Dynamic Wavelength and Bandwidth Allocation in Hybrid TDM/WDM EPON Networks

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***Abstract*—We discuss a wavelength-division-multiplexed-based passive-optical-network (PON) architecture that allows for incremental upgrade from single-channel time-division multiple-access PONs in order to provide higher bandwidth in the access network. Various dynamic-wavelength and bandwidth-allocation algorithms (DWBAs) for wave-division multiplexed PON are presented; they exploit both interchannel and intrachannel statistical multiplexing in order to achieve better performance, especially when the load on various channels is not symmetric. Three variants of the DWBA are presented, and their performance is compared. While the first variant incurs larger idle times (and, hence, poor performance), the other two algorithms achieve better but different performance with critical dissimilarities. Our analysis also focuses on the fair assignment of excessive bandwidth in the upstream direction to highly loaded optical network units. We compare the performance of DWBA to another algorithm that relies on static-channel allocation. Furthermore, a study is presented wherein the number of wavelengths increases, and a comparison with interleaved polling with adaptive cycle time is shown. We use extensive simulations throughout this paper.**

***Index Terms*—Dynamic-bandwidth allocation (DBA), ethernet passive optical network (EPON), simulation and modeling, wavelength-division-multiplexed (WDM)-passive optical network (PON).**

I. Introduction

THE INCREASED demand for more bandwidth and bandwidth services [1] in the access network has been growing rapidly, and there have been great efforts to develop economical subscriber networks based on optical technology [2]–[6]. Currently, the predominant broadband-access solutions developed are the digital-subscriber-line and cable-modem-based networks. Both of these technologies have limitations, because they are based on infrastructure that was originally built for carrying voice and analog TV signals, and their retrofitted versions to carry data are not optimal [2]. Passive optical networks (PONs) and Ethernet PONs (EPONs) [4], [8] are viewed by many as an attractive and promising solution for the broadband-access-network bottleneck. EPON is a point-to-multipoint access network with no active element in the signal's path from source to destination; the only interior elements used in this architecture are passive components such as optical splitters and optical fibers. EPON has been standardized by the IEEE 802.3ah working group, and it comprises one optical-line terminal (OLT) and multiple optical-network units (ONUs). Currently, EPON systems deploy two wavelengths: typically 1310 nm for the upstream transmission and 1550 nm for the downstream transmission. In the downstream, Ethernet frames are broadcast by the OLT and are selectively received by each ONU. Alternatively, in the upstream, multiple ONUs share the same transmission channel to send data and control packets to the OLT. Since ONUs are unable to detect collision occurring at the OLT, and due to the difficulty to implement a carrier-sense multiple access with collision detection, it is necessary to design a mechanism that arbitrates the access of ONUs to the shared medium. This is achieved by designing medium-access-control (MAC) protocols to prevent collision between Ethernet frames of different ONUs transmitting simultaneously. Current MAC supports time-division multiplexing (TDM), where each ONU is allocated a fixed or dynamic time slot (transmission window). Transmissions from different ONUs to the OLT are arbitrated through the use of the multipoint-control protocol (MPCP).

Given the steadily increasing number of users and emerging bandwidth intensive applications, current single-channel TDM EPONs are likely to be upgraded in order to satisfy the growing traffic demands in the future. One approach for upgrading EPON systems is to increase the current line rate from 1 to 10 Gb/s [2]. However, this implies that all EPON nodes need to be upgraded by installing new higher speed transceivers, resulting in a rather costly upgrade. Another approach is to deploy multiple wavelengths in the upstream/downstream directions, resulting in a wavelength-division-multiplexed (WDM)-based topology. WDM provides a cautious upgrade, wherein wavelengths can be added as needed. Furthermore, only EPON nodes with higher traffic may be WDM upgraded by either deploying fixed-tuned and/or tunable transceivers [7].

In this paper, we introduce an architecture for incremental migration from TDM-PON to TDM/WDM-PON. Dynamic-bandwidth-allocation (DBA) algorithms initially designed for EPON require appropriate modifications to handle the multiple-channel architecture and to exploit the interwavelength statistical multiplexing. We present the new bandwidth-allocation schemes for the hybrid WDM/TDM PON, and we show their differences. These schemes enable different ONUs to efficiently share (both in time and wavelength domains) the access-network bandwidth. In Section II, we do an overview

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of related literature. Section III presents the proposed architecture, and in Section IV, we present our bandwidth-allocation schemes. Section V presents a comparison between the proposed schemes. In Section VI, we study numerically the performance of these schemes, and finally, Section VII concludes this paper.

II. Related Work

Various early work has considered the deployment of WDM technology in the access network, and some WDM-PON architectures have been proposed, namely the composite PON, the local-access router network, the remote integration of terminal network, the multistage AWG-based WDM-PON, and, more recently, the WDM-Super PON. See [2] for a literature overview of these technologies. One straightforward approach to build a "high performance" WDM-PON is to employ a separate wavelength channel from the OLT to each ONU for each of the upstream and downstream directions [9]. This approach effectively creates a point-to-point link between the central office (CO) and each ONU; this architecture results, however, in a poor resource utilization and high deployment cost. The authors of [5] proposed a new hybrid architecture (referred to as SUCCESS), which provides a practical migration from current TDM PONs to future WDM access networks while maintaining backward compatibility for users on existing TDM PONs. The SUCCESS architecture is based on a collector ring and several distribution stars connecting the CO and the users. The authors proposed a particular WDM-PON MAC protocol for this architecture but, however, did not present any WDM-DBA algorithms. Furthermore, the architecture does not allow for any interchannel statistical multiplexing to better harness the available bandwidth on different PONs. More recently, the authors of [6] proposed a SUCCESS-DWA PON that employs dynamic-wavelength allocation (DWA) to further provide bandwidth sharing across multiple physical PONs and, hence, achieve both cost-effective and high-performance architecture. The authors presented an upstream and downstream system upgrade; tunable lasers, arrayed-waveguide grating, and coarse/fine filtering are combined to create a flexible access in the downstream. Alternatively, several distributed and centralized-access schemes are proposed for the upstream upgrade. The authors of [3] have similarly proposed a new WDM-PON, in which each upstream-wavelength channel can be shared among multiple ONUs by means of TDM. Here, the ONUs can use their wavelength-selection-free (i.e., without wavelength tuning) transmitters to operate on any wavelength. No WDM-DBAs algorithms were discussed, however.

