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Article

Energy-Saving Mechanism in WDM/TDM-PON Based on Upstream Network Traffic

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Abstract: One of the main challenges of Passive Optical Networks (PONs) is the resource (bandwidth and wavelength) management. Since it has been shown that access networks consume a significant part of the overall energy of the telecom networks, the resource management schemes should also consider energy minimization strategies. To sustain the increased bandwidth demand of emerging applications in the access section of the network, it is expected that next generation optical access networks will adopt the wavelength division/time division multiplexing (WDM/TDM) technique to increase PONs capacity. Compared with traditional PONs, the architecture of a WDM/TDM-PON requires more transceivers/receivers, hence they are expected to consume more energy. In this paper, we focus on the energy minimization in WDM/TDM-PONs and we propose an energy-efficient Dynamic Bandwidth and Wavelength Allocation mechanism whose objective is to turn off, whenever possible, the unnecessary upstream traffic receivers at the Optical Line Terminal (OLT). We evaluate our mechanism in different scenarios and show that the proper use of upstream channels leads to relevant energy savings. Our proposed energy-saving mechanism is able to save energy at the OLT while maintaining the introduced penalties in terms of packet delay and cycle time within an acceptable range. We might highlight the benefits of our proposal as a mechanism that maximizes the channel utilization. Detailed implementation of the proposed algorithm is presented, and simulation results are reported to quantify energy savings and effects on network performance on different network scenarios.

Keywords: PON; WDM/TDM-PON; energy-saving; channel utilization

1. Introduction

It is likely that, from a technological outlook, the Future Internet will be an integration of long-haul high-speed optical networks; a number of wireless networks at the edge; and, in between, several access technologies. Among these access technologies, the Passive Optical Networks (xPON) are very suitable to succeed, due to their simplicity, low-cost, and bandwidth [1,2]. PONs can be used to backhaul both fixed and mobile traffic, therefore it is expected that next generation optical access networks will adopt the wavelength division/time division multiplexing (WDM/TDM) technique [3,4] to increase PONs capacity.

One of the main challenges of PONs is the resource (bandwidth and wavelength) management [5,6]. As it has been shown that access networks consume a significant part of the overall energy of the telecom networks [7], the resource management schemes should also include energy minimization strategies.

The main contributors to energy consumption in PONs are the Optical Network Units (ONUs) and the Optical Line Terminal (OLT). In a WDM/TDM-PON we argue here that if we are able to operate with fewer wavelengths, while still serving all bandwidth demands, the energy consumption can be minimized by shutting down idle receivers/transceivers at the OLT.

Several techniques have been proposed to increase energy efficiency in PONs. Such techniques are regarded as either hardware (or physical), or software (or data-link) approaches [8,9]. Typically, physical approaches introduce new energy-efficient optical device architectures, while data-link proposals require extensions of resource management algorithms to include "energy awareness", but only few of them so far have addressed the case of WDM/TDM-PONs.

In order to strengthen research on energy-saving besides technical studies, standardization works have been carried out by IEEE and ITU-T [10,11] to describe power saving methods. However challenging tasks, such as the parameter values for the timers, are out of standards scope and thus left vendor-dependent.

This paper is an extension of our previous work [12], where we have presented a novel energy-efficient resource management mechanism for WDM/TDM-PON. Additional contributions are mainly oriented to show new results such as the relationship of the channel utilization with energy savings as well as the impact of the cycle time (the cycle is a time period for the transmissions from ONUs, being the cycle length definition an important factor regarding delay issues) on these savings.

The rest of the paper is organized as follows: in Section 2, we provide an overview of existing energy-saving strategies for PONs. Section 3 provides a description of the proposed mechanism for energy savings at the OLT side in WDM/TDM-PON. In Section 4, results are presented to validate our proposal. Finally, Section 5 concludes this paper.

2. An Overview of Existing Energy-Saving Strategies

The energy-saving strategies in PON are designed primarily for ONUs and consist in exploiting the variations of upstream/downstream traffic load, according to a defined threshold, by enabling the ONUs to switch among different power saving modes (shedding, dozing, or sleeping) [10]. The definition of the threshold is a key issue, as an appropriate values can lead to relevant performance improvements in terms of delay.

With power shedding the ONU turns off non-essential components while a fully operational optical link is maintained. Dozing mode turns off the ONU transmitter function while the receiver function is always on. With sleeping mode both functions, transmitter and receiver are deactivated. Among the power saving modes, enabling sleep mode in ONU is the most studied approach.

