Resource Management in STARGATE-Based Ethernet Passive Optical Networks (SG-EPONs)

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Abstract—At present there is a strong worldwide push toward bringing fiber closer to individual homes and businesses. Another evolutionary step is the cost-effective all-optical integration of fiber-based access and metro networks. STARGATE (IEEE Commun. Mag., vol. 45, no. 5, pp. 50–56, May 2007) is an all-optical access-metro architecture that does not rely on costly active devices, e.g., optical cross connects or fixed wavelength converters, and allows low-cost passive optical network (PON) technologies to follow low-cost Ethernet technologies from Ethernet PON (EPON) access into metro networks, resulting in significantly reduced cost and complexity. It uses an overlay island of transparency with optical bypassing capabilities. We first propose optical network unit architectures and discuss several technical challenges, which allow STARGATE EPONs (SG-EPONs) to evolve in a pay-as-you-grow manner while providing backward compatibility with legacy infrastructure and protecting previous investment. Second, and considering all the hardware constraints, we present the corresponding dynamic bandwidth allocation algorithm for effective resource management in these networks and investigate their performances (delay, throughput) through simulation experiments.

Index Terms—Dynamic bandwidth allocation (DBA); Ethernet passive optical network (EPON); Fiber-to-the-home (FTTH); Long-reach PON; Scheduling; Simulation and modeling; Wavelength division multiplexing (WDM).

I. INTRODUCTION

At present, there is a strong worldwide push toward bringing fiber closer to individual homes and businesses. Fiber-to-the-home or -business (FTTH or FTTB) or close to it networks are poised to become the next major success story for optical fiber communications [1]. In fact, FTTH connections are currently experiencing double-digit or even higher growth rates; e.g., in the United States the annual growth rate was 112% between September 2006 and September 2007, and their presence can add a value of U.S. $4,000–$15,000 to the selling price of a home [2]. FTTH networks have to unleash their economic potential and societal benefit by opening up the first or last mile bandwidth bottleneck, thereby strengthening our information society while avoiding its digital divide. FTTH networks hold great promise to enable the support of a wide range of new and emerging services and applications, such as triple play, video on demand, video conferencing, peer-to-peer (P2P) audio–video file sharing, multichannel high-definition television (HDTV), multimedia and multiparty online gaming, telemedicine, telecommuting, and surveillance [3].

Typically, FTTH or FTTB networks are built as passive optical networks (PONs), which provide numerous advantages such as longevity, low attenuation, huge bandwidth, and cost sharing of feeder-fiber infrastructure and optical line terminal (OLT) equipment among subscribers. PONs come in various flavors, with broadband PON, gigabit PON, and Ethernet PON (EPON) being currently installed worldwide by a number of network operators. Significant progress has been made in terms of cost reduction, multichannel upgrades of PONs by means of wavelength division multiplexing (WDM), and design of so-called colorless optical network units (ONUs), each connecting one or more subscribers to the PON [4]. Colorless ONUs are wavelength independent and require either no light source at all or only a broadband light source, resulting in decreased costs, simplified maintenance, and reduced stock inventory issues.

After paving in FTTH or FTTB networks all the
way to the end user with optical fiber, the next evolutionary step is the all-optical integration of fiber-based access and metro networks with the objective to avoid costly optical-electrical-optical (OEO) conversion at intermediate nodes (e.g., OLT) and thereby achieve major cost savings [5]. Very recently, research on optically integrated access-metro network architectures and protocols has gained momentum. One of the first research projects on the all-optical integration of access and metro edge ring networks was the so-called next-generation Internet optical network for regional access using multiwavelength protocols (ONRAMP) testbed [6,7]. The ONRAMP network architecture consists of a bidirectional feeder WDM ring network that connects multiple access nodes with one another and with the backbone network. The ONRAMP testbed implements and demonstrates, apart from optical flow switching, other features such as protection, media access control (MAC) protocols, control, and management. Another interesting research project is the Stanford University access (SUCCESS) network [8]. Its design objective is to provide a smooth migration path from currently widely deployed time division multiplexing (TDM) PONs to future WDM PONs and their all-optical integration by means of an optical single-fiber collector feeder ring, while guaranteeing backward compatibility with existing TDM PON customer premises equipment and providing increased capacity to users on new WDM PONs. The so-called metro access ring integrated network (MARIN) optically integrates hybrid TDM–WDM PONs into interconnected metro access ring networks by using optical reconfigurable and parametric wavelength conversion devices [9]. In MARIN, metro access ring networks can dynamically share and leverage light sources that were originally used to serve only the attached access network, resulting in a more efficient utilization of network resources and improved network performance [10]. A new all-optical access-metro network based on optical burst switching (OBS) was recently proposed and investigated in [11]. The optical access network segment consists of a hybrid WDM–TDM PON with reflective ONUs, a frequency-cyclic arrayed waveguide grating (AWG) at the remote node used as a wavelength (de)multiplexer, and a tunable laser and tunable photodetector stack at the OLT. Multiple WDM–TDM PONs are transparently interconnected by using a so-called OBS multiplexer (OBS-M), which optically interfaces with a distant metro router. The OBS-M deploys an optical cross connect that interfaces with the attached WDM–TDM PONs and a number of fixed wavelength converters. The OBS-M deploys a stack of tunable laser diodes to send optical continuous-wave (CW) signals to the attached reflective ONUs, each equipped with a reflective semiconductor optical amplifier (RSOA), for remote modulation of upstream data. The basic architecture of a single OBS-M and distant router can be extended to all-optically interconnect multiple OBS-Ms with a distant router through a reconfigurable optical add–drop multiplexer-based metro network with either a tree or a ring topology. According to [11], the all-optical OBS-based access-metro network is strictly nonblocking in the wavelength, time, and space domains. On the downside, however, the OLT and OBS-M architectures with the required tunable laser stacks, tunable photodetector stacks, wavelength converter banks, and optical cross connect significantly add to the cost, power consumption, footprint, and complexity of the all-optical access-metro network nodes.

In this paper, we take a different approach to all-optically integrate access and metro networks. Instead of deploying costly active devices, e.g., an optical cross connect or fixed wavelength converters, we rather rely on low-cost passive yet powerful optical devices. The all-optical access-metro architecture under consideration is referred to as STARGATE. STARGATE lets low-cost PON technologies follow low-cost Ethernet technologies from EPON access networks into metro networks, resulting in significantly reduced costs and complexity. It makes use of an overlay island of transparency with optical bypassing capability of OLTs. The rationale behind STARGATE and its basic operation was recently introduced in [12]. Note, however, that no particular ONU architectures nor dynamic bandwidth allocation (DBA) algorithms were specified in [12]. The contributions of this paper are twofold. First, we propose three different ONU architectures that allow STARGATE EPONs (SG-EPONs) to evolve in a pay-as-you-grow manner while providing backward compatibility with legacy infrastructure and protecting previous investment. Second, we design a DBA algorithm for SG-EPONs and investigate its performance by means of analysis and simulation.

The remainder of the paper is structured as follows. In Section II, we provide a brief overview of the STARGATE architecture and elaborate on the various proposed ONU structures for SG-EPONs. Section III outlines the operation of SG-EPONs, and Section IV describes our proposed DBA algorithm for SG-EPONs in great detail. Results are presented in Section V. Section VI concludes the paper.