With respect to bandwidth and resource management, access control, and quality of service (QoS), some work only recently started to appear and remains very limited. The authors of [7] have presented extensions to the MPCP protocol for WDM-PON, where wavelength channels, in addition to time windows, can be assigned; they presented both online and offline scheduling. The authors of [10] proposed WDM IPACT-ST scheme, based on the interleaved polling with adaptive cycle time (IPACT) [12]. Here, IPACT protocol was adopted and applied on a multichannel WDM-PON, where the ONUs are equipped with fixed transceivers. Furthermore, they applied strict priority scheduling to support QoS in WDM-PON. A byte-size clock (BSC) protocol [11] with QoS support that allocates wavelengths on a user-basis rather than ONU-basis is proposed. The approach is scalable in bandwidth assignment and achieves reduction in packet delays; however, in BSC, all nodes need to be synchronized and, as a result, the TDM frame does not comply with IEEE 802.3ah.

III. WDM-PON Architecture

The protocols and algorithms for WDM-PON are currently at their initial stage of study, and while various types of architectures have been proposed, no specific one is dominant yet [2]. We assume two different architectures [14] for this paper: The first (scheme A_1) assumes a fixed grouping of ONUs [6, scheme A]. Here, the ONUs are divided into multiple subsets, each allocated a fixed wavelength channel for upstream transmission. Hence, every ONU maintains a fixed transceiver, whereas the OLT maintains a bank of fixed transceivers. Within each subset, the transmission of different ONUs is arbitrated by the OLT through either a fixed or dynamic time-division slot-assignment scheme. Clearly, this architecture limits the shareability of different wavelengths among ONUs, since a single wavelength is statically allocated to each subset of ONUs, and hence, no interchannel statistical multiplexing is possible. This architecture can be viewed as a straightforward upgrade from conventional TDM-PON and provides a baseline for comparison with the proposed WDM-DBAs. The second architecture (scheme A_2) is more flexible and allows for simultaneous time-sharing and wavelength sharing [14]. This architecture is similar to scheme C presented in [6]. For upstream transmission, every ONU can be equipped with one or more fixed transmitters, allowing for an incremental upgrade depending on the traffic demand at the ONU. In this case, the ONU informs, during the registration process, the OLT of the wavelength(s) it can support for appropriate resource allocation and management. The OLT, upon receiving bandwidth requests, allocates transmission windows for the various ONUs, taking into account the wavelengths they support. Alternatively, the ONU could optionally maintain a fast tunable laser to allow for more flexibility. To develop our dynamic-wavelength and bandwidth-allocation (DWBA) algorithms, we assume in this paper the latter approach and we assume a tuning speed in the range of microseconds. This architecture enables the ONU to tune its upstream transmission from one wavelength to another at different times depending on the DWBA algorithm deployed at the OLT. Here, the WDM-PON resources act as a pool, and all ONUs share these resources; resource sharing is arbitrated by the OLT using DWBA. This scheme makes the implementation of the DWBA more challenging and requires an upgrade in the MAC. In our architecture, we upgrade the MAC to support both time and wavelength assignment, where each ONU will be allocated both a transmission window and a wavelength. The OLT may have a bank of fixed transceivers to be able to simultaneously receive data from the various ONUs on different wavelengths and transmit data and control messages to the ONUs.

IV. WDM/TDM DBA

To develop our DWBAs, we assume MPCP extensions for WDM-PON, as proposed in [7]. The MPCP GATE message proposed in the standard is modified by adding an additional field (1 B) indicating the channel number assigned by the OLT to the ONU. Thus, the OLT will provide each ONU with its appropriate transmission start time T_{start}, transmission length T_{length}, and corresponding wavelength-channel identifier.

A. Static Wavelength Dynamic Time (SWDT)

This scheme relies on the simple architecture A_1; the OLT allocates wavelengths statically among ONUs, and the upstream bandwidth is assigned dynamically depending on the request of each ONU. Here, ONUs are divided into as many classes as the number of wavelengths, and each class will share a predetermined wavelength. Since the number of ONUs on each wavelength is identified, SWDT runs on each channel separately (the OLT waits until all reports from one subset is received and then runs the allocation algorithm). This scheme is easy to implement; however, it may under utilize the network bandwidth, since it does not exploit the interchannel statistical multiplexing. Namely, when the load on one particular channel is light and high on another, the OLT cannot use the available bandwidth on that lightly loaded channel and reassign it to highly loaded ONUs on another wavelength, which therefore, could result in better performance. Note that this scheme although does not allow for dynamic channel allocation, it however allows for DBA [13] on one particular wavelength. Hence, SWDT is used as a basis for our comparative study. In order to motivate the need for dynamic channel allocation, we first consider a rather uncommon case, wherein the ONUs (highly loaded and lightly loaded)[1] are not symmetrically distributed on the channels. This scheme is referred to as SWDT-WC (WC for worst case). We also consider a more common case, where the ONUs are evenly distributed on the channels (SWDT-BC, where BC means best case). Now, although this case is likely more common, it essentially is similar to multiple EPON networks, where each EPON runs a single DBA for optimal performance. It is worth noting that SWDT falls short in the case where the load on various channels is not symmetric or not evenly distributed.

B. Dynamic Wavelength Dynamic Time (DWDT)

Unlike the previous approach where the channel is predetermined and fixed for every ONU and the OLT arbitrates only the transmission of ONUs, the second approach relies on the second architecture A_2 and enables the dynamic allocation of bandwidth for different ONUs in both wavelength and time domains. Here, the OLT maintains a variable for every channel that designates the time T_{free}^k for wavelength k when the next transmission is possible on that particular channel. For every REPORT message received from any ONU, the OLT allocates a channel with the least T_{free}^k to this ONU; furthermore, it also determines the length (e.g., in bytes) of the transmission window allocated to this ONU on the assigned channel. We refer to this procedure as DWBA, and we present three variants namely DWBA-1, DWBA-2, and DWBA-3. In these variants, the minimum bandwidth guaranteed B_{MIN} defined in [8] is dependent on the weight assigned to each ONU, based on the service-level agreement (SLA) between the service provider and users. We consider a PON access network with N ONUs. The transmission speed of the PON is R_N (in Megabits per second). Let T_{cycle} be the granting cycle, which is the time during which all ONUs can transmit data or/and send REPORTs to the OLT. Let T_g be the guard time that separates the transmission window for ONU_n and ONU_{n+1} and w_i be the weight assigned to each ONU based on its SLA such that $\sum_{i=1}^N w_i = 1$. Therefore, the minimum bandwidth guaranteed per cycle the OLT can allocate for an ONU(i) is computed as follows:

$$B_i^{\mathrm{MIN}} = \frac{(T_{\mathrm{cycle}} - N \times T_g) \times R_N \times K \times w_i}{8} \tag{1}$$

where K is the total number of wavelengths. In case of no SLA classification per ONU, $w_i = w = 1/N, \forall i$, and $\sum_{i=1}^N w_i = 1$; then

$$B_i^{\mathrm{MIN}} = B_{\mathrm{MIN}} = \frac{(T_{\mathrm{cycle}} - N \times T_g) \times R_N \times K}{8 \times N}. \tag{2}$$

