Energy Conservation in Passive Optical Networks: A Tutorial and Survey

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***Abstract*—The Passive Optical Network (PON) has been evolving continuously in terms of architecture and capacity to keep up with the demand for high-speed Internet access in the access network segment. Recently, integration of Software-Defined Networking (SDN), which provides programmable and (logically) centralized network control, with PON has attracted intensive research interest to further enhance PON performance and reduce operational and capital expenditure. Although PON is regarded as an energy-efficient a ccess n etwork s olution, i t is a major contributor for increasing energy consumption in the access network segment because of its higher penetration rate than other access network technologies. Over the past several years, the major standardization bodies like IEEE and research communities have engaged in introducing energy-efficient PON solutions.**

This article familiarizes readers with PON evolution in terms of capacity, architecture, and its integration with virtualization and SDN based control. We present a comprehensive survey of the energy conservation research efforts in PON starting from conventional PON to SDN based PON leveraging virtual and physical network functions. This article also presents contemporary energy-efficient standardization activities in IEEE and ITU. To the best of our knowledge, to date, this article is the first most comprehensive survey on energy saving research and standardization on PON. We summarize the lessons learned from the recent advancements, identify important challenges ahead and outline several future research directions that can contribute to further advancement of energy-efficient PON.

***Index Terms*—Passive optical network, software defined-networking, energy-efficient PON, sleep mode, virtual and physical network functions.**

I. Introduction

Passive Optical Network (PON) has been evolving continuously to cope with end users' demands for high data rate internet access with low latency. For example, Broadband PON (BPON), which was introduced by ITU-T in 2001, can provide a maximum 1.24 Gbps downlink data rate, whereas the ITU-T's Next Generation PON2 (NG-PON2), introduced in 2014, is able to provide a downlink data rate of 80 Gbps. The main variants of PON are: Time Division Multiplexing PON (TDM-PON), Wavelength Division Multiplexing PON (WDM-PON), and Time and Wavelength Division Multiplexed PON (TWDM-PON). In a PON system, there are two primary components: an Optical Network Unit (ONU), which is installed at the customer premises and an Optical Line Terminal (OLT), which is housed in a rack in the Central Office (CO) of a network operator.

In recent years, one of the emerging networking technologies is Software-defined Networking (SDN). An SDN provides a global view of a network and enables dynamic and efficient programming, allowing on-the-fly decision making and dynamically fine-grained traffic control to maximize network resource utilization, minimize energy consumption and meet Quality of Service (QoS) requirements of end users. To further enhance the performance of PON, over the past few years, the SDN controlled PON has gained significant traction in the industry and academia. To date, a growing number of research studies (e.g., [1]–[7]) have presented how SDN can be adopted in the variants of PON. Besides, we have been witnessing continuous industry efforts towards the development of SDN controlled PON. For example, Open Networking Foundation (ONF) initiated the Virtual OLT Hardware Abstraction (VOLTHA) project [8], [9], where a vendor-agnostic management system was introduced to facilitate SDN based PON control.

With the ever increasing demand for ubiquitous and high-speed internet access, there is a growing concern among the researchers from industries and academia regarding the overall carbon footprint of the Information Communications Technology (ICT) sector. Findings in [10] impart that the utilization of access network equipment is only 15%. However, interestingly, the energy consumption footprint of access network equipment is approximately 70% of the overall energy demand of ICT [11], [12]. As the volume of data traffic grows due to increasing device use and bandwidth-intensive applications, access network energy consumption will only increase over time.

In 2021, the global PON market size has already surpassed 10 billion USD with more than 250 million units of shipment [13]. PON has also been widely adopted not only to connect the residential and business users but also to serve wireless access segments, such as fourth-generation (4G) and fifth-

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generation (5G), as a backhaul [14], [15]. The upcoming sixth-generation (6G), which envisions to offer high data and ultra-low latency mobile Internet and ubiquitous intelligence [16], is expected to use PON as an optical transport solution as a backhaul [17]. Despite the fact that PON is regarded as an energy-efficient access network technology, PON would be one of the major contributors for energy consumption in the access network segment due to its high penetration rate [18]. To cope up with the situation, both standardization bodies (e.g., IEEE and ITU) and academia are striving to introduce a new generation of PON systems to cope with future customer demand while reducing the energy consumption as much as possible.

A commonly applied approach for energy conservation in PON is sleep mode, where ONUs and OLTs switch off some of their power-hungry components (e.g., transceivers) when they have no usage. For example, it was found that an OLT serving 64 ONUs with 4 wavelengths in a TWDM-PON consumes around 25% of the overall power required to operate the PON [19]. However, at low load if some of the transceivers at the OLT are switched off, energy consumption of the PON can be reduced [19]. Another approach is to use low-power consuming and more compact chips for an OLT and ONU. There are several other approaches for conserving energy in PON as we will see later in this article. Depending on PON architecture and operational procedures, the energy conservation approach may vary. For instance, in an Ethernet PON (EPON), which uses Time Division Multiple Access (TDMA) based uplink and Time Division Multiplexing (TDM) based downlink transmission, the ONUs can only turn off their transceivers following an instruction from the OLT. In this case, the OLT has almost no opportunity to turn off its transceiver as a single downlink and uplink wavelength is shared among all the ONUs. Conversely, both an ONU and OLT in a TWDM-PON may have an opportunity to turn off some their transceivers when bandwidth demand is low, since the PON system deploys several wavelengths in both directions [20]–[22].

A. Existing Surveys and Tutorials on Energy Conservation in PONs

The general principles of PONs with relatively little overview on their energy conservation aspects have been covered in several surveys (e.g., [24], [25]); however, most of them are outdated and lack discussion on state-of-the-art developments. To date, there exists no comprehensive survey on the contributions from academia and standardization bodies for PON energy conservation. In 2010, Bolla *et al.* [37] have shed some light on the overall global footprint of ICT and presented an overview of energy consumption of different telcos and ISPs. Furthermore, they have summarized the most representative approaches for saving energy in the core, edge and access network segments. Similarly, in 2010, Zhang *et al.* [23] have reviewed the energy saving approaches for Optical core, metro, and access network (PON). For the energy saving approach in the access network, the authors only restrict their discussion to a very limited set of energy saving approaches in TDM-PONs, including sleep mode, User Network Interface (UNI) speed control and energy-efficient chips. They also presented a brief overview of PON evaluation, standardization efforts of IEEE and ITU-T, and sleep mode based schemes.

In 2011, Kantarci *et al.* [24] have conducted a comprehensive survey on the Dynamic Bandwidth Allocation (DBA) schemes for Long-reach PONs (LR-PONs) between 2007 to 2012. However, they have briefly covered early PON standards and architectures. Although the authors have highlighted the significance of sleep mode for energy conservation in PON, they have not presented a survey on sleep mode based energy saving solutions. In [25], Kani provides a detailed explanation on the standardized approaches for energy saving in ONUs introduced in ITU-T G-Sup.45 [38]. Furthermore, the author has elucidated the techniques for saving energy in OLTs of NG-PONs. However, the author neither includes any discussion on IEEE standardization work for PON energy conservation nor provides a comprehensive review on sleep mode based energy saving solutions.