II. SG-EPON Architecture

In this section, we will first briefly review the salient features of STARGATE and then describe our proposed ONU and OLT architectures for SG-EPONs at length.

A. STARGATE

In the following, we briefly review STARGATE. For a technically detailed description of STARGATE the
interested reader is referred to [12]. STARGATE all-optically integrates multiple WDM–TDM EPON access networks with a resilient packet ring (RPR) metro edge ring network. RPR, specified in IEEE 802.17, aims at combining SONET/SDH’s carrier-class functionalities of high availability, reliability, and profitable TDM (voice) support with Ethernet’s high bandwidth utilization, low equipment cost, and simplicity (see [13] for further details on RPR). The rationale behind STARGATE is based on (i) evolutionary space division multiplexing upgrades using additional P2P or point-to-multipoint (P2MP) fiber links in WDM–TDM EPONs; (ii) optical bypassing of the OLT, thus avoiding the need for OEO conversion and additional transceivers at the OLT; and (iii) letting low-cost passive optical networking technologies follow low-cost Ethernet technologies from access networks into metro networks.

The network architecture of STARGATE is shown in Fig. 1. The RPR network comprises $P$ central offices (COs) that are interconnected via a single-hop WDM star subnetwork whose hub is based on a passive wavelength-broadcasting $P \times P$ passive star coupler (PSC) in parallel with a passive athermal (i.e., temperature-insensitive) wavelength-routing $P \times P$ AWG. Each CO is attached to a separate input–output port of the AWG and PSC by means of two pairs of counterdirectional fiber links. Each fiber going to and coming from the AWG carries $\Lambda_{\text{AWG}} = PR$ wavelength channels, where $R$ denotes the number of AWG free spectral ranges (FSRs) used. Each fiber going to and coming from the PSC carries $\Lambda_{\text{PSC}}$ wavelength channels, consisting of one control channel $\lambda_c$ and a number of data wavelength channels. All COs (except the CO bridging the RPR network to the Internet) are collocated with a separate OLT of an attached WDM–TDM EPON. In each WDM–TDM EPON, $\Lambda_{\text{OLT}}$ wavelength channels are used for communication between a given OLT and its attached ONUs. Furthermore, each WDM–TDM EPON deploys an additional P2P or P2MP downstream fiber link from the CO to a single ONU or multiple ONUs, respectively. Each downstream fiber link carries $\Lambda_{\text{AWG}}$ wavelength channels coming from the AWG of the star subnetwork. Note that the $\Lambda_{\text{AWG}}$ wavelength channels are carried on the separate P2P or P2MP fiber link only in the downstream direction, while in the upstream direction they are carried on the WDM–TDM EPON tree network (along with $\Lambda_{\text{OLT}}$) and optically bypass the CO and OLT and are guided directly onward to the AWG by using a WDM coupler placed on the tree network in front of the OLT. Similarly, the $\Lambda_{\text{AWG}}$ wavelength channels coming from the AWG optically bypass both the CO and the OLT and directly travel on the P2P–P2MP link onward to the subset of attached ONUs. As a result, the ONU(s) attached to the P2P–P2MP links are able to communicate all-optically with each other in a single hop across the AWG of the star subnetwork, resulting in a long-reach (LR) optical island-of-transparency overlay.

In each WDM–TDM EPON, the OLT is equipped with an array of fixed-tuned transmitters and fixed-tuned receivers, as described in greater detail shortly. It is important to note that STARGATE does not impose any particular WDM node structure on the ONU, except for ONUs that receive data over the AWG. Those ONUs must be equipped with a multiwavelength receiver operating on the $\Lambda_{\text{AWG}}$ wavelength
channels in order to avoid receiver collisions (destination conflicts). STARGATE does not specify any particular WDM structure for all other ONUs, thus allowing these decisions to be dictated by economics, current state-of-the-art transceiver manufacturing technology, traffic demands, and service provider preferences. This approach allows for cautious pay-as-you-grow WDM upgrades of individual ONUs and thus helps operators realize their survival strategy for highly cost-sensitive access networks.

In each WDM/TDM EPON, IEEE 802.3ah MPCP REGISTER messages with appropriate WDM extensions are deployed for the discovery and registration of ONUs [14]. After registration, the OLTs exchange via the PSC the MAC addresses of their attached ONUs that are able to receive data over the AWG. As a result, all OLTs know which MAC addresses can be reached via the AWG and to which AWG ports the corresponding ONUs are attached. Upstream transmission on the \( \Lambda_{\text{OLT}} \) wavelength channels within each WDM–TDM EPON as well as all-optical transmission on any of the \( \Lambda_{\text{AWG}} \) wavelength channels to an ONU located in a different EPON is arbitrated by using MPCP REPORT and GATE messages with appropriate WDM extensions. Thus, STARGATE facilitates DBA within each WDM–TDM EPON (on \( \Lambda_{\text{OLT}} \)) as well as among different WDM–TDM EPONs (on \( \Lambda_{\text{AWG}} \)). Note, however, that similar to IEEE 802.3ah EPON, STARGATE does not specify any particular DBA algorithm.

B. SG-EPON Architecture

Taking the above mentioned requirements and restrictions of STARGATE into consideration, we propose a cost-effective STARGATE EPON (SG-EPON) that is designed to capitalize on the unique properties of STARGATE. SG-EPON is based on the standardized IEEE 802.3ah EPON [15] that comprises one OLT connecting to multiple ONUs in a tree topology manner. Nonetheless, in order to integrate SG-EPON with STARGATE, some modifications to the OLT and ONUs need to be done. We have studied many possible solutions and architectures while putting an emphasis on the technoeconomic factor that most EPON architects are concerned about [16]. In addition, we have studied the hardware cost and installation factor versus the complexity of software in EPONs and favored the software complexity, since its cost is minimal in comparison with that of hardware.

Figure 2 depicts the proposed SG-EPON architecture. The OLT is connected to the ONUs by using a single feeder-fiber link and a passive coupler at the remote node that splits and combines optical signals going to and coming from ONUs, respectively. Moreover, a WDM coupler is placed on the shared feeder-fiber link in order to guide AWG upstream traffic sent on the \( \Lambda_{\text{AWG}} \) wavelength channels directly onward to the AWG, possibly amplified if needed. Recall from Subsection II.A that the purpose of this coupler is to install all-optical communication channels between ONUs located on different WDM–TDM EPONs. This is done by bypassing the OLT and connecting directly to the AWG of the metro network of STARGATE, resulting in an all-optical single-hop path between these ONUs and thereby eliminating costly OEO conversions at the CO and OLT. The OLT as well as ONU structures are described in greater detail in the following.

![Fig. 2. SG-EPON single feeder-fiber network for smooth migration from legacy TDM ONUs to WDM-enhanced ONUs and LR ONUs.](image-url)
C. ONU Structures

SG-EPON is designed to enable a smooth migration path where nodes (OLT and ONUs) are upgraded in a pay-as-you-grow manner according to given traffic demands and/or cost constraints, while at the same time protecting existing ONU infrastructure investment. As outlined in greater detail shortly, current legacy TDM EPON ONUs typically deploy a laser diode (e.g., Fabry–Perot) and photodetector operating on two different coarse WDM wavelength channels. The objective of our proposed evolutionary upgrade approach is to build on these widely installed ONU transceivers rather than replacing them. As we will see shortly, this approach not only protects existing infrastructure investment and extends its amortization period but also helps improve the network performance considerably.