1) DWBA-1: The OLT waits until all the REPORTs are received from all ONUs (on all channels). Upon that, the OLT runs a bandwidth-allocation algorithm to determine the bandwidth and channel for every ONU. Here, if $B_{\mathrm{req}}^i \leq B_{\mathrm{MIN}}$, where B_{req}^i is the requested bandwidth by ONU_i, and B_{MIN} is the minimum bandwidth guaranteed [4], [8], then $B_{\mathrm{assign}}^i = B_{\mathrm{req}}^i$, and a GATE message is sent to ONU_i. Alternatively, if $B_{\mathrm{req}}^i > B_{\mathrm{MIN}}$, then the OLT computes the excessive bandwidth resulting from the lightly loaded ONUs and assigns to ONU_i a bandwidth B_{assign}^i, depending on the excess bandwidth-allocation type, and sends a GATE message accordingly. There are two ways to assign transmission windows using the excess bandwidth, namely controlled excess (CE) and uncontrolled excess (UE). In UE scheme, the OLT collects from the received REPORTs all the excessive bandwidth available for the next cycle and assigns this total excess uniformly to all highly loaded ONUs, regardless of their requested bandwidth. The total excess bandwidth is

$$B_{\mathrm{excess}}^{\mathrm{total}} = \sum_{i=1}^{N} (B_{\mathrm{MIN}} - B_{\mathrm{req}}^i) | B_{\mathrm{req}}^i \leq B_{\mathrm{MIN}}. \tag{3}$$

Then

$$B_{\mathrm{excess}} = B_{\mathrm{excess}}^{\mathrm{total}} / M \tag{4}$$

where "M" denotes the number of overloaded ONUs. The advantage of this uncontrolled scheme is that highly loaded ONUs are assigned enough bandwidth to satisfy their high demands

[1] A highly (lightly) loaded ONU is one that requests bandwidth more (less) than the minimum bandwidth guaranteed [B_{MIN}, (2)] by the OLT in each cycle.

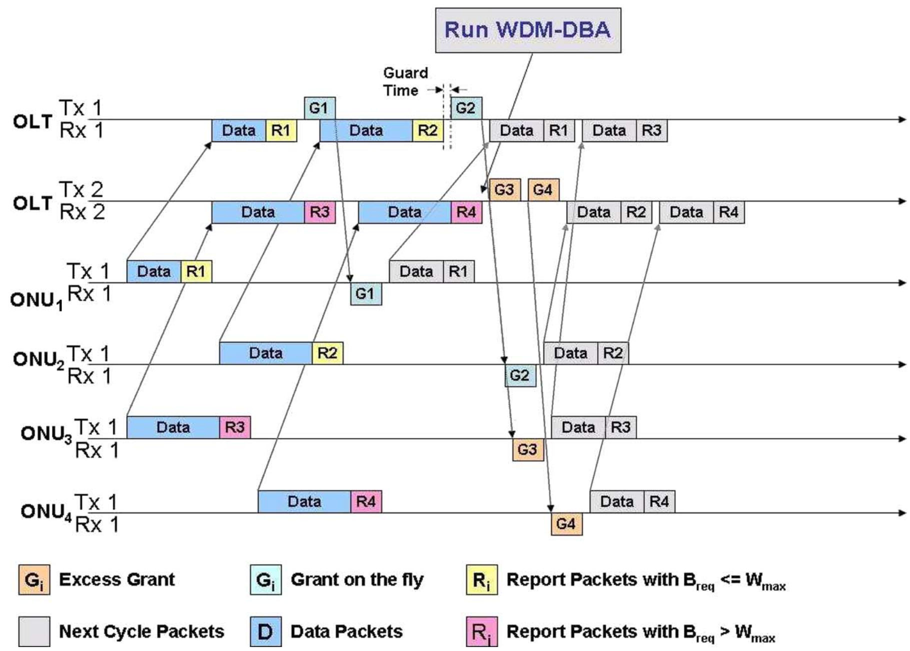


Fig. 1. DWBA-2 protocol.

(assuming the excess is enough); however, if some ONUs are only "slightly" highly loaded, they are being assigned an unfair share of the excess bandwidth that could ultimately be not utilized. Hence, the assignment of the excess bandwidth must be controlled (i.e., CE) by the OLT in order to guarantee a fair bandwidth allocation for all highly loaded ONUs. A more controlled scheme may work as follows:

$$B^i_{\text{assign}} = \begin{cases} B^i_{\text{req}}, & \text{if } B^i_{\text{req}} \leq B_{\text{MIN}} \\ B^i_{\text{req}}, & \text{if } B_{\text{MIN}} < B^i_{\text{req}} \leq B_{\text{MIN}} + B^i_{\text{excess}} \\ B_{\text{MIN}} + B^i_{\text{excess}}, & \text{if } B_{\text{MIN}} < B_{\text{MIN}} + B^i_{\text{excess}} < B^i_{\text{req}} \end{cases} \tag{5}$$

where the assignment of the excess bandwidth is controlled in the following way. Let $\chi = \{\text{ONU}_i\}_{i=0,\ldots,M-1}$ be the set of highly loaded ONUs. Then, B^i_{excess} is computed as follows:

$$B^i_{\text{excess}} = \begin{cases} B^{\text{total}}_{\text{excess}}/(M-i), & \text{if } B_{\text{MIN}} + \left(B^{\text{total}}_{\text{excess}}/(M-i)\right) < B^i_{\text{req}} \\ B^i_{\text{req}} - B_{\text{MIN}}, & \text{otherwise} \end{cases} \tag{6a}$$

where the total excess $B^{\text{total}}_{\text{excess}}$ is updated as follows every time B^i_{excess} is assigned

$$B^{\text{excess}}_{\text{total}} = B^{\text{excess}}_{\text{total}} - B^i_{\text{excess}}. \tag{6b}$$

