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Delay fairness in reconfigurable and energy efficient TWDM PON

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ABSTRACT

In Time and Wavelength Division Multiplexed (TWDM) Passive Optical Networks (PONs), dynamically (de)activating Optical Subscriber Units (OSUs) and assigning Optical Network Units (ONUs) to the active OSUs helps improving the OLT energy efficiency and balancing the network load.

However, energy efficiency improvement is traded with a delay increase due to the finite ONU tuning speed and the potential increase of the normalized load with respect to the number of active OSUs. Moreover, even though load balance potentially assures delay balance, the scheduling and assignment of ONUs to OSUs might cause ONU delay unbalance (i.e., delay unfairness). Indeed, if an ONU is forced to tune at each reconfiguration it suffers a high delay penalty due to its limited tuning time.

In this study, the impact of the ONU scheduling and assignment to OSUs upon network reconfiguration on the average frame delay unbalance is evaluated. Then, a method that balances the average frame delay by swapping the tuning ONU upon reconfiguration is proposed, for some critical scenarios. Simulation and experimental results show that the delay unbalance is large when the number of active ONUs is small (e.g., at network start up or when the majority of the ONUs is inactive/sleeping). In this case, the proposed method effectively balances the delay experienced by ONUs without impacting the OLT energy savings.

1. Introduction

Time- and Wavelength-Division Multiplexed (TWDM) PONs (also known as hybrid TDM-WDM PONs) are currently under standardization by ITU-T as part of the Next Generation PON 2 (NG-PON2) [1]. The colorless nature of the ONU transceivers, as proposed in most of the architectures [2], potentially provides better bandwidth utilization and energy savings at the OLT during low traffic through the aggregation of ONUs into a subset of OSUs and the switching to sleep mode of idle OSUs.

The first studies on Dynamic Wavelength and Bandwidth Allocation (DWBA) in TWDM-PON focused on schemes and protocols to either minimize the number of utilized wavelengths at the OLT to save energy [3,4] or to hitlessly (i.e., avoiding frame loss) perform wavelength reconfiguration [5,6]. Recently, attention has been focused on DWBAs reducing penalties due to ONU tuning time overhead. For example in [7], a DWBA is proposed that minimizes the number of wavelength reallocations and, as of consequence, the tuning time overhead penalties while attaining fairness in distributing traffic to OSUs. Such DWBA is experimentally demonstrated with 512 ONUs in [8]. Furthermore, an automatic load balancing DWBA algorithm has been proposed in [9] that activates load balancing when upstream OSU congestion is detected. The proposed algorithm is also capable of reducing the impact of long ONU tuning times by triggering reconfigurations with a period longer than the ONU tuning time. Finally, in [10] a method for decreasing the latency degradation due to the simultaneous reallocation and tuning of ONUs with different tuning times is presented.

However, when DWBA is utilized, if an ONU is tuning, the traffic destined to/originated by the ONU must be buffered. Thus, traffic belonging to tuning ONUs experiences delay, while traffic belonging to non-tuning ONUs keeps being received/transmitted. Therefore the impact of the tuning time overhead on average frame delay is unbalanced toward ONUs which tune.

This paper evaluates the impact of such issue on the delay experienced by each ONU. Then, it proposes a DWBA that balances the delay experienced by the ONUs in scenarios where the number of ONUs is small. Such scenarios can encountered at network start-up or when the majority of the ONUs is inactive/sleeping during low traffic regime. The evaluation by means of simulations and experiments, show that the proposed method successfully balance the impact among the ONUs without reducing the achieved energy savings.

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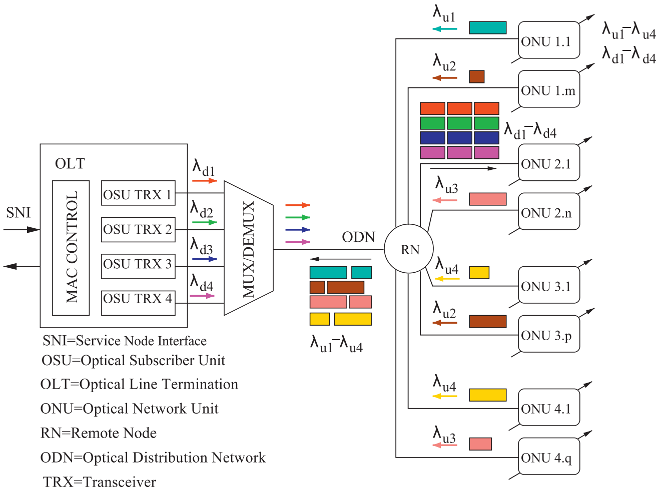


Fig. 1. TWDM PON architecture.

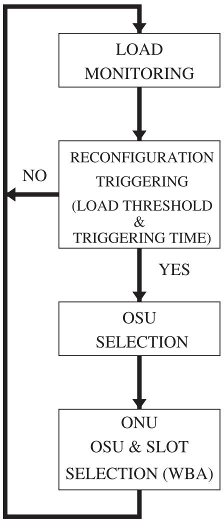


Fig. 2. Decision flow.

2. TWDM PON system model

2.1. Network architecture

The considered TWDM PON system architecture is depicted in Fig. 1. The OLT is equipped with OSUs transmitting and receiving at fixed wavelength pairs. The wavelength pairs are (de)multiplexed by means of a MUX/DEMUX into a single optical fiber and then distributed to all the ONUs by means of a passive splitter (RN). ONUs are equipped with tunable transceivers. Thus they are capable of transmitting and receiving at any wavelength. However, an overview of how some factors impact reconfigurable TWDM performance, in terms of both average frame delay and energy efficiency, is also presented in this section.