Liu *et al.* in [26] have reviewed Fiber-Wireless (FiWi) architectures and their enabling technologies. In particular, the work covers the common aspects in FiWi architectures which are: scalability, reliability, availability and energy conservation. While discussing the energy saving aspects of a FiWi architecture, the authors briefly review about the sleep mode approach of the PON segment which is used as a backhaul in FiWi. In particular, they provide a brief overview of PON evolution, PON energy saving standardization activities and the sleep mode based energy saving solutions. Abbas *et al.* in [27] have provided a comprehensive review about PON standards (their coverage is from APON to NG-PON2). Specifically, the authors have intensively reviewed NG-PON2 and its related technologies. However, the PON technologies have now evolved beyond NG-PON2. Their work only briefly summarizes ITU-T contribution to PON energy saving, overlooking relevant standards the IEEE developed for conserving energy in PON (e.g., IEEE 1904.1 [39]). Thyagaturu *et al.* [28] have reviewed SDN managed optical networks, including optical metro and PONs. They provide a detailed overview on SDN managed optical equipment. However, their discussions lack detail analysis about the architectures for SDN controlled PONs proposed by standardization bodies like Broadband Forum (BBF) [40] and ONF [8], [9]. Additionally, it reviews only a few solutions applying sleep mode approach for saving energy in SDN controlled PONs.

All the aforementioned surveys are published until 2016. More recently, Butt *et al.* [29] have made a survey on energy saving approaches used in conventional PONs. In contrast to our work, they study a few IEEE and ITU-T standards for PON energy saving and review only few works that use sleep mode approach for energy conservation in TDM-PONs and TWDM-PONs without a detailed discussion and critical analysis. Lingas *et al.* [32] provide a short survey on energy saving techniques for PON. The study is limited by the lack of information on how different energy saving approaches are used in variants of PONs. Furthermore, it barely explores the existing contributions applying sleep mode approach for energy conservation in different PON variants.

TABLE I: Comparison of our work with other similar survey papers. Here, archi., stand., equip, and func. represent architecture, standard, equipment, and function, respectively.

Ref. year	Evolution of PONs (e.g., archi. & stand.) (C1)	SDN managed PON equip. (C2)	Virtualization of PON equip. func. relevant stand. & research (C3)	ITU-T and IEEE standards for PON energy saving (C4)	Existing solutions applying sleep mode approach for saving energy in conventional PON variants			Existing solutions applying sleep mode approach for saving energy in SDN controlled PON variants			Remarks
					TDM (C5)	WDM (C6)	TWDM (C7)	TDM (C8)	WDM (C9)	TWDM (C10)	
[23], 2010	✓	×	×	✓	✓	×	×	×	×	×	For C1, C4 and C5, it provides a very brief overview
[24], 2011	✓	×	×	×	×	×	×	×	×	×	– For C1, it provides brief overview about early standards and architectures.
[25], 2012	×	×	×	✓	✓	×	✓	×	×	×	– For C4, it comprehensively reviews relevant ITU-T standards until 2011, hence dated. – For C5 and C7, it reviews a few energy saving solutions.
[26], 2016	✓	×	×	✓	✓	×	×	×	×	×	– For C1, it briefly summarizes PON variants and standardization activities until 2016, hence not up-to-date. – For C4, it briefly summarizes ITU-T contributions; however, barely covers IEEE standardization effort for PON energy conservation. – For C5, only few solutions are discussed.
[27], 2016	✓	×	×	✓	×	×	×	×	×	×	– For C1, it covers early PON standards in detailed. – For C4, it summarizes briefly ITU-T contributions; however, ignores IEEE standardization effort for PON energy saving.
[28], 2016	×	✓	×	×	×	×	×	✓	×	✓	– For C2, it provides a comprehensive review about SDN controlled optical equipment until 2016; however, a detailed overview on standardization activities for SDN based control of PON is missing. – For C8 and C10, it reviews only a few works on energy saving. therefore, coverage is insufficient and is of limited use.
[29], 2018	×	×	×	✓	✓	×	✓	×	×	×	– For C4, briefly summarizes IEEE and ITU-T standardization works until 2014, hence not up-to date. – For C5 and C7, it covers only few solutions and therefore, lacks comprehensiveness.
[30], 2018	✓	×	×	×	×	×	×	×	×	×	– For C1, it provides a thorough review, but overlooks the recent PON standards (e.g., ITU-T G.9806 [31]) and architectures.
[32], 2018	×	×	×	×	✓	✓	✓	×	×	×	– For C4, C5, and C6, it reviews only few solutions with insufficient discussions; hence, the work has limited use.
[33], 2020	✓	×	×	✓	×	×	×	×	×	×	– For C1, recent standards (e.g., IEEE 802.3ca [34], [35] and ITU-T G.9806 [31]) and emerging PON characteristics and architectures are missing. – For C4, it covers very briefly only a few ITU-T contributions for PON energy saving.
[36], 2020	✓	×	×	×	×	×	×	×	×	×	– For C1, it makes a comprehensive review, but misses detail operational procedures of different PON variants (covers not as detailed as ours).
Ours	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	– For C1 to C10, it provides a comprehensive and recent review. It includes in-depth discussion, analyses, challenges, and future research directions.

Kumari *et al.* [30] have provided a thorough review about PON evolution up to NG-PON2 (ITU-T G.989 series) and included an insightful discussion about the challenges in NG-PONs. However, their work does not shed light on the recent (e.g., ITU-T G.9806 [31]) and emerging PON standards. Horvath *et al.* in [33] provide an outline of the standardization efforts for PON. However, it lacks detailed discussions on the recommended energy saving guidelines mentioned in those PON standards. A detailed discussion on early PON standards is also missing from this work. To the best of our knowledge, the most recent and comprehensive survey on PON is presented by Wey in [36]. Besides providing a well-rounded review on the existing generations and standards of PON, the author presents insightful discussions on the factors that act as the key drivers for PON evolution. However, the author does not provide detailed operational procedures of different PON variants.

Undoubtedly, the existing surveys and tutorials have paved the way for a number of subsequent research contributions for advancing PON research domain. Among them, to the best of our knowledge, there are only three works [25], [29], [32] where the prime objective is to explore PON energy saving research in academia and standardization bodies. These surveys emphasize that sleep mode is an economical and effective approach to reduce energy consumption in OLTs and ONUs. Furthermore, the work in [32] identifies that high utilization of OLT by increasing resource sharing is an effective means to minimize energy consumption. Additionally, the survey in [29] stresses that network transmission capacity improvement using technology like Orthogonal Frequency Division Multiplexing (OFDM) as well as energy-efficient Digital Signal Processing (DSP) technology should be an avenue for further study in PON. Note that all these surveys [25], [29], [32] cover conventional PONs only while recent research has focused on SDN based PON operation.