However, the CE scheme allocates the excessive bandwidth in a round-robin fashion. Thus, some highly loaded ONUs might not have the chance to receive any share of this bandwidth due to the fact that $B^{\text{excess}}_{\text{total}}$ will be ≈ 0 before visiting all ONUs, or in a very common case, these "last" ONUs might get a less share than the "first" ones. For that reason, we propose a fair-excess (FE)-allocation scheme that assigns portions to highly loaded ONUs according to their bandwidth demand. Let $B^{\text{excess},i}_{\text{req}} = B^i_{\text{req}} - B_{\text{MIN}}$ be the excess bandwidth requested from a highly loaded ONU$_i$ and $B^{\text{req}}_{\text{excess}} = \sum_{i=0}^{N} B^{\text{excess},i}_{\text{req}}$ be the total excess requested bandwidth from all ONUs; then

$$B^{\text{portion},i}_{\text{excess}} = \frac{B^{\text{excess},i}_{\text{req}} \times B^{\text{excess}}_{\text{total}}}{B^{\text{req}}_{\text{excess}}} \tag{7a}$$

where $B^{\text{portion},i}_{\text{excess}}$ is the computed portion of excess bandwidth for each highly loaded ONU$_i$. Hence, to prevent the waste of bandwidth, B^i_{excess} is computed as follows:

$$B^i_{\text{excess}} = \min\left(B^{\text{excess},i}_{\text{req}}, B^{\text{portion},i}_{\text{excess}}\right). \tag{7b}$$

As a result, FE will ensure fair excess bandwidth allocation among all highly loaded ONUs. Note that unlike CE, FE ensures a fair bandwidth allocation but might not satisfy any highly loaded ONU; on the other hand, CE makes sure to satisfy the demand of a highly loaded ONU, if enough excess bandwidth is available, but not all ONUs, in case all the total excess bandwidth is fully exploited. Now, for the wavelength selection criteria, as mentioned before, the OLT maintains, for every wavelength k, the time it becomes available for next transmission $T^k_{\text{free}}, k = 1, \ldots, K$, where K is the total number of wavelengths in the WDM PON. The channel with smallest T^k_{free} is selected for next transmission.

2) DWBA-2 (see Fig. 1) : Here, upon receiving a REPORT from ONU$_i$, the OLT checks whether $B^i_{\text{req}} \leq B_{\text{MIN}}$; in this case, the OLT assigns "on the fly" a GATE to that ONU with bandwidth $B^i_{\text{assign}} = B^i_{\text{req}}$. Otherwise, the OLT waits until all the REPORTs from the other ONUs are received and, then, assigns a bandwidth of B^i_{assign} computed using UE, CE, or FE. The difference here is that ONUs that are lightly loaded can be scheduled immediately on the particular channel without waiting for the rest of the ONUs to send REPORTs. This early allocation will result in improved delay performance. However, such a scheme may increase the complexity of the design and implementation of the DWBA due to the fact that the OLT will have to keep track of each REPORT message received from each ONU (e.g., sometimes one ONU can send two or more REPORTs before the OLT receives all the other REPORTs because of the grant-on-the-fly manner). Hence, the OLT will have to store excess information that holds the status of each ONU (highly or lightly loaded) to be able to assign the appropriate transmission window.

3) DWBA-3: Here, the OLT will always assign "on the fly," a GATE to the ONU regardless of its requested bandwidth. However, the size of the transmission window is dependent on the requested bandwidth. Upon receiving a REPORT from ONU$_i$, the OLT checks if $B^i_{\text{req}} \leq B_{\text{MIN}}$. In this case, as in DWBA-2, the OLT will assign, "on the fly," a GATE with $B^i_{\text{assign}} = B^i_{\text{req}}$; otherwise, it will assign, "on the fly," a GATE with $B^i_{\text{assign}} = B_{\text{MIN}}$. Subsequently, the OLT waits until it receives all the REPORTs from all ONUs and collects the information about the excess bandwidth from each channel as well as the number of "highly loaded" ONUs "M." Each highly loaded ONU$_i$ is allocated its share of the excess bandwidth in either an uncontrolled manner [B^i_{excess} as in (4)], in a controlled manner as in (6a), or in a fair manner as in (7b). Note, here, the REPORT message is always transmitted once by the ONU in the first assigned transmission window (i.e., not in the excess window) regardless of whether an excess bandwidth is assigned or not. This is because 1) the allocation of the excess window cannot be guaranteed for a particular ONU and 2) since the OLT sends a GATE upon the receipt of a REPORT (i.e., on the fly), the ONU should not send a second REPORT (i.e., in the excess window) in the same cycle. That is because the OLT may already have done the scheduling of other ONUs over the same channel, and this second REPORT cannot "void" the first received one. This scheme is considered complex as well, since the OLT will have to use its excess table and, at the same time, will have to keep track of the two to-be-sent (if applicable) GATE messages to each ONU.

V. Comparison and Analysis

As mentioned earlier, SWDT relies on a static and predetermined allocation of wavelengths to the ONUs and the OLT performs DBA on each channel. In the case where the load on different wavelengths is not symmetric (i.e., some wavelength channels are more loaded than others), SWDT cannot exploit the bandwidth available on one channel (i.e., the lightly loaded) to allocate it for ONUs residing on another more congested channel. This results in under utilizing the available resources and, hence, in increased delays on the congested channel, and it is mainly attributed to the lack of interchannel statistical multiplexing. Note that when the load is evenly distributed among the PON wavelengths, the problem reduces to performing efficient bandwidth allocation on each individual channel.

Alternatively, DWDT enables ONUs to share the network resources both in time and wavelength domains. First, DWBA-1 is straightforward; the OLT allocates GRANT messages only after receiving all the REPORTs from all the ONUs (N) in the network. Evidently, this simple algorithm has deficiencies; namely, consider a two-channel PON network, where t_1 and t_2 are the times where each of the channels is available (assume $t_1 \geq t_2$) for transmissions. We can compute the period during which channel 1 is not being utilized:

$$T_1^{\text{idle}} = (t_2 - t_1) + \zeta \tag{8}$$

where $\zeta = \tau + T_{\text{transmission}} + T_{\text{DWBA}}$. Here, τ and $T_{\text{transmission}}$ are the RTT and the transmission time of a GATE message from the OLT to the ONU. T_{DWBA} is the computation time. Clearly, the upper bound of T_1^{idle} corresponds to the maximum of $(t_2 - t_1)$. This maximum, in turn, corresponds to the case where the last ONU in this cycle starts its transmission (on channel 2) at time $t_{\text{start}} \geq t_1$. Accordingly, the upper bound of $(t_2 - t_1)$ is T^N_{assign} (the time window in seconds assigned to the last ONU). Therefore

$$T_1^{\text{idle}} \leq T^N_{\text{assign}} + \zeta. \tag{9}$$

Moreover, if $t_2 - t_1$ is large (e.g., when the majority of ONUs on channel 1 are lightly loaded and highly loaded on channel 2), then the period of time where channel 1 is idle is much larger than that of (8). Overall, this idle time experienced by a channel results in poor bandwidth utilization and, thus, increased overall packet delays.

