Shared Wavelength Assignment Algorithm in Multi-profile WDM-EPONs to Support Upstream Bandwidth Guarantees

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Abstract. A novel wavelength and bandwidth allocation algorithm in WDM-EPON is proposed to provide subscriber differentiation by ensuring guaranteed bandwidth levels in the upstream direction. Contrary to previous schemes, the new algorithm is designed to save cost at both ends of the network, especially at the users' side, as it restricts the number of upstream wavelengths which can be used by them. Simulation results show that ShaWaG achieves better performance than other bandwidth allocation algorithms in WDM-EPONs but simultaneously it requires lower number of upstream wavelengths. The novel algorithm makes fairer bandwidth distribution than those methods as it ensures efficiently a minimum guaranteed bandwidth to every subscriber for a larger number of ONUs when compared to existing methods.

Keywords: Wavelength Division Multiplexing (WDM), Dynamic Bandwidth Allocation (DBA), Ethernet Passive Optical Network (EPON), Service Level Agreement (SLA), Wavelength Dynamic Assignment.

1 Introduction

Passive Optical Networks (PONs) are an excellent technology to develop access networks, as they provide both high bandwidth and class of service differentiation [1-2]. The PON technology uses a single wavelength in each of the two directions and such wavelengths are multiplexed on the same fiber by means of Wavelength Division Multiplexing (WDM). Since all users share the same wavelength in the upstream direction, a Medium Access Control (MAC) is necessary to avoid collision among packets from different Optical Network Units (ONUs). Dynamic Bandwidth Allocation (DBA) algorithms, based on the Time Division Multiplexing Access (TDMA) protocol, are the best choice as they dynamically distribute the available bandwidth depending on the current demand of ONUs [3-8].

Although PON infrastructures can provide enough bandwidth for current applications, the gradual increase of the number of users and the bandwidth requirements of

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the new emerging services, demand an upgrade of such access networks. The addition of new wavelengths to be shared in the upstream and downstream direction in PON infrastructures leads to the so-called Wavelength Division Multiplex PONs (WDM-PONs). The pure WDM-PON architecture assigns one dedicated wavelength per ONU, which implies more dedicated bandwidth and security in the system. However, the related cost associated with such deployment makes pure WDM-PONs as the next-generation architectures. Hence, the combination of the WDM technology with Time Division Multiplexing (TDM) techniques the best near future approach. These hybrid architectures exploit the advantages of wavelength assignment of WDM techniques and the power splitting of TDM techniques. Consequently, the most important challenge of WDM-PON networks is the costs associated with the deployment of such architectures. As it was said before, pure WDM-PON architectures, do not allow bandwidth redistribution and they present high deployment cost. Besides, if the number of ONUs highly increases, they can overload the available wavelengths of the transmission band (1530 nm-1560 nm). To deal with it, novel WDM-PON prototypes assume that ONUs can simultaneously transmit in several wavelengths in the upstream direction instead of having one dedicated wavelength. To do that, each ONU is equipped with several fixed transceivers or a tunable transceiver. However, the use of tunable transceivers provides less bandwidth due to the dead tuning time necessary to switch wavelengths. Hence, it is required transceivers of high tuning speeds, especially if the number of supported upstream wavelengths is quite high. As a consequence, it is preferable intermediate architectures between the previous architectures that simultaneously provide flexibility and future scalability in WDM-PONs.

On the other hand, end users contract a Service Level Agreement (SLA) with a provider, normally related to a minimum guaranteed bandwidth. It forces that DBA algorithms ought to support various service levels with different guarantees. The Bandwidth Guaranteed Polling (BGP) method proposed in [5] divides ONUs into two disjoint sets of bandwidth guaranteed ONUs and best effort ONUs. However, this scheme only differs between guaranteed ONUs and best effort ONUs, but it does not distinguish other profiles with specific restrictions. A typical way to offer customer differentiation is to use a fixed weighted factor assigned to each ONU associated with a specific SLA. The bandwidth is allocated depending on these weights. In the methods presented in [6-7], the OLT distributes the available bandwidth by assigning different weights to each client depending on their SLA. Therefore, ONUs associated with a higher weight will be assigned more bandwidth. In contrast, the algorithm proposed in [8] distributes the bandwidth to each subscriber changing the value of the initial weights to adapt them to the service conditions of every profile according to the mean packet delay of the most sensitive traffic.

In this paper, we present a novel DBA algorithm applied to a hybrid WDM-TDM EPON architecture for a gradual upgrade of the existing TDM EPON infrastructures. Unlike other DBA algorithms proposed in WDM-EPONs, it deals with the cost of these architectures, by only allowing each ONU to transmit in a limited set of wavelengths which depends on the requirements of users. Besides, the new algorithm can differ between service level profiles with the aim to ensure minimum guaranteed bandwidth levels to each of them. The Ethernet protocol has been considered as it is a well-known inexpensive technology and interoperable with legacy equipment [1-2].