The considered factors are depicted in Fig. 2 and are: the decision whether and when to trigger reconfiguration (i.e., reconfiguration triggering), the decision about which OSUs are (de)activated (i.e., OSU selection), the assignment of ONUs to OSUs, and the scheduling of the ONU transmissions/receptions in each wavelength (i.e., the Wavelength and Bandwidth Allocation).

2.2. Reconfiguration triggering

Reconfiguration triggering depends on two main factors: the load threshold at which OSUs are (de)activated and the time elapsing between the instant when the load threshold is overcome and the instant when the reconfiguration procedures start.

2.2.1. Load threshold at which OSUs are (de)activated

Network reconfiguration can be dynamically triggered based on either a traffic threshold or a timer. However, in both cases it is important to carefully choose the load threshold at which *OSUs* are (de)activated and, in turn, the number of OSUs (i.e., wavelength pairs) to keep active. If, for example, the policy for (de)activating OSUs described in Section 3 is applied there might be situations in which the resulting load on the active OSUs after a reconfiguration is high. Thus, peaks of delay can occur. This phenomenon has been shown in several papers as in [4], [11], and [12].

2.2.2. Reconfiguration triggering time

The reconfiguration triggering time is the time elapsing between the instant when the network overcome the load threshold that requires reconfiguration and when reconfiguration procedures start. Indeed upon load variation and verification of the possibility reconfiguring the network (e.g., the decision of turning OFF some OSUs), the reconfiguration triggering might be performed with a certain delay (e.g., for example to avoid reconfiguring the network too often upon short peaks of traffic). However the time elapsing between the decision of reconfiguring the network and the triggering of the reconfiguration might impact network performance. In particular, this is also true when the ONU tuning time T_t is null.

2.3. OSU selection and DWBA optimality

The selection of the OSUs to keep active and to switch to sleep impacts also network performance. Indeed, if the decision is taken independently of the number of ONUs that were assigned to an OSU before reconfiguration, it might require a large amount of ONUs to tune, thus, potentially increasing the average frame delay.

Another important factor that impacts reconfigurable TWDM PON performance is the optimality of the DWBA. As stated in [13] the problem of optimally assigning ONUs to wavelengths and slots can be reduced to a bin-packing optimization problem, that is NP-hard. However, some additional constraints must be considered. For example, in the architecture depicted in Fig. 1, one ONU cannot transmit/receive contemporarily at two different wavelengths. Therefore, even if the traffic generated by the ONUs is greater than the capacity of single wavelength only one OSU can be exploited. ONU tuning time, OSU turn-on time, RTT must be also be considered. Last but not least, the discrete nature of the number of wavelengths together with the constraint for the ONU not to transmit/receive contemporarily at two different wavelength pairs, might cause, itself, DWBA suboptimality. Consider, for example, the case in which three wavelengths are available and only two ONUs are present. In this case, even if ONUs generate traffic that can fill out the capacity provided by the three wavelengths, each ONU can exploit the capacity of a single wavelength at the most. More in general, therefore, an ONU, irrespectively of the traffic that it generates can exploit, at the most, the capacity of a wavelength, that is, based on the proposed standards, 10 Gb/s.

2.4. ONU transceiver tuning time

The ONU transceiver tuning time is one of the main factors impacting DWBA performance [14]. More than the tuning time of the tunable transmitter, which can be sensibly reduced, the issue is

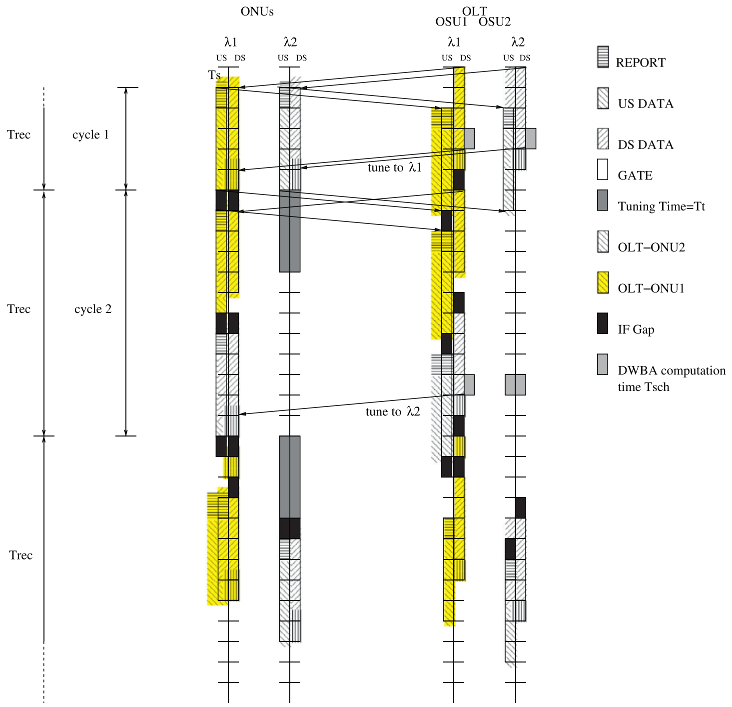


Fig. 3. Network control protocol.

represented by the tuning time of the tunable receiver. ONU tunable receiver architectures have been proposed that achieve rapid tuning [5]. The solution is based on receiving each of the signal transmitted at each wavelength by means of an optical demultiplexer followed by four receivers. The desired wavelength is selected electronically then. Although such solution shows very short tuning time values, it implies considerable hardware expenses and energy. Moreover, the ONU tuning process might impact not only the performance of the tuning ONU but also the other ONU transmissions. Indeed, if the tuning ONU finishes its tuning process before the timeslot assigned to it, the ONU can disturb the transmission of an ONU transmitting at the same wavelength. Therefore, if specific architectural countermeasures for the tuning ONU are not adopted (e.g., by enabling laser transmission only at the beginning of the assigned slot) the possibility for other ONUs of transmitting while some ONUs are tuning might not be feasible. Finally, the process of tuning an ONU between two wavelengths periodically might cause unexpected delays. Indeed, by looking at Fig. 3, while, when the ONUs tune to a single wavelength, the tuning process can exploit the contemporary transmission of other ONUs in TDM fashion, when the ONUs tune to a different wavelength the tuning might not be done in parallel with another ONU transmission. Therefore, as it is the case for ONU2 in the figure, an additional delay is introduced.