Recent advancements in research and standardization efforts warrant a new updated review article on this topic for the following reasons:

- Recently, there has been an increasing interest of using SDN to manage PON and disaggregation and virtualization of PON equipment functions. Review of such works that deal with virtualization and disaggregation aspects of PON have not been covered at all in any of the previous survey articles, as shown in the Column #3 of Table I. Standardization bodies like ONF and BBF have not been covered either. This necessitates a new review article covering these aspects to fill the gap in existing survey articles.
- Energy saving in SDN controlled PON systems (Column #8 (TDM), #9 (WDM) and #10 (TWDM) in Table I) has been not covered in literature except in [28]. Even [28] did not consider SDN managed WDM-PON system, was published in 2016 and reviewed only a few papers. Hence, it is already outdated as a review article.
- In addition, the existing surveys fall short of providing a detailed discussion on different energy saving approaches applied in PONs to date. The sleep mode approach based energy saving in different PON variants has been widely investigated by researchers to date. However, an exhaustive survey, insightful discussions and critical analysis on those research contributions are missing in the existing surveys.
- Existing surveys lack coverage of standardization efforts on energy saving in PON. To the best of our knowledge, [25] (published in 2012) is the only work that extensively reviews the ITU-T's standardized energy saving approaches in PON and, to date there is no detailed review on the standardization activities of IEEE for PON energy saving.
- In relation to architecture, capacity, multiplexing, reach and other related aspects of PON evolution, even the most recent surveys does not cover standardization efforts beyond 2020. This necessitates new survey covering the most recent emerging architecture and characteristics, including standards like ITU-T G.9806-Corrigendum 1 ([31], 2022) & ITU-T G.9806 Amendment 3 ([106], 2024), which our paper aims to cover. Also, note that, recently PON architecture is evolving beyond FTTH and reaching further deeper to "Fiber-to-everywhere". All these recent developments are presented in Section II-B, not covered in the earlier surveys.

Table I presents a comparison between our contributions in this article and the existing related surveys and tutorials stated in this Subsection I-A. Our review article is timely in providing a comprehensive survey on recent research and standardization activities for energy-efficient PONs, PON evolution towards architectural and softwarized control, and research challenges ahead to meet the requirements of performance stringent emerging applications (e.g., immersive extended reality [41] and haptics and robotics [42]) while conserving energy. It presents researchers with a complete overview of ongoing state-of-the-art research and familiarizes them with future research directions.

B. Contributions and Structure of the Article

As alluded in the previous subsection highlighting the gap in existing survey articles, we make the following contributions in this article to fill that gap, making an extensive coverage of the topic.

- First, we explain the variants and evolution of PONs, covering the architecture and operational procedures for each of the variants. We then explain how PON has been evolving since 1998 when the first Asynchronous Transfer Mode (ATM) PON (APON) was introduced.
- We provide a detailed overview of SDN as well as SDN controlled PON equipment (e.g., OLT). We also discuss the major opportunities SDN brings in PON and provide a comprehensive overview on the standardization and academic research activities for SDN controlled PONs, and disaggregation and virtualization OLT/ONU functions.
- To provide readers with a broad overview about the existing energy conservation approaches in PON, we review various approaches introduced by academia and standardization bodies (i.e., IEEE and ITU-T). We also provide an overview on the standardized operational guidelines for the energy saving approaches considered by these bodies for PON energy conservation.
- Among the energy saving approaches, sleep mode based energy saving approach has been the most widely studied by the scientific community. Therefore, for the conventional (i.e., those not controlled by SDN) and SDN controlled PONs, we present a comprehensive state-of-the-art survey of the existing works applying sleep mode. Additionally, we present discussions with critical evaluation and insightful observations.
- Towards the end of the survey, we present timely insightful insights based on this survey, and identify challenges and future research directions for improving energy conservation in PONs.

Fig. 1 presents the structure of this article. We explain different PON variants and evaluation of PON in the Section II. Section III provides an overview on SDN integration with PON. Section IV includes an overview on different energy saving approaches. In Section V, we provide an in-depth overview on the standardized operational mechanisms for the energy saving approaches considered in IEEE and ITU-T PONs. We provide the readers an in-depth survey and taxonomy of state-of-the-art solutions applying sleep mode approach to reduce energy consumption in conventional and SDN controlled PONs in Section VI and Section VII, respectively. In Section VIII, we highlight the lesson learned, identify research challenges and elaborate future research directions. Finally, we conclude this article in Section IX.

II. Variants and Evolution of PONs

In this section, we will first describe the evolution of PONs. Following this, we will briefly describe the variant of PON. In a PON, there are three important segments: a CO, a Remote Node (RN) and Customer Premises Equipment (CPE). A PON architecture facilitates a master-slave relationship between the OLT and ONUs. The CO, where OLTs are placed, connects the