The main challenges of power saving modes in PONs are the slow transition from active mode to sleep mode (time needed during the wake-up process), the sleep time definition and the combination with bandwidth and wavelength allocation algorithms. In [13], the authors propose a Sleep and Periodic Wake-up (SPW) regime for ONUs in order to save energy. The OLT activates or deactivates the ONU, depending on the presence or absence of downstream traffic. The OLT determines the presence or absence of downstream traffic by monitoring the average frame interval. Based on the SPW regime, the authors in [14] propose a Sleep-aware Dynamic Bandwidth Allocation (SDBA) algorithm that maximizes the ONU energy-saving while guaranteeing QoS requirements. Unlike other proposals, the SDBA algorithm is experimentally evaluated in an FPGA-based testbed. The SDBA combines cyclic sleep mechanisms with DBA while consider QoS constrains. It implements an online-based scheduling and increases the polling cycle time as much as possible to improve energy-saving. Regarding the sleep time definition, the authors in [15] propose a sleep-time sizing and scheduling framework namely Sort-And-Shift (SAS), the framework comprises an analytical model that provides a closed-form expression of the ONU sleep time based on the maximum delay requirements.

Physical approaches to address energy efficiency in PONs introduce new optical devices architectures. In [16], the authors experimentally demonstrate a sleep mode ONU architecture that enables ONU the transition from sleep mode to active mode in short time using fast clock and data recovery (CDR) circuit. In [17], same authors also addressed the ONU wake-up time through a novel just-in-time sleep control scheme. In [18], the authors use a hybrid ONU equipped with a low-cost, low energy IEEE 802.15.4 module that turns on the ONU when it needs to receive traffic. The PON architecture is formed by one or more coordinator ONUs that periodically receive information from OLT to notify, using a Wireless Sensor Network (WSN), when those ONUs should enter active mode to receive downstream traffic.

The aforementioned studies focus in the ONU energy-saving in TDM-based PON, but in WDM-based PON and WDM/TDM-based PON new strategies, not only in the ONU, but also in OLT, are needed to effectively control the energy consumption. Authors in [19] propose a sleep control function for energy-saving in PON systems where the configuration of OLT consists of multiple PON-interfaces and two layer-2 switches that provide the multiplexing function to combine upstream and downstream signals and the redundant functions to assure redundancy against failures. Based on traffic predictions, the sleep control function allows switching to sleep mode one of the duplicated layer-2 switches in OLT.

A similar proposal can be found in [20], where an OLT comprises multiple OLT line cards, each of which serves a number of ONUs. The authors propose a new OLT hardware configuration by placing an optical switch at the OLT to configure the connections between OLT line cards and ONUs, thus in low load traffic conditions the switches can be configured such that the same OLT line card provides services to multiple ONUs and other OLT line cards can be turning off.

In WDM/TDM based PON, energy-saving has been addressed to effectively control the energy consumption of the OLT according to downstream traffic. The authors in [21] propose an energy-efficient architecture that reserves a single wavelength and a single low speed transceiver to handle all narrow-band downstream traffic to save energy at the OLT.

In [22] the authors propose to insert a remote channel combine/split module (CCS) in the remote active node of an extended-reach WDM/TDM PON system to reduce initial investment and achieve good energy efficiency. The key function of the CCS is to selectively aggregate optical signals from active subscribers such that a minimal number of OLTs and remote amplifiers are operated. The adding of the new CCS module requires some modification in the MAC layer and setting up a communication channel to the remote node. Thus, DBA modules will decide which OLTs remain active, become active, or inactive. To do so a new mechanism to de-register and reregister ONUs from different OLTs is proposed in [23]. In [24] the energy consumed by the OLT is reduced by using fewer wavelengths and setting idle transmitters to sleep. Authors proposed to use thresholds to determine, based on downstream network traffic, when switch on and off one or more wavelength. Unlike the proposal in [24], in our work we base our energy-saving mechanism on the upstream traffic, *i.e.*, we propose a mechanism that uses DBA information to save energy at the OLT receivers.

An overview of studies and works to address the energy-saving issue in the optical access network is presented in [25,26].

In general, while previous proposals have targeted energy savings by using the sleep mode at the OLT transceivers or at the ONUs (based on downstream traffic), in this paper for the first time to the best of our knowledge, we propose a novel energy-aware mechanism to save energy at the OLT in a WDM/TDM-PON based on *upstream network traffic*. Note that by adopting the proposed mechanism, resource management can be performed using any of the existing DBA and DWA algorithms.

3. Minimizing Energy Consumption at the OLT

This section presents our energy-saving mechanism. To implement our mechanism, we exploit the multi-point control protocol (MPCP) in EPON (standard IEEE 802.3ah) that the ONUs employ to report their upstream queue lengths and to transmit their traffic to the OLT. The protocol information exchanged in the control messages between OLT and ONUs is exploited to disclose the use of resources and based on that information to decide how much energy can be saved (*i.e.*, how many OLT receivers can be switch off). Table 1 defines the notation used hereafter.