2.5. OSU turn-on time

Another issue increasing not only the average frame delay but also the energy consumption is the OSU turn-on time. Often this aspect is neglected but, similarly to the ONU turn-on time, even the OSU might require some time to wake up after a sleep period. Therefore, energy is consumed in this phase as well.

2.6. Extended control message format

In this paper, both `GATE` and `REPORT` control messages are extended based on the conventional 10 GbE `GATE` and `REPORT` multi-point control protocol (MPCP) messages defined in IEEE 802.3-2012 Section 5 [15]. The DS and US bandwidth request are based on the DS and US queue report at the time a `GATE` message is generated [16].

2.7. Network control protocol

For simplicity but without loss of generality the time is assumed to be slotted as depicted in Fig. 3. The frame length is assumed to be one slot T_s. ONU-OSU transmissions in the upstream (US) and in the downstream (DS) direction are locked. Periodically, with a period T_{rec}, the OLT monitors the average network load ρ, defined as the ratio between the sum of the average frame arrival probabilities at the ONUs and the number of OSUs. The monitored average network load is then utilized by the reconfiguration triggering policy to decide whether reconfiguration must be initiated. If so, the number of OSUs to turn ON/OFF is decided and an offline WBA is performed to assign ONUs to OSUs and slots. Then, GATEs are sent to the ONUs. The GATEs carry the wavelength(s) and the slot(s) which ONUs are assigned to in the next cycle. GATEs are sent to the ONUs at the wavelength utilized in their latest scheduled slot. This signaling requires a time that is dependent on the DWBA computation time T_{sch} and on the signaling time T_{gate}, that is, in turn, proportional to RTT. Upon reception of the GATEs, the ONUs tune to the wavelengths of their first transmission slot, if needed. ONUs that do not tune (e.g., ONU1 in Fig. 3) keep transmitting while the other ONUs tune. OSUs are turned OFF during the ONU tuning process, which lasts T_t, if they do not need to serve other ONUs.

3. Dynamic wavelength and bandwidth allocation

In this section the considered DWBA schemes are described. The first scheme, namely the *DWBA with proportional ONU assignment and longest-first, first-fit wavelength allocation (DWBA-PLF)*, can be applied to a TWDM PON with a generic number of OSUs and ONUs and it is utilized, in the simulations, to evaluate when delay unbalance is an issue. The remaining two schemes refer to

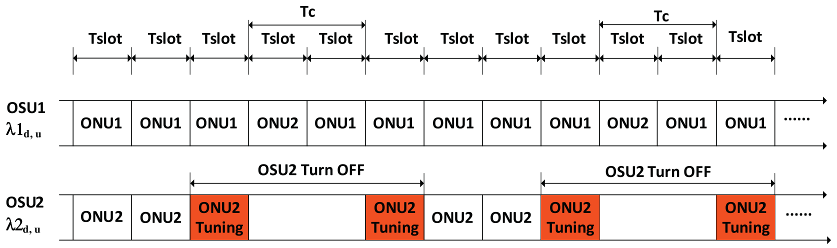


Fig. 4. Illustrates implemented DWBA protocol with only ONU2 tuning.

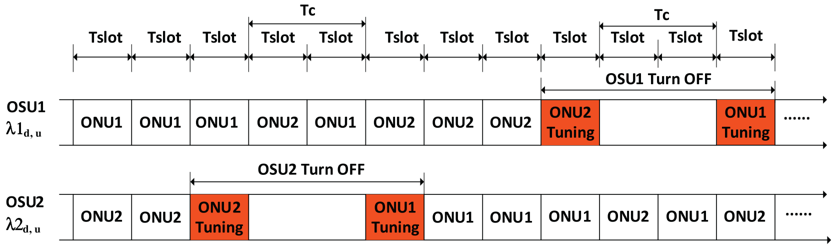


Fig. 5. Illustrates implemented DWBA protocol with both ONUs swapping.

a TWDM-PON where two ONUs and two OSUs are present. One scheme, namely the *DWBA with only Tuning ONU Buffering*, does not take into account which ONU is tuning upon reconfiguration. The second scheme, namely the *DWBA with ONU Swapping*, is proposed, in this paper, to balance the average frame delay experienced by the ONUs.

As described in [17] the features that characterize a DWBA are: the decision whether and when to trigger reconfiguration (i.e., reconfiguration triggering), the decision about which OSUs are (de)activated (i.e., OSU selection), and the scheduling of the ONU transmissions/receptions in each wavelength (i.e., the Wavelength and Bandwidth Allocation). They are described in the following subsection for each scheme.

3.1. DWBA with proportional ONU assignment and longest-first, first-fit wavelength allocation

In the *DWBA with proportional ONU assignment and longest-first, first-fit wavelength allocation (DWBA-PLF)* a transmission cycle T_c is defined as a number of slots equal to the number ONUs. The reconfiguration triggering is based on what follows. The OLT monitors the average network load ρ periodically, every T_c. If, for example, the OLT is equipped with four OSUs (i.e., wavelength pairs) and if $\rho < 0.25$, one OSU only is activated. If $0.25 \leq \rho < 0.5$ two OSUs are activated. If $0.5 \leq \rho < 0.75$ three OSUs are activated. If $\rho \geq 0.75$ all four OSUs are activated. In addition, a periodic reconfiguration is triggered, with a period T_{rec} (multiple of T_c), to take into account of traffic source variation (i.e., ONU generating traffic) even if ρ does not change.