DWBA-2 and DWBA-3 solve this efficiency problem by sending GATE messages "on the fly" to all ONUs requesting bandwidth less than the minimum guaranteed (B_{MIN}). This "on the fly" bandwidth assignment mitigates the effects of the channel idle time experienced by DWBA-1 and results in a better throughput and delay performance. However, these two schemes exhibit different behaviors. Namely, under DWBA-2, the OLT defers ONUs with $B_{\text{req}} > B_{\text{MIN}}$ until all REPORTs are received, and then, it performs its assignment. DWBA-3 rather assigns "on the fly" all ONUs including those with $B_{\text{req}} > B_{\text{MIN}}$. In other words, the bandwidth allocated to a highly loaded ONU in DWBA-2 is a single entity, whereas DWBA-3 segregates the excess from the minimum bandwidth. This results in two transmission windows being allocated at different times to a highly loaded ONU in the same cycle. The immediate implication of this segregation is that a large packet may not fit in the first granted window and gets deferred to the second granted window (or perhaps to a subsequent cycle), blocking other packets and wasting a fraction of the allocated bandwidth. This implication increases the packet delays by holding unnecessarily these packets. On the other hand, in DWBA-2, every ONU is allocated only one transmission window in the same cycle; this window (combining both B_{MIN} and B_{excess}) is large enough and may thus mitigate the impact of the previous problem. We demonstrate this through an example. First, let $B_{\mathrm{MIN}}^{\mathrm{Total}}$ be the total number of bytes of transmitted data in the window allocated for B_{MIN}; let $B_{\mathrm{excess}}^{\mathrm{Total}}$ be the total number of bytes of transmitted data in the window assigned for the excess bandwidth B_{excess}. Let $B_{\mathrm{MIN+excess}}^{\mathrm{Total}}$ be the total number of bytes of transmitted data in the window assigned for B_{MIN} combined with B_{excess}. Let x be the remaining bandwidth from B_{MIN}, y from B_{excess} (when DWBA-3 is used), and z from $B_{\mathrm{MIN+excess}}$ (when DWBA-2 is used). In DWBA-3, since the allocated bandwidth in one cycle is split into two windows (B_{MIN} and B_{excess}), one packet P of large size "p" may not fit in x and, hence, gets deferred to the next transmission window. This will effectively prevent other packets from being transmitted and result in inefficient use of the allocated bandwidth. A total bandwidth of $(x+y)$ is, hence, not being utilized by the ONU under DWBA-3. On the other hand, in DWBA-2 combining B_{MIN} and B_{excess} in one transmission window, enables the transmission of P and, hence, releases or unblocks the rest of the buffered packets. This ultimately allows the transmission of larger number of packets; therefore, reduced packet delays and increased bandwidth efficiency (wasted allocated bandwidth is only z, $z \le x+y$).

Another implication of allocating two windows in the same cycle for a high loaded ONU stems from the fact that the ONU reports its buffer occupancy in the first window of cycle $n-1$, and subsequently, after some time, some already reported packets for the next cycle will be transmitted during the excess window. The OLT will allocate bandwidth for cycle n based on the reported traffic from the previous cycle. This will result in granting bandwidth more than needed since the buffer occupancy has decreased. Let $t_{\mathrm{end}}^{1,n-1}$ be the time where the REPORT message is transmitted by the ONU in cycle $n-1$ and $Q(t_{\mathrm{end}}^{1,n-1})$ be the buffer occupancy (in bytes) at time $t_{\mathrm{end}}^{1,n-1}$. Similarly, let $t_{\mathrm{end}}^{2,n-1}$ be the time where the same ONU finishes sending traffic in the excess window of cycle $n-1$ and $Q(t_{\mathrm{end}}^{2,n-1})$ be the buffer occupancy (in bytes) at time $t_{\mathrm{end}}^{2,n-1}$. Here, the requested bandwidth for cycle n is $B_{\mathrm{req}}^{n} = Q(t_{\mathrm{end}}^{1,n-1})$. Now, we can write

$$\tilde{B}_{\mathrm{req}}^{n} = B_{\mathrm{req}}^{n} - \left(Q\left(t_{\mathrm{end}}^{1,n-1}\right) - Q\left(t_{\mathrm{end}}^{2,n-1}\right)\right) \tag{10}$$

where $\tilde{B}_{\mathrm{req}}^{n}$ is the amended value of B_{req}^{n} before the OLT performs DBA in cycle n, and $Q(t_{\mathrm{end}}^{1,n-1}) - Q(t_{\mathrm{end}}^{2,n-1})$ is the size of the excess window of cycle $n-1$, which is known by the OLT. Hence, the OLT will allocate more bandwidth than the ONU requires at the time $t_{\mathrm{end}}^{2,n-1}$. This will result in increasing the cycle time and, hence, inefficient use of the allocated bandwidth. To overcome this deficiency, we propose a modified version of DWBA-3 (DWBA-3a) that eliminates the effect of the outdated information at the OLTs. Here, the OLT keeps track of the allocated excess bandwidth $B_{\mathrm{excess}}^{i,n-1}$ in cycle $n-1$ and, then, extracts this excess out of the allocated bandwidth in cycle n. Consequently, the allocated bandwidth, in cycle n, $B_{\mathrm{alloc}}^{i,n}$ is computed as follows:

$$B_{\mathrm{alloc}}^{i,n} = B_{\mathrm{req}}^{n} - B_{\mathrm{excess}}^{i,n-1}. \tag{11}$$

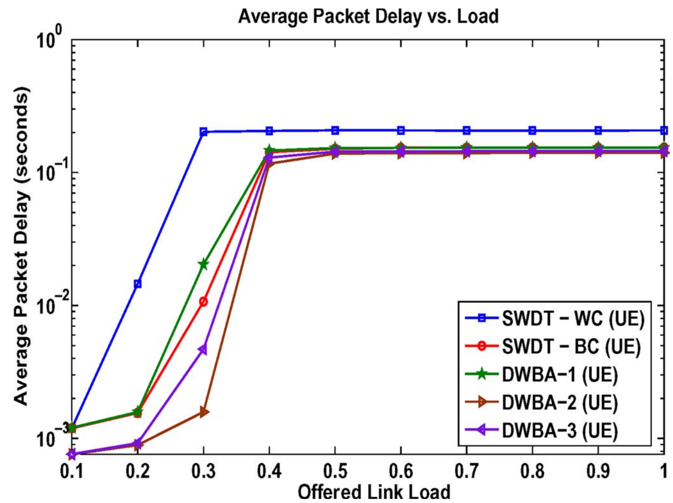


Fig. 2. Average packet delay comparison ($K = 2$).

