M.S. Rogge, S. Yamamoto, L.G. Kazovsky, A highly flexible and efficient passive optical network employing dynamic wavelength allocation, IEEE/OSA J. Lightwave Technol. 33 (January) (2005) 277–286.

[2] M. De Andrade, M. Tornatore, S. Sallent, B. Mukherjee, Optimizing the migration to future-generation passive optical networks (PON), IEEE Syst. J. 4 (December) (2010) 413–423.

[3] H. Song, B.-W. Kim, B. Mukherjee, Long-reach optical access networks: a survey of research challenges, demonstrations, and bandwidth assignment mechanisms, IEEE Commun. Surveys Tutor. 12 (2010) 112–123 (First quarter).

[4] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, Y. Ma, Time-and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON Stage 2 (NG-PON2), J. Lightwave Technol. 31 (February) (2013) 587–593.

[5] T.-P. Lee, C.E. Zah, R. Bhat, W.C. Young, B. Pathak, F. Favire, Paul S. D. Lin, N.C. Andreadakis, C. Caneau, A.W. Rahjel, M. Koza, J. K. Gamelin, L. Curtis, D.D. Mahoney, A. Lepore, Multiwavelength DFB laser array transmitters for ONTC reconfigurable optical network testbed, J. Lightwave Technol. 14 (June) (1996) 967–976.

[6] J. Zhang, N. Ansari, Design of WDM PON with tunable lasers: the upstream scenario, J. Lightwave Technol. 28 (January (15)) (2010) 228–236.

[7] M.P. McGarry, M. Reisslein, M. Maier, A. Keha, Bandwidth management for WDM EPONs, J. Opt. Netw. 5 (2006) 637–654.

[8] B. Kantarci, H. Mouftah, Bandwidth distribution solutions for performance enhancement in long-reach passive optical networks, IEEE Commun. Surveys Tutor. (99) (2011) 1–20.

[9] M. Lehan, C.M. Assi, M. Maier, A.R. Dhaini, Resource management in STARGATE-based ethernet passive optical networks (SG-EPONs), IEEE/OSA J. Opt. Commun. Netw. 1 (September (4)) (2009) 279–293.

[10] H.-T. Lin, Z.-H. Ho, H.-C. Cheng, W.-R. Chang, SPON: a slotted long-reach PON architecture for supporting internetworking capability, in: Military Communications Conference, 2009, MILCOM 2009, October 2009, IEEE, pp. 1–8, 18–21.

[11] J. Segarra, V. Sales, J. Prat, OLT design approach for resilient extended PON with OBS dynamic bandwidth allocation sharing the OLT optical resources, in: Transparent Optical Networks, 2008, ICTON 2008, 22–26 June 2008.

[12] A. Dhaini, C. Assi, M. Maier, Dynamic wavelength and bandwidth allocation in hybrid TDM/WDM EPON networks, J. Lightwave Technol. 25 (January) (2007) 277–286.

[13] J. Zheng, H.T. Mouftah, A survey of dynamic bandwidth allocation algorithms for ethernet passive optical networks, J. Opt. Switch. Netw. 6 (July) (2009) 151–162.

[14] K. Kanonakis, I. Tomkos, Improving the efficiency of online upstream scheduling and wavelength assignment in hybrid WDM/TDMA EPON networks, J. Sel. Area Commun. 28 (August) (2010) 838–848.

[15] H. Song, A. Banerjee, B.-W. Kim, B. Mukherjee, Multi-thread polling: a dynamic bandwidth distribution scheme in long-reach PON, in: Global Telecommunications Conference, 2007.

[16] J. Zhang, N. Ansari, Scheduling hybrid WDM/TDM passive optical networks with nonzero laser tuning time, IEEE/ACM Trans. Netw. 19 (August) (2011) 1014–1027.

[17] M. Zhu, S. Xiao, Z. Zhou, W. Guo, L. Yi, M. Bi, W. Hu, B. Geller, An upstream multi-wavelength shared PON based on tunable self-seeding Fabry–Pérot laser diode for upstream capacity upgrade and wavelength multiplexing, in: Proceedings of OFC 2011, 8–10 March, Los Angeles, CA, USA.

[18] T. Yoshida, S. Kaneko, S. Kimura, Yoshimoto, An automatic load-balancing DWBA algorithm considering long-time tuning devices for λ-tunable WDM/TDM-PON, in: Proceedings of ECOC 2013, 22–26 September 2013, London, UK.

[19] A. Buttaboni, M. De Andrade, M. Tornatore, Dynamic bandwidth and wavelength allocation with coexisting transceiver technology in WDM/TDM PONs, in: Proceedings of NETWORKS 2014, 17–19 September 2014, Funchal, Madeira Island, PT.

[20] Standard, IEEE 802.3, Available from: ⟨http://ieee802.org/3/⟩, June 2004.

[21] M.P. McGarry, M. Maier, M. Reisslein, WDM ethernet passive optical networks (EPONs), IEEE Commun. Mag. 44 (February (2)) (2006) 15–22.

[22] M.S. Kiaei, L. Meng, C.M. Assi, M. Maier, Efficient scheduling and grant sizing methods for WDM PONs, J. Lightwave Technol. 28 (July) .

[23] A. Buttaboni, M. De Andrade, M. Tornatore, A multi-threaded dynamic bandwidth and wavelength allocation scheme with void filling for long reach WDM/TDM PONs, J. Lightwave Technol. 31 (April (15)) (2013) 1149–1157.

[24] G. Kramer, DESL User Manual, Available from: ⟨http://www.glenkramer.com/ucdavis/code/desl.html⟩.