2 Dynamic Bandwidth Allocation in Hybrid WDM-TDM PONs

Several WDM-TDM architectures have been proposed recently, although the deployment of the WDM technology in the access network is still in its first stages. One extended WDM-PON approach employs one separate wavelength for the transmission between the OLT and each ONU. In general, this architecture does not allow bandwidth redistribution and presents high deployment cost. Other type of architectures, such as the proposed in [9-11], consider a smooth upgrade of TDM-PONs, allowing several wavelengths to be used in the upstream transmission. Authors in [9-10] propose that the OLT consists of an array of fixed laser/receivers and the ONUs of either an array of fixed laser/receivers or one or more tunable laser/receivers. From the providers' point of view is more likely the utilization of either tunable laser/receivers or fixed laser/receiver arrays, but not both simultaneously. In the prototype proposed in [11], every ONU employs one or more fixed transceivers, permitting a gradual upgrade depending on the traffic demand of ONUs. Then, the OLT assigns the bandwidth to each ONU in those wavelengths they support. In addition, the fixed transceivers at the ONU can be interchanged by a fast tunable laser. In that case, the OLT only can transmit in one single wavelength at any given time, which may lead to poor bandwidth utilization due to the dead tuning time every time there is a wavelength switch.

Most of the existing bandwidth allocation algorithms in WDM-PONs assume this kind of architecture, in which several wavelengths are shared by ONUs. The algorithm proposed for the prototype shown in [11] presents three variants to assign the excess bandwidth among ONUs with great traffic demand (high loaded ONUs). In the controlled variant, the one which achieves the best performance, the OLT waits until all reports messages from one cycle are received in order to apply the allocation algorithm for the next cycle. However, in the other two approaches the OLT permits that ONUs with low traffic demand can transmit before the reception of every report. Since several wavelengths are available in the upstream channel, the channel allocation is based on the first-fit technique (i.e. the first available free wavelength).

In contrast, the algorithm proposed in [13] is an extension of the Interleaved Polling Adaptive Cycle Time (IPACT) and it permits that every ONU transmits just after receiving each single report message. It also applies the first-fit technique to dynamically select each channel wavelength. However, the algorithm also provides Class of Service (CoS) differentiation by means of the extended strict priority queue scheme. In other to compare both policies, authors in [10] developed an extension of the Multi-Point Control Protocol (MPCP) for WDM-PONs to support dynamic bandwidth allocation. They implemented two scheduling paradigms, namely online and offline. In the former, the OLT applies bandwidth and wavelength allocation based on the individual request of each ONU. On the contrary, in the offline policy the OLT applies scheduling decisions taking into account the bandwidth requirements of all ONUs. The simulations demonstrated that the online scheduling method obtained lower delays than the offline scheduling, especially at high ONU loads. The method proposed in [15], which follows the same online philosophy, is designed to ensure minimum guaranteed bandwidth levels to different profiles. This scheme assumes that every ONU simultaneously transmits on several wavelengths in the upstream and all of them support the same set of wavelengths. Other proposals support Quality of

Service (QoS) in a differentiated service framework. The algorithm proposed in [14] allows each ONU to simultaneously transmit on two channels, each channel dedicated to a different type of traffic.

3 Description of the WDM-PON and the WDM-DBA Algorithm

3.1 Proposed WDM-PON Architecture

Although it does not exist a predominant WDM-PON architecture, the gradual WDM upgraded will be limited by technological costs and based on the necessity of service providers. Consequently, it is preferable flexible WDM-PON architectures which could be upgraded in a cost-effective way. However, legacy WDM-PON architectures employ one separate wavelength for the transmission between each ONU to the OLT. These infrastructures do not allow bandwidth redistribution and presents high deployment costs. In contrast, recent WDM-PON prototypes assume that ONUs can simultaneously transmit in the same set of upstream wavelengths. Typically, each ONU is equipped with a tunable transceiver, as the use of them is very interesting because it can provide several wavelengths with only one device. However, it may provide low throughput due to the dead tuning time necessary to switch among wavelengths. Therefore, it is necessary tunable transceivers with a tuning speed of microseconds. Furthermore, the more number of wavelengths each ONU are allowed to transmit, the more expensive the ONU is. As a consequence, we agree with intermediate architectures which allow future flexibility and we propose a hybrid WDM-TDM architecture which minimizes the related costs, especially at the ONUs. A novel DBA algorithm has been proposed for such architecture, so that the WDM-EPON effectively supports QoS by means of subscriber differentiation. The DBA algorithm is designed to ensure a minimum guaranteed bandwidth to each connected user, in the presence of several Service Level Agreements (SLAs) contracted by them. In this way, each ONU is allowed a number of wavelengths limited by the requirements of the connected subscribers.