The OSU (de)activation policy is to activate OSUs following an increasing OSU ID order and deactivating them following a decreasing OSU ID order.

The utilized WBA assigns slots to ONU first and then ONUs to wavelength pairs (i.e., OSUs). One slot is assigned to each ONU generating traffic, independently of the queued frames. Then, the remaining slots, belonging to the active wavelengths, are assigned to the ONUs proportionally to the number of queued frames by utilizing a method based on the largest remainder method (also known as Hare–Niemeyer method). In the proposed method, the probability of assigning a slot to an ONU n is computed as:

$$P(n) = \frac{Q(n)}{\sum_{k=0}^{N-1} Q(k)}, \tag{1}$$

where N is the number of ONUs and $Q(n)$ is the number of frames queued at ONU n as reported by the REPORT message. The number of slots assigned to ONU n is:

$$T_{slot}^{n} = \min\{nint((T_c - 1) * P(n)), Q(n)\}, \tag{2}$$

where $nint(\cdot)$ denotes the nearest integer function. It must be noted that an ONU cannot transmit/receive at multiple wavelengths contemporarily because it is equipped with only one transceiver. If, based on Eq. (2), more slots are assigned than the available ones, slots are taken from ONUs starting from the ONU for which the difference $nint((T_c - 1) * P_i) - (T_c - 1) * P_i$ is the highest (i.e., the ONU whose number of assigned slots is the farthest from the upper integer), until the number of available slots is reached. If less slots are assigned, slots are assigned starting from the ONU for which the difference $nint((T_c - 1) * P_i) - (T_c - 1) * P_i$ is the lowest (i.e., the ONU whose number of assigned slots is the farthest from the lower integer), until the number of available slots is reached. It must be noted, however, that, because an offline DWBA is employed, if a frame arrives to an ONU during a cycle it can be transmitted only in the next cycle, even if slots are available in the current one.

Once slots are assigned to the different ONUs, ONUs are assigned a transmission/reception wavelength pair (i.e., an OSU). A longest-first (in terms of slots assigned to an ONU), first-fit scheme is utilized. If no OSU can accommodate all the slots assigned to an ONU, the OSU that can host the highest number of slots assigned to an ONU is chosen after that all the ONUs whose assigned slots can be hosted by an OSU are assigned.

3.2. DWBA with only tuning ONU buffering

The second considered scheme is the *dynamic wavelength and bandwidth allocation with only tuning ONU buffering (DWBA-TOB)*. The DWBA-TOB, depicted in Fig. 4, was originally proposed in [16]. In DWBA-TOB one OLT-ONU communication (i.e.,OSU1-ONU1) is assigned to a fixed wavelength pair (e.g., $\lambda 1_{d,u}$) always, while the communication between the OLT and the other ONU (i.e., ONU2) is alternatively assigned either to the same or to a different wavelength pair. Thus, the network alternates between a TWDM phase, where each ONU is assigned a wavelength pair (i.e., OSU), and a TDM phase, where a single wavelength pair is time shared between the two ONUs. When ONU2 is tuning to the wavelength pair $\lambda1_{d,u}$, only ONU2 frames are buffered and ONU1 exploits the timeslots at wavelength pair $\lambda1_{d,u}$ until the ONU2 tuning process completes. Once the ONU2 tuning process successfully completes, the tuned ONU (i.e., ONU2) is assigned the first available slot on wavelength pair $\lambda1_{d,u}$. After the TDM phase, the OLT sends another tuning `GATE` to reassign the wavelength pair $\lambda2_{d,u}$ to ONU2 instead of ONU1. Even during this tuning process ONU2 must buffer frames until the tuning is complete. Hence, in DWBA-TOB, ONU2 is the only one that tunes.

3.3. DWBA with ONU swapping

Fig. 5 illustrates the proposed Dynamic Wavelength and Bandwidth Allocation with ONU Swapping (DWBA-OS) scheme. The objective of this scheme is to balance the impact of tuning time overhead among the ONUs. DWBA-OS consists in carefully choosing, upon each reconfiguration, which ONUs are assigned to which OSUs (i.e., the OSU-ONU pairings) so that the distribution of the number of times ONUs tune is as uniform as possible. The network architecture which the DWBA-OS is applied to consists, as for the DWBA-TOB, of two OSUs (i.e., two wavelength pairs) and two ONUs. Thus, in this particular case, the ONUs tune alternatively. At system startup each ONU is paired to a different OSU: ONU1 to OSU1 (i.e., wavelength pair $\lambda1_{d,u}$) and ONU2 to OSU2 (i.e., wavelength pair $\lambda2_{d,u}$). When reconfiguration is triggered, the ONUs are aggregated to OSU1. While ONU2 is tuning to the wavelength pair ($\lambda1_{d,u}$), ONU1 uses the available slots at wavelength pair ($\lambda1_{d,u}$) to send/receive traffic while ONU2 buffers US traffic. Once the ONU2 tuning process completes, ONU2 is assigned a slot at wavelength pair ($\lambda1_{d,u}$) and the two ONUs share the wavelength pair in a TDM fashion. In the successive reconfiguration, ONU1 is instructed to tune to the wavelength pair ($\lambda2_{d,u}$) and traffic to/from ONU1 is buffered until the tuning process completes. ONU2, which in this second reconfiguration does not tune, keeps transmitting/receiving traffic at the wavelength pair ($\lambda1_{d,u}$). Therefore, at every reconfiguration, the DWBA-OS swaps the ONU-OSU pairings.

4. Performance evaluation

Performance evaluation of the presented schemes is based on both simulations and an experimental evaluation. Simulations aim at highlighting in which scenarios the delay unbalance among ONUs becomes an issue. The experimental evaluation mainly aims at verifying the effectiveness of the DWBA-OS scheme in balancing the delay increase among the ONUs.