For increased flexibility, we allow an SG-EPON to comprise different types of ONUs with different specifications and capabilities. In the following, we introduce three different types of ONUs that can be customized according to given network needs and cost constraints. Note that any of the following ONUs can be smoothly upgraded from one type to another, depending on given network requirements and preferences.

1. TDM ONU. A TDM ONU is identical to an ONU found in widely deployed legacy single-channel TDM EPONs. As shown in Fig. 2, a TDM ONU is equipped with one fixed-tuned transmitter \( TX_{\text{TDM}} \) to send upstream data and control traffic to the OLT on upstream wavelength channel \( \lambda_{\text{up,TDM}} \), and one fixed-tuned receiver \( RX_{\text{TDM}} \) to receive downstream data and control traffic from the OLT on downstream wavelength channel \( \lambda_{\text{down,TDM}} \). Each TDM ONU may have multiple queues, each designated for a specific class of service. However, in this paper we do not consider quality-of-service differentiation. Thus, we assume that each TDM ONU is equipped with one queue to store incoming end user data packets.

2. WDM ONU. A WDM ONU has the same transmitting and receiving capabilities as the TDM ONU, i.e., one transmitter for \( \lambda_{\text{up,TDM}} \) and one receiver for \( \lambda_{\text{down,TDM}} \). In addition, a WDM ONU is designed to operate on multiple wavelengths (designated for ONUs with high traffic demand and/or a higher number of users), in both the downstream and the upstream directions. This could be achieved by installing an array of fixed-tuned transmitters, one for each upstream wavelength channel, and an array of fixed-tuned receivers, one for each downstream wavelength channel. Clearly, this approach limits the smooth upgrade of the ONU, especially if more wavelengths need to be added in the future to accommodate more users and increased bandwidth demands. Many alternatives have been studied with the design objective to achieve a more scalable ONU structure, while meeting low cost requirements [14,17–22]. One of the most promising low-cost ONU design solutions is the one that uses an RSOA for remote modulation of upstream data [22].

RSOAs are widely considered a strong candidate for realizing future low-cost ONUs in FTTH networks. An RSOA is much cheaper than a tunable laser diode and is expected to have similar cost to a fixed-tuned one. Moreover, it was shown that, considering expected prices of optical components, a WDM PON using an AWG as a wavelength demultiplexer at the remote node and RSOA-based ONUs has costs similar to a power-splitter-based TDM PON [16]. WDM PONs using a \( 1 \times N \) AWG as a wavelength demultiplexer at the remote node and RSOA-based ONUs, such as that in [11], provide some advantages, e.g., each of the \( N \) attached ONUs has a secure P2P wavelength channel. On the downside, however, WDM PONs based on a \( 1 \times N \) AWG suffer from several shortcomings. Among others, each wavelength channel is dedicated to a different ONU and thus cannot be shared by other ONUs, leading to (i) scalability issues, since the number of required wavelength channels has to be equal to the number of ONUs, and (ii) low wavelength utilization under bursty, unbalanced, and/or low traffic loads due to the lack of statistical multiplexing gain. To improve the wavelength utilization, SG-EPON leaves the coupler found in most of today's EPON tree networks untouched, thus allowing each wavelength channel to be shared and dynamically assigned to all ONUs, whereby the number of wavelength channels is independent of the number of ONUs. As shown in Fig. 2, WDM ONUs deploy an additional RSOA with a tunable bandpass filter (BPF) placed in front of it to select any of the \( W \) WDM wavelength channels \( \lambda_{1}, \ldots, \lambda_{W} \). Note that the \( W \) wavelength channels are used in addition to the two legacy TDM channels \( \lambda_{\text{up-down,TDM}} \) for upstream and downstream transmission of data traffic only. Control traffic between OLT and WDM ONUs is sent on the legacy TDM channels for backward compatibility with IEEE 802.3ah MPCP [14]. Similar to TDM ONUs, we assume that each WDM ONU deploys one queue to store incoming user data packets. Nonetheless, the selection of packets is synchronized between the RSOA and the fixed-tuned transmitter \( TX_{\text{TDM}} \), since both simultaneously operate on different wavelengths. Finally note that moving the AWG from the remote node of each PON toward the metro area and use it as a multiport wavelength router (rather than wavelength demultiplexer) enables extensive spatial wavelength reuse, where each wavelength channel can be simultaneously used at all AWG ports without resulting in channel collisions, translating
into a dramatically increased number of available communication channels and network capacity.

3. LR ONU. An LR ONU has the same transmitting and receiving capabilities as a WDM ONU. In addition, an LR ONU has the capability of all-optically communicating with another LR ONU in a different or in the same WDM–TDM EPON (e.g., for bulk data transfer such as database synchronization or file sharing). As shown in Fig. 2, a multichannel receiver RXₜ₉ₒ₉ₒ₉₉ operating on all λₐₕ₉₉₉₉ wavelength channels is used to enable receiving downstream data traffic coming from the AWG. Furthermore, the BPF of the RSOA is now tunable over the wavelength channels λ₁, ... , λₜ₉ₙ₉₉₉₉ where λ denotes the above-mentioned WDM wavelength channels. L denotes the number of additional wavelength channels used for optical upstream data transmission across the AWG (i.e., L = Lₐₕ₉₉₉₉ = PR).

On the intra-ONU level, in addition to the queue used to store TDM and WDM wavelength traffic, each LR ONU is equipped with a separate buffer for each destination SG-EPON. In other words, each LR ONU deploys L additional virtual output queues. The deployment of L virtual output queues is done in order to classify packets according to the destination SG-EPON (packet classification is described in greater detail shortly). Similar to WDM ONUs, the selection of packets is synchronized between the RSOA and the legacy fixed-tuned transmitter TXₜ₉₉₉₉₉.