VI. Performance Evaluation

In this section, we study the performance of the different wavelength and bandwidth-allocation algorithms we presented. We developed a WDM-PON event driven simulator in C++. The following are some parameters used in our simulation: number of ONUs $N = 64$; number of wavelengths $K = (2, 4, 6, 8)$; maximum cycle time $= 2$ ms; speed of each wavelength is 1 Gb/s; guard time $= 1$ μs; distance between OLT and ONU is 20 km; distance between ONU and end-users is 5 km; and buffering queue size is 1 MB. Out of the 64 ONUs, 32 ONUS are lightly loaded, whereas the remaining ONUs are highly loaded. A lightly loaded ONU generates traffic at a rate of 10 Mb/s (load $= 0.1$). We consider bursty traffic; to model its bursty nature, we generated self-similar traffic based on a Pareto distribution with a hurst parameter $H = 0.8$, and packet sizes are uniformly distributed between 64 and 1518 B. Fig. 2 presents the network average delay for the various allocation algorithms presented earlier when $K = 2$, all under the UE scheme. The traffic load of a high loaded ONU is varied between 0.1 and 1 (i.e., 10 and 100 Mb/s). The results first show clearly that when the traffic load is not symmetric and evenly distributed on the various channels, SWDT shows the worst performance (i.e., SWDT-WC), especially at medium and higher loads. This is due to the lack of interchannel statistical multiplexing, wherein the OLT could allocate available resources on one channel and ONUs on another channel, since the channels in SWDT are already preallocated and the allocation is fixed. Alternatively, when the load is more evenly distributed (i.e., lightly and highly loaded ONUs are uniformly distributed on the channels), SWDT (SWDT-BC here) exhibits a good performance, in comparison with the other schemes, especially DWBA-1. This shows that under such circumstance, there is no need for dynamic channel allocation, and hence, only DBA on each channel is required. However, as the load becomes less symmetric, dynamic channel allocation becomes essential (as shown in the other extreme, SWDT-WC) in order to exploit all the available network resources. It is worth noting that SWDT-WC and SWDT-BC at very light load (e.g., 0.1) perform alike since both channels have similar light loads. Note also

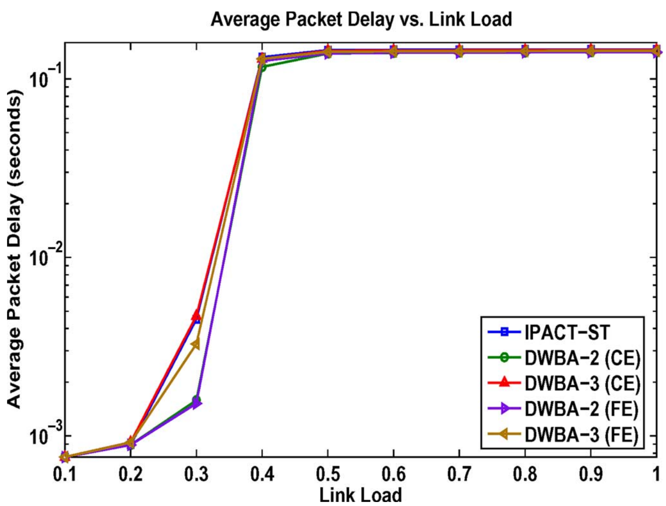


Fig. 3. Delay measurements with CE and FE $(K = 2)$.

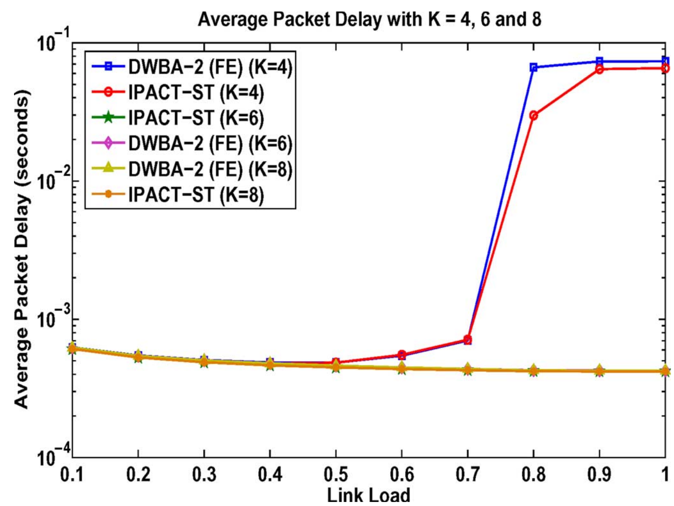


Fig. 4. Delay measurements with $K = 4, 6,$ and 8.