The considered performance parameters are the *average frame delay*, the *Jain's fairness index* computed on the average frame delay [7], and the OLT *average energy savings*.

The average frame delay is defined as the interval of time between the arrival of a frame to the buffer of the source node (i.e., either the OLT or the ONU) and the delivery of the frame at the destination node (i.e., either the ONU or the OLT).

The Jain's fairness index F is computed as in the following equation:

$$F = \frac{\left[\sum_{i=1}^{N} D_i\right]^2}{N\sum_{i=1}^{N} D_i^2}, \tag{3}$$

where D_i is the average frame delay experienced by ONU i and N is the number of ONUs. The closer F is to one the more balanced are the average frame delays experienced by the ONUs.

The OLT average energy savings are defined as the percentage of energy saved at the OLT when the OSUs are dynamically turned ON and OFF with respect to the energy consumed when all the OSUs are always ON. The OSU power consumption values during the ON and the OFF phase of the OSU can differ based on the OLT hardware [18,19]. In this study we considered a factor α which is the ratio between the power consumed by an OSU when it is OFF and when it is ON (i.e., $\alpha = P^{OSU,OFF}/P^{OSU,ON}$).

4.1. Simulation setup

Simulations are performed by means of a custom-made time-driven simulator. Different numbers of ONUs and OSUs are considered. Downstream and upstream transmissions are assumed to be locked (i.e., when an ONU is allowed to transmit frames upstream, downstream frames are transmitted as well by the OSU). Upstream and downstream traffic is symmetric and it is generated based on a Bernoulli arrival process. Thus upstream and downstream statistics are the same. In each slot, an ONU i generates a frame, whose duration is one slot, with a probability p_i. The average network load ρ can be therefore computed as:

$$\rho = \frac{\sum_{i=1}^{N} p_i}{\Lambda}, \tag{4}$$

where Λ is the number of OSUs. For simplicity, in the performed simulations, all the ONUs generate the same traffic, that is $p_i = p \forall i \in 1, N$.

4.2. Simulation results

Fig. 6 shows the Jain's fairness index F computed as a function of the average network load ρ, for three sets of OSU-ONU pairs: {4, 16}, {4, 4}, and {2, 2}. Simulations are run with eighty random seeds for generating different traffic patterns. Moreover T_{rec} and T_t also vary. Table 1 describes the parameters characterizing the scenarios whose results are depicted in Fig. 6. In general, when the number of ONU is large, as in scenarios 1, 2, 3, and 4, F is high. Thus, even if the DWBA-PLF scheme does not target balancing the ONU delay, delay balance is achieved anyway. However, even if F is high it can be observed that the longer is T_{rec} the higher is F while T_t only slightly impact fairness. On the other hand, if the number of ONUs is small (i.e., scenarios 5, 6, 7, 8) F decreases, especially when ρ is close to the reconfiguration threshold. In particular, by looking at the scenario 7 results, it can be observed that F can be as low as 0.5. Results obtained for scenario 8 shows that the utilization of DWBA-OS increases the Jain's fairness index to almost one for any value of the load ρ. Thus, when the number of ONUs is small, a DWBA scheme targeting average frame delay balance is helpful.

Fig. 7 shows the energy efficiency as a function of ρ of the DWBA-PLF scheme in the scenario 1 of Table 1 and with $\alpha = 0.15$. It is shown that the maximum achievable energy savings are about 60%. If $\rho > 0.7$ no savings can be achieved because all the OSUs must be always ON.

4.3. Experimental setup

Fig. 8(a) illustrates the testbed configuration. In the testbed the DWBA-TOB and the DWBA-OS only are implemented. The OLT DWBA agent allocates bandwidth and wavelength pairs to the ONUs. The OLT and the ONU contain two 10 Gigabit Ethernet systems (10G-ETH) with two transceiver (TRX) channels enabled OSU MAC Ctrl. The two channels emulate the two US/DS wavelength pairs ($\lambda1_{d,u}$ and $\lambda2_{d,u}$). Moreover, the ONU can transmit/receive traffic only at one channel/wavelength at a time, thus emulating the behavior of the tunable transceiver. The ONU tunes its