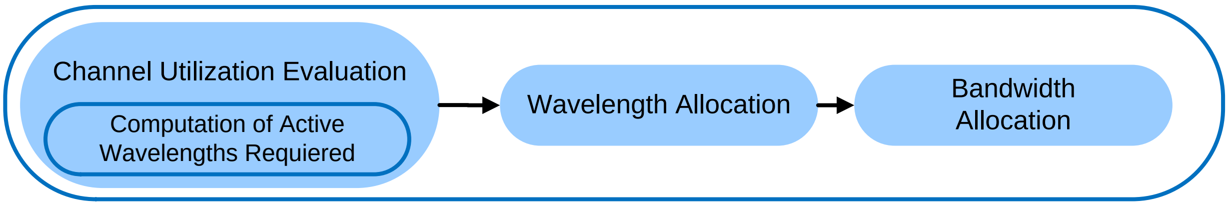
Table 1. Notation.

T_D	Time needed by the ONUs to transmit the granted length of data.
T_{cycle}	Time needed by the ONUs to transmit the granted length of data together with their associated guard intervals.
T_g	Interval of time between any two adjacent timeslots.
N	Number of active ONUs.
R	Data rate of the upstream link from an ONU to the OLT.
B_i	Amount of data requested by ONU_i (bits).
$Ball_{i,j}$	Amount of data granted to ONU_i on wavelength j (bits).
$Bmax_j$	Maximum amount of data among all the ONUs on the same wavelength j (bits).
$Bmax_{i,j}$	Maximum allowed amount of data for ONU_i on wavelength j (bits).
W	Number of supported wavelengths.
W_c	Number of current utilized wavelengths.
W_a	Theoretical minimum number of wavelengths needed.
W_{off}	Number of receivers in OLT to be switched to sleep mode.
W_{on}	Number of receivers in OLT to be switched to active mode.
T_c	Current Time.
U_{high}	Observation period for high channel utilization.
U_{low}	Observation period for low channel utilization.

3.1. Energy-Aware Wavelength Assignment (EWA)

Let us define as *Energy-aware Wavelength Assignment* (EWA) the energy-saving mechanism performed by the OLT, based on the evaluation of the channel utilization, to decide whether receivers can be put to sleep mode, and consequently perform the bandwidth and wavelength allocation on the remaining wavelengths. So, an OLT implementing EWA performs the functions that are shown in Figure 1.

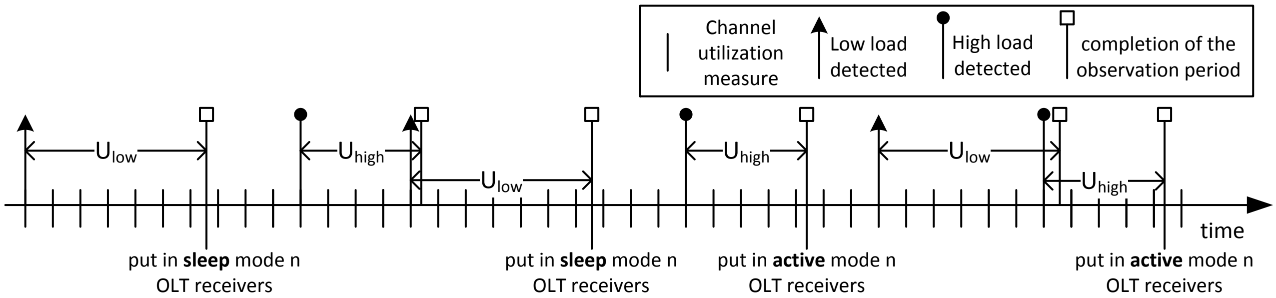
Figure 1. EWA.



Once low channel utilization is detected, a counter is triggered for an observation period U_{low}. If along such timespan the level of utilization does not change we infer that one or more receivers at the OLT should be switched to the sleep mode. Similarly, when high utilization is detected, another counter is triggered as well for an observation period U_{high} and if along such timespan the level of utilization does not change, then one or more receivers at the OLT should be switched to the active mode.

In this study we test different values of U_{low}, and we also introduce a threshold to define high-load observation period U_{high}. In this manner, through channel utilization evaluation, the OLT switches the receivers to sleep/active mode after U_{low} and U_{high} thresholds are reached. Figure 2 illustrates the operation of the energy-saving mechanism.

Figure 2. Energy saving mechanism.



3.1.1. Channel Utilization Evaluation

Our algorithm deduces if has to switch off receivers only if, during a predefined observation period U_{low}, the OLT detects low channel utilization. The OLT evaluates the channel utilization by summing the current timeslots requested by each ONU, *i.e.*, by checking if:

$$\sum_{i=1}^{N} B_i/R < (W_c - 1)T_D \tag{1}$$

where T_D is the data cycle, *i.e.*, the time needed for the transmission of data in a set of timeslots of different ONUs on the same wavelength j, computed as:

$$T_D = Bmax_j/R \tag{2}$$

where $Bmax_j$ is the sum of the maximum transmission length of all ONUs on the same wavelength $\sum_{i=1}^{N} Bmax_{i,j}$. The cycle size with guard intervals is:

$$T_{cycle} = T_D + N(T_g) \tag{3}$$

If $\sum_{i=1}^{N} B_i/R < (W_c - 1)T_D$, then all reported ONU requests might be accommodated in a cycle, and this is regarded as a low channel utilization.