The proposed architecture agrees with the principles of the architectures in [11-12]. The proposal of the upstream direction with the presence of several SLAs is shown in Fig. 1 (with three SLAs). In the scenario of our proposal, all ONUs which belong to one specific SLA share the same dedicated wavelength. The OLT schedules the transmission of the different ONUs over this wavelength using a dynamic time division allocation scheme. Moreover, there is one more wavelength simultaneously shared by every ONU (λ_{backup}), only used to accommodate the extra bandwidth needed by ONUs to fulfill their minimum guaranteed bandwidth. To supply the upstream wavelengths, each ONU is equipped with a cost-effective laser to transmit on the dedicated laser. However, it is considered the deployment of a second laser for the backup wavelength. Then, by means of coarse WDM (CWDM) techniques it is permitted a smooth upgrade to a WDM scenario. This architecture lacks of poor bandwidth utilization due to the dead time imposed every time there is a wavelength switch because of laser tuning times. However, when technology is mature enough and fast tunable lasers with low tuning times are achieved, the deployment of tunable laser will allow more flexibility and scalability, in case more backup wavelengths are needed to accommodate traffic or a higher number of ONUs will be connected. The wavelength channels are routed from the ONUs to the OLT by a passive arrayed waveguide grating (AWG) router. Regarding the OLT, for the upstream direction, it employs a WDM demultiplexer together with an array of receivers to detect the information of every upstream wavelength. This infrastructure can be easily scaled as it can be added other ports to the AWG in order to support more types of profiles with different bandwidth requirements. On the other hand, this equipment permits a gradual upgrade of the WDM-EPON architectures as if the ONUs increased their bandwidth requirements, the developed DBA algorithm assigns to them more frequently the backup wavelength. In case more backup wavelengths are needed in the network it can be possible to upgrade the infrastructure of ONUs with higher bandwidth requirements. Then, the DBA algorithm can be easily adapted to the new set of wavelengths supported. However, when technology provides very fast tunable lasers, their deployment inside the ONU will permit more future scalability.

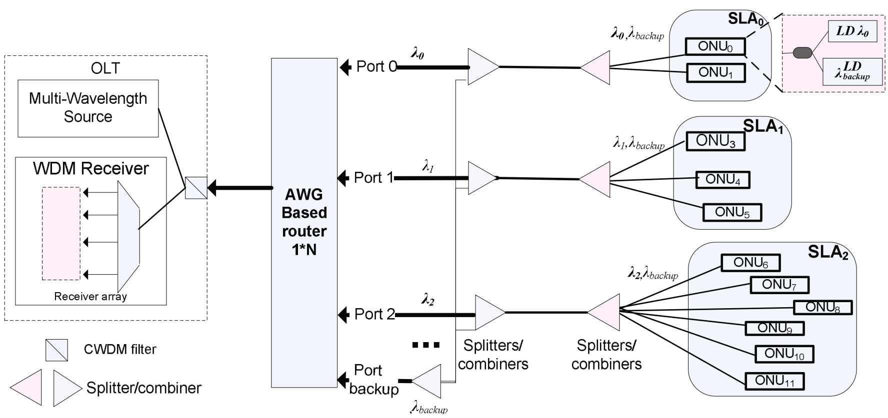

Fig. 1. Basic proposed upstream architecture for users belonging to different SLAs

In the downstream direction, the wavelength channels are routed from the OLT to the ONUs by means of the same AWG router. As the upstream and downstream wavelengths are located in a different wavelength window, these two windows are separated using coarse CWDM at the OLT (as shown in Fig. 1). Moreover, the OLT is equipped with a multi-wavelength laser in order to transmit the corresponding wavelengths to each ONU. They can be a bank of fixed lasers or a tunable laser if the delay constraints permit its deployment.

3.2 Wavelength Allocation Scheme in the WDM-DBA Algorithm

To distribute the available bandwidth among users in WDM-EPONs our algorithm follows the joined time and wavelength assignment, as most of the studies consider this policy as it permits multidimensional scheduling. The algorithm, called Shared Wavelength allocation algorithm with bandwidth Guarantees (ShaWaG), distinguishes between profiles with different bandwidth requirements. It has been designed to offer a minimum guaranteed bandwidth to each profile when their demand excesses the available bandwidth in the upstream channel. In contrast to other existing DBA algorithms in WDM-EPONs, ShaWaG focus on save costs at ONUs by restricting the number of wavelengths that ONUs are allowed to use.

Since the novel algorithm obliges ONUs of the same SLA to transmit over the same wavelength, the fixed scheme is used for the ONUs of the same SLA, which makes the wavelength allocation very simple to implement. However, when the number of ONUs or the demanded bandwidth is increased, the backup wavelength is dynamically activated by certain ONUs in order to be satisfied their guaranteed bandwidth levels. Under this situation, a different wavelength allocation policy is needed to arbitrate the dynamic allocation of the backup wavelength among ONUs. The study carried out in [10] demonstrated that the random, the least assigned and the least loaded methods excessively overload certain wavelengths. In contrast, the first fit method in which ONUs are able to transmit in the first free wavelength, leads to an efficient solution [13]. Consequently, we assumed the first fit scheme to dynamically assign the two supported wavelengths, the dedicated $(\lambda_{sla \in onu_i})$ and the backup wavelength (λ_{backup}), when the second one is activated. If ONUs of several profiles require the employment of the backup wavelength, ShaWaG gives preference to the highest priority profile. Once ONUs of this profile are ensured their guaranteed bandwidth, ShaWaG assigns this wavelength to the next profile. In order to activate the backup wavelength, the OLT keeps a track of the mean allocated bandwidth to each ONU $(\overline{B_{alloc}^{onu_i}})$. When this value is lower than its minimum guaranteed bandwidth and its demanded bandwidth is higher than this guaranteed level, the OLT activates the backup wavelength and decides on which wavelength the ONU transmits in the next cycle $(\lambda_{alloc}^{onu_i})$. Otherwise, if every ONU complies with its guaranteed bandwidth the backup wavelength keeps switched off. Fig. 2 shows a flow diagram to explain the performance of the developed WDM-DBA algorithm ShaWaG.

