IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 25 March 2023, accepted 9 May 2023, date of publication 16 May 2023, date of current version 24 May 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3276861

RESEARCH ARTICLE

Energy-Efficient Sleep-Aware Slicing-Based Scheduler (SA-SBS) for Multi-Operators Virtualized Passive Optical Networks

KHALID H. MOHAMMADANI[1], (Member, IEEE), RIZWAN A. BUTT[2], WAQAS NAWAZ[3], SAFIULLAH FAIZULLAH[3], (Senior Member, IEEE), AND ZAHEER AHMED DAYO[1], (Member, IEEE)

[1]College of Computer Science, Huanggang Normal University, Huangzhou, Huanggang 438000, China
[2]Department of Telecommunications Engineering, NED University of Engineering, Karachi 75270, Pakistan
[3]Faculty of Computer and Information Systems, Islamic University of Madinah, Medina 42351, Saudi Arabia

Corresponding authors: Khalid H. Mohammadani (hussain@hgnu.edu.cn) and Waqas Nawaz (wnawaz@iu.edu.sa)

This work was funded by the Deanship of Scientific Research of the Islamic University of Madinah, Saudi Arabia, through the research group (first) project, under Grant 956.

ABSTRACT Due to the long reach of the next-generation passive optical network (PON), the idea of sharing infrastructure between multiple PON operators has emerged to reduce capital and operational expenditures. However, the standard transmission convergence layer requires an independent virtual bandwidth management process for each operator. Each operator uses a virtual dynamic bandwidth assignment (vDBA) for upstream bandwidth control. An additional bandwidth scheduler is required to create a single physical bandwidth map (phyBW-map) with non-overlapping time slots for each optical network terminal (ONT) or optical network unit (ONU) in the upstream frame. However, the existing slicing-based scheduler (SBS) using dynamic bandwidth assignment schemes does not perform well with the cyclic sleep process (CSP) for energy conservation in PON due to inefficient utilization of the residual bandwidth of the asleep ONUs of an operator. This work introduces an energy-efficient sleep-aware slicing-based scheduler (SA-SBS) for the multi-operator scenario of ten gigabit-capable symmetric PONs (XGS-PONs). Our approach (SA-SBS) achieves 7-10% better energy savings than the existing slicing-based scheduler (SBS) without compromising upstream delays and delay variance. Moreover, we demonstrate that our scheme outperforms the original SBS, resulting in an average delay(s) reduction of up to 28.5% for operators 1, 2, 3, and 4, respectively. Our findings can significantly improve the energy efficiency and latency performance of virtual PONs in multi-operator scenarios, paving the way for a sustainable and reliable communication infrastructure.

INDEX TERMS Bandwidth assignment, bandwidth efficiency, energy efficiency, MT-vPON, vPON.

I. INTRODUCTION

Internet usage has taken the shape of a necessity in our lives. The bandwidth demand for Internet connections with higher speed, quality of service (QOS), and quality of experience (QoE) continuously increases. The current COVID-19 pandemic situation has further accelerated the bandwidth demand globally. Recently, it was estimated that 66% of the world's population, or approximately 5.3 billion people, used the Internet in 2022 out of 8 billion people [1]. Modern optical access technologies play a crucial role in meeting these rising demands. The end-to-end optical-fiber-based connection from a central office to the home, known as Fiber-to-Home (FTTH), has become a reality in the last decade thanks to the emergence of passive optical networks (PONs) [2]. FTTH PON has experienced notable growth in bandwidth support and improved service quality [3], and research on its bandwidth and energy efficiency has become a significant focus

The associate editor coordinating the review of this manuscript and approving it for publication was Tianhua Xu.

of attention in recent years. The deployment of ITU-T PON and IEEE PON standards is continuously increasing globally, with a larger market share of ITU-T PON standards, such as giga-bit passive optical networks (GPON) [4]. The XGS-PON with 10Gbps data line rates on a single wavelength and time wavelength division multiplexing (TWDM) PON with 40Gbps line rates [5] with four wavelengths are the current GPON evolutions. Some PON vendor companies have also introduced a 50G PON, including ZTE [6], [7]. Next-generation PON (NGPON) technologies have improved the capacity and split ratios to 256 [8]. The coverage in the local loop also increases from 20 to 40 km, reducing PON vendors' operational expenses. The future prospects for NGPON are very bright, as they are expected to play a key role in future smart cities [9], front haul, and the backhaul of 5G wireless communication technologies [10], [11].

NGPON benefits are achieved at the cost of higher capital expenditure (CAPEX) owing to the more extended optical fiber infrastructure, which requires extensive digging and labor costs. Higher CAPEX costs discourage smaller and medium-sized vendors from entering the PON business. To address this issue, researchers have created solutions in the form of a virtual PON (vPON). In a vPON, multiple network operators coexist as virtual network operators (VNOs) in the same PON. Each VNO has an upstream (US) and downstream (DS) bandwidth scheduler called a virtual dynamic bandwidth allocator(vDBA), which prepares traffic schedules for downstream and upstream links. In addition to the schedulers of virtual network operators (VNOs), a slice scheduler engine sublayer is configured at the top of the transmission convergence (TC) layer of the physical optical line terminal (OLT). The slice scheduler engine sublayer receives individual traffic schedules from all VNOs and assigns overall upstream bandwidth independently to each VNO in a fixed time slot of 125 μs [12]. The merging scheduler engine sublayer can also be configured at the top of the TC layer of physical OLT, which is the aggregation mechanism to ensure high resource utilization without compromising the isolation of each VNO [13]. By implementing a multi-VNO scenario, the vPON can effectively utilize the physical capacity of XGS-PON, thereby increasing the network throughput. Moreover, by adopting this scenario, each VNO can operate independently without interference from other VNOs, thereby ensuring complete isolation.

A. CHALLENGES AND OPPORTUNITIES IN IMPLEMENTING ENERGY-EFFICIENT VPONS WITH SLEEP-AWARE CYCLIC SLEEP PROCESS FOR MULTIPLE VNOs

Virtual passive optical networks (vPONs) have recently become popular because of their energy efficiency and cost-effectiveness. Although XGS-PON is known to be one of the most energy-efficient broadband access networks, its high split ratio requires the use of the cyclic sleep process (CSP) to reduce further the power consumption of the optical network unit (ONU) [14], [15]. In virtual passive optical networks (vPONs) with multiple virtual network operators (VNOs), the use of the cyclic sleep process (CSP) can be challenging due to several factors. First, the current standard CSP process does not support the multi-operator concept. It treats all-optical network units (ONUs) equally, making it difficult to ensure efficient operation and operator isolation. The CSP process is necessary to support the VNO principle, guarantee productive operation, and keep operators separate in light of these changes. Second, the diversity of customers, services, and applications running on a vPON serving different quality of service traffic classes can significantly impact the performance of different VNOs. For instance, bursty traffic demand can result in traffic demands that significantly affect the performance of various VNOs. Third, the traditional slicing-based bandwidth scheduler (SBS) used in vPONs allocates bandwidth to ONUs based on predefined time slots, regardless of their actual traffic load or power consumption. However, this approach can result in inefficient bandwidth allocation and reduced network efficiency. The ONUs in a sleep state during periods of low traffic is still allocated bandwidth, even though they cannot use it.

Our proposed approach incorporates current energy efficiency approaches and tailors them to the unique challenges of vPON networks. Specifically, we introduce a sleep-aware slicing-based bandwidth scheduler (SA-SBS) that coordinates with the virtual dynamic bandwidth allocation (vDBA) process to optimize energy consumption and bandwidth allocation in vPONs. By utilizing the sleep-aware state of ONUs during periods of low traffic and optimizing bandwidth allocation to ONUs in different states, our approach aims to enhance energy efficiency and reduce the wastage of valuable network resources. Although our proposed approach incorporates current energy efficiency approaches, it is specifically adapted to the unique challenges and requirements of vPON networks, making it a new and innovative approach for this scenario.

In a vPON, combining the individual traffic schedules of each VNO in the downstream direction is straightforward because ONUs send traffic frames to a splitter on a first-come-first-served basis [16], [17]. However, in the upstream direction, ensuring fair distribution of available bandwidth among different ONUs is challenging because of the need to synchronize and coordinate with the virtual dynamic bandwidth allocation (vDBA) process of each VNO. The upstream virtualization process is complex and requires sophisticated techniques to ensure optimal performance, especially with the additional requirement of operator isolation when using the cyclic sleep process (CSP) for energy conservation. The existing virtualization process is not energy efficient as it considers all ONUs during the scheduling process, irrespective of their CSP state. Since an ONU in a sleep state cannot utilize the assigned bandwidth, this results in wasted bandwidth. Thus, sharing unused bandwidth across VNOs can improve network efficiency. However, this approach requires effective coordination between the CSP and vDBA processes and carefully considering the diverse traffic demands of different VNOs to ensure fair distribution of available bandwidth while maintaining QoS and operator isolation. Therefore, developing an effective sleep-aware virtual scheduling mechanism that considers the CSP states of ONUs and the traffic demands of different VNOs is crucial for minimizing ONU power consumption and efficiently allocating available bandwidth in a multi-operator vPON environment. The cyclic sleep process (CSP) for energy conservation in vPON severely degrades the upstream link performance due to the higher traffic queueing in the Asleep ONUs. The lack of coordination between the DBA and CSP processes reduces energy savings due to the early triggering-up of local wakeup indication (LWI) events. A CSP-aware DBA process with a slicing mechanism improves energy savings with better QoS due to better utilization of the available bandwidth.

B. LIMITATIONS OF THE TRADITIONAL SLICING-BASED BANDWIDTH SCHEDULER IN ENERGY-EFFICIENT vPONs

Understanding the current energy efficiency approaches for conventional PONs helps to analyze energy efficiency in vPONs. Conventional PONs has been widely deployed but suffer from limitations in terms of energy consumption due to their static bandwidth assignment. In contrast, vPONs provide a more flexible and efficient bandwidth allocation. Still, they also pose new challenges for energy efficiency due to the dynamic and adaptable nature of the network. The traditional Slicing-Based Bandwidth Scheduler (SBS) used in vPONs has limitations regarding energy efficiency and efficient bandwidth allocation to ONUs in different states. Specifically, the SBS does not consider the power consumption of ONUs during periods of low traffic, leading to inefficient energy usage. In addition, the bandwidth allocation to ONUs in the SleepAware or Asleep states is not optimized, wasting valuable network resources. Therefore, a power-saving mechanism that utilizes the SleepAware state and coordinates with the virtual dynamic bandwidth allocation (vDBA) process is required to address these limitations and enhance the energy efficiency and bandwidth allocation in vPONs. By proposing a novel energy-efficient approach for vPONs that incorporates the ITU-T recommended energy-saving processes, we aim to contribute to developing more efficient and sustainable vPON networks.

Table 1 provides a list of the essential acronyms used in this study.

TABLE 1. Table of acronyms.

Acronyms	Definition
ρ	Server Utilization Ratio
µs	Microseconds
AB (min, max, and surp)	Allocated Bytes (minimum, maximum, and surplus)
AF / T_{AF} / P_{AF}	ActiveFree / Active Free Time /Power consumption during AF state
AH / T_{AH} / P_{AH}	ActiveHeld / Active Held state Time / Power consumption during AH state
Alloc	Allocation
AS / T_{AS} / P_{AS}	Asleep / Asleep Time / Power consumption during AS state
B	Bytes / Bandwidth
CSP	Cyclic Sleep Process
DR	Delayed-Release
DS	Downstream / Delayed Sleep
EE	Energy Efficiency
K	Operators
LWI	Local Wakeup Indication
NFV	Network Function Virtualization
QoS	Quality of service
QR	Quick Release
RTT	Round Trip Time
SA-SBS	Sleep-Aware Slicing-Based Scheduler
SDN	Software Defined network
SI	Service Interval
T_{SLA}	Sleep Aware Time
TCONT	Transmission Container
T_{SIM}	Total Simulation time
US	Upstream
vBWMap	Virtual bandwidth map
vDBA	Virtual dynamic bandwidth allocation
VNO	Virtual network operator
VPON	Virtual passive optical network
XGs-PON	10 giga-bit passive optical network

C. NOVELTY AND SIGNIFICANCE OF THE PROPOSED SOLUTION

1) The study proposes a new version of the slicing-based bandwidth scheduler (SBS), called the Sleep-Aware Slicing-Based Bandwidth Scheduler (SA-SBS), for Virtual Passive Optical Networks (vPONs) with multiple Virtual Network Operators (VNOs) sharing a single Optical Line Terminal (OLT).
2) The SA-SBS is a power-saving mechanism that utilizes the SleepAware state of the Cyclic Sleep Process (CSP) to reduce the power consumption of Optical Network Units (ONUs) in vPONs.
3) In addition, the SA-SBS coordinates with the Virtual Dynamic Bandwidth Allocation (vDBA) process to efficiently allocate bandwidth to ONUs in the ActiveHeld or ActiveFree states while utilizing the bandwidth of ONUs in the SleepAware or Asleep states, which would otherwise go to waste.
4) The proposed SA-SBS scheme achieves a remarkable 7-10% performance gain compared to the simple SBS scheme due to the prolonged ONU asleep states and resultant energy savings. It also results in an average delay reduction of up to 28.5% for operators 1, 2, 3, and 4, respectively.
5) The proposed approach enhances the overall energy efficiency of virtual optical access networks while minimizing the wastage of valuable network resources.