If $\sum_{i=1}^{N} B_i/R > W_cT_D$, then there is not enough room to allocate all the requests and therefore we deduce that the channel utilization is high.

3.1.2. Number of Active Wavelengths Required

If the OLT detects low-load channel utilization during U_{low} then W_{off} is calculated as:

$$W_{off} = W_c - W_a \tag{4}$$

where $W_a = \lceil B/T_D \rceil$ is the theoretical minimum wavelengths needed in the current time T_c and where B is the total ONUs request $\sum_{i=1}^{N} B_i/R$.

If, on the contrary, the OLT detects high-load channel utilization during U_{high} then W_{on} is computed as:

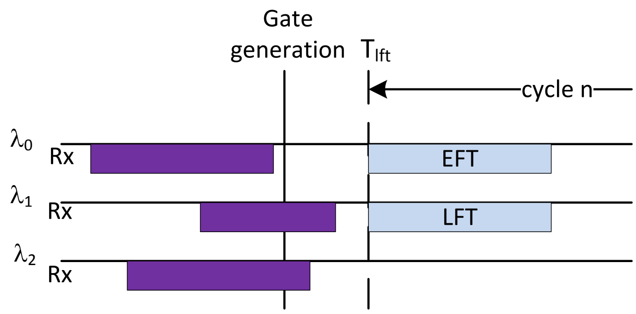
$$W_{on} = W_a - W_c \tag{5}$$

3.1.3. Wavelength Allocation

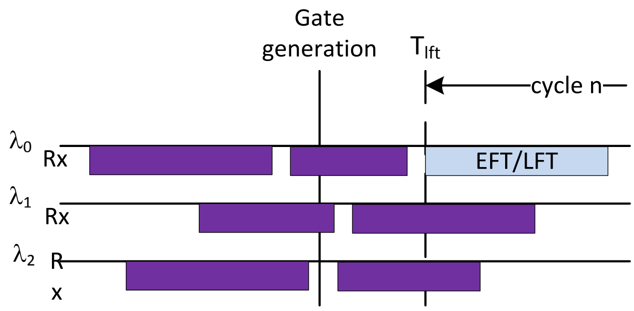
As mentioned previously, our resource management scheme is able to work with any DWA. For sake of illustration we refer to two well known algorithms to perform wavelength allocation, called Earliest Finish Time (EFT) and Latest Finish Time (LFT) [27]. We also use EFT and LFT for the computation of the active wavelengths required such that we can then select the OLT receivers to be switched in sleep or active mode.

In EFT the wavelength with the earliest-finish time is allocated to the next transmission, while in LFT the wavelength with the latest-finish time is allocated, as long as this time is not later than a threshold T_{lft} (Figure 3a). If no channel has a finish time lower than T_{lft}, then the LFT algorithm works as EFT in the current cycle (Figure 3b).

Figure 3. Wavelength Allocation. (**a**) EFT operation; (**b**) LFT operation.



(**a**)



(**b**)

3.1.4. Bandwidth Allocation

We assume that each ONU is able to transmit only on one wavelength j in a cycle, so the OLT updates the value of $Bmax_{i,j}$ for the next cycle according to the new value of W_c. If all the ONUs have the same traffic load then:

$$Bmax_{i,j} = T_D/(N/W_c) \tag{6}$$

The scheduling in time, *i.e.*, the bandwidth allocation is:

$$Ball_{i,j} = min(B_i, Bmax_{i,j}) \tag{7}$$

where B_i is the ONU queue size in bits.

3.2. Summary

Algorithm 1 summarizes the EWA mechanism implemented at the OLT. EWA computes the number of OLT receivers in active or sleep mode.

Algorithm 1 Energy-aware wavelength assignment (EWA)

1: Channel utilization evaluation

IF $\sum_{i=1}^{N} B_i/R < (W_c - 1)T_D$ THEN low-load

IF $\sum_{i=1}^{N} B_i/R > (W_c - 1)T_D$ THEN high-load

2: Computation of active wavelengths required

IF low-load during U_{low} THEN $W_a = \lceil B/T_D \rceil$; $W_{off} = W_c - W_a$; $W_c = W_a$

Switch OFF W_{off} OLT receivers.

IF high-load during U_{high} THEN $W_a = \lceil B/T_D \rceil$; $W_{on} = W_a - W_c$; $W_c = W_a$

Switch ON W_{on} OLT receivers.