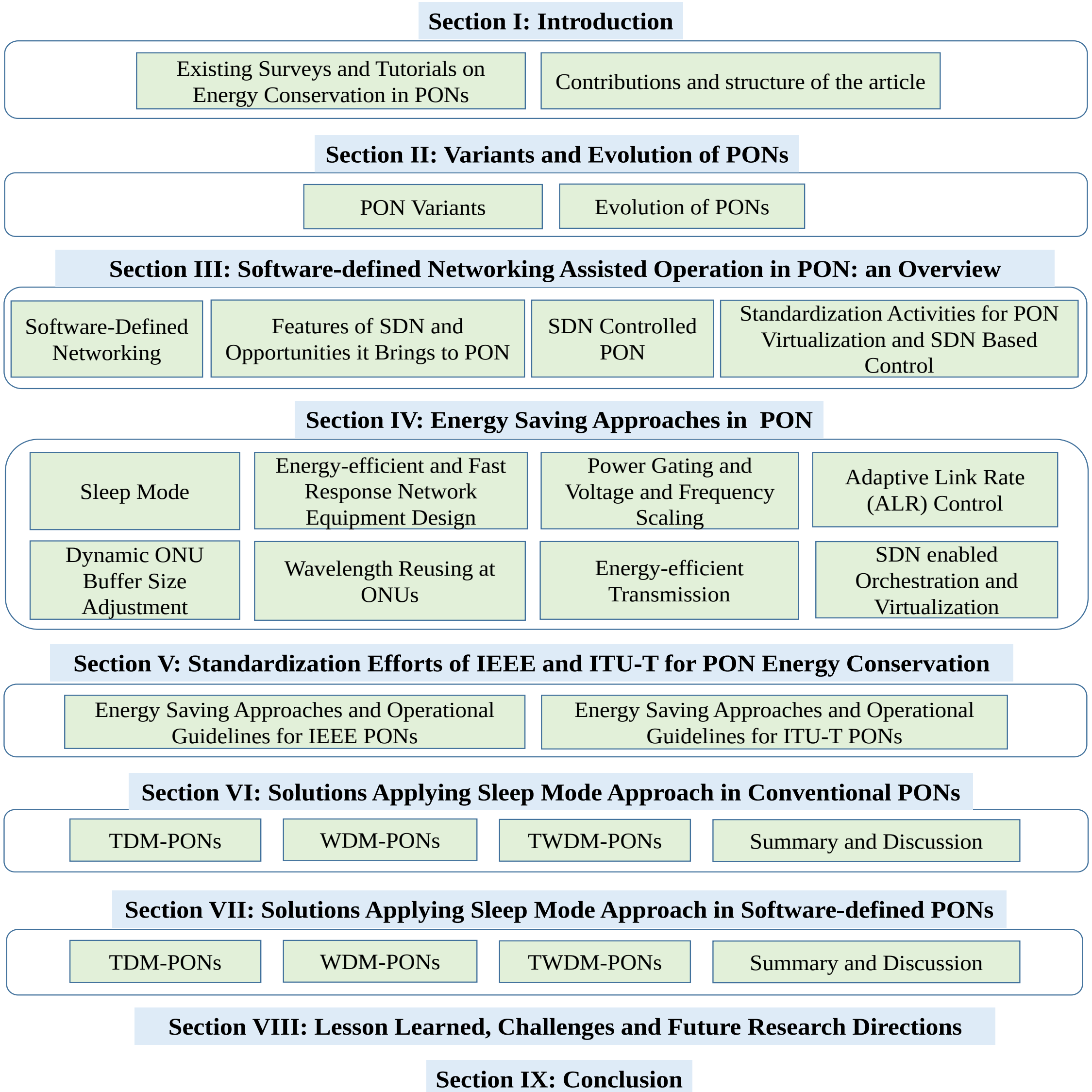

Fig. 1: Outline of this article.

core and access network segments. Generally, a single Feeder Fiber (FF) connects the RN from which multiple Distribution Fibers (DFs) connect the ONUs in a customer premises.

A. PON Variants

From a multiplexing architectural perspective, this subsection classifies PON into three major variants: TDM, WDM and TWDM.

1) TDM-PONs: The basic building blocks of a TDM-PON system are: a number of ONUs, an OLT and a splitter. In order to provide network access to the end users, a Point to Multipoint (PMP) architecture is formed using an OLT, the central intelligence of the network, and N number of ONUs, which are installed at the customer premises and connected to the OLT by optical fibers. The splitter is a passive device (does not require any power supply) and it is installed between the OLT and the ONUs. The splitting ratio of a splitter is defined as *1:N*, where N can be 16, 32, or 64 ONUs. For downlink (OLT to ONUs) and uplink (ONUs to the OLT) communication, two separate wavelengths are applied, as shown in Fig. 2 (a). Both IEEE and ITU-T proposed to use TDM technology for their early generation of PONs, i.e., APON, BPON, Gigabit-capable PON (GPON), EPON, 10G-EPON and XG(S)-PON.

The main principle for downlink communication is the broadcast and select mechanism—a splitter broadcasts all the input signal (multiplexed data) received from the OLT through optical fiber to all the connected ONUs. The OLT adds a unique identifier to each downlink frame (i.e., 'Alloc ID' in GPON [43] and unique Logical Link Identifier (LLID) in EPON [44]), so that, an ONU can select its frames from the downlink broadcast signal. Since the ONUs share the same wavelength for the uplink communication, the OLT maintains uplink communication in a TDMA fashion (each of the ONU receives a transmission opportunity within a transmission cycle, T_{cycle} and the uplink frames are transmitted in burst mode [45]). The decision on the amount of time each ONU

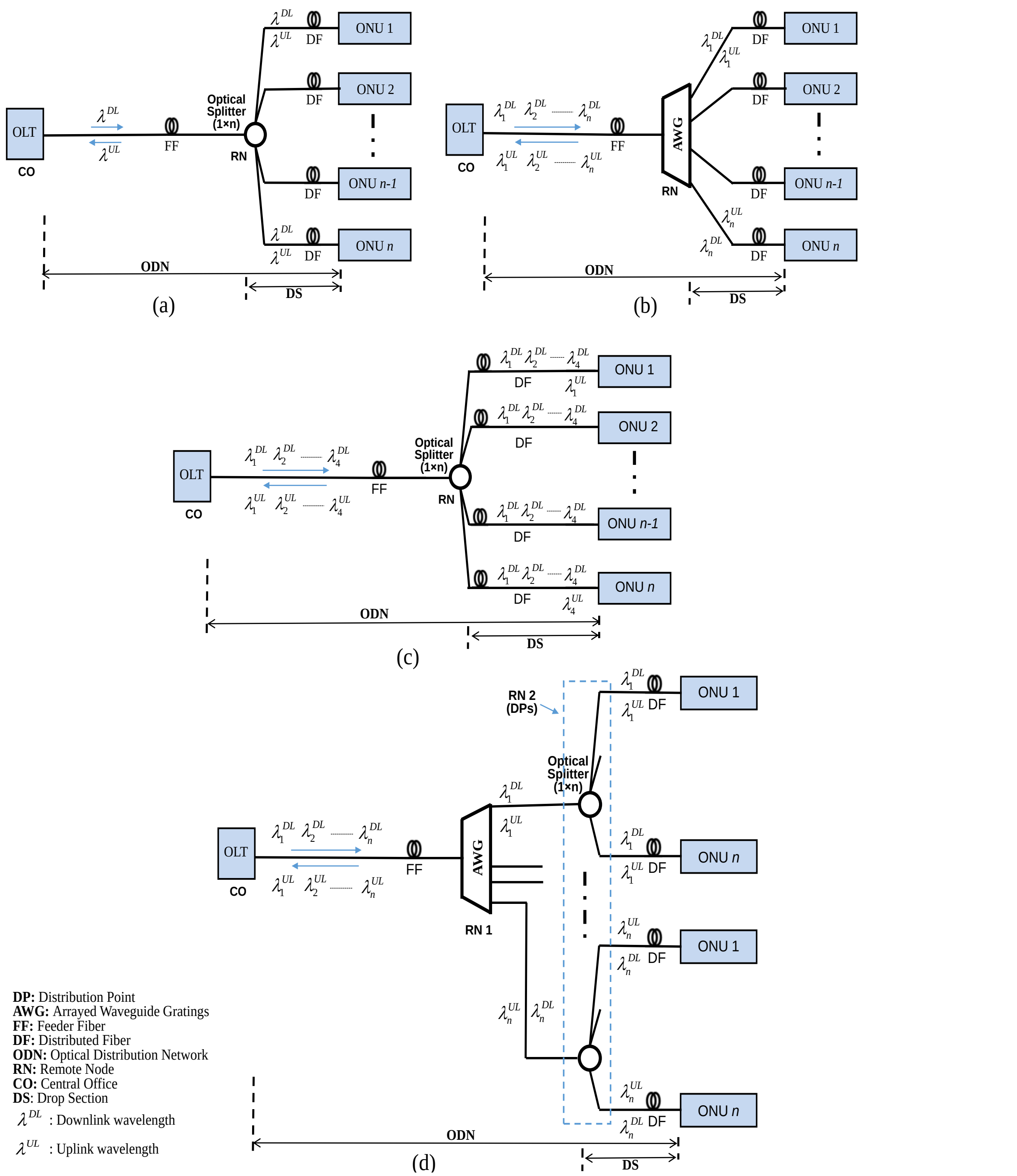

Fig. 2: PON architectures: (a) TDM-PON; (b) WDM-PON; (c) Multi-Wavelength TDM-PON (Type-1 TWDM-PON); (d) Wavelength-Routed hybrid WDM/TDM PON (Type-2 TWDM-PON).

will transmit within a T_{cycle} is decided using a DBA scheme. After each T_{cycle}, which is generally referred as polling cycle or DBA cycle, the OLT sends a message invoking the ONUs to share the amount of bandwidth they require and, in reply, the ONUs send a feedback message mentioning the amount bandwidth they need to have in order to forward traffic stored in their buffer.