D. OLT Structure

Similar to ONUs, the OLT will be exposed to evolutionary add-ons to accommodate the upgrades of the shared media (TDM, WDM, and AWG wavelength channels) and of ONUs with respect to both hardware and software (i.e., wavelength and bandwidth assignment), as shown in Fig. 2. Besides using a circulator to separate upstream and downstream wavelengths in conjunction with a wavelength multiplexer (MUX) and demultiplexer (DEMUX), the OLT is equipped with one fixed-tuned transmitter TXₜ₉₉₉₉₉ dedicated for the downstream transmission of data and control traffic on legacy wavelength λₜ₉₉₉₉₉₉ down and one fixed-tuned receiver RXₜ₉₉₉₉₉₉ for receiving upstream data and control traffic on legacy wavelength λₜ₉₉₉₉₉₉. In addition, an array of W fixed-tuned WDM transmitters TXₜ₉₉₉₉₉₉ plus L fixed-tuned LR transmitters TXₜ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉ₒ₉_o
One way to mitigate the detrimental effect of backreflections is to increase the linewidth of the seed light at the OLT. In fact, the effect of backreflections becomes negligible if incoherent light sources are used at the OLT, e.g., filtered amplified spontaneous emission [25]. Given that in SG-EPON the OLT is intended to deploy an array of coherent light sources that provide a higher bandwidth–distance product than incoherent ones, as needed for LR communication across the AWG, we have to resort to a different solution. To completely avoid the impact of backreflections on upstream transmissions, the authors of [12] suggested delaying the next upstream data transmission of a given ONU by the round-trip time (RTT), which is twice the propagation time $t_{\text{propagation}}$ from the OLT to the ONU. As shown in Fig. 4, suppose that the OLT first sends downstream data during the time interval $t_{\text{data}}$ using one of its fixed-tuned transmitters $\text{TX}_{\text{WDM}}$ or $\text{TX}_{\text{LR}}$. After propagation delay $t_{\text{propagation}}$, the data arrives at the destination ONU. The upstream data transmission from the ONU to the OLT is a bit more involved because the RSOA does not have its own light source. As a consequence, the OLT has to generate light by using one of its WDM transmitters $\text{TX}_{\text{WDM}}$ (in the case of a WDM ONU or LR ONU) or one of its LR transmitters $\text{TX}_{\text{LR}}$ (only in the case of an LR ONU) and send it downstream to the ONU. In Fig. 4, suppose that after transmitting its downstream data, the OLT sends the generated light to the ONU during the time period $t_{\text{carrier}}$, which can be of any arbitrary length. The ONU uses the carrier light reflected by the RSOA for sending its upstream data to the OLT during the time interval $t_{\text{propagation}}$. The upstream data transmission takes $t_{\text{propagation}}$ to arrive at the OLT. Now, to guarantee that the upstream data is received by the OLT without collision, the OLT must not use the same wavelength for downstream data transmission until the upstream data is completely received by the OLT. In other words, after generating the light and sending it downstream to the ONU, the OLT has to wait for one RTT until it is allowed to use the same wavelength again for downstream transmission of data. To better understand this constraint, Fig. 4 illustrates the case where the OLT does not wait for one RTT and starts its next downstream data transmission before one RTT has elapsed. The second downstream data transmission might be reflected at a reflection point (e.g., splice or connector) somewhere between the OLT and ONU and interfere with the upstream data transmission of the ONU, resulting in a collision. Clearly, by deferring its next downstream data transmission by at least one RTT the OLT can avoid any collisions. However, note that while waiting for the wavelength to become available, the OLT may use the downstream wavelength channel $\lambda_{\text{down}}$ to send data to any WDM, LR, and TDM ONU. Also note that this restriction holds only for data but not for a carrier sent in the downstream direction. For instance, in Fig. 4 the OLT might generate a second carrier on the same wavelength destined for a different ONU right after $t_{\text{carrier}}$, provided that the upstream data transmission of the second ONU does not overlap with the first one due to different propagation delays between the OLT and the two ONUs.

This solution is straightforward and efficient as in [11] because wavelengths are dedicated to each WDM ONU. However, some performance penalty is observed due to the RTT delay, especially in the case of shared wavelength resources among all WDM and LR ONUs. Applying this solution in SG-EPON, the OLT has to wait for one RTT between two consecutive CWs for two different ONUs ready to send on the same wavelength channel, leading to a waste of bandwidth. To overcome this problem, we propose a simple solution that meets the hardware restrictions of SG-EPON. We dispose $0 \leq D \leq W$ wavelengths (see Fig. 2) for the OLT to send downstream data (but no CW) to LR ONUs and WDM ONUs, i.e., the $D$ wavelength channels cannot be used by ONUs for upstream data transmission by means of remote modulation. Not only will this solve the problem, but it will also improve the bandwidth utilization. As a result, in its detection mode, the RSOA of an LR ONU or a WDM ONU will detect unmodulated CWs sent by the OLT on the remaining $W-D+L$ or $W-D$ wavelength channels and will then...

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**Fig. 4. Avoidance of effect of backreflections on the upstream transmission from ONU to OLT [11].**
perform the remote modulation and upstream data transmission on any of these same wavelength channels, respectively.

Clearly, SG-EPONs must take these constraints into account in order to efficiently utilize the available network resources, as discussed next.

III. SG-EPON Operation

Similar to IEEE 802.3ah EPON, SG-EPON has two modes of operation. The first is auto-discovery and registration, where the OLT learns about its connected ONUs and their hardware capabilities (i.e., number of transmitters–receivers, their tuning range, etc.) [15]. This information is mapped into the reserved fields of the REGISTER_REQ MPCP protocol data unit, which is WDM extended as recommended in [14]. The second is normal (on-service) operation, where the OLT utilizes the MPCP REPORT and GATE protocol data units to arbitrate the transmission of ONUs in the upstream direction. These two operation modes are mainly applied with TDM and WDM ONUs. For LR ONUs, however, we extend the registration mode to include a provisioning phase where they have to acquire some information from the OLT. Both provisioning and on-service phases are described in greater detail in the following.

A. Provisioning Phase

In the initialization phase, each OLT gathers information about ONUs local to its WDM–TDM EPON and broadcasts this information on the PSC to all other OLTs [12]. More specifically, each OLT shares with the other OLTs how many ONUs it is connected to and which ones are LR ONUs, including their MAC addresses and logical link identifiers (LLIDs). In doing so, each OLT is provisioned with a routing table that contains information about all WDM–TDM EPONs connected to the metro network. This table is used by the DBA algorithm (to be defined shortly) when assigning transmission grants to ONUs. This information is in turn broadcast by the OLT to its local ONUs. TDM and WDM ONUs may ignore it, since it is designated mainly for LR ONUs that will use this information for their traffic classifiers. Hence, unlike TDM and WDM ONUs, LR ONUs are provisioned with routing information (MAC address, LLID), appropriate wavelength channel in \( \lambda_{AWG} \) about remote ONUs residing in different WDM–TDM EPONs.

B. On-Service Phase

Similar to IEEE 802.3ah EPON, SG-EPON uses MPCP to exchange control messages between ONUs and the OLT. MPCP defines a polling-based access mechanism to facilitate dynamic bandwidth allocation for upstream data transmissions. MPCP makes use of two messages: REPORT and GATE. The OLT broadcasts GATE messages to the ONUs specifying the assigned transmission window (TW), start time, and length. Each ONU strips these grants based on its unique LLID and transmits traffic in the upstream direction accordingly. It then reports its current traffic requirements (queue occupancies) using the REPORT message at the end of its assigned window. For backward compatibility with conventional TDM EPONs, we run MPCP on the legacy wavelength channels \( \lambda_{TDM}^{up} \) and \( \lambda_{TDM}^{down} \), which are shared by all types of ONUs. More precisely, \( \lambda_{TDM}^{down} \) is used by the OLT to broadcast GATE messages as well as downstream data traffic. In addition to sending upstream data traffic, \( \lambda_{TDM}^{up} \) is used by any type of ONU to send REPORT messages. In SG-EPON, MPCP is extended to support both the time and wavelength domains by using the WDM extensions recommended in [14]. The OLT allocates TWs to each ONU based on its hardware capability and compliance with available resources. It is important to note that instead of specifying a particular DBA algorithm, MPCP provides only a control framework for developing a wide range of bandwidth allocation schemes. The design of a specific DBA algorithm is left to manufacturers and equipment vendors. For an overview of DBA algorithms proposed for WDM–TDM EPONs the interested reader is referred to [17, 26–28].