3: Wavelength Allocation (EFT or LFT)

4: Bandwidth Allocation

$Bmax_{i,j} = T_D/(N/W_c)$ according the new value of W_c

$Ball_{i,j} = min(B_i, Bmax_{i,j})$

4. Results and Discussion

This section is devoted to evaluate the performance of our proposal in terms of energy-saving and its impact mainly on the packet delay. We carried on simulations using the OPNET Modeler tool. Performance of PONs can be conveniently characterized formulating realistic system models to optimize metrics of interest such as packet delay and energy consumption under different simulation scenarios. We refer to them as balanced/unbalanced input traffic and residential and business user input traffic. Details of traffic models are provided in the following subsections.

We use a single (tunable) transmitter and receiver at the ONU side and multiple receivers/transmitters at the OLT. We assume that each ONU can support all wavelengths (tunable ONU), but it might be only allocated on one wavelength in a cycle. We implemented EWA based on EFT and LFT, for wavelength allocation, and we implemented two different versions of EWA according to the way we switch to sleep/active mode the OLT receivers: *i.e.*, 1-by-1 or n-by-n approach. In the 1-by-1 approach, if OLT decides to save energy, EWA switches to sleep mode only one OLT receiver (even if the number of unused channels is greater than one). In the n-by-n approach EWA can switch to sleep/active mode more than one receiver simultaneously.

Bandwidth allocation is performed according to limited service as described in [28], where $Bmax_i \leq T_D/N$. The energy consumption of each receiver at the OLT was set to 0.5 Watt (W) based on the energy consumption of commercial transceivers/receivers modules [21]. Therefore, the total energy consumption by OLT receivers in our simulation setup is set to 4 W. The input traffic is of the self-similar type and packet length is uniformly distributed based on Ethernet frame size. We assume that the wake-up time for OLT receivers is lower than the Round Trip Time (RTT), which is in the order of 0.2 ms. Note that, in general, the operation of our proposed mechanism is not affected as long as the wake-up time is less than RTT. If the wake-up time is significantly higher then other values such as U_{low} and U_{high} should change accordingly. Details of simulations setup are provided in Table 2.

Table 2. Simulations Setup.

Number of ONUs (N)	64
Number of upstream channels (W)	8
Maximum cycle time (T_{cycle})	2 ms
PON upstream channel data rate (R)	1 Gb/s
Guard time (T_g)	2 µs
OLT-ONU distance (d)	$18 < d < 20$ Km
Hurst parameter (H)	0.7
Packet size (uniform distribution)	64 - 1518 bytes

Other physical aspects such as transmission power, burst mode reception, optical power losses are already taken care of the physical layer of OLT and ONU by performing the ranging operation as stated by the standard. We assume that physical layer parameters are under acceptable operational levels. However the proposed algorithm does not directly consider physical level parameters. We also assume that the network has been designed properly, and in this paper we focus on the operational aspects, *i.e.*, after the network design has been performed. Since our mechanism is based on Dynamic Bandwidth and Wavelength Allocation (MAC layer) we only have considered the physical parameters mentioned in Table 2. This is a common approach employed in studies regarding dynamic bandwidth allocation in PONs and it follows the same assumptions as in many other works [5].

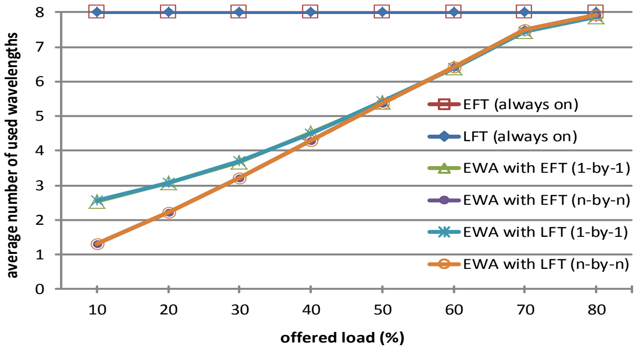
The U_{low} and U_{high} thresholds values were set in the order of a cycle time (2 ms and 1 ms respectively) because we consider that during a cycle we can have a global knowledge of the channel utilization. If we use more than one cycle is a very long time to make a decision, but if the cycle is smaller, then is a short time to decide. We have tried other values in the range of 1 to 3 ms and the results have not changed significantly.

4.1. Balanced Input Traffic

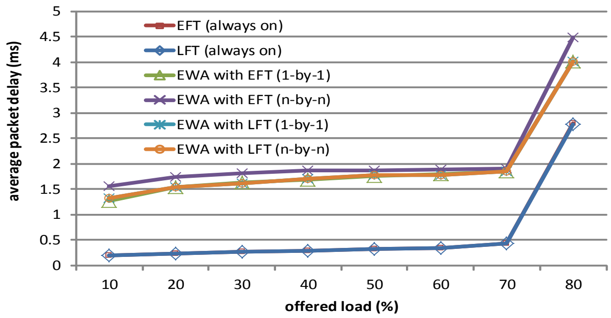
The first simulation evaluates the performance of EFT and LFT algorithms in terms of average number of used wavelengths and average packet delay. We refer to balanced input traffic when the input traffic is equally balanced among ONUs, *i.e.*, the input traffic is the same for all ONUs.