For uplink traffic in GPON, the dynamic bandwidth allocation is achieved by considering one of the five T-Count classes (T-Count 1, T-Count 2, T-Count 3, T-Count 4, and T-Count 5). GigaPON access network DBA algorithm (GIANT) is considered as the first DBA algorithm for GPON [46]. This algorithm prioritizes the weighted round robin where the weights depend on the Service Level Agreement (SLA) and service interval. For XG-PON, one of the promising DBA schemes is demand forecasting DBA wherein future demands of the ONUs are predicted using the statistical modeling of previous demand patterns and the grant is assigned to an ONU if the required bandwidth can be allocated [47].

For uplink data in EPON, one of the first introduced DBA schemes is Interleaved Polling with Adaptive Cycle Time (IPACT) that allocates bandwidth to ONUs based on the polling process. An ONU generates a request message at the end of its slot telling the number of remaining buffered bytes at the time of sending the request. In a given T_{cycle} duration, the registered ONUs under an OLT are scheduled in a such a way that the first bit of an ONU arrives at the OLT immediately after the guard time has elapsed [48]. To guarantee a minimum bandwidth under high traffic load, researchers proposed a two-layer bandwidth allocation algorithm [49]. This scheme allows the ONUs to report its traffic load of different traffic class separately. First, the OLT allocates bandwidth for different traffic classes and then, the OLT distributes the allocated bandwidth of any particular class among the requesting ONUs. It is worth highlighting that DBA has been still an active area of research both in academia and standardization bodies due to the advent of emerging applications demanding low latency and jitter performance (e.g., [50], [51]).

2) Wavelength Division Multiplexing (WDM)-PON: In WDM-PONs several channels are transmitted simultaneously over a single FF (i.e., a single shared fiber connects the CO and RN) [52], [53]. From the RN, each dedicated fiber connects an ONU located at the customer premises [54]. In a WDM-PON, an ONU can have a pair of dedicated uplink and downlink channel to communicate with the OLT. Generally, unlike a TDM-PON, at the RN, an Arrayed Wave Guide (AWG) router is used to route a wavelength to a particular ONU. A WDM-PON is a Point-to-Point (PtP) communication system [55]. Fig. 2 (b) depicts a WDM-PON with an AWG facilitating dedicated wavelength based PtP communication between an ONU and the OLT. In this PON architecture, the OLT is equipped with a Multiplexer/Demultiplexer (MUX/DEMUX) to aggregate and dis-aggregate the operating wavelengths deployed for downlink and uplink communication.

A WDM-PON is expensive as the number of transmitters and receivers required is significantly higher than that of a TDM-PON system. However, a WDM-PON offers several advantages. First, it provides more secure communication between the OLT and the ONU (a PtP communication reduces the chance of eavesdropping). Second, as it provides PtP connections between the OLT and the ONU, the protocol implementation is far simpler than a TDM-PON. Finally, a WDM-PON provides higher bandwidth to its customers compared to a TDM-PON by several folds [56]. Though it has been commercially available for a long time (around 10 years), only a few countries embraced WDM-PON so far—among them, the most notably is South Korea [54]. Recent and future generations of PONs such as NG-PON2, NG-EPON and Higher Speed PON (HS-PON) utilize WDM technology.

3) TDM and WDM (TWDM) PON: Similar to [27], [57], [58], we categories TWDM-PON into two types: Multi-Wavelength TDM-PON and Wavelength-Routed hybrid WDM/TDM PON, which are referred as Type-1 TWDM-PON and Type-2 TWDM-PON in the subsequent part of this article, respectively.

a) Multi-wavelength TDM-PON (Type-1 TWDM-PON): A Type-1 TWDM-PON has the capability of bandwidth re-balancing, providing higher network availability and reducing power consumption. A basic structure of this type of TWDM-PON deploys four to eight pairs of wavelengths for uplink and downlink communication [59]–[61]. Each downlink and uplink channel provides peak data rates of up to 10 Gbps and 2.5 Gbps data rate, respectively [62]. Therefore, it can have up to 80 Gbps and 20 Gbps aggregate capacity in the downlink and uplink, respectively [60], [61]. Similar to a TDM-PON, in a Type-1 TWDM-PON, an OLT and ONUs are the active components in the network. That is, a passive splitter is used in the Optical Distribution Network (ODN) part [62], [63]. The OLT has an array of transmitters and receivers for the N number of ONUs connected with the ODN [64], [65]. An ONU in this network is also equipped with a tunable transmitter and a receiver, which allows it to tune to any of the downlink and uplink wavelengths at any given time [21], [22], [66]. Tunable transmitters and receivers at the ONUs provide the network with full flexibility and reconfigurability. As the ODN uses passive splitter, all the wavelengths transmitted from the OLT reach to all the ONUs, as shown in Fig. 2 (c). However, an ONU would be tuned to a particular wavelength at a specific time. The tuning time to a particular wavelength may vary depending on the characteristics of the tunable device—the tuning time could range from 10 μs to 1 s [64].

b) Wavelength-routed hybrid WDM/TDM PON (Type-2 TWDM-PON): In EPON and GPON, with a split size of 32, the maximum reach of the OLT from a CO would not be more than 20 km to keep the loss budget within an acceptable range [24], [67]. This problem triggered many research initiatives to increase the transmission coverage and split size, thereby accommodating more customers while reducing the Capital Expenditures (CAPEX) and Operating Expenses (OPEX). Among the solutions researchers introduced, the Type-2 TWDM-PON (Wavelength-Routed hybrid WDM/TDM PON) is considered to be a very viable solution [68]. This PON architecture allows wavelength routing by means of the combination of an AWG and passive splitters [27], [57], [58], as shown in Fig. 2 (d).

In this type of PON, to begin with the downlink, the downlink signals from different light sources of the OLT are multiplexed by an AWG at the CO and then forwarded towards the downlink direction through a single FF [69]. This PON has at least two RNs. The FF connects the OLT to the RN (RN1) where an AWG is deployed to guide the optical channels to the passive splitters, which are located at the Distribution Points (DPs), as shown in Fig. 2 (d). Each passive splitter connects a group of ONUs through optical fiber and it has the role to broadcast downlink traffic and combine the uplink traffic [70]. Similar to a TDM-PON, for the downlink communication broadcast and select mechanism is used. Media Access Control (MAC) layer is in charge of scheduling time slots and wavelengths among a group of users connected with a passive splitter, which is located at the 2nd RN (RN2) of the network [71]. In the case when each uplink channel is shared among multiple ONUs, the OLT needs to maintain multiple DBA cycles [72]). The optical amplification can be used in Type-2 TWDM-PON to compensate power loss due to fiber attenuation and splitter loss [73]. It is worth highlighting that Type-2 TWDM-PON can also have a ring-and-spur topology [24], [74]–[76], as illustrated in Fig. 3.