IV. DYNAMIC BANDWIDTH ALLOCATION IN SG-EPON

Having presented the SG-EPON architecture and its operation, a DBA algorithm is required to arbitrate the transmission of ONUs over the available shared wavelength channels. The OLT is responsible for assigning both bandwidth (to all ONUs) in addition to wavelengths (to WDM ONUs and LR ONUs) for upstream transmission.

Because of the hardware constraints imposed by SG-EPON, a DBA algorithm has to resolve many challenges. In the following, we outline the main factors that any DBA algorithm in SG-EPON needs to consider in order to provide efficient and fair scheduling of upstream transmissions:

1) The fact that there exist various shared resources makes the OLT the best candidate responsible for keeping track of all these resources in terms of bandwidth availability, fair sharing, and congestion control, as well as wavelength selection and availability.

2) The existence of various types of ONUs sharing various resources makes the OLT responsible for assigning different TWs on different wavelength channels. For instance, TDM ONUs are scheduled on the TDM wavelength channel only while
WDM ONUs are scheduled on the TDM and WDM wavelength channels and LR ONUs are scheduled on the TDM, WDM, and AWG wavelength channels.

3) The deployment of one RSOA per WDM ONU or LR ONU makes the arbitration of these ONUs over the AWG and WDM wavelength channels hardware dependent. For instance, the OLT has to take into account that it is impossible to assign two simultaneous TWs for a given WDM ONU or LR ONU. Furthermore, the DBA algorithm has to compensate for the consequence of such a restriction, which can result in waste of bandwidth, and should mitigate this fact by allowing, for instance, excess bandwidth allocation [17,26] and/or deciding to move traffic from one overloaded wavelength to another lightly loaded one, while keeping track of all TWs on all wavelength channels.

A. Preliminaries

Let us first define the various parameters used by our proposed DBA algorithm for bandwidth and wavelength allocation:

- $N_{\text{TDM}}$, total number of ONUs in SG-EPON.
- $N_{\text{WDM}}$, total number of TDM ONUs, where $0 \leq N_{\text{TDM}} \leq N$.
- $N_{\text{WDM}}$, total number of WDM ONUs, where $0 \leq N_{\text{WDM}} \leq N$.
- $N_{\text{LR}}$, total number of LR ONUs, where $0 \leq N_{\text{LR}} \leq N$.
- $L$, total number of available AWG wavelength channels in $\Lambda_{\text{AWG}}$; hence, the total number of AWG queues at each LR ONU equals $L$.
- $W$, total number of WDM wavelength channels in $\Lambda_{\text{OLT}}$.
- $D$, total number of downstream WDM wavelength channels.

Similar to other DBA algorithms presented for EPON in the literature, and in particular IPACT [29], time is divided into cycles (of maximum length $T_{\text{MAX}}$), and ONUs in each SG-EPON are allocated transmission opportunities in each cycle according to their bandwidth requirements (buffer occupancies). Specifically, each TDM and WDM ONU reports $B_{\text{req}}^{i}(n-1)$, since they have one buffer for traffic that is sent to the OLT, where $n$ is the cycle number. In addition to $B_{\text{req}}^{i}(n-1)$, each LR ONU reports $B_{\text{req}}^{j}(n-1)$ ($i=1, \ldots, L$), where AWG traffic, i.e., traffic sent across the AWG, is classified based on the MAC address in the packet header and is subsequently buffered in the corresponding AWG queue. As we mentioned earlier, all the REPORTs and GATEs are sent on the legacy TDM wavelengths.

On receiving the REPORTs from all ONUs, the OLT runs the DBA algorithm to schedule transmissions in cycle $n$ for these ONUs. If ONU $i$ is a TDM ONU, it will be assigned a window with start time $t_{\text{start}}^{\text{TDM},i}$ and length $t_{\text{length}}^{\text{TDM},i}$ on the TDM channel. If it is a WDM ONU, in addition to $t_{\text{start}}^{\text{TDM},i}$ and $t_{\text{length}}^{\text{TDM},i}$, the OLT has the choice of allocating one or more windows on one or more of the $W-D$ WDM wavelengths. Indeed, assigning more than one channel per cycle to a WDM ONU is feasible but introduces some overhead resulting from tuning the BPF when switching between wavelengths. Accordingly, our DBA assigns only one WDM wavelength $\lambda_j$, and hence a TW $t_{\text{start}}^{\text{WDM},j}$ and $t_{\text{length}}^{\text{WDM},j}$ per each WDM or LR ONU $i$ in one cycle. As a result, each upstream WDM channel is shared on average by no more than $[N_{\text{LR}}+N_{\text{WDM}}/(W-D)]$ ONUs. Finally, if ONU $i$ is an LR ONU, then in addition to $t_{\text{start}}^{\text{TDM},i}$, $t_{\text{length}}^{\text{TDM},i}$, $t_{\text{start}}^{\text{WDM},j}$, and $t_{\text{length}}^{\text{WDM},j}$, it will be allocated a window of $t_{\text{start}}^{\text{LR},i}$ and $t_{\text{length}}^{\text{LR},i}$ for each of the corresponding AWG wavelengths $\lambda_l (l=1, \ldots, L)$, which all-optically interconnects source and destination LR ONUs.

As mentioned above, the OLT is responsible for assigning wavelength channels to WDM and LR ONUs in addition to TWs. Note that the WDM wavelength selection differs from that of the AWG. For the WDM wavelength selection, the OLT maintains a variable for every channel, which is the channel free time $T_{\text{free}}^{\lambda}$ [17] of wavelength $\lambda$, when the next transmission is possible on this particular channel. For every REPORT message received from any WDM ONU, the OLT allocates a channel with the smallest $T_{\text{free}}^{\lambda}$ to this ONU and also determines the length (e.g., in bytes) of the TW allocated to this ONU on the assigned wavelength channel. On the other hand, the wavelength selection for LR ONUs on the AWG wavelengths is destination dependent. Thus, each LR ONU will be assigned a window together with a wavelength $\lambda_l$ that interconnects the source LR ONU with the corresponding AWG port to which the destination LR ONU is attached.

B. Minimum Bandwidth Guaranteed

Indeed, our main objective is to design an efficient, and yet simple DBA algorithm where the three factors mentioned previously are taken into account. For this purpose, we choose the grant length allocation to be based on the limited service, as proposed in [15]. In our DBA algorithm, each ONU is either granted what is requested or a minimum guaranteed bandwidth $B_{\text{min}}$ as in [26]. $B_{\text{min}}$ is dependent on the weight assigned to each ONU based on the service level agreement between the service provider and users. For simplicity, we consider equal weights for all ONUs.