This article is organized as follows. Section II reviews related works. Section III explains the material and methods, including the system model, CSP states, and the proposed energy-efficient SA-SBS scheme. Section IV describes the simulation setup, while Section V presents numerical results and a discussion. Finally, Section VI concludes the paper by outlining future research directions.

II. RELATED WORK

The use of network function virtualization (NFV) and software-defined networking (SDN) facilitates the implementation and update of network control and management policies [18]. NFV virtualizes specific network functions, whereas SDN separates network control and data to enable centralized management and programmability [19]. Previous works [20], [21] investigated the usage of SDN and NFV in optical and core networks. This study focuses on the concept of NFV in the context of a virtual Passive optical network. Virtual PONs (vPONs) are promising technology for delivering service to end users. However, designing practical algorithms that can manage and allocate bandwidth in real-time is crucial for achieving high performance and efficiency. In vPON literature, the NFV concept has been implemented in two ways: Multi-OLT virtual PON (MO-vPON) and Multi-Tenant(Operators) virtual PON (MT-vPON) [22], [23]. An OLT process manages the downstream traffic to ONUs in the network. In the multiple OLT process approach, multiple OLTs are used to manage and control downstream traffic to the subset of ONUs in vPON, while in the single OLT process approach, a single OLT is used to perform this task. The choice of approach has significant implications for network performance and efficiency. To create a taxonomy of the different approaches in the literature to support vPONs, we can categorize them based on the use of multiple or single OLT processes for managing the downstream traffic to the ONUs, as well as the virtualization of PON to support multiple operators and the investigation of energy efficiency in vPON.

a) MO-VPON: In the MO-vPON approach of NFV, a centralized physical OLT (main server OLT) virtualizes multiple OLT processes or manages multiple client OLTs. Each client OLT is responsible for a subset of respective ONUs in vPON and has its bandwidth allocation policies and upstream bandwidth maps [24]. The client OLT processes can cooperate with the help of the centralized physical OLT to provide better services to their ONUs. This approach enables the efficient use of the network while the chance of high latency is possible due to the regrouping of their ONUs via centralized OLT. Conversely, the MT-vPON approach allows multiple PON operators to coexist virtually in a single shared OLT, with each operator controlling its group of ONUs.

b) MT-VPON: Another approach MT-vPON of NFV is a more attractive option for small network operators (NOs) since they can save huge CAPEX and maintenance costs by only paying the rent to the vendor for their services. It also gives the freedom of Pay-As-You-Grow with an increasing number of customers in the future. However, in such scenarios, the isolation of operators and efficient utilization of available resources may be somewhat challenging, particularly in the upstream direction. Each VNO should be able to assign its portion of assured and best-effort traffic to its customers without affecting or being affected by other VNOs. Various approaches have been proposed for the second case of NFV vPON without considering the power consumption [12], [13], [25], [26]. The study [12] proposes a mechanism for sharing bandwidth on the XG-PON transmission convergence layer in scenarios involving multiple operators. The primary focus of that work was to periodically assign the full upstream slot of 125μs to each operator. However, the chance of high latency is available in this framework due to poor vendor isolation. Another study addressed this weakness [13], where the authors considered frame level sharing framework for XGS-PON. They presented a merging concept to combine the individual virtual BWmaps of all VNO into a single physical BWmap during a single downstream frame slot (i.e., 125μs). To better distribute the bandwidth among tenants in the merging engine, the authors of [21] proposed a Priority-Based Merging Algorithm (PBMA). The PBMA approach reduces low-priority traffic in congested traffic; therefore, this approach is reliable for distributing the physical bandwidth resource to high-priority tenants. Nevertheless, the PBMA technique is unsuitable for the same priority traffic if numerous tenants simultaneously demand the same downstream frame slot. The study in Ref [26] noted inconsistency with the PBMA approach and presented a Load adaptive merging algorithm (LAMA) for the same scenario. The proposed mechanism operates in three phases. In phase 1, the authors consider a sequential bandwidth merging process without reducing any assigned virtual bandwidth. In Phase 2, the authors employ a higher-to-lower priority-based scheme and reduce low-priority virtual assigned bandwidth to fulfill the requirement of physical bandwidth. Lastly, in phase 3, residual bandwidth is allocated to each client of each VNO adaptively so that all the priority traffic can get some portion of the downstream frame, leading to control delay of all priority traffic. The proposed scheme has shown better network performance when compared with the PBMA scheme.

c) 5G and Network Slicing in vPON: In addition to the literature on vPON, several recent studies have investigated the potential of 5G radio access network (RAN) slicing to improve resource allocation in multi-tenant environments. Among these studies is the work of [27], who proposed a dynamic single-tenant radio resource orchestration framework for eMBB traffic within a multi-slice scenario. Another promising approach for optimizing 5G RAN resource allocation is using flexible and functional splits in a multi-tenant environment. This idea is explored in the work of [28], who developed a resource-slicing framework for 5G RAN with flexible and functional splits. To further improve resource orchestration in 5G networks, several researchers have focused on developing network slicing frameworks. One such framework is proposed by [29], who presented a multi-service single tenant 5G fronthaul resource orchestration framework based on network slicing. The studies proposing 5G RAN slicing solutions for resource allocation in multi-tenant environments using technologies such as SDN, NFV, virtualization, and cloud but lack focus on energy consumption. Significant investment may be required to implement these solutions on a large scale, and they may not be compatible with existing networks or delay-sensitive service requests. Future research can explore energy savings and efficiency factors to overcome these limitations. To the best of our knowledge, only a few studies have investigated the energy efficiency in the case of virtualization of PON [30], [31], [32], [33]. The first study [30] applied the concept of sleep to the virtual servers connected to an ONU. They only activate the minimum number of required servers subject to the user's bandwidth demand to achieve energy savings. The second study [31] achieved energy savings by activating only the minimum wavelengths in a 5G front-haul scenario interfaced with the TWDM PON. The study in [32] used dynamic activation of virtual BBU functions in cloud fog nodes to achieve energy efficiency. In [33], the author proposed a software-defined network (SDN) based vPON architecture to save energy at OLT for a TWDM PON. A fundamental limitation of this research is that it does not address the problem of multiple operators at the SD OLT.

TABLE 2. Comparison of Virtualized PON architectures and implementations.

Ref	Approach	Main Contribution	Limitations	EE
[12]	NFV vPON	Bandwidth sharing on the TC layer of XG-PON	High latency due to poor vendor isolation	No
[13]	NFV vPON	Frame level sharing framework for XGS-PON	Does not handle a large number of VNOs	NO
[25]	NFV vPON	Priority-Based Merging Algorithm (PBMA) for multi-tenants	Not well-suited for the same priority traffic, which needs the same slot as the DS frame	NO
[26]	NFV vPON	Load adaptive merging algorithm (LAMA) for multi-tenants	Limited handling of congestion control.	NO
[27] [29]	NFV	Network Slicing Techniques for 5G	Multi-Tenant and Multi-Services	NO
[30]	VPON	Sleep concept for vServers connected to an ONU	Limited to single fixed OLT, not shared OLT	YES
[32]	VPON	Activating virtual BBU functions in fog nodes	Not addressing the problem of Multi-Operators in PON	YES
[33]	SDN vPON	SDN-based OLT for vPON architecture	Not address the problem of multiple operators	YES
This Work	NFV vPON	Enhancing power efficiency in Multi-Operator vPON using optimized Cyclic Sleep mode	Limited to slicing bandwidth scenarios and not well suited for merging bandwidth scenario	YES

Table 2 compares the limitations of the previous and proposed works in this study. Above all, a few studies have considered virtualization PON. While these earlier works have addressed essential aspects of bandwidth allocation and network performance, they have not considered the crucial energy conservation factor, which is becoming increasingly important today. Previous studies have neglected the energy-saving processes recommended by ITU-T, such as the cyclic sleep process (CSP), the cyclic doze mode (CDM), and the watchful sleep mode (WSM) [34], [35], [36]. This knowledge gap highlights the need for new research incorporating these energy-saving processes into the design of network scheduling mechanisms. By comparing these different approaches in the literature, this research study takes a novel approach to contribute to developing a more efficient and sustainable vPON network for multi-operator scenarios. Unlike previous studies, this study proposes a sleep-aware slicing-based bandwidth scheduler (SA-SBS) that incorporates the ITU-T-compliant cyclic sleep process (CSP) to conserve the energy of ONUs. Our approach minimizes energy consumption while maintaining acceptable upstream and downstream delays, leading to a more sustainable and cost-effective broadband access network.

III. PROPOSED METHODOLOGY

In this section, we analyze and contrast the advantages and disadvantages of traditional PONs designed for a single operator versus virtual PONs intended for multiple operators using a shared OLT. The cyclic sleep process (CSP) technique is then introduced and explained. We then elaborate on our proposed approach that combines a delayed LWI-based CSP process with an energy-efficient bandwidth scheduler. Additionally, we discuss the complexity of the proposed scheduling algorithm.

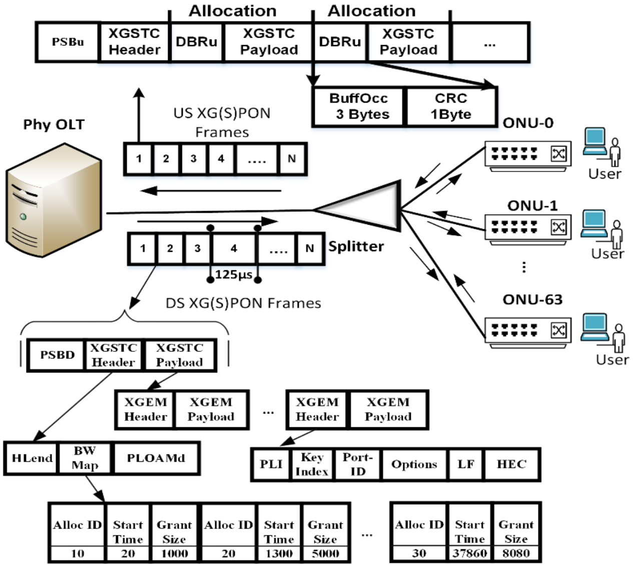


FIGURE 1. Single-operator(unshared OLT) with downstream allocation in XGS-PON.

A. TRADITIONAL PON ARCHITECTURE V.S. vPON ARCHITECTURE

The traditional XGS-PON architecture with a single unshared OLT, as shown in Fig. 1, presents limitations for private operators, who invest large sums of money in network deployment and consume large amounts of energy. For instance, deploying private broadband network infrastructure in the same geographical area by multiple operators leads to increased costs and a high risk of expensive capital expenditure (CAPEX) costs due to sudden changes in the number of subscribers with high bandwidth requirements.

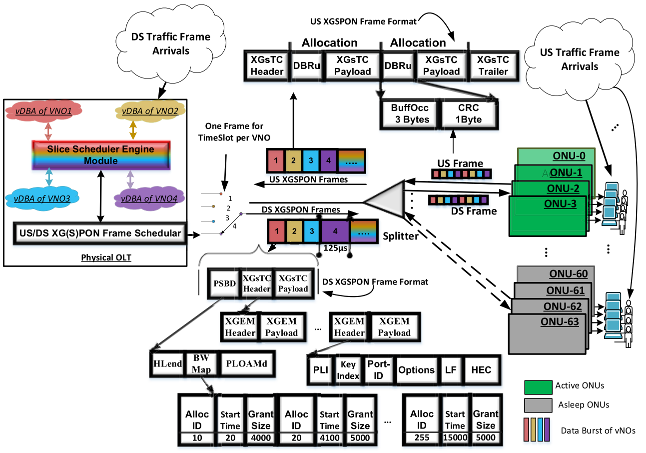


FIGURE 2. Multiple virtual network operators (VNOs) and their allocation for their active ONUs in XGS-PON.

To address the limitations of traditional XGS-PON architecture, we have modified the VPON architecture described in [12] to implement the energy consumption-based vPON architecture for multiple operators. The modified architecture, depicted in Fig. 2, includes the slicing scheduler engine process with active and asleep ONUs. In the vPON framework, different virtual network operators' (VNOs) processes work simultaneously inside a single shared OLT, eliminating the need for private infrastructure in the same geography. The network-shared infrastructure reduces the CAPEX of the private infrastructure and power consumption. The main benefit of this shared network is that each VNO has complete freedom to use its own vDBA process and create its vBW-map for the upstream transmission of its active group of ONUs.