3.3 Dynamic Bandwidth Allocation in Each Wavelength

The designed algorithm achieves efficient upstream channel utilization because ONUs can transmit as soon as the previous ONU ends its transmission in each channel, since it follows a polling policy. The EPON standard and its extension to WDM-EPON architectures, uses the Multi-Point Control Protocol (MPCP) to properly schedule the communication between the OLT and the ONUs. Two control messages of MPCP are used to assign bandwidth in each upstream channel, the *Report* and the *Gate* messages. In the *Report*, the ONU sends the demanded bandwidth (in bytes) for the next cycle and the OLT sends a *Gate* message with the allocated bandwidth for that cycle. Therefore, the OLT allocates bandwidth to each ONU just after receiving its updated demand (i.e. *Report*). Hence, the OLT assigns bandwidth to each ONU independently of the status of the remaining ONUs, and the OLT does not have to wait for the queue information of every ONU. This leads to an efficient bandwidth utilization and avoids long packet delay.

To avoid that the upstream channel is over used by some ONUs or the cycle time becomes quite longer, we limit the window length of every ONU in every cycle time

[16]. In this scheme, the OLT gives the required bandwidth to each ONU as long as the demand is lower than a maximum bandwidth imposed. When the demand is higher than this bandwidth, the OLT gives this latter maximum. This performance makes the cycle adaptive depending on the updated demand of each ONU. The cycle is the total time in which all ONUs transmit in a round robin discipline.

As the network allows different service levels profiles (SLAs), the new algorithm ShaWaG has been designed to distinguish between profiles with different requirements. In fact, it ensures a guaranteed bandwidth to each profile when their demand excesses the available bandwidth in the shared upstream channel. This is implemented by assigning a minimum guaranteed bandwidth factor to each SLA which ensures them a different bandwidth level. The OLT uses these factors to allocate the available bandwidth to each channel. Thus, ShaWaG sets different maximum bandwidths $\left(B_{max}^{sla_k}\right)$, one for each SLA. The allocated bandwidth in one cycle time for each ONU $(B_{alloc}^{onu_i})$ can be defined by Eq. 1:

$$B_{alloc}^{onu_i} = minimum\left\{B_{demand}^{onu_i}, B_{max}^{sla_j}\right\} \tag{1}$$

where $B_{demand}^{onu_i}$ is the aggregated bandwidth demand in bits of ONU i. The maximum allocated bandwidth permitted to each ONU depending on its SLA (j) in each cycle time $\left(B_{max}^{sla_j}\right)$ is calculated using Eq. 2. In Eq. 2, R^{sla_j} is a factor which represents the minimum guaranteed bandwidth (bits/s) associated with the SLA j and $B_{cycle\_available}$ is the available bandwidth in the maximum cycle considered (i.e. 2 ms set by EPON). The term $N_{onus}^{sla_m}$ is the number of ONUs associated with the SLA m in the presence of n profiles. The term N_{λ} is the number of supported wavelengths in the upstream.

$$B_{max}^{sla_j} = \frac{B_{cycle\_available} \cdot R^{sla_j} \cdot N_{\lambda}}{\sum_{m=0}^{m=n-1} R^{sla_m} \cdot N_{onus}^{sla_m}} \tag{2}$$

4 Simulation Results

4.1 Simulation Scenario

Simulations were initially made considering a WDM-EPON with both scenarios of 48 and 52 ONUs and one user connected to each ONU using OPNET Modeler 14 [17]. However, the simulation study has been extended to show the results for a different number of ONUs from 32 to 64 ONUs. The transmission rate of the upstream link between ONUs and the OLT is set to 1 Gbit/s and the access link from the user to each ONU to 100 Mbit/s [6,16-18]. The distance between ONUs and the OLT is set to 20 km, which is near the maximum permitted distance for a typical EPON [18]. To avoid collisions between adjacent ONUs, a guard time of 1 μs is chosen, a value within the limits specified by the standard IEEE 802.3ah D1.414 [19]. Packet generation follows a Pareto distribution with a Hurst parameter, H, equal to 0.8, considering them of variable length (from 64 to 1518 bytes). Moreover, ONUs have one buffer of 10 Mbits where packets are queued according to their arrival [16].