Each type of wavelength (TDM, WDM, or AWG) is shared by a different number of ONUs. The TDM channel is shared among $N_{\text{TDM}}+N_{\text{WDM}}+N_{\text{LR}}$ ONUs. Hence,
where \( R_N \) (given in megabits per second) denotes the data rate, \( T_{\text{cycle}} \) denotes the cycle time, and \( T_g \) is the guard time that separates the TWs of two consecutive ONUs. Now, the minimum guaranteed bandwidth on an AWG wavelength \( \lambda_i \), assuming \( \lambda_i \) is shared by all LR ONUs in the same EPON, is

\[
B_{\text{min}}^a = \frac{(T_{\text{cycle}} - (N_{\text{TD}} + N_{\text{WDM}} + N_{\text{LR}}) T_g) R_N}{8 (N_{\text{TD}} + N_{\text{WDM}} + N_{\text{LR}})},
\]

(1)

Clearly, an LR ONU may be allocated with as much as \( LB_{\text{min}}^a \) in a cycle on all AWG wavelengths. Notice that if \( LB_{\text{min}}^a \) is close to \( T_{\text{cycle}} \), then the RSOA at that ONU is always busy transmitting AWG traffic. Since there is only one RSOA at each LR ONU, the remaining WDM wavelengths cannot be used by this ONU in the same cycle. Therefore, we modify the computation of \( B_{\text{min}}^a \) to consider the number of WDM wavelengths an ONU may use during one cycle:

\[
B_{\text{min}}^a = \frac{(T_{\text{cycle}} - N_{\text{LR}} T_g) R_N}{8 N_{\text{LR}}},
\]

(2)

where \( W_k \) can be the number of either one or more WDM wavelengths selected for upstream and downstream transmission (as described before). Since each LR ONU is not allowed to be allocated more than \( B_{\text{min}}^a \), then the minimum bandwidth guaranteed for LR ONUs on AWG and WDM channels is the same.

Similarly, each upstream WDM wavelength channel \( \lambda_j \) can either be shared by \( N_{\text{LR}} + N_{\text{WDM}} \) ONUs or by no more than \([N_{\text{LR}} + N_{\text{WDM}}/(W - D)]\) ONUs. Therefore, the minimum bandwidth guaranteed on \( \lambda_j \) is computed as follows:

\[
B_{\text{up}}^a = \frac{(T_{\text{cycle}} - (N_{\text{LR}} + N_{\text{WDM}}) T_g) R_N}{8 \max(N_{\text{LR}} L + W_k)},
\]

(3)

where \( D \) WDM wavelengths for downstream data, the OLT is also responsible for providing a bandwidth allocation scheme on these \( D \) wavelengths. As a result, the size of downstream TWs will also be bounded by a minimum bandwidth guaranteed \( B_{\text{up}}^a \), such that

\[
B_{\text{up}}^a = \frac{(T_{\text{cycle}} - (N_{\text{LR}} + N_{\text{WDM}}) T_g) R_N}{8 (N_{\text{LR}} + N_{\text{WDM}})}.
\]

(4)

\[\text{C. Bandwidth Allocation}\]

On receiving a REPORT message from any ONU, the OLT checks the type of this ONU. If ONU \( i \) is a TDM ONU, then the allocated bandwidth \( A_i \) on the TDM channel is computed as follows:

\[
A_i = \min(B_{\text{req}}^i, B_{\text{min}}^i).
\]

(6)

If ONU \( i \) is a WDM ONU, the allocation is achieved differently. For the assignment of non-AWG traffic (i.e., traffic that is not sent across the AWG), because the WDM channels are shared by fewer ONUs than the TDM channel and because they possess more bandwidth, the DBA algorithm tries to satisfy each ONU on the WDM channels first, then on the TDM channel. This will allow for an interchannel statistical multiplexing, which will increase the bandwidth efficiency of our proposed DBA algorithm. More specifically, on receiving a REPORT message from any WDM ONU, the OLT assigns bandwidth for cycle \( n \) based on the following conditions:

Condition 1: \( B_{\text{req}}^i \leq B_{\text{up}}^i \),
Condition 2: \( B_{\text{up}}^i < B_{\text{req}}^i \leq B_{\text{up}}^i + B_{\text{up}}^i \),
Condition 3: \( B_{\text{req}}^i > B_{\text{up}}^i + B_{\text{up}}^i \).

Consequently, the assigned bandwidth for the WDM ONU \( i \) on a WDM channel is computed as follows:

\[
A_i = \begin{cases} 
B_{\text{req}}^i & \text{Condition 1} \\
B_{\text{up}}^i, & \text{Conditions 2, 3}.
\end{cases}
\]

(7)

Similarly, WDM ONU \( i \) is allocated bandwidth on a TDM channel as follows:

\[
A_i = \begin{cases} 
0 & \text{Condition 1} \\
B_{\text{req}}^i - B_{\text{up}}^i & \text{Condition 2} \\
B_{\text{up}}^i & \text{Condition 3}.
\end{cases}
\]

(8)

When ONU \( i \) is an LR ONU, the computation of both \( A_i \) and \( A_i \) is done in the same fashion as the WDM ONU, except that \( B_{\text{up}}^i \) is replaced with \( \min(B_{\text{up}}^i, B_{\text{up}}^i) \) for the reasons described above.

As for the AWG traffic, each AWG output port corresponds to traffic destined to a separate destination SG-EPON, and hence no interchannel statistical multiplexing is possible. Thus, the bandwidth assigned on each AWG wavelength \( \lambda_i \) is computed as follows:

\[
A_i^{\lambda_i} = \min(B_{\text{req}}^\lambda_i, B_{\text{up}}^\lambda_i, B_{\text{up}}^\lambda_i).
\]

(9)

Note that since an ONU is equipped with only one RSOA, simultaneous transmissions on different wavelengths (AWG or WDM) is not allowed. Furthermore, while allocating bandwidth, the OLT needs to make sure that the length of the TW allocated to the ONU does not exceed the cycle length. In other words, \( \sum_{i=1}^{L} A_i^{\lambda_i} + A_i = B_{\text{cycle}} \), where \( B_{\text{cycle}} \) is the available bandwidth in a cycle (excluding the overhead).

Note that the assignment of WDM channels to LR ONUs depends on the total number of ONUs sharing the channels, which includes \( N_{\text{WDM}} \) as well as \( N_{\text{LR}} \). For that reason, we always select the minimum be-
between $B_{w,up}\text{min}$ and $B_{w,up}\text{max}$ rather than just selecting $B_{w,up}\text{max}$. Similarly, in the downstream direction, the OLT allocates bandwidth $A_{w,ds}$ to WDM or LR ONU, on the D WDM downstream wavelengths in the following manner:

$$A_{w,ds} = \min(Q_{w,ds}, B_{w,ds}\text{min}),$$

where $Q_{w,ds}$ is the buffer queue size located at the OLT and designated for buffering the downstream traffic destined to ONU$_i$.

On performing the bandwidth allocation, the OLT schedules the transmission of each ONU on the available wavelengths. The following section discusses the scheduling process.

D. Transmission Scheduling

As mentioned earlier, since in our current design each ONU (except the TDM ONUs) is equipped with only one RSOA, careful scheduling of these ONUs to different wavelength resources is required. In particular, an LR ONU can have access to both AWG and WDM wavelengths but cannot transmit on more than one channel simultaneously. Therefore, the task of the scheduler is twofold: checking the availability of a wavelength and that of the RSOA. The OLT must ensure that transmission conflicts are avoided while wavelengths are efficiently utilized. Indeed, scheduling these transmissions to different wavelengths can be formulated as an optimization problem where the objective is to maximize the system utilization. In this paper we will present a simple, conflict-free approach.

First, note that scheduling ONU transmissions on the TDM channel is straightforward and is done in a round-robin fashion. For scheduling a WDM ONU, on WDM wavelengths, only one upstream wavelength per cycle (for the reason described in Subsection IV.A) is allowed, and the first available wavelength is allocated (denoted $T_a$, the time when wavelength $\lambda_a$ becomes free). For downstream transmission, the same wavelength selection scheme is adopted on one of the $D$ downstream wavelengths, and TW is assigned to ONU$_i$, provided that it does not overlap with the TW allocated for upstream transmission of the same ONU$_i$ (the computation of the size of the TW is explained in Subsection IV.C).