A Type-2 TWDM-PON can have an alternative architecture where instead of using an AWG at the RN1 a passive splitter is used [71]. The implementation cost of this type of network might be lower as compared to the AWG based solution. Nevertheless, in such an architecture, the downlink signals experience more power loss due to multistage splitters and ONUs might be a victim of eavesdropping as all the downlink signals reach to all the ONUs in the network. Furthermore, wavelength routing is no longer possible in this type of architecture.

To further extend the coverage and split ratio, Long-reach WDM/TDM PON (LR WDM/TDM PON) was introduced [76]–[78]. It extends its coverage span up to 100 km and beyond by using optical amplifier(s) and WDM technologies [79]. It can have a splitting ratio up to 1:1024 by using multi-stage splitters [24]. To amplify the signal, it uses various optical amplifier technologies at its RNs, including the Erbium-doped-fiber Amplifier (EDFA) and the Semiconductor Optical Amplifier (SOA) [24], [79], [80]. This network can have a tree-and-branch or ring-and-spur topology where one or more wavelengths can be deployed [24], [67]. Similar to a WDM-PON, a TWDM-PON requires its OLT to come with a MUX/DEMUX to multiplex and demultiplex the downlink and uplink wavelengths. Note that TWDM technology is used in current and future generations of PONs, including NG-PON2 and HS-PON.

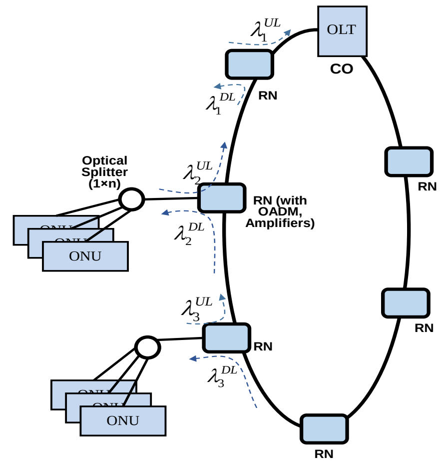

Fig. 3: A ring-and-spur topology based wavelength-routed hybrid WDM/TDM PON architecture.

B. *Evolution of PONs*

Fig. 4 illustrates the road-map indicating the standards and technologies for PON evolution from year 1998 [81]. In the late 1990s, the Full Service Access Network (FSAN) group, which was formed by several telecom carriers [45], initiated a unified standard for PON equipment (the main objective was to specify common requirements) and later on, this effort became part of the ITU-T G.983 series [82]. This first standard of PON was developed considering Asynchronous Transfer Mode (ATM) technology as bearer protocol. Therefore, this standardized PON system was named as ATM PON (APON). Later, based on APON, ITU-T introduced BPON with higher transmission capacity than APON (BPON provides 1244.16 Mbps and 622 Mbps data rate for downlink and uplink communication, respectively [83]).

Ethernet PON (EPON), which has been standardized in IEEE 802.3ah [84], and GPON, which is standardized in ITU-T G.984 [85], are widely adopted TDM-PON solutions across the globe. The GPON defines downlink and uplink data rates at 2.48832 Gb/s ($\approx$ 2.5 Gb/s) and 1.24416 Gb/s ($\approx$ 1.25 Gb/s), respectively [85]. Both GPON and EPON allow a maximum splitting ratio of 32 where the fiber can reach around 20 km from the central office. APON, BPON, GPON and EPON are a TDM-PON.

The increasing demand for bandwidth in the access network segment has necessitated further evolution of PON. Continuous efforts have been made by the standardization bodies to achieve PON systems offering high capacity at a low cost and consequently, Next Generation PONs (NG-PONs) come to the forefront of the scientific community: 10G-EPON and XG(S)-PON. ITU-T/FSAN developed NG-PON1 solution keeping in mind that it can coexist with existing fiber installations while providing more bandwidth. With regard to performance, ITU-T/FSAN aimed at introducing PON solutions that reduce energy consumption, increase security, extend network reach and provide high bandwidth. FSAN and ITU-T envisage two phases for the evolution process of NG-PON: NG-PON1 and NG-PON2 [56]. NG-PON1 is a mid-term upgrade of the initially deployed PONs which is compatible with both GPON and EPON based ODNs. In 2009, IEEE released 10G-EPON (IEEE 802.3av) with data rate of 10 Gb/s in both downlink and uplink direction using the 64B/66B line encoding technique [87]. Afterwards, ITU-T standardized an asymmetric (downlink: 10 Gb/s, uplink: 2.5 Gb/s) TDM-based NG-PON, namely, XG-PON [88]. ITU-T recommended a TDM-based symmetric PON, XG(S)-PON, to offer 10 Gb/s in both downlink and uplink data transmission [89]. XG-PON is a subclass of NG-PON1 [88].

The IEEE 802.3 specifications for 1G-EPON and 10G-EPON solely focus on Layer 1 and Layer 2 aspects (physical layer and data link layers and link management functions) [90]. However, as the specifications encompass only Layer 1 and Layer 2 aspects, it impedes interoperability among EPON equipment from multiple vendors. To facilitate multivendor interoperability of an EPON equipment, the IEEE Communications Society initiated the P1904.1 project, where carriers, chip vendors, and manufacturers were unitised [91], for standardizing SIEPON based on existing EPON standards. This project aimed at developing international system-level specifications to facilitate interoperability of EPON equipment from multiple vendors [90], [91]. The most important technical issues that SIEPON addresses are [90]: management, QoS guarantees, multicast and broadcast service management over EPON, power consumption reduction, Virtual LAN (VLAN) modes and tunneling, protection switching, ONU authentication, discovery and maintenance and data encryption [90]. IEEE Standards Association approved the SIEPON standard (IEEE Std 1904.1) in June, 2013. The reader is refereed to [90] for a more detailed summary of the technical specifications of