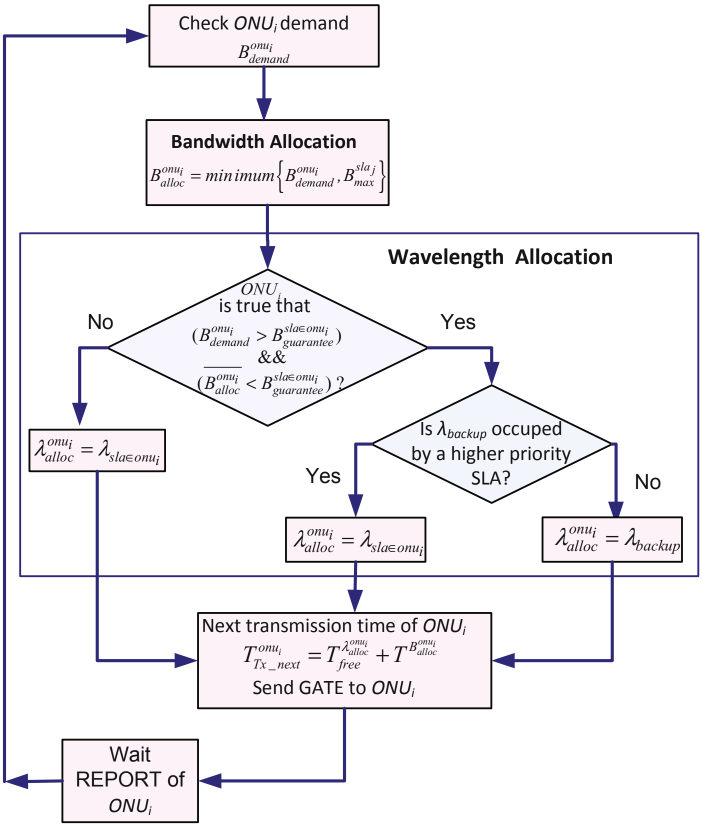

Fig. 2. Main diagram of the WDM-DBA algorithm

As the WDM-EPON copes with the presence of several SLAs, it is presented a scenario with three SLAs: SLA_0 as the highest priority service level, SLA_1 as the medium priority service level and SLA_2 as the lowest priority service level. In general, a very few conventional users contract high level agreement conditions, whereas users tend to contract medium or low priority profiles. In this study it has been considered that the 12% of users contract high level conditions, the 31% contract medium level conditions and the 56% contract the lowest. Regarding the minimum guaranteed bandwidths factors to each SLA, it has been set the values $R^{sla0} = 100$, $R^{sla1} = 70$ and $R^{sla2} = 50$ as well as other studies [7, 15]. These factors are chosen to comply with the NTT DSL service plans (100/70/50 Mbit/s) [20]. Hence, each SLA should be given this guaranteed bandwidth when the bandwidth demand of every SLA exceeds the available bandwidth of the upstream channel.

ShaWaG is compared with DyWaS-SLA [15], as it also applies weighted factors to guarantee bandwidth levels to different SLAs. As well as other schemes in WDM-EPONs [13,15] DyWaS-SLA assumes that ONUs transmit on several wavelengths in the upstream direction, initially set to three wavelengths. As this number can be upgraded depending on the service provider requirements and the number of ONUs, we show a complete simulation study where it is assumed different number of wavelengths from two to four, as well as other published works [11, 12]. Thus, this kind of architecture will be compared to the one proposed by ShaWaG, which limits the number of wavelengths at the upstream channel to minimize costs and complexity.

4.2 Simulation Results

One of the most important characteristics of ShaWaG is the offered bandwidth to each subscriber depending on the guaranteed bandwidth contracted with the service provider. In Fig. 3 it is shown the offered bandwidth to one ONU of each SLA versus the ONU load when ShaWaG and DyWaS-SLA are compared for a initial set of 52 ONUs. As all ONUs have the same traffic distribution, all of them demand the same bandwidth (B_{demand}), as it is represented in the figure. The demanded bandwidth follows a linear function from 0 Mbit/s until the maximum user transmission rate set to 100 Mbit/s. In the same way, every algorithm offers the same quantity of bandwidth in Mbit/s to every ONU of the same SLA$(B_{offered})$, since all ONUs have the same traffic distribution. Consequently, in Fig. 3 the bandwidth offered by each algorithm to each SLA is represented with only one line. This figure shows how ShaWaG is able to efficiently guarantee the establish bandwidth levels to every profile. In contrast, DyWaS-SLA cannot deal with such bandwidth guarantees for the two lowest priority subscribers (SLA_1 and SLA_2). Furthermore, it is noticeable that ShaWaG always give to the highest priority profile (SLA_0) its total demanded bandwidth. In conclusion, the new algorithm ShaWaG, which only allows a maximum of two wavelengths to each ONU, achieves higher throughput than DyWaS-SLA, which uses three operating wavelengths in the upstream direction.