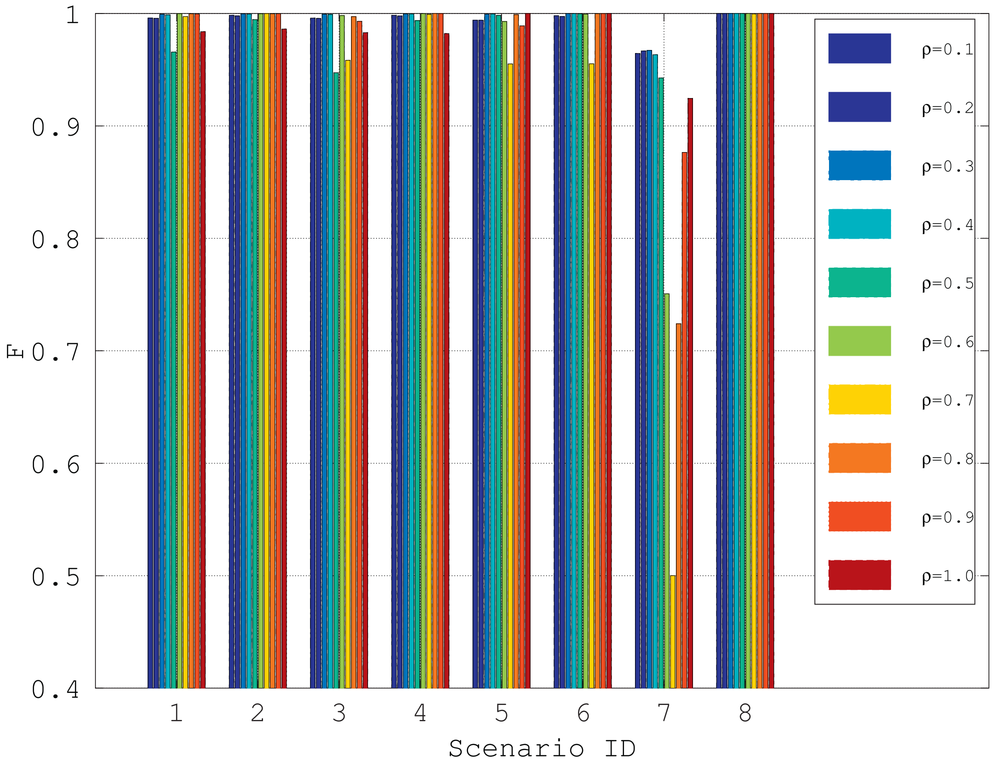


Fig. 6. Jain's fairness index for the average frame delay for different simulation scenarios.

Table 1
Simulation parameters for the considered scenarios.

Scenario	Scheme	#OSU-#ONU	$T_c[T_s]$	$T_{rec}[T_c]$	$T_t[T_s]$
1	DWBA-PLF	4-16	16	2	4
2	DWBA-PLF	4-16	16	8	4
3	DWBA-PLF	4-16	16	2	12
4	DWBA-PLF	4-16	16	8	12
5	DWBA-PLF	4-4	4	2	1
6	DWBA-PLF	4-4	4	8	1
7	DWBA-TOB	2-2	2	2	1
8	DWBA-OS	2-2	2	2	1

transceiver to a specific wavelength based on the information received in the tuning `GATE` message, which is initiated by the OLT DWBA agent. On the other hand, the OLT can transmit/receive data along two channels/wavelength pairs ($\lambda1_{d,\,u}$ and $\lambda2_{d,\,u}$) at the same time, thus emulating the behavior of two fixed wavelength OSUs. When the two ONUs utilize the same wavelength pair for DS and US communication, the two channels are multiplexed in a TDM fashion. The MUX/DEMUX is used for splitting/combining the DS/US data going to/coming from the two ONUs, emulating the optical passive splitter functions.

Fig. 8(b) illustrates the implemented testbed. The two ONUs and one OLT (with two OSUs) of the 10 Gb/s Ethernet-based TWDM-PON are implemented on two Altera Transceiver Signal Integrity Development Kits equipped with an FPGA (i.e., Stratix IV GT edition-EP4S100G2F40I1N) that is capable of supporting a data rate of up to 11.3 Gb/s per channel. In addition, the development kits provide sub-miniature version A (SMA) connectors to support transceiver channels from/to the FPGA device. The SMAs of both OLT and ONUs are connected with four SFP+ evaluation boards equipped with four optical transceivers to enable two pairs of DS/US optical transmission channels. Traffic is internally generated by frame generators. However, real traffic can be injected by interfacing the FPGA designs with user applications (e.g., video streaming) via service node interface (SNI) and user network interface (UNI) as shown in Fig. 8(a). The ONU transceiver tuning time overhead is emulated by implementing a tuning timer. The tuning ctrl block is implemented inside the ONU FPGA to enable transmission/reception by the ONU based on the tuning timer expiration.

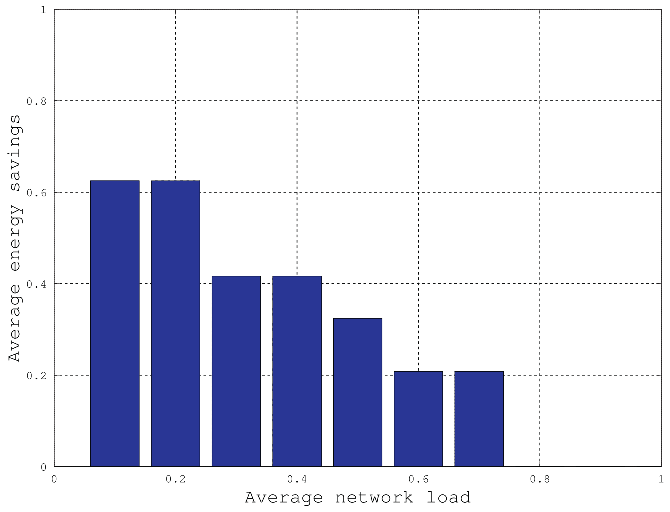
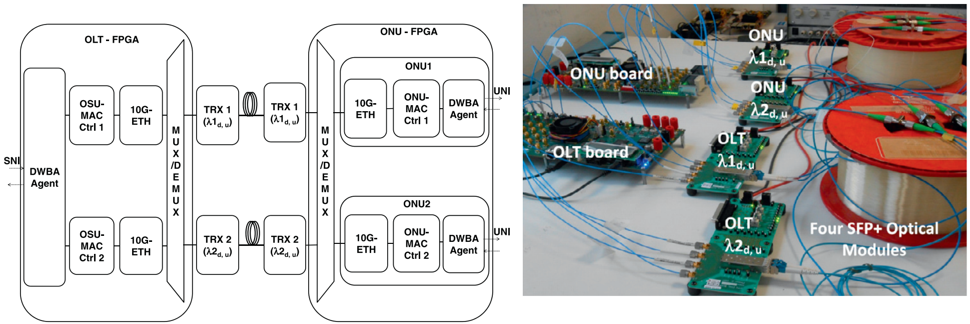