that SWDT performs similar to DWBA-1 at light load, while DWBA-2 and DWBA-3 slightly outperform the other schemes because they both allocate bandwidth on the fly for lightly loaded ONUs (i.e., almost all ONUs are at light load), whereas the other schemes wait until all REPORT messages are received (e.g., SWDT waits until REPORT from ONUs on each channel are received and DWBA-1 waits until REPORTs from all ONUs are received). As the load gets higher, DWBA-1 performs better than SWDT-WC because the former allows for sharing the resources on all channels and slightly underperforms SWDT-BC. Moreover, as the load gets higher, the DWBA-2 and DWBA-3 schemes outperform both SWDT algorithms; first, they outperform SWDT-WC, since the latter lacks the resource sharing property due to the static-channel allocation. They also outperform SWDT-BC, although the load is symmetric under SWDT-BC, for two reasons: 1) DWBA-2 and DWBA-3 allocate lightly loaded ONUs on the fly, and 2) although the load is evenly distributed among the channels, we have seen in some instances that a channel could have some free resources that could be immediately exploited by DWBA to allocate for ONUs on another channel. This is mainly due to the bursty nature of traffic used in our simulations. Fig. 2 also shows that at a load of 0.3, the average packet delay under DWBA-2 (DWBA-3) is 18.78 ms (15.66 ms) better than that under DWBA-1. Furthermore, our simulation results show a better performance of DWBA-2 over DWBA-3. The main reason is due to the fact that in DWBA-3, the OLT allocates the excess bandwidth to a high loaded ONU in a separate window in the same cycle. This results in under-utilizing the allocated bandwidth. The average packet delay of DWBA-2 is slightly better than that of DWBA-3; for example, at load $= 0.4$, a difference of 12.8 ms is shown. Note, when the assignment of the excess is controlled by the OLT (as discussed in Section IV), better results are obtained in terms of overall average packet delays; however, the relative difference between the different algorithms is the same. Fig. 3 shows the delay performance of DWBA-2 and DWBA-3 using both CE and FE allocation schemes and presents a comparison with IPACT-ST [10] when $K = 2$. Clearly, DWBA-2 and DWBA-3 exhibit better performance than IPACT-ST. For example, at load $= 0.4$, there is ≈ 16-ms improvement of DWBA-2 (CE) over IPACT-ST. Here, although IPACT-ST assigns bandwidth for every ONU on the fly as soon as it receives its REPORT, it does not benefit from the excess bandwidth, which may be available in the network to assign it for highly loaded ONUs (as in DWBA schemes). Hence, the available excess bandwidth in each transmission cycle is efficiently utilized under DWBA, and as a result, the overall network performance is ameliorated. Moreover, FE improves the performance of DWBA-3 over CE, while it shows a similar performance for DWBA-2 using the CE allocation. This is due to the fact that FE fairly allocates the excess bandwidth among highly loaded ONUs, in contrast to CE, that concentrates on satisfying highly loaded ONUs until the available bandwidth is fully consumed. Next, we study and compare the performance of DWBA-2 and IPACT-ST when the number of wavelengths $K = 4, 6,$ and 8 (Fig. 4). It is important to first note that increasing the number of wavelengths while using the same number of ONUs (64 is the limit)[2] yields fewer ONUs on the same wavelength channel, and accordingly, the minimum bandwidth guaranteed $[B_{\mathrm{MIN}}, (2)]$ increases. This has clear implications on the performance of DWBA. Recall that DWBA assigns “on the fly,” like IPACT-ST, those ONUs requesting bandwidth less than B_{MIN} and, unlike IPACT-ST, defers the allocation for ONUs requesting more. Now, as B_{MIN} becomes larger, when an ONU becomes highly loaded, it would be still requesting either less than B_{MIN} or slightly more than B_{MIN} (the most loaded ONU sends at 100-Mb/s rate). If the ONU requests less than B_{MIN}, it will then be allocated bandwidth on the fly, just like IPACT-ST does. Therefore, IPACT-ST and DWBA-2 show similar performance, as is clearly shown in Fig. 4 for loads varying between 0.1 and 0.7. However, as the load increases further, interestingly, IPACT-ST outperforms DWBA-2. This is mainly due to those ONUs requesting more than B_{MIN}, as it is the only difference with IPACT-ST. When B_{MIN} is large, as we have mentioned earlier, a highly loaded ONU may only request a bandwidth

[2]This is determined by the physical limitations of the optical splitter.

that is slightly higher than B_{MIN}. In such a case, the ONU will be deferred until all REPORT messages arrive in order to receive only a "small" excess bandwidth (this is not because there is no excess bandwidth available, but because the ONU needs only little excess). In such a case, there is no clear payoff for a highly loaded ONU to wait until all REPORT messages to arrive in order to only receive a small excess bandwidth. IPACT-ST, unlike DWBA-2, allocates bandwidth to all ONUs on the fly. This difference leads IPACT-ST to outperform DWBA-2 at very high loads. Now, as the number of wavelengths increases further (e.g., 6 and 8), each wavelength will support fewer ONUs, and the minimum bandwidth guaranteed gets further larger. Under such a circumstance, regardless of the load at each ONU (with an exception if the load is allowed to go beyond 100 Mb/s), all or most ONUs will be granted on the fly, similar to IPACT-ST, and all channels will be less loaded. For example, when the number of wavelengths is six (i.e., 6 Gb/s of bandwidth available), the total highest load generated in the network is 32×10 Mb/s $+ 32 \times 100$ Mb/s $=$ 3.520 Gb/s, which is much smaller than the total bandwidth available. This clearly shows that all wavelengths are not fully utilized, and hence, smaller delays (Fig. 4) are experienced under DWBA-2 and IAPCT-ST. Furthermore, the performance of both DWBA-2 and IPACT-ST become similar; as K gets larger, the average packet delays remain almost fixed at various loads. The average delay equals to almost 0.4 ms, which accounts for the cumulative guard times, the round-trip propagation delays, as well as the packet-queuing delays. Although the average packet delay is small and similar at various wavelengths, we note that the maximum packet delays have exhibited some differences. That is, as the number of wavelengths increases, the maximum packet delay slightly decreases [e.g., a difference of 2 ms between DWBA-2 ($K = 6$) and DWBA-2 ($K = 8$)]. Finally, we should note that increasing the number of wavelengths beyond the overall highest load the ONUs can send to the network may not be wise from a design and operation perspective. We now study the dissimilarities between DWBA-2 and DWBA-3 schemes. Recall that the main difference between DWBA-2 and DWBA-3 is the efficient use of the total allocated bandwidth for high loaded ONUs. Clearly, if the allocated bandwidth is not fully utilized (as in DWBA-3), the buffer occupancy of the high loaded ONU will increase substantially, and therefore, more bandwidth will be requested for the subsequent cycle(s). Since in our experimental setup, about half of the ONUs are highly loaded, more high bandwidth requests will arrive at the OLT and each ONU will be rewarded "excess" from whatever is available. This inefficiency of utilizing the allocated bandwidth may occur more often, and thus, may accumulate throughout the duration of the burst and after. Alternatively, under DWBA-2, the behavior is conversed. Namely, the allocated bandwidth is used more efficiently, and hence, fewer ONUs will be requesting additional bandwidth. To validate our reasoning, we measure the probability density function (pdf) of the number of ONUs with $B_{\text{req}} \geq B_{\min}$ for both algorithms and under the two allocation schemes of excess bandwidth (UE and CE) and when $K = 2$. Clearly, as Fig. 5 shows, more ONUs will be requesting bandwidth more than $B_{\min}$ under DWBA-3 (both under UE and CE). However, under DWBA-2, fewer ONUs are always requesting more than $B_{\min}$. This clearly indicates that 1) the inefficient use of allocated bandwidth and 2) the misguided allocation of bandwidth in DWBA-3 both result in increased queuing of ONUs' traffic (higher occupancy), and hence, more ONUs are requesting bandwidth larger than the minimum guaranteed from the OLT. To further compare the performance of the two algorithms with respect to their efficient use of the allocated bandwidth, we measure the number of bytes wasted in each cycle for a highly loaded ONU under CE scheme: $B_{\text{wasted}} = B_{\text{alloc}} - B_{\text{sent}}$, where B_{alloc} and B_{sent} are the amount of bandwidth allocated to the ONU and effectively used by the ONU, respectively. Fig. 6 shows the results of this experiment, where we plot B_{wasted} collected in each cycle throughout the simulation at a particular high loaded ONU. Clearly, the figure shows that, under DWBA-2, there exists no cycle where $B_{\text{wasted}} \geq 1518$ B (maximum packet size). By conclusion, DWBA-2 will defer at most one packet from one transmission cycle to the following one; however, there is an excessive waste of allocated bandwidth under DWBA-3. This is largely due to the over-allocation of unnecessary bandwidth by the OLT. Overall, this allocation results in increased average cycle times, inefficient bandwidth utilization, and therefore, increased overall packet delays. We mitigate this problem by proposing a modified version of DWBA-3, namely DWBA-3a (see Section V). We have seen (results are skipped) that DWBA-3a significantly decreases the waste of bandwidth found in DWBA-3 and shows a similar behavior to the one observed using DWBA-2 (i.e., $B_{\text{wasted}} \leq 1518$ B).