In the modified vPON architecture, each operator (k) serves its own set of ONUs (L) and prepares a vBW-map, which maps the available bandwidth to different traffic classes, TCONT types, and ONUs. Each operator's vDBA process assigns bandwidth to TCONT types (T1, T2, T3, and T4) in a strict priority order as QoS traffic classes. It sends the assigned bandwidth to the slicing scheduler engine (SSE), which arranges them as bursts for each group of active ONUs belonging to each operator(k). These bursts are scheduled for the next upstream frame in the physical BWmap field of the current downstream frame, as depicted in Fig. 3. Within each burst, the bandwidth slots allocated to each ONU for its T1 to T4 traffic classes are rescheduled contiguously to form a burst.

A scheduling strategy based on slicing is employed to address the issue of non-overlapping time-slots and avoid collisions of ONU traffic belonging to different VNOs. The slicing scheduler engine (SSE) allows each VNO to send a vBW-map to its ONUs individually in a TDMA round-robin fashion. This approach enables individual ONUs to receive their assigned bandwidth slots non-overlapping, ensuring efficient and effective traffic transmission. Using this approach, different VNOs can transmit their traffic without any interference. The slicing and vBW-maps can map the available bandwidth to different traffic classes, TCONT types, and ONUs, allowing for efficient bandwidth allocation. The modified vPON architecture helps to ensure that QoS requirements are met, reduces costs and energy consumption, and provides high-quality broadband services to subscribers.

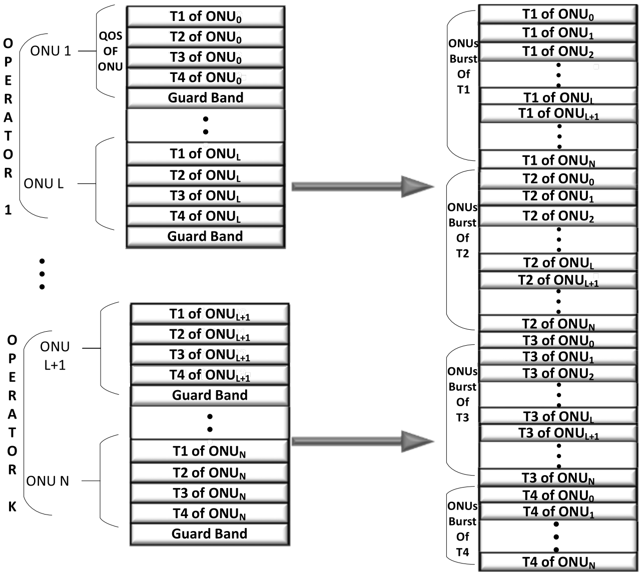


FIGURE 3. Conversion of the Operator K allocations to ONU burst by SS.

The vDBA process dynamically allocates bandwidth based on the current demand for different types of traffic. This process ensures that bandwidth is allocated reasonably and efficiently based on the available capacity and the QoS requirements of other traffic classes. The service rate of the vDBA process of each operator(k), μ_k^{vDBA}, is defined in Eq (1):

$$\mu_k^{vDBA} = K \times (\frac{B_{US}[k]}{SI}) \tag{1}$$

Here, $B_{US}[k]$ represents the total upstream bandwidth of operator[k], and SI represents the service interval of the vDBA scheme.

The service rate (μ_k^{vDBA}) represents the bandwidth allocated to the ONUs of operator[k] in each time interval based on the available upstream bandwidth and the service interval. Adjusting the service interval or the total upstream bandwidth can increase or decrease the service rate accordingly. This equation is a vital component of the vDBA process, as it allows for efficient bandwidth allocation to different types of traffic and ensures that QoS requirements are met.

B. QUICK RELEASE(QR) AND DELAYED-RELEASE (DR) BASED CSP PROCES

The CSP process comprises of SleepAware (SLA), ActiveHeld (AH), ActiveFree (AF), and Asleep (AS) states of the

ONU [34]. The energy savings of the ONU depend on the length of its sojourn in these states, with a higher sojourn in AS state resulting in higher energy savings and lower power consumption. Local wakeup indication (LWI) events at the OLT and the ONU control the sojourn of the ONU in these states, which are generally configured based on some traffic conditions. Three methods were proposed to control the LWI events: Quick Release (QR) [37], Delayed Sleep (DS) [38], and Sleep Buffer (SBR) [39]. The QR method minimizes the ONU sojourn in the AS state and provides the least energy savings with a slight increase in upstream and downstream delays. The SBR method maximizes energy savings but results in much higher upstream and downstream delays that do not exceed predefined delay targets. The DR method delays the LWI event for a fixed period of T_ONU at the ONU and T_OLT at the OLT, providing medium savings with a medium increase in delays. A comparison of these three methods has been presented in [39], and the DR approach results in consistent energy savings at all loads due to a fixed delay time holding the LWI events. The traffic flow between the OLT and the ONU can be modeled by an M/G/1 queuing system, as discussed in Reference [40]. When the CSP process is introduced in the PON system, this modeling scenario becomes a special case of a queuing system with a server on vacation. In this situation, the upstream and downstream delays can be written as Eqs. (2)-(3), Where λ_{DS} and λ_{US} are the downstream and upstream traffic frame arrival rates, $\bar{V}$ is the mean vacation time of ONU, ρ is the server utilization ratio defined as; $\rho = \frac{\lambda}{\mu}$, $\bar{X}^2$ is the second moment of the service time, RTT is the round trip time and is equal to twice the channel delay T_{ch}.

$$D_{DS} = \frac{\lambda_{DS}\bar{X}^2}{2\,(1-\rho)} + \frac{\bar{V}^2}{2\bar{V}} + \frac{RTT}{2} + T_{init}, \tag{2}$$

$$D_{US} = \frac{\lambda_{US}\bar{X}^2}{2\,(1-\rho)} + \frac{\bar{V}^2}{2\bar{V}} + \frac{RTT}{2} + \frac{SI}{2} + T_{init}, \tag{3}$$

The SI is the service interval that defines the time session after which the DBA process sends the upstream bandwidth and T_{init} is the ONU transceiver initialization time when it switches from AS state to AH, AF, or SLA state. In the case of the DR approach with a fixed AS state time of $\mathrm{T_{AS}}$. The mean vacation time of the ONU and the OLT can be resolved in terms of the LWI holding time T_{LWI}. Thus, we can rewrite the delays equations as Eqs. (4) - (5).

$$D_{DS} = \frac{\lambda_{DS}\bar{X}^2}{2\,(1-\rho)} + \frac{\overline{(T_{LWI})^2}}{2(\bar{T}_{LWI})} + \frac{T_{ch}}{2} + T_{init}, \tag{4}$$

$$D_{US} = \frac{\lambda_{US}\bar{X}^2}{2\,(1-\rho)} + \frac{\overline{(T_{LWI}+T_{AS})^2}}{2(T_{LWI}+T_{AS})} + \frac{T_{ch}}{2} + \frac{SI}{2} + T_{init}, \tag{5}$$

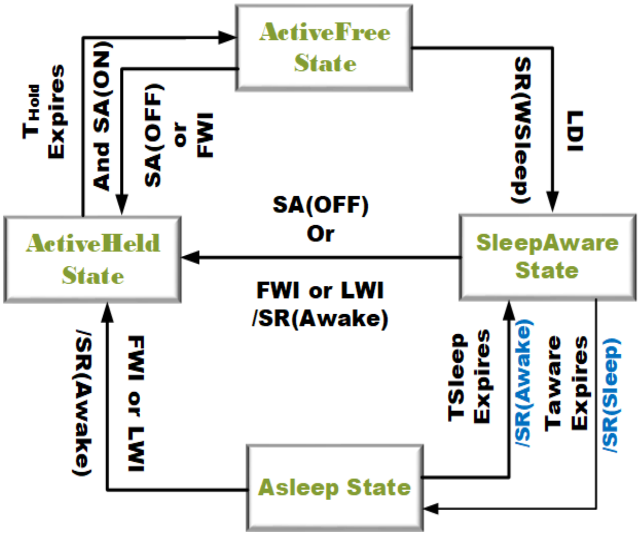


FIGURE 4. Improved cyclic sleep state for ITU PONs [41].

A PON's average energy efficiency (EE) using CSP process can be computed using Eq. (4), as in (6), shown at the bottom of the page, where P_{AH}, P_{AF}, P_{SLA} and P_{AS} are the power consumption of the ActiveHeld, ActiveFree, SleepAware, and Asleep states, respectively and T_{Sim} is the total simulation time for which the network was running. Here the time-period T_{AS} was not used for the sleep duration of the ONU; rather, the ONU average AS state time $\overline{T_{AS}}$ was used, which represents the average value of the actual time that the ONUs was in AS state during the T_{Sim}.

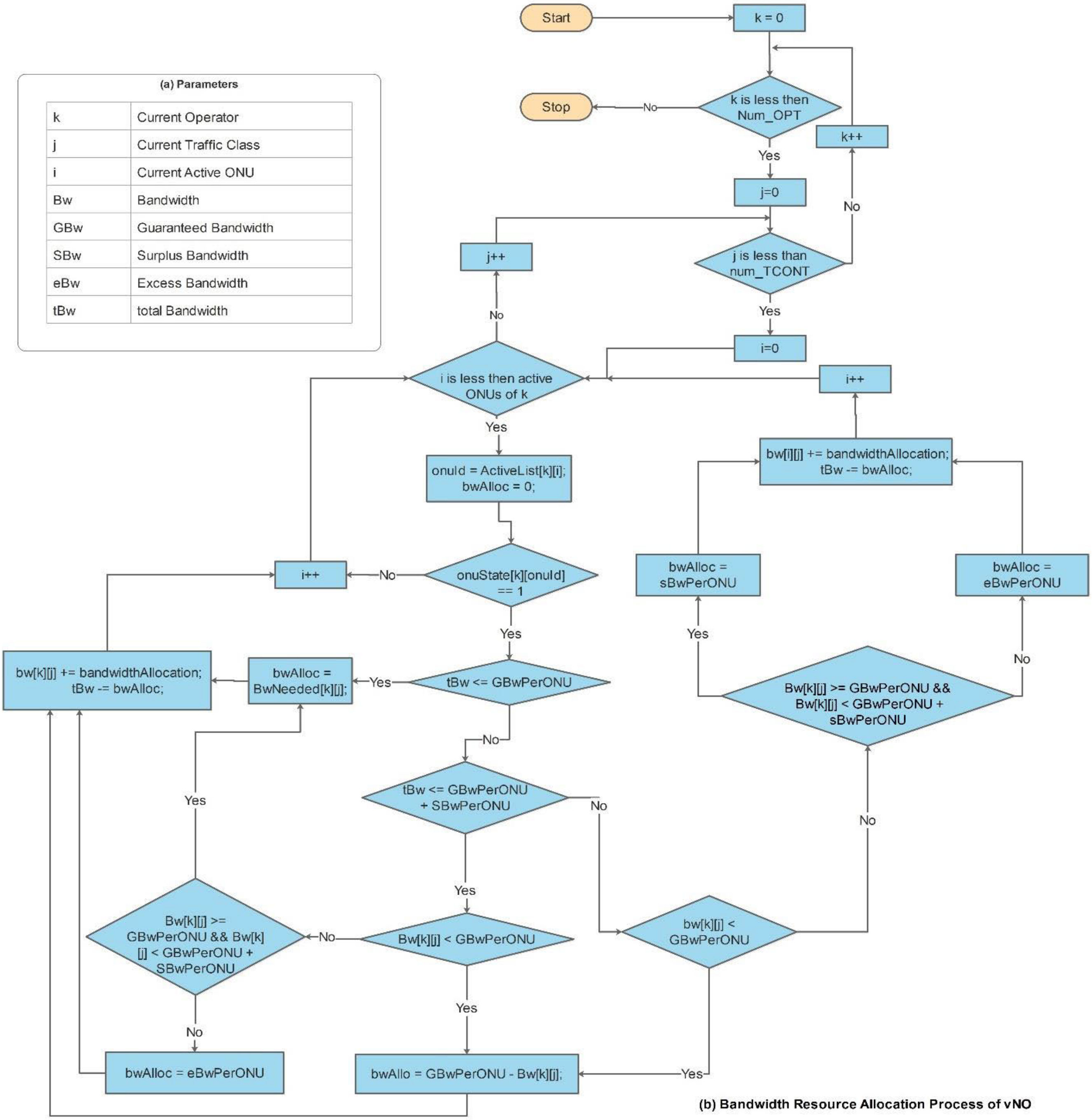
C. PROPOSED ENERGY EFFICIENT SLEEP-AWARE BASED BANDWIDTH SCHEDULER AND CSP STATES

In this subsection, we propose an energy-efficient and bandwidth allocation scheme for the bandwidth scheduler (SBS) that includes an optimized cyclic sleep state approach. To illustrate our approach, we utilize a flowchart and a modified version of the SBS algorithm to outline the step-by-step process of the proposed scheme. In addition, we describe how we handle the ONU wakeup and sleep processes, which are integral to the overall performance of the scheme. Our proposed scheme aims to enhance network efficiency and energy consumption while maintaining optimal network performance.