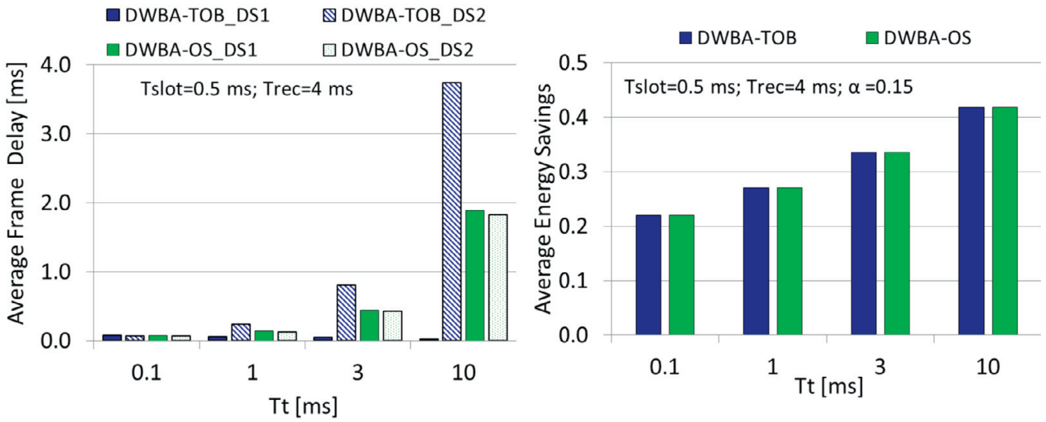
Fig. 7. Energy savings of the DWBA-PLF scheme as a function of ρ.

The experimental evaluation is performed with the following parameters. Both US and DS frame arrival processes follow a Poisson distribution with constant frame size of 1250 bytes. Data buffer size is 1 MB. The OLT contains one DS buffer per ONU. Both DS and US transmission rates are 10 Gb/s. DS1 data rate is 256 Mb/s and the remaining transmissions (i.e., DS2, US1, and US2) data rates are set to 128 Mb/s. The value of RTT is negligible. DS and US transmissions are locked, i.e., both DS and US transmissions take place in the same timeslot as specified in [20]. The ex-



(a) Testbed Configuration (b) Testbed equipped with Altera Stratix IV GT

Fig. 8. Testbed of energy efficient 10G-EPON featuring DWBA.



(a) DS Average frame delay (b) OLT average energy savings

Fig. 9. Impact of the tuning time overhead on the DS average frame delay and the OLT average energy savings.

periment duration is set to 2 s for all transmissions between the OLT and the ONUs. The performed experiments consist in periodically triggering reconfiguration with a period T_{rec} multiple of T_{slot}. Thus, the network alternates between a TWDM and a TDM phase as described in the DWBA-TOB and DWBA-OS schemes. The derived confidence intervals with a 90% confidence level are negligible.

In the considered experimental scenario, the OLT average energy savings for the DWBA-TOB and the DWBA-OS can be computed as follows by starting from the derivation in [16]:

$$\eta = 1 - \frac{E_{rec}}{E_{ON}} == 1 - \frac{\frac{3+\alpha}{2} T_{rec} + T_t}{2(T_{rec} + T_t)}, \tag{5}$$

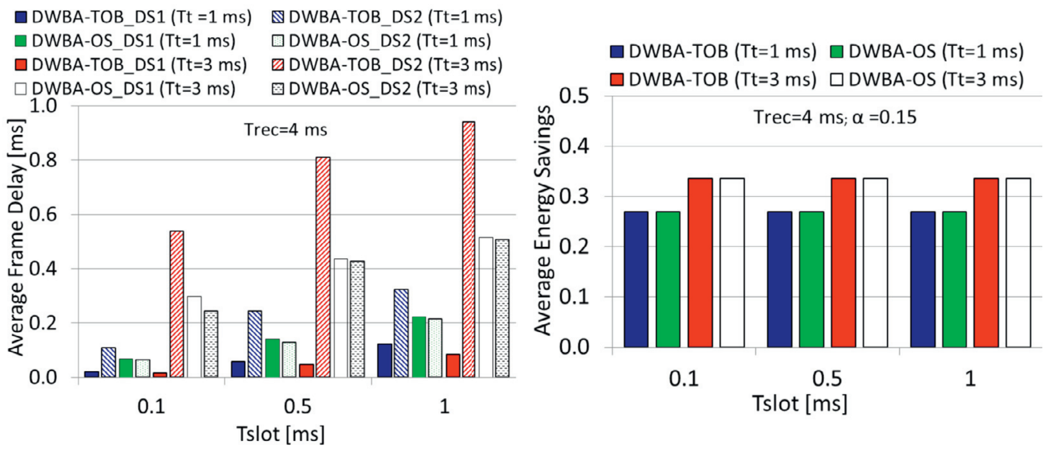
where E_{rec} is energy consumed when reconfiguration is implemented, E_{ON} is energy consumed when both OSUs are always ON, T_{rec} is the reconfiguration period, and T_t is the tuning time overhead. To obtain Eq. (5) two consecutive periods of length T_{rec} are considered. In the first period both the OSUs are always ON, while in the second period only one OSU is ON. Moreover, it is assumed that the OSU transceiver is turned OFF during tuning (i.e., T_t) as shown in Figs. 4 and 5. As in the results obtained for the DWBA-PLF $\alpha = 0.15$.

4.4. Experimental results

Fig. 9(a) shows the DS average frame delays for the traffic destined to ONU1 and ONU2 when either the DWBA-TOB or the DWBA-OS scheme is utilized (i.e., DWBA-TOB_DS1, DWBA-TOB_DS2, DWBA-OS_DS1, DWBA-OS_DS2) as a function of `tuning time overhead` T_t. All the delays are obtained by setting the timeslot T_{slot} to 0.5 ms, and the reconfiguration period T_{rec} is set to 4 ms. When the T_t is less than the T_{slot}, DWBA-TOB and DWBA-OS have a similar average frame delay because, in the DWBA-TOB, the ONU1 and ONU2 have the same transmission opportunities (i.e., there is no additional timeslot available for ONU1 while ONU2 is tuning). If $T_t \geq T_{slot}$ the DWBA-TOB DS2 experiences a higher average frame delay than DS1 because only the tuning ONU (i.e., ONU2) buffers frames during the tuning process. Moreover, when the T_t increases the DS1 average frame delay slightly decreases because ONU1 has more transmission opportunities during the tuning process. In the DWBA-OS, ONU1 experiences a larger DS average frame delay while ONU2 experiences a lower DS average frame delay than in the DWBA-TOB. Thus, the DWBA-OS successfully balances the impact of the ONU tuning overhead on the average frame delay between the two ONUs.