On the other hand, another important strength of ShaWaG, is the limited number of wavelengths that it permits each ONU to use in order to minimize costs and complexity. In this study, we analyze the wavelength utilization of each SLA versus de ONU load made by ShaWaG and DyWaS-SLA. The next graphs represent the percentage of the wavelength utilization of each SLA (SLA_0, SLA_1 and SLA_2). It should be mentioned that in DyWaS-SLA each ONU initially supports three wavelengths in the upstream (λ_0, λ_1, λ_2). Meanwhile, in ShaWaG each ONU supports a maximum of two wavelengths, one dedicated wavelength depending on the SLA, λ_0, λ_1 and λ_2 for SLA_0, SLA_1 and SLA_2 respectively, and another for the backup transmission ($\lambda_{3)}$. Regarding the highest priority profile SLA_0, Fig. 4 shows the percentage of the wavelength utilization when 52 ONUs share the upstream. As it can be seen, DyWaS-SLA simultaneously uses the three wavelengths, which means that the OLT has to constantly switch the laser at the ONUs. Moreover, ONUs are allocated the three supported wavelengths in the same proportion along the time. On the contrary, the novel algorithm ShaWaG only needs to use the dedicated wavelength for the SLA_0 profile (λ_0) for every ONU load. It means that the OLT has not to switch among several wavelengths and it simplifies the upstream transmission. For the profile SLA_1, Fig. 5 represents the percentage of the wavelength utilization versus the ONU load. One more time, DyWaS-SLA simultaneously uses the three wavelengths and they are assigned in the same proportion along the time. In contrast, ShaWaG only needs to employ the dedicated wavelength (λ_1) up to loads relatively high. The backup wavelength, λ_3, is only used for loads higher than 0.6 (i.e. ONUs transmitting at 60 Mbit/s) to ensure the level of 70 Mbits. The results confirm that in DyWaS-SLA the OLT is constantly changing the assigned wavelength to each ONU. Meanwhile, with ShaWaG the OLT employs the dedicated wavelength and it only uses the backup wavelength to fulfil the bandwidth requirements for certain loads. Finally, Fig. 6 shows the results for the SLA_2 profile. In that case, ShaWaG uses the dedicated wavelength (λ_2) for loads up to 0.4 (ONUs transmitting at 40 Mbit/s).

However, it starts to assign the backup wavelength (λ_3) for loads higher than this value to ensure the guaranteed bandwidth of 50 Mbit/s. Whereas ShaWaG only activates the backup wavelength when it needs to fulfil the bandwidth requirements,

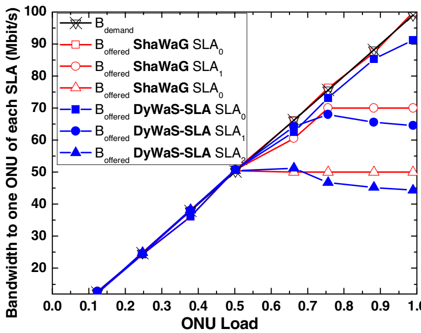

Fig. 3. Demanded and offered bandwidth to one ONU of each SLA versus the ONU load for ShaWaG and DyWaS-SLA for 52 ONUs

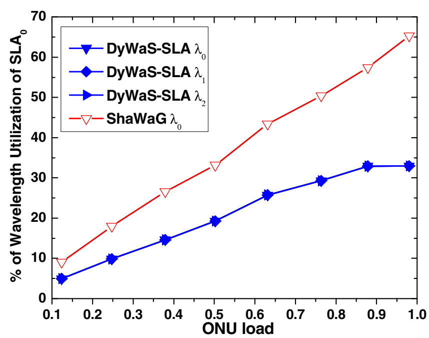

Fig. 4. Percentage of the wavelength utilization versus the ONU load for the SLA_0 for ShaWaG and DyWaS-SLA and 52 ONUs

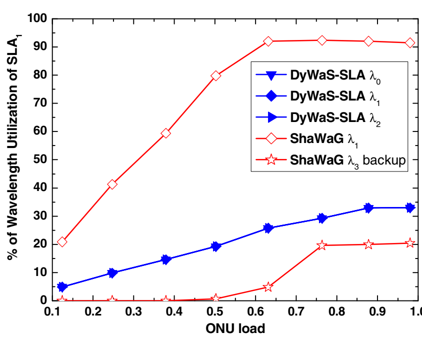

Fig. 5. Percentage of the wavelength utilization versus the ONU load for the SLA_1 for ShaWaG and DyWaS-SLA and 52 ONUs

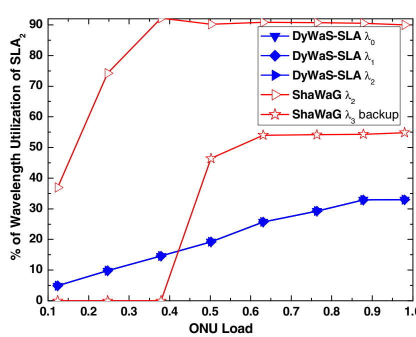

Fig. 6. Percentage of the wavelength utilization versus the ONU load for the SLA_2 for ShaWaG and DyWaS-SLA and 52 ONUs

DyWaS-SLA uses in both scenarios the three wavelengths an the OLT keeps on switching the assigned wavelength to each ONU in every cycle. Finally, it is noticeable that ShaWaG keeps the dedicated wavelength overloaded even for low loads as the number of ONUs associated with this profile is higher than the ONUs of SLA_0 and SLA_1 profiles.