Alternatively, for LR ONUs, scheduling transmissions is more challenging, because they may have traffic to send on multiple wavelengths in a cycle. Similar to WDM ONUs, LR ONUs can be scheduled to transmit on WDM channels by using the same principle. However, to schedule transmissions on AWG wavelengths, the OLT assigns each LR ONU with a transmission opportunity on one or more wavelengths ($\lambda_{w,j}$, $j=1,\ldots,L$); these allocated TWs must not overlap with each other, as well as those TWs assigned for the same ONU on WDM wavelengths. In particular, if ONU$_1$ is scheduled to transmit or receive on a WDM wavelength $\lambda_{w,k}$ during the interval $[t_0, t_1]$, then ONU$_i$ cannot be scheduled during the same interval to transmit on any AWG wavelength $\lambda_{a,j}$. Furthermore, if ONU$_i$ cannot be scheduled on wavelength $\lambda_{a,j}$ (because ONU$_i$ is scheduled on another wavelength at the same time), then $\lambda_{a,j}$ is assigned to another ONU and ONU$_i$ is scheduled at some other time that does not conflict with its current schedule.

Figure 5 depicts a simple example of how the scheduling is done for LR ONUs. Assume there are three LR ONUs (ONU$_{1,2,3}$) and two WDM ONUs (ONU$_{4,5}$) in the SG-EPON. Each of these ONUs is granted bandwidth on an upstream $(\lambda_{up})$ and downstream $(\lambda_{ds})$ WDM wavelength. Moreover, each LR ONU is also allocated bandwidth on both AWG wavelengths $\lambda_a$ and $\lambda_{w,1}$. We assume the bandwidth allocation is done in a limited-service manner, as described in Section IV.B.

On determining the different transmission opportunities for each ONU, the OLT starts scheduling these transmissions on WDM wavelengths first and then on AWG wavelengths (we assume that the scheduling of WDM ONUs has been done). Note that in Fig. 5, the already scheduled ONUs have been designated in gray. ONU$_{1,2,3}$ are all scheduled for upstream transmission on $\lambda_{up}$, starting at the time the wavelength becomes available. For scheduling these ONUs on AWG wavelengths, we start by $\lambda_a^1$; clearly neither ONU$_1$ nor ONU$_3$ can be scheduled to transmit at $T_a^1$, since that will overlap with the upstream transmission on $\lambda_{up}$ (for ONU$_1$) and with downstream transmission on $\lambda_{ds}$ (for ONU$_3$). Hence ONU$_2$ is scheduled on $\lambda_a^2$, followed by ONU$_3$, then ONU$_1$. The OLT then schedules these ONUs on $\lambda_{w,2}$ (we assume they have traffic to be transmitted to some other LR ONUs). None of the ONUs can be scheduled at $T_a^2$; the earliest time an ONU can be scheduled is $T_a^2 + \Delta t$, where $\Delta t$ corresponds to the earliest time that one of these ONUs (1, 2 or 3) will have its RSOA free to be allocated a TW. Hence ONU$_1$ is scheduled, followed by ONU$_2$ and then ONU$_3$.

Clearly, simple scheduling may result in many unused gaps, which yields to a poor resource utilization.
One approach for reducing this gap (in Fig. 5) is through splitting the transmission opportunity of ONU3 into two intervals; the first one between $T_a$ and $t_x$, where there is no conflict, and the rest of the transmission opportunity after $T_a + \Delta t$. In the rest of the paper, we have implemented only the simple scheduling mechanism.

In fact, the simple scheduling scheme does not guarantee any optimal allocation, but our ongoing work will focus on building a mathematical model to obtain some bounds on the performance and develop more efficient heuristics.

V. PERFORMANCE EVALUATION

In order to study the performance of STARGATE EPON as well as its corresponding DBA, a simulation of STARGATE based on OMNet++ is presented in this section.

There are various parameters to control in this metro-access network (e.g., FSR, the number free spectral ranges at the AWG; WDM upstream–downstream and AWG wavelengths; number of TDM–WDM–LR ONUs per SG-EPON; traffic pattern; transmission scheme). In our work, we study the impact of the upgrade we presented on the legacy TDM ONU traffic (Figs. 6–8) and on the WDM–LR ONU traffic (Figs. 9 and 10), as well as the overall throughput performance of SG-EPON (Figs. 11 and 12). This is the first performance analysis of SG-EPON. Further, since the Rayleigh effect affects the operation of the dynamic bandwidth allocation algorithm, a bidirectional transmission scheme is included in our study. The contention among TDM–WDM–LR ONUs on available bandwidth resources will also be investigated in Figs. 6–8. We note here that some performance penalty may occur on TDM ONUs due to traffic overflow from newly upgraded WDM ONUs, which indicates that a judicious upgrade should be followed by adding more WDM resources to the SG-EPON, which will be further explained in the following discussion.

Our simulation parameters are shown in Table I. Note that an EPON generally has a span of 20 km, and our STARGATE metro network interconnects several SG-EPONs. Those LR ONUs in our SG-EPON are capable of all-optically communicating with one another across the entire metro network. This means that the distance between different LR ONUs is variable, since they could be located in different SG-EPONs (e.g., over 100 km in distance) or in the same SG-EPON (e.g., less than 20 km). For this consideration, we set the average distance between an LR ONU and the AWG to be 40 km, indicating a 400 $\mu$s propagation delay.
In each simulation run, CBR (constant bit rate) traffic is generated and terminated at ONUs located at four SG-EPONs. The OLTs that reside on the PSC–RPR network simply take the responsibility for packet forwarding and do not inject any traffic into the network.

Figure 6 presents the average packet delay (with a confidence interval of 95%) experienced by legacy TDM ONUs on the TDM channel, when we vary their loads (20, 40, and 60 Mbits/s) and as the load on other ONUs (namely, the WDM and LR ONUs) varies. The varied load on other ONUs consists only of non-AWG traffic; here, we attempt to determine the impact this may have on the traffic delay on the TDM channel. Here, the total number of WDM wavelengths is 2, one for upstream and one for downstream traffic. Clearly, the higher the non-AWG load on WDM–LR ONUs, the more resources will be needed on the TDM channel (recall that the OLT assigns bandwidth for these ONUs on the TDM channel as well), and that will affect the delay experienced by TDM ONUs. First, we observe from the figure that as the load on TDM ONUs increases (e.g., from 20 to 60 Mbits/s), the delay increases substantially. This is because at lower loads the assigned TW is sufficient to carry the incoming traffic and the cycle duration is shorter (e.g., at \( x = 0.2 \) Gbits/s, 20/40 Mbits/s load, the observed traffic delay does not exceed 1 ms at these loads), hence the TDM channel delay is low. As the load increases, the length of the scheduling cycle increases, and the size of the assigned window may not be sufficient to transmit all packets in the buffer. Those packets that cannot be transmitted in this current cycle will be buffered until the next cycle (or more), and hence the delay will increase.