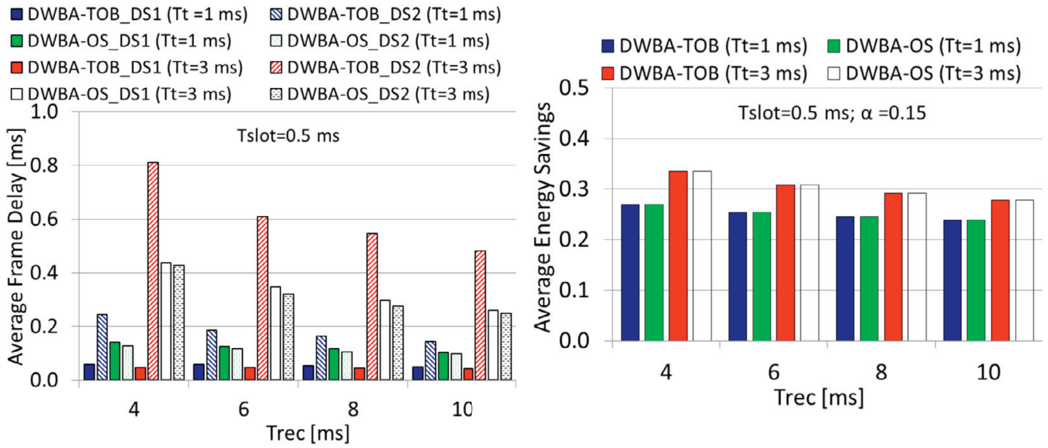
Fig. 9(b) shows the OLT average energy savings as a function of the `tuning time overhead` T_t. The timeslot T_{slot} is set to 0.5 ms and the reconfiguration period T_{rec} is set to 4 ms. In both the schemes, when the T_t increases the OSU OFF time increases. As a results, the average energy savings increase for all T_t values. Moreover, there is significant energy savings (i.e., more than 20%) with low average frame delays even though the T_t is short (i.e., 0.1 ms).

Fig. 10(a) shows the DS average frame delays as a function of `timeslot` T_{slot} for two different T_t values (i.e., 1 ms and 3 ms). The reconfiguration period T_{rec} is set to 4 ms. In both schemes, the DS average frame delay increases as T_{slot} increases because the cycle time increases in the TDM phase. Similarly to what is shown



(a) DS Average frame delay (b) OLT average Energy savings

Fig. 10. Impact of the timeslot on the DS average frame delay and the OLT average energy savings.



(a) DS Average frame delay (b) OLT average Energy savings

Fig. 11. Impact of the reconfiguration period on the DS average frame delay and the OLT average energy savings.

in Fig. 9(a), in the DWBA-TOB scheme the DS average frame delays experienced by the two ONUs have a gap that increases as T_{slot} and T_t increase while the DWBA-OS is successful in providing similar delays for both the ONUs.

Fig. 10(b) shows the OLT average energy savings as a function of `timeslot` T_{slot}. The larger is the T_t the larger are the average energy savings. However, the average energy savings are not affected by the T_{slot} duration because the OSUs turn ON/OFF time does not depend on T_{slot}, as also shown by Eq. (5).

Fig. 11(a) shows the DS average frame delay as a function of the `reconfiguration period` T_{rec} with different T_t values (i.e., 1 ms and 3 ms). The timeslot T_{slot} is set to 0.5 ms. For both schemes, the average frame delay decreases with the increase of T_{rec} because fewer reconfigurations are performed, hence less delay due to the tuning overhead is accumulated. In DWBA-TOB, the T_{rec} does not affect DS1 average frame delay because the traffic is not buffered during tuning. On the other hand, the T_{rec} sensibly impacts DS2. In DWBA-OS, both DS1 and DS2 delays decrease when T_{rec} increases and the delays are similar. However, when T_{rec} is 10 ms and T_t is 1 ms, the gap between the experienced average frame delays in the two schemes is small.

Fig. 11(b) shows the OLT average energy savings as a function of `reconfiguration period` T_{rec} with different T_t values (i.e., 1 ms and 3 ms). When the T_{rec} increases, less reconfigurations are performed. As a result, the OSU ON time increases, hence, energy savings decrease. However, the larger is the T_t the slightly larger are the OLT energy savings because the OSU is turned OFF during ONU tuning overhead. Nevertheless, when the T_{rec} is 10 ms, the average energy savings are not much affected by the T_t even if it is long (i.e., 3 ms).

5. Conclusions

This paper studied the potential average frame delay unbalance that ONU can experience in a TWDM-PON that periodically reconfigure the number of active OSUs and the assignment of ONUs to OSUs. Indeed, due to the finite tuning overhead, if an ONU is forced to tune often its experienced average frame delay can be larger than the one experienced by ONUs that do not tune. Simulations results showed that, when all the ONUs generate the same traffic, such unbalance happens when the number of active ONUs is small while when the number of active ONUs is large the average frame delay is naturally balanced. Simulation and experimental results showed that a scheme, proposed in this paper, that carefully chooses the ONU that must tune upon reconfiguration achieves its objective of balancing their average frame delay when the number of ONUs is small.

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