The novel algorithm ShaWaG, assumes the utilization of one shared wavelength (λ_3) among every profile (SLA_0, SLA_1 and SLA_2) only when ONUs of one SLA needs to ensure their stipulated guaranteed bandwidth. In case several SLAs require this backup wavelength, ShaWaG gives preference to the highest priority profile. Once the highest priority profile is ensured its guaranteed bandwidth, ShaWaG assigns λ_3 to the next profile which needs it. Otherwise, this backup wavelength is not activated. In this way, Fig. 7 represents the wavelength utilization of the backup wavelength λ_3 for the three profiles SLA_0, SLA_1 and SLA_2, when different number of ONUs (from 32 to 64 ONUs) is considered in the upstream. It can be noticed that the highest priority profile SLA_0 does not need this wavelength even when the number of ONUs is set to 64. Thus, only SLA_1 and SLA_2 profiles demands its utilization for a number of ONUs higher than 36. It can be observed that the lowest priority profile (SLA_2) requires more its utilization because the number of ONUs related to this profile is higher that the ONUs related to the medium priority profile SLA_1. However, when the number of ONUs is higher or equal than 56, ShaWaG assigns more frequently the backup wavelength to SLA_1 to the detriment to SLA_2. It happens because ShaWaG is designed so that if several SLAs demand the backup wavelength, it gives priority to the highest profile which needs it more to satisfy its bandwidth requirements.

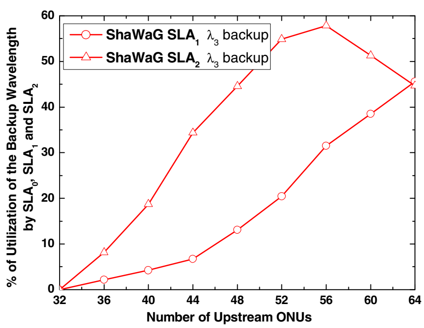

Fig. 7. Percentage of the wavelength utilization of the backup wavelength (λ_3) versus the number of ONUs in ShaWaG to each profile

On the other hand, in the initial simulation scenario, DyWaS-SLA was assumed to support three upstream shared wavelengths. However, in Fig. 3 it was demonstrated that DyWaS-SLA cannot efficiently comply with the guaranteed bandwidth levels for SLA_1 and SLA_2 profiles. Besides, this number of wavelengths can be changed depending on the service provider requirements and the number of ONUs connected to the WDM-EPON. In this way, we have analyzed the performance of both algorithms when DyWaS-SLA supports a different number of wavelengths in the upstream. In particular, we consider scenarios with a range of wavelengths from two to four. As the guaranteed bandwidth is the most important aim of both algorithms, it is going to be studied the maximum offered bandwidth to each profile for a different number of ONUs. This study permits to determine the limit of both algorithms for each set of upstream wavelengths when different number of ONUs shared the upstream. Regarding the highest priority profile SLA_0, Fig. 8 (a) represents the maximum offered bandwidth to one ONU of this SLA (in Mbit/s) when different number of ONUs (from 32 to 64 ONUs) share the upstream and it supports different number of wavelengths (for two to four). It should be noticed that the bandwidth offered to every ONU of the same SLA is the same, as all of them have the same traffic distribution. In this figure, it can be observed that DyWaS-SLA offers more bandwidth to each ONU as the number of wavelengths increases. When the number of upstream wavelengths is set to four, DyWaS-SLA provides the stipulated guaranteed bandwidth for the highest number of represented ONUs (i.e. 64 ONUs). However, when the upstream supports three wavelengths, DyWaS-SLA only ensures the guaranteed bandwidth up to 48 ONUs. Furthermore, if the upstream only allows two wavelengths, DyWaS-SLA is not able to guarantee the stipulated bandwidth to the SLA_0 even when the considered ONUs is set to 32. It happens since the two wavelengths have to be shared by every ONU and the total demanded bandwidth of ONUs is higher than the contained bandwidth within these two wavelengths. On the contrary, ShaWaG provides the guaranteed bandwidth independently of the number of ONUs which shares the upstream.