Now, as the non-AWG load increases on other ONUs, the delay experienced by TDM ONUs on the TDM channel increases as well, although the load on the legacy TDM ONU is kept unchanged (e.g., 20 Mbits/s). This is because as more non-AWG traffic arrives to those other ONUs, they will start requesting from the OLT more bandwidth than the \( B_{\text{min}}^{\text{up}} \) that they can get on the WDM wavelengths. The OLT will then assign them their bandwidth share on the TDM channel. This will indeed affect the traffic arriving at TDM ONUs, since the length of the cycle will start increasing, and hence we see an increase in the delay. Once the non-AWG traffic load reaches a certain intensity, the delay saturates (around 3.3 ms in Fig. 6) because the cycle reaches its maximum length; this means that a packet may be delayed on average by at most one cycle. A similar argument is used when the load on the TDM ONUs is 40 and 60 Mbits/s; however, at these higher loads, more packets will not get a chance to be transmitted as they arrive, but rather they are queued for a larger number of cycles, and hence the substantial increase in the delay (more than 300 ms).

Next, we study the effect of adding more WDM

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PARAMETERS</th>
</tr>
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<tbody>
<tr>
<td>No. of SG-EPONs</td>
<td>4</td>
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<tr>
<td>Data rate of metro wavelengths</td>
<td>10 Gbits/s</td>
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<tr>
<td>Data rate of TDM, WDM, AWG wavelengths</td>
<td>1 Gbits/s</td>
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<tr>
<td>Propagation delay between OLTs</td>
<td>200 ( \mu s ) (40 km)</td>
</tr>
<tr>
<td>Propagation delay between ONU and local OLT</td>
<td>100 ( \mu s ) (20 km)</td>
</tr>
<tr>
<td>No. of TDM, WDM, LR ONUs in each EPON</td>
<td>16, 8, 8</td>
</tr>
<tr>
<td>Queue size at OLT, ONU</td>
<td>10, 1 Mbytes</td>
</tr>
</tbody>
</table>
wavelengths. Figure 7 shows the average packet delay for traffic on TDM ONUs when \( W=4 \) and \( D=2 \) (i.e., two upstream and two downstream). The average delay behaves as in Fig. 6; when the non-AWG load is very low, the delay is exactly the same in both figures for 20, 40, and 60 Mbit/s TDM-ONU loads. When the aggregate non-AWG load increases (e.g., 1.1 Gbits/s), the delay starts to show some differences. For example, when the TDM ONU load is 40 Mbits/s, the delay is close to 1.4 ms, as opposed to 280 ms for the same load in Fig. 6. This is because adding more WDM wavelengths will increase the minimum bandwidth guaranteed (\( B_{\text{min}}^{sp} \)) that non-TDM ONUs can receive on these WDM channels. Hence, less non-AWG traffic will overflow to the TDM channel, and that will also result in shorter cycle lengths (as opposed to Fig. 6) and hence lower delays. As the non-AWG load continues to increase (\( \geq 2 \) Gbits/s), the cycle length reaches its maximum, and the average delay saturates (both WDM channels and the TDM channel are all saturated) to the same values observed in Fig. 6.

Finally, Fig. 8 shows the average delay when bidirectional transmission is used on all wavelengths (\( W=4 \)). Here, the RTT delay (close to 0.2 ms) between each upstream and downstream TW degrades the performance of WDM–LR ONUs on WDM channels; as we explained earlier, the ONU (in receiving mode) has to wait for this RTT after it sends its upstream data (recall one RSOA per ONU). Since these ONUs are allocated fewer resources on the WDM channels, they will request additional bandwidth on the TDM channel, which will clearly increase the cycle length and affect the TDM ONU traffic delay (packets at TDM ONUs will be buffered for a longer time before being transmitted).

Figure 9 shows the non-AWG traffic delay of WDM ONUs as the non-AWG traffic load varies. The traffic load of each TDM ONU is fixed to 40 Mbits/s. As expected, the delay increases as the load increases, with smaller delays obtained when the number of used wavelengths increases. For example, when the load is close to 2.2 Gbits/s, the delay reduces from 104 ms (\( W=2, D=1 \)) to 55 ms (\( W=4, D=2 \)). Note that the network saturates at higher load (close to 3 Gbits/s) in the experiment, corresponding to \( W=4 \) and \( D=2 \), which is almost 1.5 times that of \( W=2 \) and \( D=1 \) (between 1.2 and 2 Gbits/s).

The AWG traffic delay is depicted in Fig. 10 as we vary the AWG load intensity (four AWG wavelengths in total). Since the number of AWG wavelengths is fixed (FSR=1), we choose to change the number of LR ONUs (8, 12, and 20) in the SG-EPON in order to observe the variation of AWG traffic delay. Clearly, higher traffic delays occur at a larger number of LR ONUs, since more ONUs are sharing the same amount of bandwidth resources. We also observe that the throughput achieved per each LR ONU is close to 380 Mbits/s (260 and 150 Mbits/s) when there are 8 LR ONUs (12 and 20) in the network. In comparison with WDM ONUs (e.g., when \( W=4, D=2 \), the throughput per ONU is close to 150 Mbits/s), we notice the benefit we achieve from upgrading to LR ONUs wherein much higher throughput (e.g., 380 Mbits/s) can be obtained with similar traffic delays.

Next, we measure the SG-EPON throughput by counting the amount of received traffic (in bits) per time period (second) at the OLT. Figure 11 shows the throughput as we vary the non-AWG traffic load on all ONUs existing in one SG-EPON. The figure presents the throughput for three network setups: \( W=2, D=1; W=4, D=2 \); and \( W=4 \) with bidirectional transmission on each WDM wavelength. It is clear that higher saturated throughput is obtained when \( W=4 \) and \( D=2 \) (close to 2.5 Gbits/s or 83.3% utilization, where utilization=\( (2.5 \text{ Gbits/s})/\text{total capacity and total capacity} \) is two WDM upstream wavelengths and one legacy TDM upstream wavelength, 3 Gbits/s) as opposed to 1.7 Gbits/s when \( W=2 \) and \( D=1 \). Clearly, bidirectional transmission results in lower performance, which is due to the waste of one RTT per every cycle time.

For the AWG traffic, we measure the aggregate throughput at all LR ONUs in STARGATE. This is because the AWG traffic bypasses the local OLT and is directly received by the destination LR ONUs. Figure 12 depicts the AWG traffic throughput when the number of AWG wavelengths is four. The x axis represents the total AWG traffic load in STARGATE, while the y axis shows the throughput in gigabits per second. As a result of the wavelength spatial reuse property, four AWG wavelengths offer a total channel capacity of 16 Gbits/s among the four SG-EPONs. Therefore, the maximum throughput achieved of 13.2 Gbits/s indicates an 80% utilization of available bandwidth on AWG channels.

VI. CONCLUSIONS

In this paper, we presented STARGATE as a cost-effective architecture for all-optical integration of fiber-based access and metro networks. STARGATE is an all-optical access-metro architecture that does not rely on costly active devices and allows low-cost PON technologies to follow low-cost Ethernet technologies from EPON access into metro networks. We proposed several ONU architectures and discussed associated technical challenges, which allow STARGATE EPONs (SG-EPONs) to evolve in a pay-as-you-grow manner while providing backward compatibility with legacy infrastructure and protecting previous investment. We also presented the first dynamic bandwidth allocation and wavelength selection for the proposed
SG-EPON and evaluated the delay and throughput performance through extensive simulation studies.

REFERENCES