1) IMPROVED CSP STATES FOR ITU PON

The proposed energy-efficient sleep-aware slicing-based bandwidth (SA-SBS) scheme works differently than the existing bandwidth scheduler [12]. The first change is the access to the CSP state of each ONU for each operator.

$$EE = 1 - \left(\frac{\overline{T_{AS}} \times P_{AS} + T_{SLA} \times P_{SLA} + T_{Init} \times P_{AH} + T_{AH} \times P_{AH} + T_{AF} \times P_{AF}}{T_{Sim} \times P_{AH}}\right), \tag{6}$$



(a) Parameters

k	Current Operator
j	Current Traffic Class
i	Current Active ONU
Bw	Bandwidth
GBw	Guaranteed Bandwidth
SBw	Surplus Bandwidth
eBw	Excess Bandwidth
tBw	total Bandwidth

(b) Bandwidth Resource Allocation Process of vNO

FIGURE 5. (a) Parameters for flowchart (b) Flowchart of proposed bandwidth resource allocation process of vNO submodule in shared OLT.

To access this information, a data structure called ONU_State [N] with two Boolean variables, SleepFlg and ActiveFlg, is used to record all the CSP states of all ONUs. However, the problem with the standard CSP process is that the OLT is unaware of a particular ONU state, whether in the AS or SLA state. It is because the Sleep message is sent to the OLT only when it enters the SLA state and the Awake message when it quits the AS state. This problem was solved by Butt et al. [39], in which an improved CSP state transition process was introduced, as shown in Fig. 4. The ONU sends two extra PLOAM messages to the OLT in this improved CSP process, namely Awake & Sleep, whenever it enters the AS and SLA states.

2) FLOWCHART OF PROPOSED BANDWIDTH ALLOCATION FOR EACH VNO

Each vNO utilizes the proposed bandwidth allocation scheme according to the flowchart. The proposed bandwidth

Algorithm 1 The Pseudo-Code of the Proposed (SA-SBS) Scheme

Input: ONU Bandwidth object array *ONU* [N] having information about Operator and Buffer Occupancy Reports of ONUs
Output: Upstream Bandwidth array $B_{us}[K]$ containing Bandwidth share of each Operator Opt(k)

```
//Initialization Section
$K = 4, k = 1toK, AvailbleUSXGsPON_{LineRate}, TimeSlotLength = 125\mu s, UnusedBandwidth = 0$
Start of Slicing Process
   $setT = 0, L = 64, N = 256, i = 1toN, TimeSlot = 0$
  For each ONU $(i)$ do
    if $(ONU(i).Opt = kONU(i).ActFlg = 1)$ then
       $LoadActvieOpt\,[k] + = ONU\,(i)\,.Report2 + ONU\,(i)\,.Report3 + ONU\,(i)\,.Report4$
    End if
   End for
     For each $Opt(k)$ do
        $LoadActvieOpt\,[k] + = ABmin_1 \times L$
        $Total\_\_Actvie\_\_Load + =$ LoadActiveOpt[k]
     End for
     if $(Total\_\_Actvie\_\_Load > \zeta)$ then
       For each k do
          $LoadShares[k] = (LoadActiveOpt[k]/TotalActiveLoad) \times AvailbleUS$
          $B_{us}\,[k] + = Loadshare[k]$
       End for
     End if
     else
        For each Opt $(k)$ do
          if $(TimeSlot = k)$ then
           $B_{us}\,[k] = \min(\text{LoadActive}_{\text{Opt[k]}}, AvailbleUS, TimeSlotLength)$
            $TimeSlot = (TimeSlot + 1)\%K$
         End if
          $AvailbleUS- = B_{us}[k]$
       End for
        $B_{us}[K] + = AvailbleUS$
     End else
    //Allocate unused bandwidth
     For each Opt $(k)$ do
        $LoadShares[k] = LoadActiveOpt[k]/TotalActiveLoad$
     End For
      $SortedVNOs = SortVNOsByLoadShares(LoadShares, descending = True)$
     For each $Opt(k)$ in SortedVNOs do
       IF $(AvailableUS > 0)$ then
          $B_{us}[k] + = AvailableUS/K$
          $UnusedBandwidth + = AvailableUS/K$
          $AvailableUS- = AvailableUS/K$
       End IF
      End For
    End of Slicing Process
```

allocation scheme flowchart in Fig. 5 allocates bandwidth to active ONUs based on their current state and the available or total bandwidth. The flowchart calculates the unlimited bandwidth needed, the number of active ONUs, and guaranteed, surplus, and excess bandwidth per active ONU for each operator and traffic class. For each active ONU within the operator and traffic class, the flowchart determines the amount of bandwidth to allocate based on the current bandwidth and available bandwidth per active ONU. The flowchart allocates bandwidth according to the total bandwidth needed, the guaranteed surplus, and the excess bandwidth. The current bandwidth and total bandwidth needed are then updated. The process continues until all active ONUs within the operator and traffic class are allocated bandwidth for that traffic class. The loop then moves on to the next traffic class and operator until all the traffic classes and operators have been processed.

3) PROPOSED MODIFIED ALGORITHM FOR SLICING ENGINE MODULE OF SHARED OLT

Algorithm 1 presents a novel pseudo code of the proposed scheme for slicing the Engine Module in shared OLT. The proposed algorithm, Algorithm 1, presents a modified version of the simple slicing-based algorithm(SBS) for upstream bandwidth allocation. The basic concept of SBS is to offer the upstream capacity to each operator periodically and somewhat based on the active group of ONUs' demand. In a previous study, each operator was given a granularity of 125μs period, meaning only the ONUs of the operator (k) could send their upstream traffic to shared OLT in one upstream XGSPON frame. Algorithm 1 improves upon the basic concept of SBS by considering the buffer occupancy reports of ONUs and the operator's load to allocate upstream bandwidth fairly and efficiently to each operator. It allocates the bandwidth in a round-robin fashion, one-time slot at a time, ensuring that each operator receives its fair share of the upstream bandwidth based on the active group of ONUs' demand. The modifications in Algorithm 1 aim to provide an improved and efficient approach for upstream bandwidth allocation in the SBS scheme, resulting in fair and efficient utilization of network resources. The proposed algorithm provides a more effective solution for upstream bandwidth allocation in the SBS scheme and can be implemented in practical scenarios to improve network performance.

Algorithm 1 takes an array of ONU bandwidth objects as input and produces an upstream bandwidth array as output. Algorithm 1 begins with an initialization section that sets the value of K (number of operators) and initializes variables such as AvailableUSXGsPON_LineRate, TimeSlotLength, and UnusedBandwidth to zero. The slicing process begins with setting variables T, L, N, and i to specific values and then iterating over each ONU in the input array. For each ONU in lines 5-13, if the operator (Opt) and active flag (ActFlg) match the current iteration, the algorithm calculates the load using ONUs buffer reports of traffic class 2, 3, and 4 and adds it to the LoadActiveOpt array for that operator.

Once the load for each operator has been calculated, the algorithm checks if the total active load exceeds a threshold value (ζ). If it does, in lines 14-19, the algorithm calculates the load shares for each operator based on their active load and the available upstream bandwidth (AvailbleUS) and allocates the bandwidth accordingly to the B_{us} array. If the total active load does not exceed the threshold, the algorithm enters a loop that allocates the bandwidth to each operator in a round-robin fashion, a one-time slot at a time. The algorithm calculates the available upstream bandwidth and allocates it to each operator based on the minimum active load, available upstream bandwidth, and time-slot length (lines 20-29). From lines 30-41, unused bandwidth is added to the UnusedBandwidth variable. If there is still unused bandwidth after all time slots have been allocated, the algorithm enters a loop that gives the unused bandwidth to each operator based on their load shares in descending order. The algorithm calculates the unused bandwidth and allocates it to each operator based on a proportional share of the unused bandwidth. Finally, the algorithm outputs the upstream bandwidth array (B_{us}) containing the allocated bandwidth for each operator.

The For-loops dominate the time complexity of Algorithm 1 in lines 5, 10, 15, 21, 31, 35, and 37. The running time of each For-loop depends on the number of iterations and the time complexity of the operations inside the loop. The initialization section in lines 2-3 has a constant time complexity of O(1). The slicing process in lines 4-42 has a time complexity that can be expressed as O(NK), where N is the number of ONUs and K is the number of operators. The worst-case scenario occurs when all ONUs are active, and all operators have a nonzero load, which leads to the execution of lines 5-19. In this case, the time complexity of the slicing process would be O(NK). The time complexity of the sorting operation in line 34 depends on the sorting algorithm used. If a comparison-based sorting algorithm is used, the time complexity would be O(K log K), where K is the number of operators. Therefore, the total time complexity of Algorithm 1 asymptotically can be expressed as O(NK + K log K), where the dominant term is from the slicing process.

4) STEPS OF HANDLING OF ONU WAKEUP AND SLEEP IN THE PROPOSED SCHEME

In our proposed scheme, each virtual Network Operator (vNO) handles the wakeup and sleep of ONUs to ensure better utilization of network resources and improved network performance while being energy efficient. The scheme utilizes PLOAM messages to detect the state of the ONUs and selects a random ONU to wake up, sets its state to Active, and adds it to the ActiveList. It also selects a random Active ONU to put to sleep, sets its state to Sleep, and removes it from the ActiveList. Following these steps, our proposed scheme provides a more practical approach for upstream bandwidth allocation, resulting in improved network performance and better utilization of network resources. Our proposed scheme aims to be energy efficient by allowing ONUs to switch to a sleep state when they are not actively transmitting data. This approach reduces the power consumption of the network and prolongs the lifespan of ONUs. This additional control on the active ONUs to allow them to switch to the sleep state when the bandwidth is unavailable ensures that ONUs is not kept awake unnecessarily, leading to improved energy efficiency and reduced operational costs. Therefore, the proposed scheme enhances network performance and contributes to sustainable, energy-efficient virtual optical access networks.

Algorithm 2 shows the steps for handling ONU wakeup and sleep in the proposed scheme. Each step is represented by its asymptotic time complexity regarding the number of ONUs (N) and iterations (M). Step 1 has a time complexity of O(N), while steps 2-3 and 6-7 have a time complexity of

Algorithm 2 additional Steps Required for Onu Wakeup And Sleep Handling in the Proposed Scheme

```
STEPS Values / Details
1  Initialize the vNO by creating a list of ONUs, each with a unique identifier and a state of "Sleep".
2  Wait a certain period for the ONU to send an Awake PLOAM message when it enters the AS state.
3  If an Awake PLOAM message is not received within the timeout period, select another ONU from the list and wait for its PLOAM message.
4  Once an Awake PLOAM message is received from the ONU, change the state of the corresponding ONU to "Active".
5  Add the active ONU to the ActiveList.
6  Wait for a certain period of time for the ONU to send a Sleep PLOAM message when it enters the SLA state.
7  If a Sleep PLOAM message is not received within the timeout period, select another ONU from the list and wait for its PLOAM message.
8  Once a Sleep PLOAM message is received from the ONU, change the state of the corresponding ONU to "Sleep".
9  Remove the sleeping ONU from the ActiveList.
10 Calculate the available bandwidth for each traffic class based on the bandwidth allocation policies.
11 Allocate the available bandwidth to each traffic class from the active ONUs to satisfy their bandwidth requirements.
12 Repeat steps 2-11 for specific ONUs.
13 Generate a report of the allocated bandwidth, the guaranteed bandwidth, the surplus bandwidth, and the excess bandwidth for each traffic class and for the entire vNO.
14 Use the report to optimize the bandwidth allocation policies and improve the performance of the vNO.
```

O(N) as well. Steps 4-5, 8-9, and 10-11 have O(1) constant time complexity for each ONU. Step 12 has a time complexity of O(NM), where N is the number of ONUs and M is the number of iterations. In the worst-case scenario where M=N, the time complexity of step 12 would be O(N^2). Therefore, the total time complexity asymptotically can be expressed as O(N + MN^2), considering the worst-case scenario for step 12, where the dominant term is still from step 12. In the best-case scenario where all ONUs are in sleep mode, and M is at its minimum, step 12 would execute only once, and the time complexity would be O(N). Therefore, asymptotically, the best-case time complexity can be expressed as O(N). Including both the best-case and worst-case time complexities provides a comprehensive analysis of the proposed scheme's scalability and performance under different scenarios.

IV. SIMULATION SETUP

In the OMNET++ environment, a simulation of a vPON in a multi-operator scenario is conducted. Each virtual network operator (VNO) is assumed to have the same service level agreement (SLA) with their clients and is equipped with 64 optical network units (ONUs). The line rate of each ONU is set at 200Mbps, as per [42]. The round trip time (RTT) value is set to 200μs [7], and the frame processing time at the ONU is set to 35 μs. A 1MB buffer size is reserved for each of the traffic class queues (T1 to T5) for upstream traffic. Traffic is generated using the probabilistic Poisson distribution model with an inter-arrival time chosen from the exponential distribution, as discussed in [43] and [44]. The offered traffic load is varied from 0.01 to 0.85. The simulation run time is terminated only after the average mean inter-arrival times converge within a 95% confidence interval (CI). To keep the VNOs separate, each ONU has a dedicated instance of the Traffic generator set up for it. To simulate an asymmetric traffic load scenario, 50% of the ONUs in each VNO have their traffic load increased by 30%, while the other 50% have their traffic load decreased by the same amount. The generated traffic frames are uniformly distributed among the T1 to T4 traffic classes.