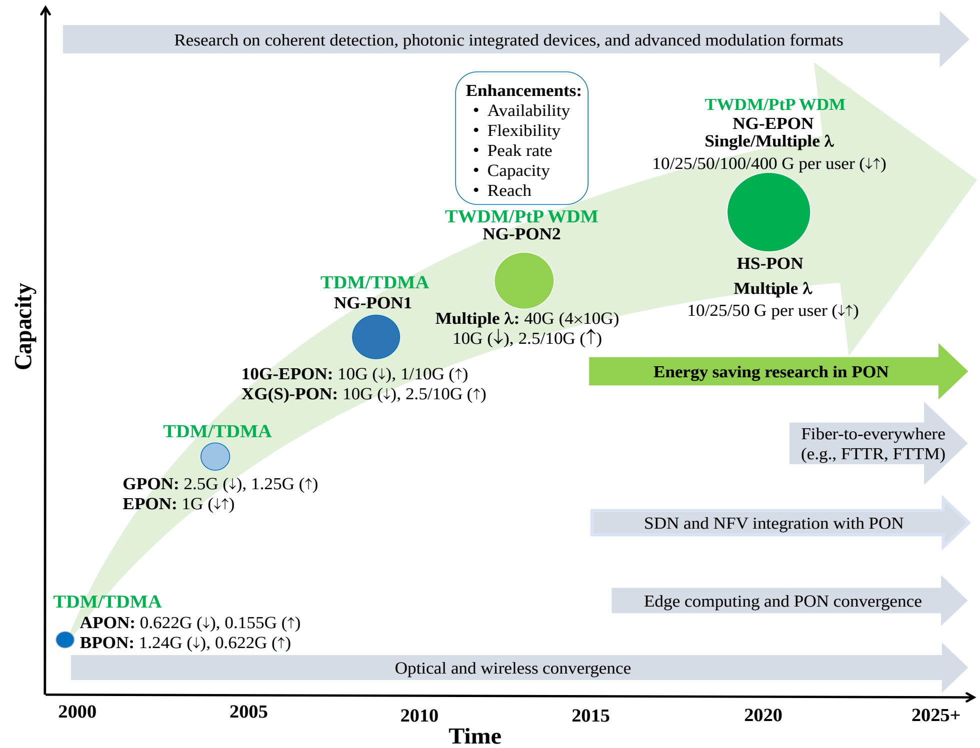

Fig. 4: Roadmap of standards and technologies for PON evolution [81], [86].

SIEPON.

ITU-T/FSAN aimed at introducing the NG-PON2 standard, defined in Recommendation G.989, where multiple wavelengths can be dispensed in both uplink and downlink direction of a PON. The first Recommendation G.989.1 of this standard was approved in 2013 [83]. NG-PON2 standard considers two solutions mainly: a TWDM-PON and a wavelength overlay PtP WDM-PON [64], [92]. We have already explained their operational procedures in Subsection II-A. Note that, NG-PON2 proposal aims at introducing power-splitter-based ODNs. Consequently, the ONUs in NG-PON2 require wavelength-tunable optics, allowing them to select the desired wavelength depending on requirements as recommended in ITUT G.989.3 [21] and ITUT G.9804.1 [22]. PtP WDM-PON can be further classified into two categories: the wavelength-selected ODN (WS-ODN), where ONUs use tunable filters to retrieve desired signal, and the wavelength-routed ODN (WR-ODN), where the ODN deploys AWG to route a wavelength to a predefined output port of the AWG [64]. We have already briefly explained the working principle of WDM-PON with WR-ODN in the Subsection II-A2. Note that WR-ODN based PtP WDM-PON can have a longer FF reach compared to WS-ODN based one due to the lower power loss at the AWG. We can consider NG-PON2 as a long-term solution of PON deployment over new ODNs because it aims at accommodating both business and residential users.

It is also worth mentioning that most of the NG-PONs are expensive and thus cost-effective solutions are required. As a result, the third generation of PONs focuses on cost-effective coherent Ultra-dense WDM (UDWDM) PONs where we can accommodate a considerably large number of dedicated channels ($\geq$ 256) with a channel separation of 6.25 or 12.5 GHz. An UDWDM based architecture utilizes a Phase Shift Keying (PSK) scheme where we can achieve a data rate of 1–10 Gb/s per user. The primary challenges of optical access networks are the coexistence of the current and future generation PONs and the proper use of optical spectrum. Because of the inclusion of RF video overlay, we have a very limited optical spectrum (1544–1575 nm) in hand. As a result, third generation PONs, i.e., NG-PON3 can occupy 1544–1575 nm for both downlink and uplink data transmission [86]. Although research works have been ongoing for designing NG-PON3 and investigating how it can co-exist with the commercially available PON systems, there is no initiative from the standardization bodies to standardize it yet.

Due to the evolution of dynamic technologies such as SDN, Network Functions Virtualization (NFV), Internet of Things (IoT), 5G, and optical wireless convergence, the demand of number of users and data rates show increasing trend. To support future applications that demand high bandwidth and low latency, we can expect new electronics & photonics revolutions and new models of optical access systems. In recent years, researchers are working on super-PONs where the objective is to provide a data rate of at least 10 Gb/s per user. Initially, four different types of data rates (10 Gb/s, 25 Gb/s, 50 Gb/s, and 100 Gb/s) were considered for symmetric/asymmetric bidirectional data transmission.

The ITU-T Q2/15 study group is working on the standardization of high speed bidirectional single fiber PtP PONs [31], [98], [106]. As a result, HS-PON comes to the forefront of the field. In 2020, ITU-T G.9806 proposed for the first time the standards of 10 Gb/s HS-PON [31]. Furthermore,

TABLE II: Summary of the primary characteristics of the current and future generation PONs [35], [36], [64], [83], [97], [98].

Standard	**APON** [99]	**BPON** [100]	**GPON** [85]	**EPON** [84]	**10G-EPON** [87]	**XG(S)-PON** [88], [89]		**NG-PON2 [60], [61], [64]**		**NG-PON3** [101]	**NG-EPON** [34]–[36], [102]–[104]	**HS-PON** [31], [105]
Recommendation	ITU-T G.983	ITU-T G.983	ITU-T G.984	IEEE 802.3ah	802.3av	ITU-T G.987	ITU-T G.9807	ITU-T G.989		–	**IEEE 802.3ca/cp** **IEEE 802.3cu**	**TU-T G.9806** **ITU-T G.9807.3** **ITU-T G.HSP.TWDM**
								TWDM PON	WDM PON			
Year of 1st publication	1998	2001	2003	2004	2009	2010	2016	2014		–	2018 2021	2020 2021
Maximum downlink aggregated capacity (Gb/s)	0.622	1.24	2.5	1	10	10	10	80	80	256	–	–
Maximum uplink aggregated capacity (Gb/s)	0.155	0.6	1.25	1	10	2.5	10	20	80	256	–	–
Multiplexing technology	TDM	TDM	TDM	TDM	TDM	TDM	TDM	TWDM	PtP WDM	UDWDM	TWDM PtP WDM	PtP WDM TWDM
No. of wavelengths (downlink/ uplink)	1/1	1/1	1/1	1/1	1/1	1/1	1/1	4-8/4-8	4-8/4-8	256	4	2 or 4
Channel spacing (GHz)	–	–	–	–	–	–	–	50–100	50–100	6.25–12.5	–	100 200
Split Ratio	1:32	1:32	1:32	1:32	1:64	1:64	1:64	1:256	1:256	1:256	–	–
Minimum fiber reach (km)	20	20	20	20	20	20	20	40	40	100	10/25/50 Gb/s: 40 100 Gb/s: 10 400 Gb/s: 6	40
Operating wavelength range for downlink transmission (nm)	1480–1580	1480–1580	1480–1500	1480–1500	1575–1580	1575–1580	1575–1580	1596–1603	1524–1625	1544–1575	10/25/50 Gb/s: 1320–1340 100 Gb/s: 1304.5–1317.5 400 Gb/s: 1264.5–1277.5, 1284.5–1297.5, 1304.5–1317.5, 1324.5–1337.5	1320–1340 (for 10 Gb/s user data rate) (25/50 Gb/s have not been decided yet)
Operating wavelength range for uplink transmission (nm)	1260–1360	1260–1360	1260–1360	1260–1360	1260–1280	1260–1280	1260–1280	1524–1544 (*wide band*) 1528–1540 (*reduced band*) 1532–1540 (*narrow band*)	1524–1625	1544–1575	10/25/50 Gb/s: 1260–1280 100 Gb/s: 1304.5–1317.5 400 Gb/s: 1264.5–1277.5, 1284.5–1297.5, 1304.5–1317.5, 1324.5–1337.5	1260–1280 (for 10 Gb/s user data rate) (25/50 Gb/s have not been decided yet)