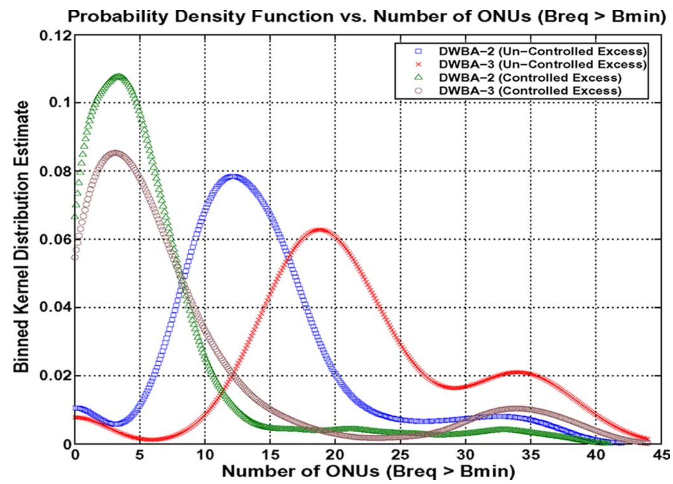
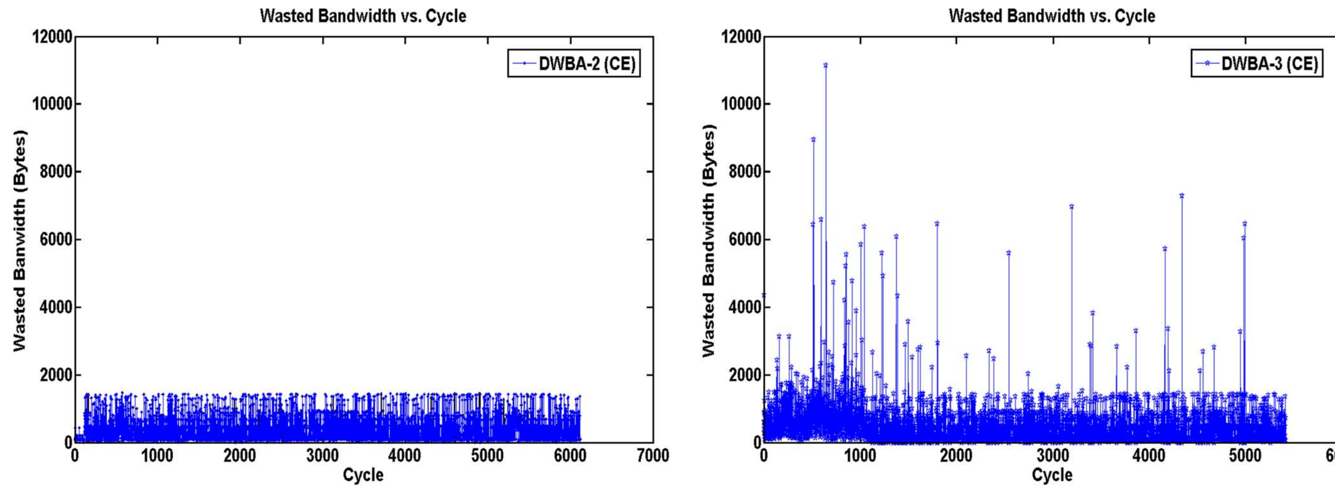


Fig. 5. "PDF" of number of ONUs (with $B_{\text{req}} > B_{\text{MIN}}$) ($K = 2$).

Finally, to compare the fairness of both CE and FE allocation schemes, we run our simulation at load $= 0.5$, and we measure the performance of two particular highly loaded ONUs. We choose the first ONU as the first highly loaded ONU (namely ONU_1) among the 64, since it is expected to be always satisfied when applying the CE scheme (see Section IV), while the second ONU (namely ONU_2) is chosen to be the last one among the 64. As expected and observed, the average packet delay for ONU_1 with FE is equal to 0.176690 s, and for ONU_2, it is equal to 0.176705 s. While with CE, it is 0.175538 s for ONU_1 and 0.176988 s for ONU_2. This shows the advantage of FE that fairly allocates the excess bandwidth and, thus, provide



(a) (b)

Fig. 6. Wasted bandwidth comparison.

almost the same performance for all highly loaded ONUs, whereas CE satisfies one highly loaded ONU over the other and mainly depends on the availability of the remaining excess bandwidth.

VII. Conclusion

We proposed a WDM-PON architecture which allows for high bandwidth utilization among multiple wavelengths. We presented new bandwidth-allocation schemes and provided a thorough comparison between them and studied their advantages and disadvantages. We showed that static-wavelength allocation may penalize ONUs with high load and will underutilize the PON resources, especially if the load is not symmetric. We showed that DWA increases the network efficiency. We presented three ways to efficiently allocate excess bandwidth among highly loaded ONUs, namely controlled, fair, and uncontrolled. We showed that by using CE bandwidth allocation, we increase the bandwidth utilization, and as a result, we improve the overall network performance. We also studied the performance of our schemes and compared with IPACT-ST as the number of wavelengths in the network increases.

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