TABLE 3. Additional simulation parameters.

Parameter	Values / Details
λ_{DS}	Varied from 2 Mbps to 170 Mbps per ONU
Frame Size	It follows a triangular distribution with probabilities of 20 %, 20 %, and 60% of 1500, 500- and 64-Bytes Ethernet frames, respectively.
λ_{US}	$\lambda_{DS}/4$
T_{SLA}	3 ms
T_{AS}	10 ms.
T_{Init}	2ms
T_{Hold}	0.5ms
T_{ERI}	$T_{AS} + T_{init}$ + RTT = 13ms [45]
$T_{ALERTED}$	Should be $\geq (T_{AS} + T_{SLA} + T_{init})$ = 15 ms
$ABmin_1$	240 bytes with SI_{min1}= 5
$ABmin_2$	7030 with SI_{min2}= 5
$ABmin_3$	3515 with SI_{min3}= 5
$ABsur_3$	3515 with SI_{max3}= 5
$ABsur_4$	315 with SI_{max4}= 5

For the CSP process, a binary model is used for the ONU power levels, where the ONU has either 5% power consumption in AS state or 100% power consumption in all other states (AH, AF, and SLA). Optical transceivers are ON in all states [39]. The complete details of the CSP and DBA-related parameters can be found in Table 3. The byte counters ABmin_1, ABmin_2, ABmin_3, ABSur_3, and ABSur_4 are assumed to be the same for all operators.

V. RESULTS AND DISCUSSION

The study investigated the performance of both the SBS scheme and the proposed SA-SBS scheme, with two different

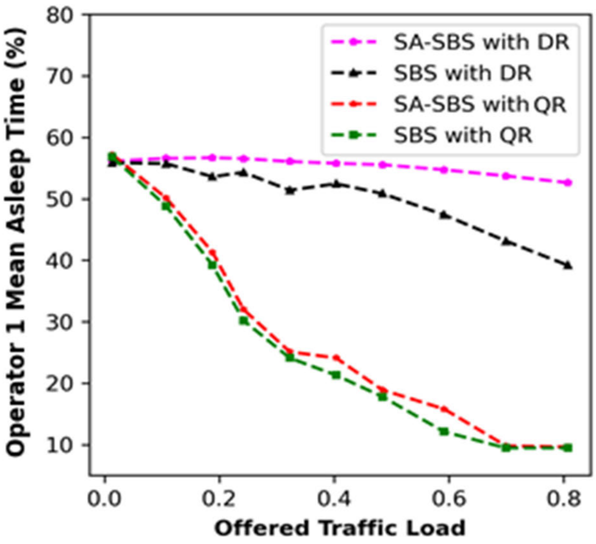


FIGURE 6. Average ONT asleep time Operator1.

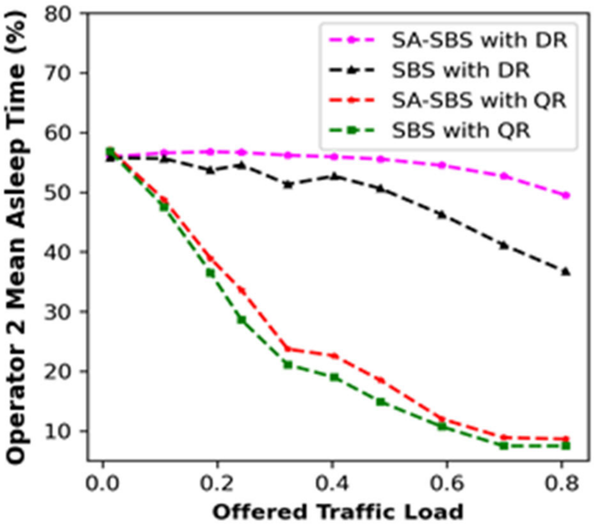


FIGURE 7. Average ONT asleep time Operator 2.

LWI activation approaches of CSP (DR and QR) discussed in section III-B. The investigation considered assured, non-assured, and best-effort traffic for all operators. The simulation ran for an hour. The results for average US and DS delays, average ONU energy savings, and average ONT AS state time were recorded and presented in Figs. (6) to (24).

A. MEAN ASLEEP TIME V.S. OFFER TRAFFIC

The main parameter that determines the energy-saving performance of an ONT/ONU is its average time spent in the AS state. If the ONU remains in the AS state longer, its energy savings will be more significant because it has the lowest power consumption. The SA-SBS scheme considers only the Active state ONUs of each operator during the slicing process. It provides bandwidth assignment to every operator in every US XGSPON cycle for its active ONUs. Thus, when an ONT switches to an Active state from the AS state, this extra bandwidth availability results in the early emptying of the traffic queues. Consequently, the OLT can meet the requirement of entering the AS state early compared to the simple SBS approach. In contrast to the original SBS scheme, which requires the ONT to wait for at least three XGSPON cycle durations of 125μs for bandwidth availability, the SA-SBS scheme reduces this delay, as seen in Figs. (6) to (9), which display the mean asleep time (%) results of the study. The results indicate that SA-SBS with DR and SBS with DR produce similar outcomes for all offered traffic loads and operators, with a mean asleep time (%) of approximately 56%. On the other hand, SA-SBS with QR and SBS with QR yield distinct findings, with SA-SBS with QR resulting in a little higher mean asleep time (%) than SBS with QR for all traffic loads and operators.

Since the DR approach holds the LWI event for 40ms, the delay values for all the traffic loads remain above 40ms with the DR-based CSP process. However, the AS state time drops exponentially as the traffic load increases in the QR-based CSP process. In both cases, the SA-SBS scheme provides comparatively higher savings for the reasons as mentioned earlier.

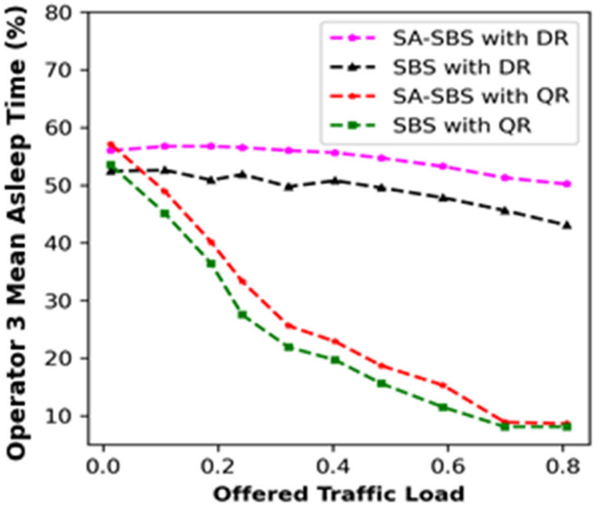


FIGURE 8. Average ONT asleep time Operator 3.

B. ENERGY SAVING (%) V.S. OFFER TRAFFIC

As discussed above, the AS state length plays a vital role in the energy savings; thus, the energy savings of ONT also show a trend like that of the AS state. Figs, (10) to (13) show the average energy savings results for all the operators. The results show that the SA-SBS algorithm performs better than the SBS algorithm regarding power savings, especially at higher traffic loads. The proposed SA-SBS algorithm with DR consistently outperforms the original SBS algorithm

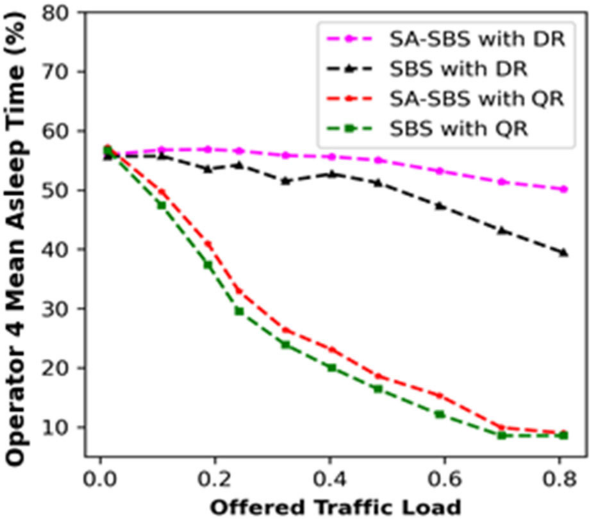


FIGURE 9. Average ONT asleep time Operator 4.

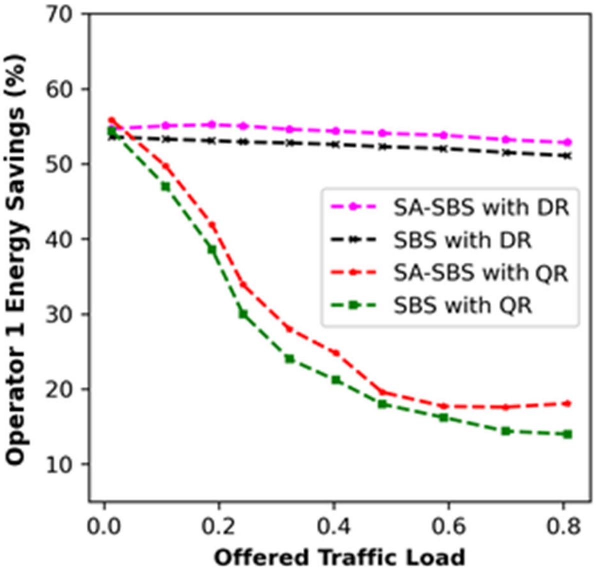


FIGURE 10. Average ONT energy savings of Operator 1.

regarding power savings, indicating a more efficient way of scheduling transmissions in virtual passive optical networks.

Furthermore, we can see that the improved CSP process also significantly impacts power savings. The DR-based CSP process offers more energy savings than the QR-based CSP process. The QR process generally performs better than the DR process at low traffic loads, whereas the DR process is more efficient at higher traffic loads.

Since a separate traffic generator is used for every ONT and an asymmetric traffic scenario is simulated for each operator, the results are not precisely the same for each operator but are close because of the same load values. The results suggest that the SA-SBS algorithm with DR and QR processes is the most efficient combination for power savings.

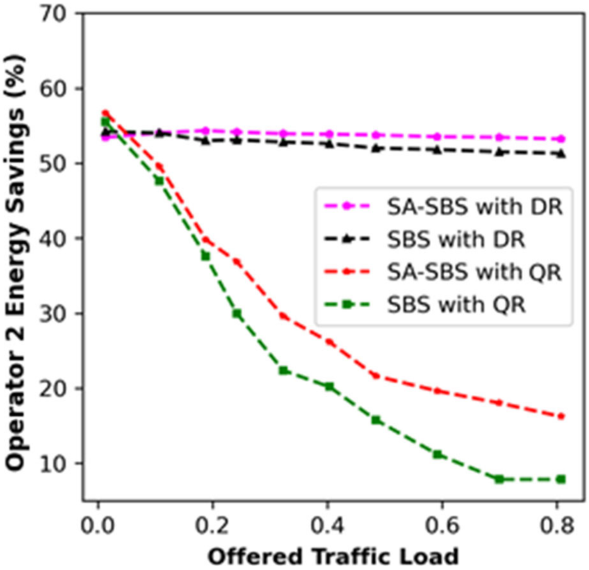


FIGURE 11. Average ONT energy savings of Operator 2.

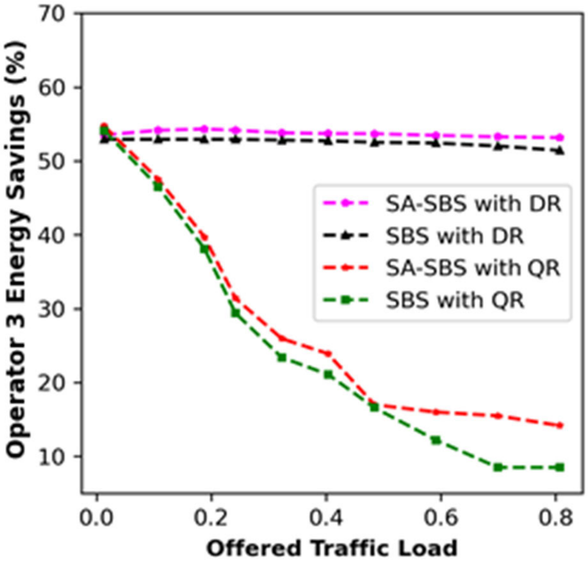


FIGURE 12. Average ONT energy savings of Operator 3.