Figure 4a shows the average number of wavelength used in function of the offered network load, which also indicates the number of receivers in OLT that can be put into sleep mode. The energy consumption is directly related to the number of wavelengths used for the upstream transmissions because in our simulative setup each wavelength represents one OLT receiver. We can observe that both algorithms yield similar results, even when not using any mechanism for energy-saving (always on). This confirms that our approach can be used with different DWA approaches and suggests that significant energy reduction can be achieved independently of the DWA approach. Also the fact that LFT and EFT yield very similar results demonstrates that LFT most of times reaches the T_{lft} and it switches to EFT. Choosing a EWA value of T_{lft} larger than the one used in our simulations, LFT could allow a better performance of EWA in terms of energy consumption. Nevertheless, with a higher T_{lft} the average packet delay will be excessively degraded. The T_{lft} in these simulations was setup as $T_{lft} = RTT + T_{cm}$ where RTT is the round trip time and T_{cm} is the time required for the transmission of control messages.

Figure 4. EWA with LFT and EFT wavelength allocation. (**a**) Number of Wavelengths used; (**b**) Average packet delay.



(**a**)



(**b**)

Figure 4b shows the effect of EWA on the average packet delay. The packet delay is defined as the time elapsed since the packet is generated until it is finally transmitted to the OLT. We noted that by applying an energy efficient mechanism, we increase the delay in the network. However, we consider that these delays remain within reasonable values (below 2 ms, *i.e.*, the duration of a data cycle), acceptable for the majority of current applications.

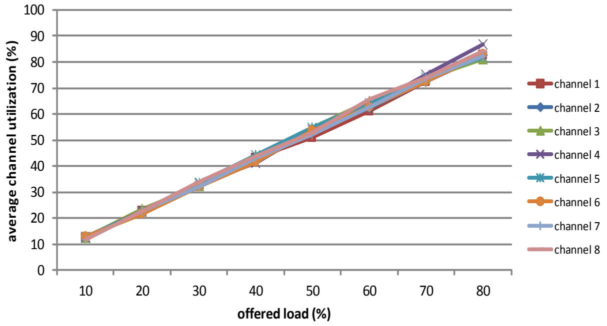
It is expected that next generation PONs will support various traffic types and services (telephony, TV, mobile backhaul, video streaming) with stringent delay requirements. If these new applications have not their delay requirements satisfied (the 2 ms average delay of our proposal is not appropriate) then EWA should be complemented with strategies based on differentiated wavelength or bandwidth allocation.

The results of channel utilization are shown in Figure 5 (wavelength allocation is performed by EFT following 1-by-1 approach). The channel utilization is the percentage of channel (wavelength) time that is used by ONUs transmissions. If we relate energy savings with the use of the channels then we can highlight the benefits of EWA as a mechanism that maximizes the use of the channels.

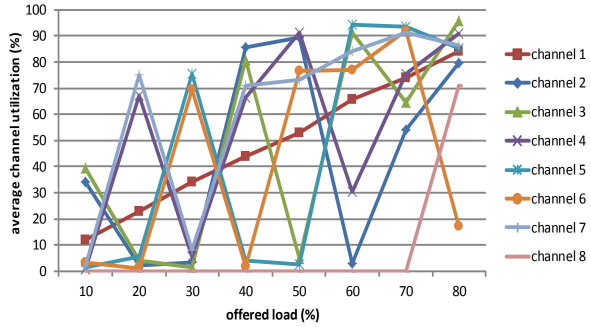
Figure 5a shows the average channel utilization for each channel when not using any mechanism for energy-saving ("Always on" with EFT 1-by-1). As expected, the average channel utilization closely reflect the amount of offered load on all the channels. The average utilization for each channel when we use EWA (with EFT 1-by-1) is shown in Figure 5b. In this figure we can clearly see that the different channels have different channel utilization for all network loads.

The effects of introducing a mechanism of energy-saving are also reflected in the cycle time. The cycle time is defined as the time between two successive transmissions of an ONU and can have a fixed or variable length.

Figure 5. Average channel utilization. (**a**) Average Channel Utilization without energy-saving; (**b**) Average Channel Utilization with energy-saving.