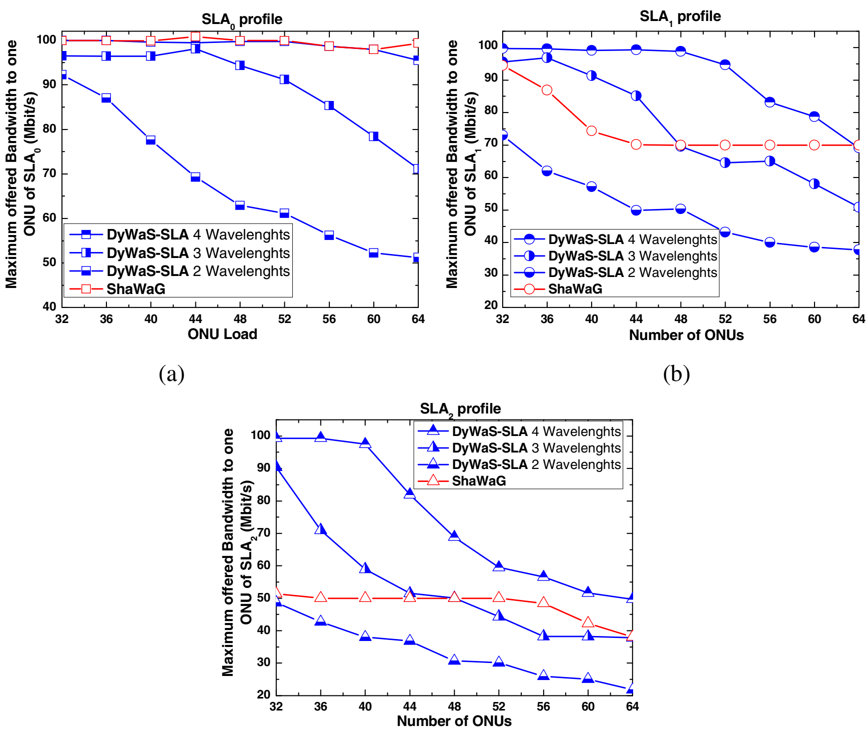

Fig. 8. Maximum offered bandwidth of DyWaS-SLA and ShaWaG to each ONU of each profile (a) SLA_0 (b) SLA_1 (c) SLA_2

Hence, for the maximum number of ONUs (i.e. 64 ONUs), ShaWaG fulfils every guaranteed bandwidth levels with only two wavelengths allowed to each ONU. In contrast, DyWaS-SLA needs four wavelengths to satisfy the same bandwidth requirements when the number of ONUs is set to 64. For the SLA_1 profile, in Fig. 8 (b) it is seen that ShaWaG ensures the guaranteed bandwidth for every set of represented ONUs with only two wavelengths. However, DyWaS-SLA needs the presence of four wavelengths to ensure the stipulated guaranteed bandwidth for every range of ONUs. Consequently, the novel algorithm deals better than DyWaS-SLA with the bandwidth requirements, using at the same time a lower number of wavelengths. Finally, for the SLA_2 profile, Fig. 8 (c) shows that although ShaWaG only supports two upstream wavelengths, it ensures the guaranteed bandwidth for up to 60 ONUs. In contrast, for the same number of wavelengths, DyWaS-SLA cannot provide the guaranteed bandwidth even the number of ONUs is only 32. Although the number of wavelengths is increased to three, DyWaS-SLA only guarantees the minimum bandwidth up to 52 ONUs, so it needs four upstream wavelengths to achieve the same performance than ShaWaG.

5 Conclusions

In this paper, it has been proposed an algorithm, called ShaWaG, to support subscriber differentiation in a WDM-EPON. The new algorithm distributes the bandwidth according to a set of weights to efficiently ensure a guaranteed bandwidth to each profile when the available bandwidth is not enough to cover the demand of every of them. In contrast to other algorithms proposed in WDM-EPONs, this algorithm deals with the related cost of these architectures, by only permitting each ONU to transmit in a limited range of wavelengths according to the bandwidth requirements of its contracted SLA.

ShaWaG has been compared with DyWaS-SLA as it is a very efficient method which also takes into consideration bandwidth guarantees in a multi-profile scenario. However, this scheme allows ONUs to transmit through the same set of upstream wavelengths. As a consequence and contrary to ShaWaG, it does not minimise the number of upstream wavelengths dedicated to each ONU to save cost. Simulation results show that ShaWaG efficiently ensures guaranteed bandwidth levels for every profile for a larger number of ONUs when compared to DyWaS-SLA. Not only ShaWaG makes a better conscious bandwidth distribution than DyWaS-SLA, but also it does with a lower number of upstream wavelengths. To achieve similar performance, DyWaS-SLA requires a higher number of upstream operating wavelengths. In fact, with only two wavelengths, ShaWaG can deal with the guaranteed bandwidth levels of up to 60 ONUs. In contrast, DyWaS-SLA needs four wavelengths to fulfill the bandwidth requirement of the same number of ONUs. As a conclusion, ShaWaG saves costs in each ONU achieving better performance than more expensive architectures which consider a higher number of upstream channels.

Regarding the percentage utilization of every upstream wavelength made by both algorithms, it has been demonstrated that DyWaS-SLA simultaneously used in the same proportion every upstream wavelength. It means that the OLT is constantly switching the laser to assign different wavelengths in each cycle. Consequently, it may lead to poor bandwidth utilization due to the dead tuning time if high speed tunable lasers are not deployed. In contrast, in ShaWaG the OLT assigns the dedicated wavelength to each profile, whereas it only employs the backup wavelength to fulfil the bandwidth requirements of certain profiles.

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