C. MEAN DOWNSTREAM (DS) DELAY (S) V.S. OFFER TRAFFIC

As discussed, the ONT's energy-saving performance depends on the AS state length, which affects US and DS delays. Longer AS state times lead to more queuing in both directions. Surprisingly, the SA-SBS scheme reduces DS delays compared to the SBS scheme with DR-based CSP, despite longer AS state times (see Figs. (14) to (17)). This is because the slicing scheduler optimizes ONUs' bandwidth utilization adaptively. However, for the QR-based CSP, both schemes have similar delay results due to sharply decreasing AS state times at higher traffic loads with low energy savings.

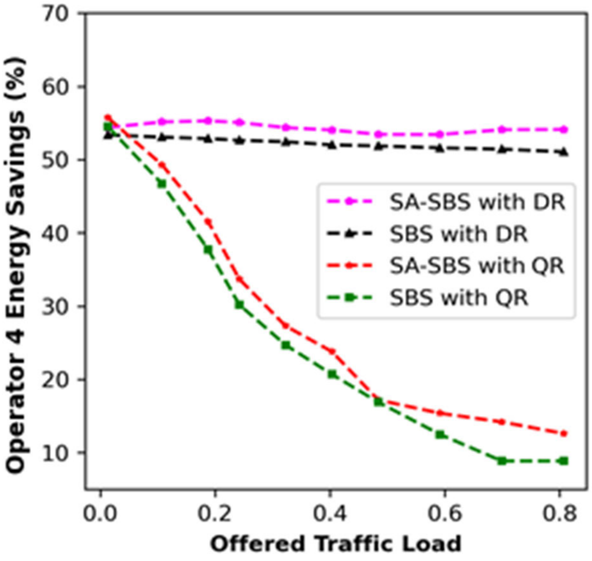


FIGURE 13. Average ONT energy savings of Operator 4.

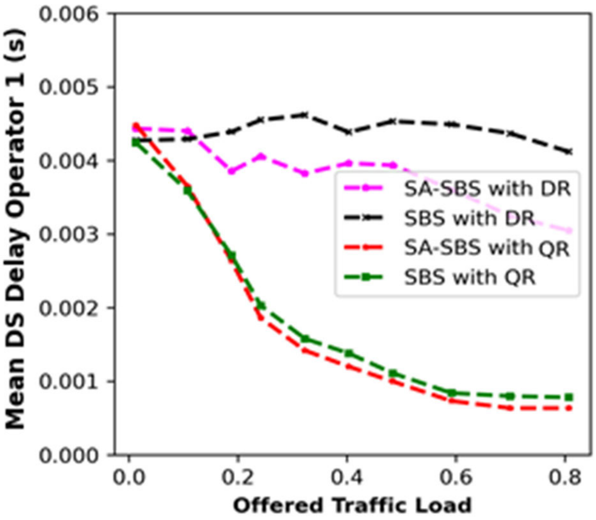


FIGURE 14. Average DS delay of Operator 1.

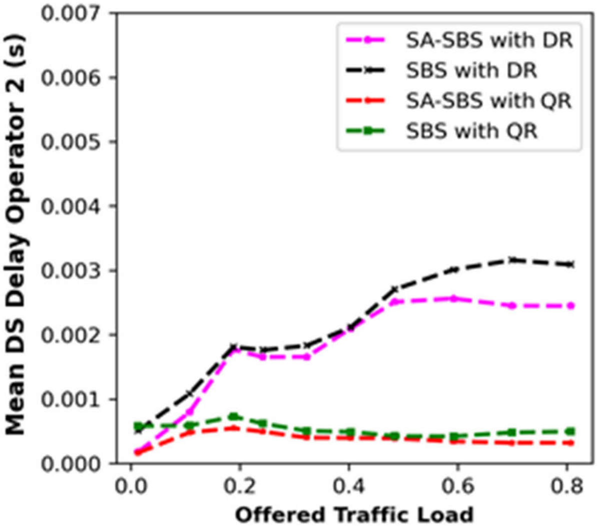


FIGURE 15. Average DS delay of Operator 2.

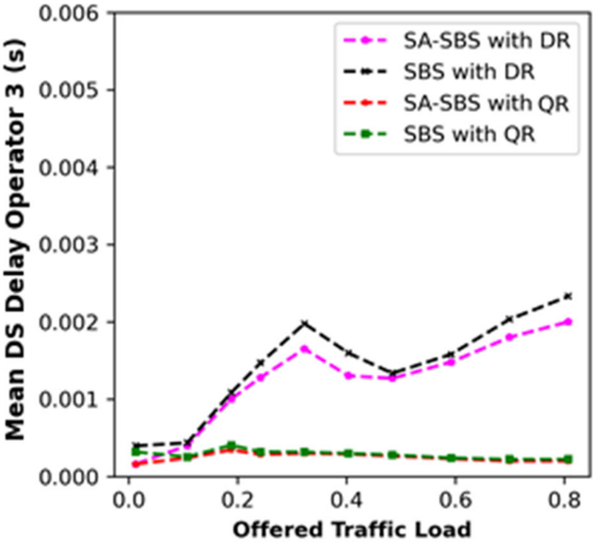


FIGURE 16. Average DS delay of Operator 3.

D. MEAN UPSTREAM (US) DELAY (S) V.S. OFFER TRAFFIC

A similar trend can be observed in upstream US delays compared to the DS delays discussed earlier, as shown in Figs. (18) to (21). However, the US delays are generally higher than the DS delays for two main reasons. The US transmissions depend on the vDBA process, where the Optical Network Units (ONUs) first report their bandwidth demand to the Optical Line Terminal (OLT). Then, based on traffic class priority, the OLT assigns bandwidth to different traffic classes, including assured, non-assured, and best effort. This process is the first aspect to consider when analyzing US transmissions. This entire process takes some time, resulting in higher delays.

Second, the best-effort traffic class has the least priority, leading to higher delays for best-effort traffic and a higher average value of the upstream delays. Despite these challenges, the SA-SBS scheme outperforms the simple SBS scheme in DR and QR-based sleep processes for efficient bandwidth utilization of the ONUs in AS state.

Comparing SA-SBS with QR to SBS with QR, it can be observed that the SA-SBS scheme results in lower upstream US delays. Specifically, the SA-SBS scheme achieves an average delay reduction of 6.25%, 44.7%, 50.6%, and 41.2% for operators 1, 2, 3, and 4, respectively.

Similarly, comparing SA-SBS with DR and SBS with DR, the SA-SBS scheme achieves lower upstream US delays. The SA-SBS scheme results in an average delay reduction of 16.2%, 21.9%, 25.3%, and 18.4% for operators 1, 2, 3, and 4, respectively. Therefore, the SA-SBS scheme outperforms the original SBS scheme in DR and QR-based sleep processes for reducing upstream US delays. These findings suggest

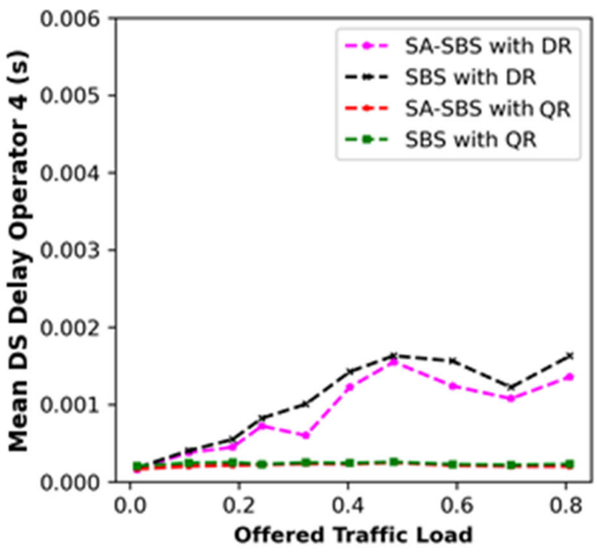


FIGURE 17. **Average DS delay of Operator 4.**

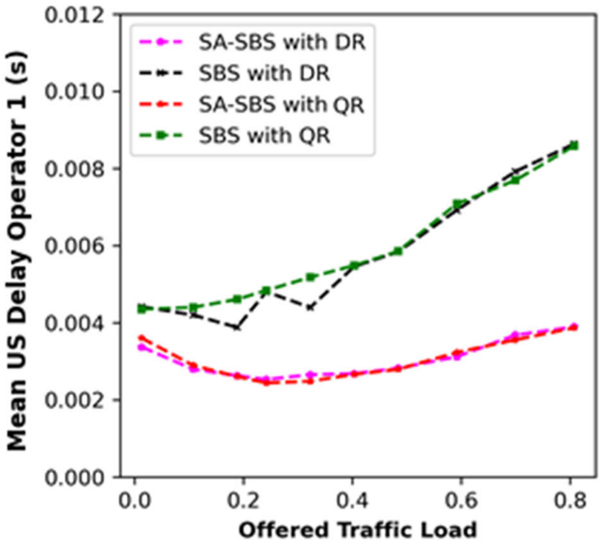


FIGURE 18. **Average DS delay of Operator 1.**

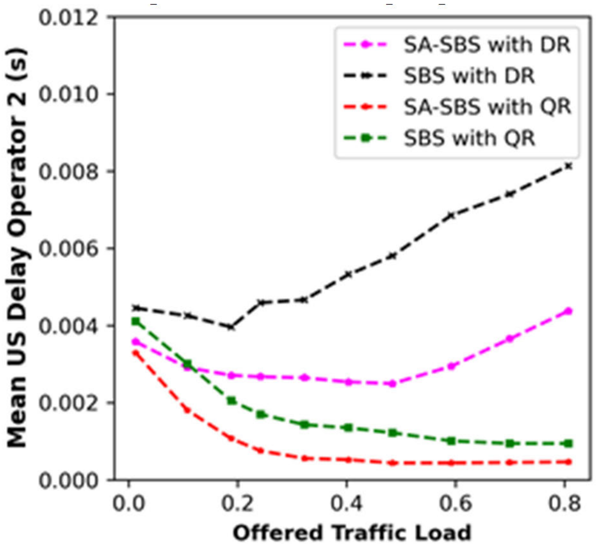


FIGURE 19. **Average DS delay of Operator 2.**

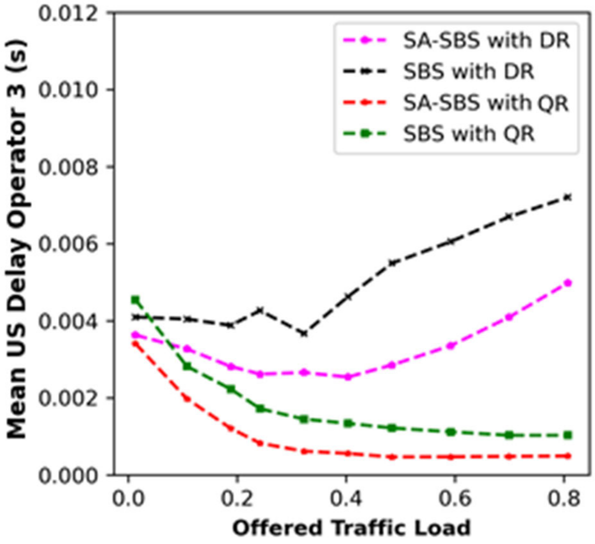


FIGURE 20. **Average DS delay of Operator 3.**

that the SA-SBS scheme can effectively enhance the network performance for multiple operators.

E. OVERALL DELAY (S) ACCORDING TO TRAFFIC CLASSES

The study includes comparative graphs in Figs. (22) to (24) illustrate the overall mean delay for sleep modes (DR and QR) and two algorithms (SA-SBS and SBS) for three types of traffic (Assured, Non-Assured, and Best Effort) at different offered traffic loads. The evidence of the arguments for the US delay can be witnessed in these graphs, which demonstrate that the SA-SBS scheme with DR and QR outperforms the original SBS scheme in reducing upstream delays for efficient bandwidth utilization of the ONUs in AS state.

The results for Assured Traffic indicate that the SA-SBS scheme with both DR and QR has lower overall mean delay values than the simple SBS scheme, especially at higher offered traffic loads. This is because assured traffic has 100% assured bandwidth, resulting in an average longer AS state of the ONT and lesser bandwidth assignment. However, the SA-SBS scheme still performs better in reducing upstream delays than the simple SBS scheme, with an average delay reduction of up to 25.3% at higher offered traffic loads.