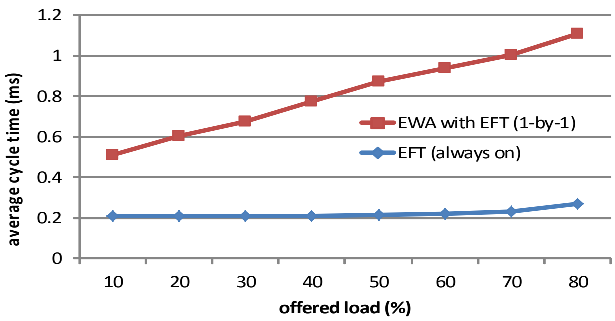
(**a**)



(**b**)

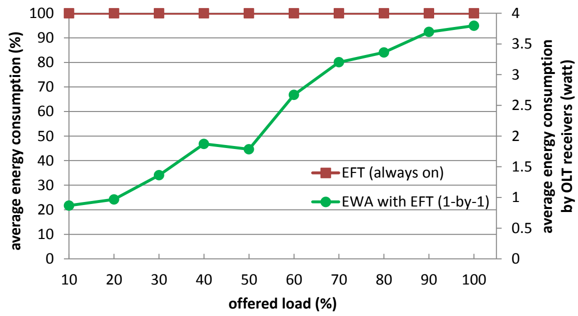
To accomplish the delay restrictions that some applications demand, a fixed cycle length should be the most appropriate. However, the coexistence of real-time and non-real-time applications suggests a mechanism with variable cycle length as it applied in our simulations. Note that a large cycle length will result in increased delay for all the packets. The results of the average cycle time that we obtained when we use EWA are shown in Figure 6. Again when EWA is applied, the average cycle time is increased but we consider that they are acceptable values since they are below the defined maximum cycle time corresponding to 2 ms.

Figure 6. Average cycle time.



To conclude we report results directly in terms of energy consumption. Figure 7 shows the average energy consumption for all offered loads. We find that for our proposed energy-saving mechanism is able to decrease energy consumption at the OLT of about 68% low-loads, and about 22% for medium and high-loads.

Figure 7. Energy Consumption.



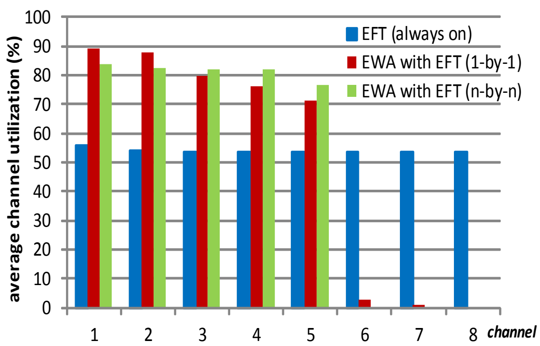
4.2. Unbalanced Input Traffic

In a similar set of simulations, we evaluated the performance of LFT and EFT, when the upstream network traffic is unbalanced among ONUs, *i.e.*, ONUs are divided in two groups with different input traffic pattern (32 ONUs high-load and 32 ONUs low-load). We consider an ONU as high-load when its load is equal or higher than 0.7, and low-load when its the load is equal or lower than 0.3. Since the results of LFT and EFT are similar also in this case, we will focus hereafter only on EWA with EFT as wavelength allocation method.

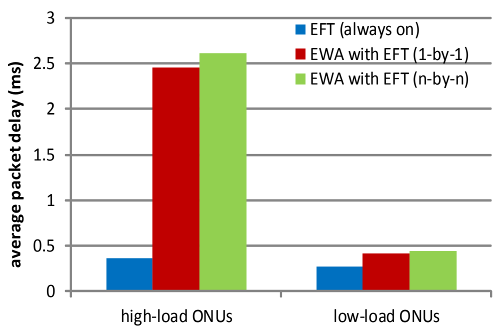
First we evaluated the average channel utilization for each channel following 1-by-1 and n-by-n approach (Figure 8a). We found that, the average channel utilization for all channel is about 50% when not using any mechanism for energy-saving (always on). So, we can save energy by maximizing the use of channels, thus energy-saving is about 30%.

Figure 8b shows the average packet delay for high-load and low-load ONUs. In this case we can see relevant variations in the delay between the different approaches, mainly for high-load ONUs. High-load ONUs are negatively affected because the maximum bandwidth guaranteed is the same for all ONUs so several cycles are needed to serve such ONUs. We conclude that EWA affect some applications or services that are delay sensitive in unbalanced traffic scenarios.

Figure 8. Average channel Utilization & Average packet delay. (**a**) Average channel Utilization; (**b**) Average packet delay of ONUs of each group.



(**a**)

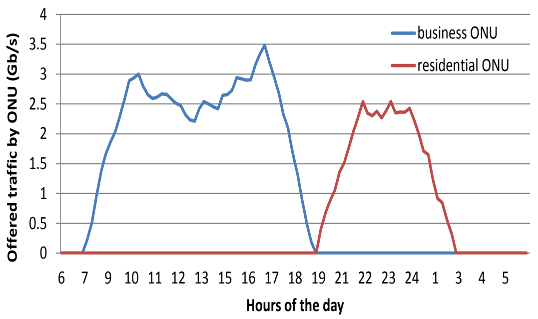


(**b**)

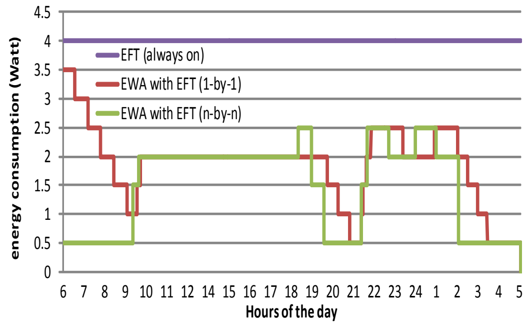
4.3. Traffic Variation during the Day

We performed a different set of simulations with different configurations settings. In this case we model a traffic with varying intensity and with two classes of users representing residential and business users. Figure 9a represents the upstream traffic behavior along the day of business and residential users.

Figure 9. Residential and Business usage behaviors. (**a**) Input traffic of each ONU; (**b**) Energy consumption.



(**a**)

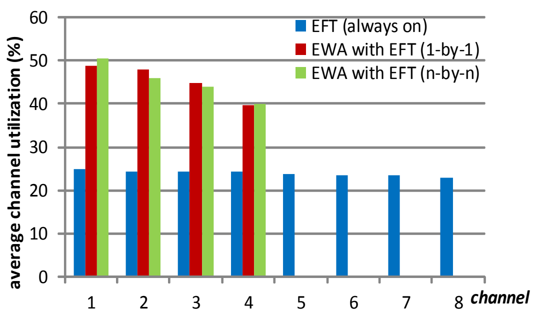


(**b**)

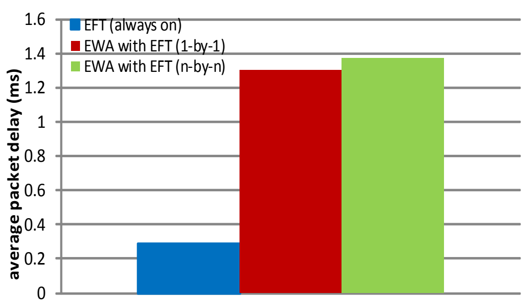
Figure 9b shows the average energy consumption in watts along the day of the OLT receivers. The scenario based on EFT n-by-n slightly outperforms the 1-by-1 in terms of energy consumption. Differences are seen mainly at the beginning of the simulation period, *i.e.*, at 6 a.m. (in the absence of traffic), because even though the number of receivers that can be shut down is the same, how they are turned off is different. Following the 1-by-1 approach at the beginning of the simulation, energy savings are achieved slowly because EWA starts considering all the available wavelengths switched on.

Figure 10a shows the average channel utilization for each channel. In this case, by using EWA we maximize the channel utilization, and we only need half of the available channels, and thus we are able to save energy. Figure 10b shows the average packet delay of business and residential traffic. The EFT n-by-n works slightly better than EFT 1-by-1 mechanism.

Figure 10. Average channel utilization & Average packet delay. (**a**) Average channel utilization; (**b**) Average packet delay.



(**a**)



(**b**)

5. Conclusions

In this paper we have presented a novel energy-aware wavelength assignment mechanism to save energy at the OLT in a WDM/TDM-PON based on upstream network traffic. Results have shown that energy consumption in OLT receivers can be reduced up to 30%. We have shown new results, compared with our previous work, where the average utilization of the available wavelengths reflects the amount of offered load on all the channels and the average cycle time is below the defined maximum cycle time.

Simulations results show that our proposal is able to save energy at the OLT, based on a periodic evaluation of channel utilization. The new results for the channel utilization show that significant energy savings can be achieved at the OLT by the proper use of upstream channels. We find that, for our simulation setup, if we consider a balanced scenario where the input traffic for all ONUs is the same, our proposed energy-saving mechanism for low-loads is able to decrease energy consumption of about 68% while for medium and high-loads about 22%.

In our study we have assumed some specific values of the duration of OLT receivers in sleep or active modes as well as the length of the observation periods U_{low} and U_{high}. Such values are crucial parameters that impact directly the delay performance. Regarding the wake-up time for elements in OLT, we found that our proposal does not introduce any penalty whenever the wake-up time in OLT receivers is less than the RTT.

As future works, we notice that the identification of effective values under different scenarios as well as a generic and suitable definition of T_{lft} for the LFT algorithm, might provide higher energy-saving and more efficient resource management.

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Author Contributions

All authors had equivalent contribution in the proposal, analysis, and revision of the work. The first author provided additional contribution in writing most of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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