Similarly, for Non-Assured Traffic, the SA-SBS scheme with both DR and QR outperforms the simple SBS scheme, resulting in an average delay reduction of up to 28.5% for operators 1, 2, 3, and 4, respectively, compared to the simple SBS scheme with DR at an offered traffic load of 0.85. Non-assured traffic has 50% assured bandwidth, resulting in lesser bandwidth assignment on average in the case of a longer AS state of the ONT. However, the SA-SBS scheme can still

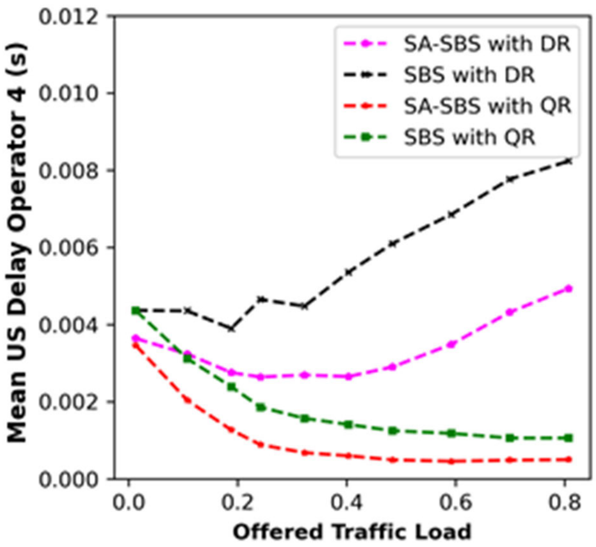


FIGURE 21. Average DS delay of Operator 4.

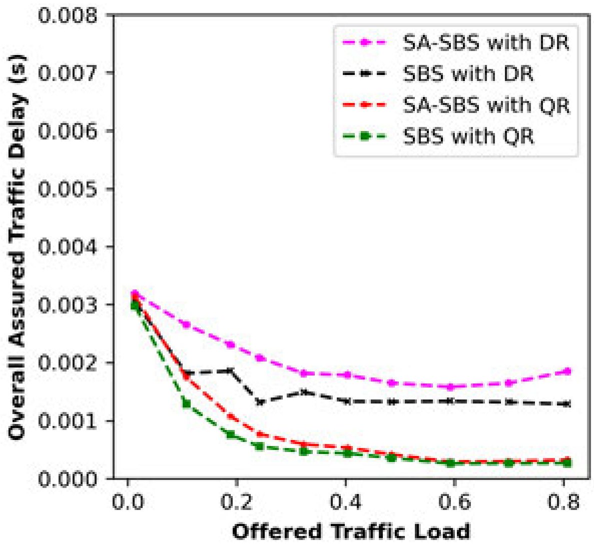


FIGURE 22. Average US delay of assured traffic class.

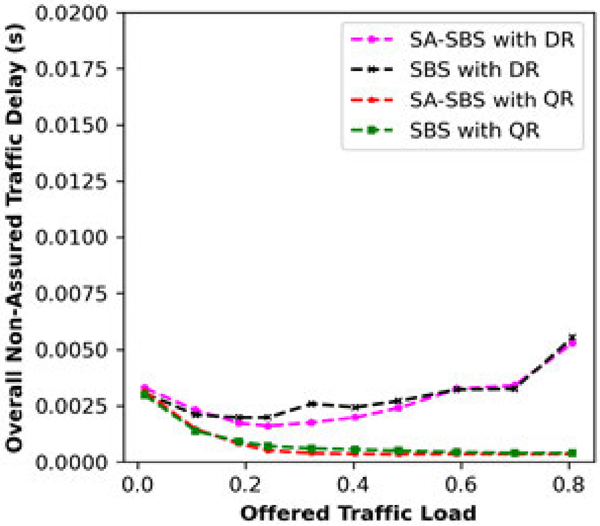


FIGURE 23. Average US delay of non-assured traffic class.

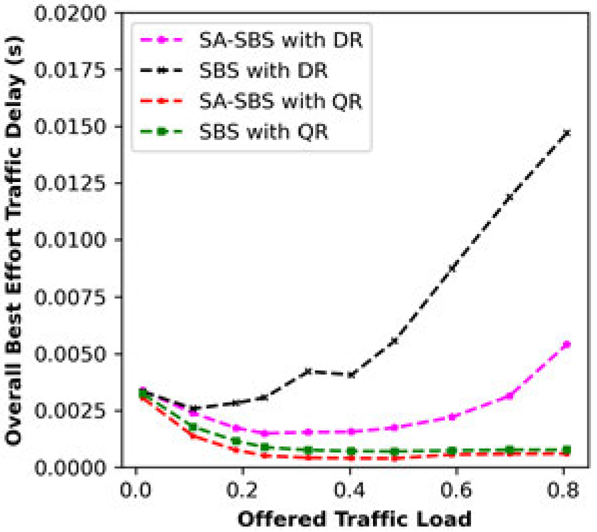


FIGURE 24. Average US delay of best effort traffic class.

better reduce upstream delays for Non-Assured Traffic than the simple SBS scheme.

For Best Effort Traffic, it can be seen that the SA-SBS scheme outperforms the original SBS scheme for QR-based CSP processes. The delays of best effort are higher than both assured and non-assured traffic, resulting in overall higher US delays compared to DS. In the case of best-effort, there is no reserved or assured bandwidth; thus, in the case of SA-SBS, higher bandwidth is available for best-effort traffic because the bandwidth of the asleep ONUs is also utilized. At higher traffic loads, the SA-SBS scheme with QR significantly reduces average delays compared to the simple SBS scheme.

The results indicate that the SA-SBS scheme can significantly improve the upstream delay reduction and efficient bandwidth utilization of ONUs in AS state, particularly for Non-Assured and Best Effort Traffic. The study also highlights the importance of selecting different schemes for optimal performance depending on the CSP process. The SA-SBS scheme with QR performs better than the original SBS scheme for best-effort traffic, while the SA-SBS scheme with DR and QR performs better for non-assurance traffic than the simple SBS scheme.

Overall, these findings provide valuable insights into the performance of various schemes and algorithms for reducing upstream delay in sleep modes of ONUs. By optimizing the XGS-PON system performance, the results can help improve the overall quality of service for different traffic types. Furthermore, the SA-SBS scheme offers better energy savings and leads to lower US and DS communication delays, making it a more favorable option than the SBS scheme.

VI. CONCLUSION

An energy-efficient version of the slicing-based upstream traffic (SA-SBS) scheduler for vPON in a multi-operator scenario has been proposed. The reported scheduler assigns the bandwidth slice to each operator keeping in view the traffic load of the active ONUs only, which results in efficient bandwidth utilization that is otherwise wasted as the ONUs in AS state cannot utilize it. The proposed scheduler also reserves a minimum fixed bandwidth share for each operator in each upstream cycle, which significantly reduces the waiting time of the ONUs to get the upstream bandwidth when they are awake from the AS state during the CSP process. These improvements resulted in improved energy efficiency of the ONUs and reduced the upstream latency of operators. Implementing the SA-SBS scheme with DR and QR results in an average delay reduction of up to 28.5% for operators 1, 2, 3, and 4, respectively, compared to the simple SBS scheme with DR at an offered traffic load of 0.85. Additionally, the proposed scheme achieves 7-10% higher energy savings for ONUs than the simple SBS scheme. Future work could include developing a CSP-compliant DBA process for merging the approach of vPONs using a 50G PON network beyond the fifth-generation fixed network (F5G).

CONFLICT OF INTEREST STATEMENT

The author declares that the research was conducted in the absence of every commercial or financial relationship that could be construed as a potential conflict of interest.

ACKNOWLEDGMENT

The authors thank the College of Computer Science at Huanggang Normal University, Huangzhou Huanggang, for providing research guidance regarding 'Power Management Techniques for Virtual Optical Networks'. Additionally, we are grateful to the Islamic University of Madinah, Saudi Arabia, for their collaboration on this work.

REFERENCES

[1] *Measuring Digital Development: Facts and Figures 2022*. Accessed: Jan. 8, 2023. [Online]. Available: https://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx

[2] L. Wu, C. Gan, H. Qiao, J. Hui, and Z. Xu, "Bandwidth allocation algorithm based on differential BRP models in Ethernet PON," *Comput. Netw.*, vol. 177, Aug. 2020, Art. no. 107291, doi: 10.1016/j.comnet.2020.107291.

[3] K. A. Memon, R. A. Butt, K. H. Mohammadani, B. Das, S. Ullah, S. Memon, and N. U. Ain, "A bibliometric analysis and visualization of passive optical network research in the last decade," *Opt. Switching Netw.*, vol. 39, Nov. 2020, Art. no. 100586, doi: 10.1016/j.osn.2020.100586.

[4] Z. Abdellaoui, Y. Dieudonne, and A. Aleya, "Design, implementation and evaluation of a fiber to the home (FTTH) access network based on a giga passive optical network GPON," *Array*, vol. 10, Jul. 2021, Art. no. 100058, doi: 10.1016/j.array.2021.100058.

[5] D. Zhang, D. Liu, X. Wu, and D. Nesset, "Progress of ITU-T higher speed passive optical network (50G-PON) standardization," *J. Opt. Commun. Netw.*, vol. 12, no. 10, pp. D99–D108, Oct. 2020, doi: 10.1364/jocn.391830.

[6] *White Paper on 50G-PON Technology—Fixed Network White Paper—ZTE Product*. Accessed: Nov. 9, 2021. [Online]. Available: https://www.zte.com.cn/global/products/access/FNWhitePaper/White-Paper-on-50G-PON-Technology

[7] K. H. Mohammadani, R. A. Butt, K. A. Memon, S. Faizullah, and M. Ishfaq, "Bayesian auction game theory-based DBA for XG symmetrical PON," *Opt. Quantum Electron.*, vol. 54, no. 5, p. 316, May 2022, doi: 10.1007/S11082-022-03721-9.

[8] *ITU-T Rec. G.9804.1 Amendment 1 (08/2021) Higher Speed Passive Optical Networks—Requirements Amendment 1. G 9804*. Accessed: Feb. 27, 2023. [Online]. Available: http://handle.itu.int/11.1002/1000/11

[9] R. Bonk, "The future of passive optical networks," in *Proc. Int. Conf. Opt. Netw. Design Modeling (ONDM)*, Jun. 2021, pp. 26–28, doi: 10.23919/ONDM51796.2021.9492398.

[10] K. H. Mohammadani, R. A. Butt, K. A. Memon, and F. Hassan, "Highest cost first-based QoS mapping scheme for fiber wireless architecture," *Photonics*, vol. 7, no. 4, pp. 1–20, 2020.

[11] L. Zhu, H. Yao, H. Chang, Q. Tian, Q. Zhang, X. Xin, and F. R. Yu, "Adaptive optics for orbital angular momentum-based Internet of Underwater Things applications," *IEEE Internet Things J.*, vol. 9, no. 23, pp. 24281–24299, Dec. 2022, doi: 10.1109/JIOT.2022.3190268.

[12] C. Li, W. Guo, W. Wang, W. Hu, and M. Xia, "Bandwidth resource sharing on the XGPON transmission convergence layer in a multi-operator scenario," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 8, no. 11, pp. 835–843, Nov. 2016, doi: 10.1364/JOCN.8.000835.

[13] A. Elrasad and M. Ruffini, "Frame level sharing for DBA virtualization in multi-tenant PONs," in *Proc. Int. Conf. Opt. Netw. Design Modeling (ONDM)*, May 2017, pp. 1–6, doi: 10.23919/ondm.2017.7958528.

[14] *ITU-T Rec. G.9807.1 Amendment 2 (10/2020) 10-Gigabit-Capable Symmetric Passive Optical Network (XGS-PON) Amendment 2. G. 9807*. Accessed: Feb. 27, 2023. [Online]. Available: http://handle.itu.int/11.1002/1000/11

[15] A. Helmy and A. Nayak, "Energy-efficient decentralized framework for the integration of fog with optical access networks," *IEEE Trans. Green Commun. Netw.*, vol. 4, no. 3, pp. 927–938, Sep. 2020, doi: 10.1109/TGCN.2020.2974820.

[16] K. A. Memon, K. H. Mohammadani, A. A. Laghari, R. Yadav, B. Das, W. U. K. Tareen, N. U. A. Memon, and X. Xin, "Dynamic bandwidth allocation algorithm with demand forecasting mechanism for bandwidth allocations in 10-gigabit-capable passive optical network," *Optik*, vol. 183, pp. 1032–1042, Apr. 2019, doi: 10.1016/j.ijleo.2019.03.003.

[17] C. A. P. Martinez, T. Abrão, and A. L. M. Martinez, "Energy and spectral efficiency trade-off in OCDMA-PON assisted by non-linear programming methods," *Comput. Netw.*, vol. 189, Apr. 2021, Art. no. 107920, doi: 10.1016/J.COMNET.2021.107920.

[18] R. F. Moyano, D. Fernandez, L. Bellido, N. Merayo, J. C. Aguado, and I. de Miguel, "NFV-based QoS provision for software defined optical access and residential networks," in *Proc. IEEE/ACM 25th Int. Symp. Quality Service (IWQoS)*, Jun. 2017, pp. 6–10, doi: 10.1109/IWQoS.2017.7969142.

[19] M. S. Bonfim, K. L. Dias, and S. F. L. Fernandes, "Integrated NFV/SDN architectures," *ACM Comput. Surv.*, vol. 51, no. 6, pp. 1–39, Feb. 2019, doi: 10.1145/3172866.

[20] A. S. Thyagaturu, A. Mercian, M. P. McGarry, M. Reisslein, and W. Kellerer, "Software defined optical networks (SDONs): A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2738–2786, 3rd Quart., 2016, doi: 10.1109/COMST.2016.2586999.

[21] A. Pagès, F. Agraz, and S. Spadaro, "SDN-based band-adaptive quality assurance scheme in support of heterogenous B5G services over sliceable multi-band optical networks," *Opt. Switching Netw.*, vol. 47, Feb. 2023, Art. no. 100721, doi: 10.1016/J.OSN.2022.100721.

[22] H. Zhang, M. Zhang, X. Liu, D. Wang, and L. Jiang, "A multi-OLTs and virtual passive optical network for hybrid network," in *Proc. 7th IEEE Int. Conf. Softw. Eng. Service Sci. (ICSESS)*, Aug. 2016, pp. 1009–1012, doi: 10.1109/ICSESS.2016.7883237.

[23] K. H. Mohammadani, M. Hossen, R. A. Butt, K. A. Memon, and M. M. Shaikh, "ONU migration using network coding technique in virtual multi-OLT PON architecture," *Opt. Fiber Technol.*, vol. 68, Jan. 2022, Art. no. 102788, doi: 10.1016/J.YOFTE.2021.102788.

[24] Z. Xu, C. Gan, L. Wu, and J. Hui, "Self-adaptive resource-allocation scheme combining traffic prediction with user satisfaction in multi-wavelength VPON," *IEEE Photon. J.*, vol. 14, no. 4, pp. 1–12, Aug. 2022, doi: 10.1109/JPHOT.2022.3193853.

[25] M. Ruffini, A. Ahmad, S. Zeb, N. Afraz, and F. Slyne, "Virtual DBA: Virtualizing passive optical networks to enable multi-service operation in true multi-tenant environments," *J. Opt. Commun. Netw.*, vol. 12, no. 4, pp. B63–B73, Apr. 2020, doi: 10.1364/JOCN.379894.

[26] K. H. Mohammadani, R. A. Butt, K. A. Memon, N. N. Hussaini, and A. Shaikh, ''Load adaptive merging algorithm for multi-tenant PON environments,'' *Opt. Switching Netw.*, vol. 47, Feb. 2023, Art. no. 100712, doi: 10.1016/J.OSN.2022.100712.

[27] M. Dalgitsis, J. S. Vardakas, and C. Verikoukis, ''5G RAN resource slicing with flexible functional splits over multi-tenant environment,'' in *Proc. IEEE Int. Workshop Comput. Aided Modeling Design Commun. Links Netw.*, Oct. 2021, pp. 1–4, doi: 10.1109/CAMAD52502.2021.9617786.

[28] M. Maule, J. Vardakas, and C. Verikoukis, ''5G RAN slicing: Dynamic single tenant radio resource orchestration for eMBB traffic within a multi-slice scenario,'' *IEEE Commun. Mag.*, vol. 59, no. 3, pp. 110–116, Mar. 2021, doi: 10.1109/MCOM.001.2000770.

[29] M. Maule, J. S. Vardakas, G. Kormentzas, and C. Verikoukis, ''Multi-service single tenant 5G fronthaul resource orchestration framework based on network slicing,'' in *Proc. IEEE Global Commun. Conf.*, Dec. 2022, pp. 3417–3422, doi: 10.1109/GLOBECOM48099.2022.10001276.

[30] A. E. A. Eltraify, S. H. Mohamed, and J. M. H. Elmirghani, ''VM placement over WDM-TDM AWGR PON based data centre architecture,'' in *Proc. 22nd Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2020, pp. 1–5, doi: 10.1109/ICTON51198.2020.9203100.

[31] R. I. Tinini, D. M. Batista, and G. B. Figueiredo, ''Energy-efficient VPON formation and wavelength dimensioning in cloud-fog RAN over TWDM-PON,'' in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jun. 2018, pp. 521–526, doi: 10.1109/ISCC.2018.8538610.

[32] R. I. Tinini, D. M. Batista, G. B. Figueiredo, M. Tornatore, and B. Mukherjee, ''Energy-efficient vBBU migration and wavelength reassignment in cloud-fog RAN,'' *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 1, pp. 18–28, Mar. 2021, doi: 10.1109/TGCN.2020.3035546.

[33] A. F. Pakpahan, I. Hwang, and A. A. Nikoukar, ''OLT energy savings via software-defined dynamic resource provisioning in TWDM-PONs,'' *J. Opt. Commun. Netw.*, vol. 9, no. 11, pp. 1019–1029, Nov. 2017, doi: 10.1364/JOCN.9.001019.

[34] R. A. Butt, M. Faheem, M. W. Ashraf, A. Arfeen, K. A. Memon, and A. Khawaja, ''Sleep-aware wavelength and bandwidth assignment scheme for TWDM PON,'' *Opt. Quantum Electron.*, vol. 53, no. 6, pp. 1–23, Jun. 2021, doi: 10.1007/S11082-021-02955-3.

[35] R. A. Butt, M. Faheem, M. Anwar, K. H. Mohammadani, and S. M. Idrus, ''Traffic aware cyclic sleep-based power consumption model for a passive optical network,'' *Int. J. Numer. Modelling: Electron. Netw., Devices Fields*, vol. 35, no. 4, Feb. 2022, doi: 10.1002/JNM.2996.

[36] X. Zeng, M. Zhu, L. Wang, and X. Sun, ''Optimization of sleep period in watchful sleep mode for power-efficient passive optical networks,'' *Photonic Netw. Commun.*, vol. 35, no. 3, pp. 300–308, Jun. 2018, doi: 10.1007/s11107-017-0747-3.

[37] P. Sarigiannidis, M. Louta, G. Papadimitriou, and M. Theologou, ''Analysing the optical network unit power consumption in the 10 GB-capable passive optical network systems,'' *IET Netw.*, vol. 5, no. 3, pp. 71–79, May 2016.

[38] R. O. C. Hirafuji, K. B. da Cunha, D. R. Campelo, A. R. Dhaini, and D. A. Khotimsky, ''The watchful sleep mode: A new standard for energy efficiency in future access networks,'' *IEEE Commun. Mag.*, vol. 53, no. 8, pp. 150–157, Aug. 2015, doi: 10.1109/MCOM.2015.7180522.

[39] R. A. Butt, S. M. Idrus, K. N. Qureshi, P. M. A. Shah, and N. Zulkifli, ''An energy efficient cyclic sleep control framework for ITU PONs,'' *Opt. Switching Netw.*, vol. 27, pp. 7–17, Jan. 2018, doi: 10.1016/j.osn.2017.06.002.

[40] M. Zhu, J. Gu, and G. Li, ''PWC-PON: An energy-efficient low-latency DBA scheme for time division multiplexed passive optical networks,'' *IEEE Access*, vol. 8, pp. 206848–206865, 2020, doi: 10.1109/ACCESS.2020.3037753.

[41] R. A. Butt, M. Faheem, M. W. Ashraf, and S. M. Idrus, ''Sleep assistive dynamic bandwidth assignment scheme for passive optical network (PON),'' *Photon. Netw. Commun.*, vol. 36, no. 3, pp. 289–300, Dec. 2018, doi: 10.1007/s11107-018-0799-z.

[42] R. Butt, S. Idrus, K. Qureshi, N. Zulkifli, and S. Mohammad, ''Improved dynamic bandwidth allocation algorithm for XGPON,'' *J. Opt. Commun. Net.*, vol. 9, no. 1, pp. 87–97, Jan. 2017, doi: 10.1364/JOCN.9.000087.

[43] H. C. Leligou, C. Linardakis, K. Kanonakis, J. D. Angelopoulos, and T. Orphanoudakis, ''Efficient medium arbitration of FSAN-compliant GPONs,'' *Int. J. Commun. Syst.*, vol. 19, no. 5, pp. 603–617, 2006, doi: 10.1002/dac.761.

[44] V. Sales, J. Segarra, and J. Prat, ''An efficient dynamic bandwidth allocation for GPON long-reach extension systems,'' *Opt. Switching Netw.*, vol. 14, pp. 69–77, Aug. 2014, doi: 10.1016/j.osn.2014.01.009.

[45] *10-Gigabit-Capable Passive Optical Networks (XG-PON): Transmission Convergence (TC) Layer Specification*, Standard G.987.3, ITU-T, Geneva, Switzerland, 2014, pp. 1–146.

KHALID H. MOHAMMADANI (Member, IEEE) received the B.S. degree in telecommunication from the University of Sindh, Jamshoro, Sindh, Pakistan, in 2008, the M.Phil. degree in computer science from Isra University, Hyderabad, Sindh, in 2015, and the Ph.D. degree from the State Key Laboratory of Information Photonics and Optical Communications (IPOC), School of Electronic Engineering, Beijing University of Posts and Telecommunications, China, in 2022. He is currently an Adjunct Lecturer with the Department of Computer Science, Huanggang Normal University, Hubei, China. His research interests include several areas related to optical and wireless networks, such as passive optical network (PON), PON virtualization for 5G and beyond, optical metro access networks, fiber wireless networks, dynamic bandwidth and wavelength allocation (DBA/DWA), AI for optical networks, network security, hybrid wireless networks, routing protocols of 2D (MANET/VANET) and 3D unmanned aerial vehicle (UAV) wireless networks, and the Internet of Things (IoT). He has published several papers on these topics in IEEE, Elsevier, and Springer journals and presented his research at several IEEE conferences. He is involved in both the Computer Science and Photonics Societies, Institute of Electrical and Electronics Engineers (IEEE).

RIZWAN A. BUTT received the bachelor's degree in electronic engineering and the master's degree in telecommunication engineering from the NED University of Engineering and Technology, Pakistan, in 2006 and 2013, respectively, and the Ph.D. degree in electrical engineering from Universiti Teknologi Malaysia (UTM), in 2017. He was an Operation Engineer with Pakistan Telecommunication Company Ltd., from 2006 to 2010. Since 2010, he has been an Assistant Professor with the Department of Telecommunication Engineering, NED University of Engineering and Technology, Pakistan. He has authored several papers in refereed journals. He has authored more than 50 journal and conference papers. His research interest includes optical and communication networks. He was a recipient of the Best Ph.D. Student Award and the Pro-Chancellor Award from UTM. He has been serving as a Reviewer for numerous journals, such as *Optical Switching and Networking*, *Optical Fiber Technology*, *International Journal of Electrical and Computer Engineering* (IJECE), *Fiber and Integrated Optics*, and IEEE Access.

WAQAS NAWAZ received the Ph.D. degree from Kyung Hee University, Republic of Korea, in 2015. He was a Postdoctoral Fellow with the Department of Computer Science, Innopolis University, Russia, for one year. He is currently an Associate Professor with the Department of Computer and Information Systems, Islamic University of Madinah, Saudi Arabia. He actively participates in various research activities as a reviewer, guest editor, and researcher. His research interests include data mining, social networks analysis, big data, graph mining, databases, image processing, and artificial intelligence.

SAFIULLAH FAIZULLAH (Senior Member, IEEE) received the B.S. and M.S. degrees in information and computer science from the King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 1991 and 1994, respectively, and the M.S., M.Phil., and Ph.D. degrees in computer science from Rutgers University, New Brunswick, NJ, USA, in 2000, 2001, and 2002, respectively. Since July 1999, he has been with Hewlett-Packard Enterprise. He was with Isra University. Since July 2013, he has also been a Visiting Research Professor with the Department of Computer Science, Rutgers University. He is currently a Full Professor of computer science with the Faculty of Computer and Information Systems, Islamic University of Madinah. He has been teaching graduates level courses on the fundamentals of software testing and cloud computing. He has authored over 25 journals and conference papers. His research interests include computer networks, cloud computing, mobile computing, wireless networks, distributed, graph theory, enterprise systems, and software testing. He is the Chair of the Curriculum Committee, the High-Performance Computing and Networking Research Group, and the Graduate Studies Program Application Committee, and an Advisor to the Dean and the IT Deanship Dean. He is a member of PMI and ACM.

ZAHEER AHMED DAYO (Member, IEEE) was born in Rustam, Shikarpur, Sindh, Pakistan, in 1989. He received the M.E. degree in telecommunication engineering and management from the Mehran University of Engineering and Technology (MUET), Jamshoro, Sindh, in 2014, and the Ph.D. degree in communication and information systems from the Nanjing University of Aeronautics and Astronautics (NUAA), China, in 2021, under the supervision of Prof. Qunsheng Cao. He has a vast research experience of more than eight years. He is currently an Associate Professor with the Department of Computer Science, Huanggang Normal University, Hubei, China. He has published several articles in international journals and conference proceedings. His research focuses on electromagnetic, mainly related to microwave and RF engineering and measurement areas. Moreover, his core research interests include multiple-input multiple-output (MIMO) techniques, designing and manufacturing of compact, broadband, high-gain antennas, array topology and optimization schemes, active and passive frequency selective surfaces (FSS), multiband and slot antennas, reconfigurable, and meta-material inspired antennas. He served as a reviewer and a TPC member of international journals and conferences.

• • •