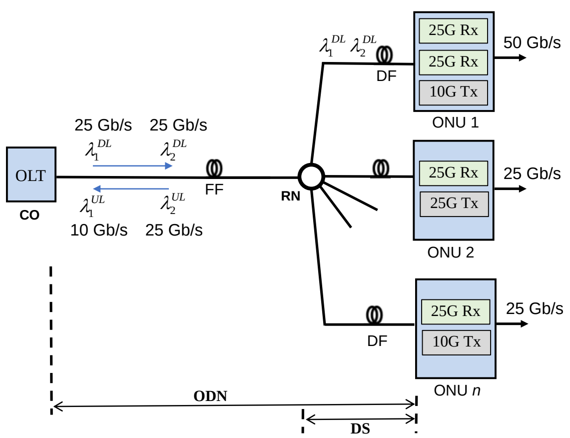

Fig. 5: NG-EPON (IEEE 802.3ca/cp) system with 50Gb/s aggregated downlink capacity (the *ONU 1* in this figure can achieve an aggregate capacity of 50 Gb/s downlink data rate by bonding two 25Gb/s wavelength channels) [36], [93]–[96].

standardization of ITU-T based HS-PON having data rate of 25 Gb/s and 50 Gb/s is still under process (bonding of two 25 Gb/s wavelength channels to achieve 50 Gb/s aggregate data rate). The 10 Gb/s HS-PON utilizes PtP WDM technology, whereas 25/50 Gb/s HS-PON utilizes TWDM technology.

In 2015, IEEE 802.3ca Task Force was established with the aim of introducing 100G-EPON by 2020 [95], [103]. The IEEE 802.3ca (N×25G-EPON) task force developed a N-channel with 25 Gb/s per channel data rate based on a non-tunable TWDM-PON system [105]. Thus, the 50G-EPON system can be achieved by bonding two 25 Gb/s wavelength channels [36], [105], as depicted in Fig 5. The IEEE 802.3ca standard considers several downlink and uplink data rate (25 Gbit/s to 100 Gbit/s for downlink and 10 Gbit/s to 100 Gbit/s for uplink [95], [107]). Seven types of ONUs can be deployed: 25/10G-ONU (single channel in each direction), 25/25G-ONU (single channel in each direction), 50/25G-ONU (two channels in the downlink and one channel in uplink direction), 50/50G-ONU, 100/25G-ONU, 100G/50G-ONU, and 100/100G-ONU [95]. Additionally, IEEE standardized four carriers bidirectional NG-EPON (IEEE 802.3cu) operating at 100 Gb/s and 400 Gb/s [104]. The proposed range for 100 Gb/s and 400 Gb/s is at least 10 km and 6 km, respectively [104]. The 100/400 Gb/s NG-EPON uses PtP WDM technology for bidirectional communication. Both standardization bodies considered the 64B66B line coding scheme for data transmission in HS-PON and NG-EPON. These PON systems are designed in such a way that, they can operate with previously deployed PONs. Table II summarizes the primary characteristics of the current and future generation PONs. PON is also evolving towards software-defined control and disaggregation and virtualization, impacting both architectural and operational aspects of PON, as we will discuss further in next Section III.

Recent architectural evolution: Over the last several years, with the growing need of faster response to any computational requests, AI assisted localized decision-making, content caching, and virtualization of network functions, edge computing co-existence with PON is gaining attention in academia and standardization bodies (e.g., [108]–[110]). In academic research efforts, various deployment scenarios of edge-computing facilities co-located with PON (as a separate entity) have been considered; for example, at CO (e.g., [108], [111]), RN (e.g., [111]–[113]), and customer on-premises (e.g., [114], [115]). Recently, there is also built-in deployment of edge computing in PON OLT/ONU has been considered in current research (e.g., [116], [117]), i.e., embodied computing and storage module in OLT and ONU. In 2023, the European Telecommunications Standards Institute (ETSI) has released documents for industrial PON deployment, where built-in network edge computing capability in OLT and ONU has been recommended (e.g., in [110]) to gain several benefits, including real-time decision making closer to data sources, reduction of uplink data volume, and protocol conversion.

PON is going beyond Fiber-to-The-Home (FTTH) deploy-

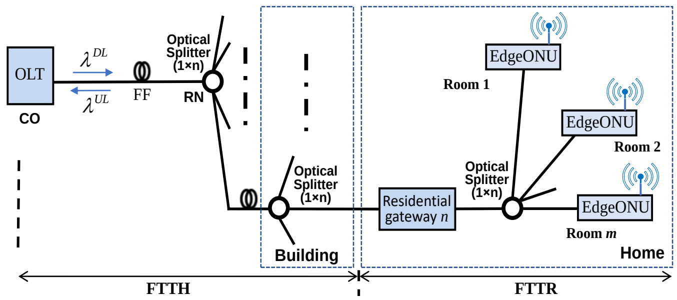

Fig. 6: FTTR supporting internal backbone connection to individual rooms in a home.

ment. In early 2020, with the objective to realize "fiber-to-everywhere", the ETSI established an Industry Specification Group (ISG) to define and enumerate the scope of Fifth Generation Fixed Network (F5G) [118]. The vision of "fiber-to-everywhere" in F5G is to push fiber further closer to the end user premises, leveraging high-speed broadband connectivity with ultra low latency for emerging applications (e.g., Cloud VR) as well as generating new revenue generating services for the PON operators, including Fiber-to-The-Room (FTTR), Fiber-to-The-Office (FTTO) and Fiber-to-The-Desk (FTTD) and Fiber-to-The-Machine (FTTM) [110], [118]–[120]. For example, in case of FTTR, optical fiber as internal backbone connects individual room within a home/apartment (e.g., in-home Wi-Fi backhauling as depicted in Fig. 6) [120]–[122]. In 2021, ITU-T also released FTTR use cases and network requirements in [122]. Additionally, in [123], it considers centralized powering from the local OLT or connected terminal powered ONUs as alternatives of power sources for private networks like FTTR. For industrial PON deployment, ETSI has delineated PON requirements in industrial settings, including multi-tier spine-leaf OLT setup and resiliency aware ODN architecture, ONU interface requirements (physical interface like RS-232 and RS-485), resource slicing, and bandwidth allocation mechanism [110]. This is worth highlighting that AI is being considered as a key pillar in F5G architecture to facilitate network automation (without need of human intervention) and ensure consistent network performance to the residential and business users in accordance to their SLA requirements [118], [119], [124].

Due to the emergence of PON for non-residential professional services and use cases (e.g., industrial communication, x-haul transport in wireless networks and intra-datacenter/edge communication) with deterministic performance demand (low latency and low jitter), new types of PON architectures, equipment and management operation are emerging. To support inter-ONU communication, an architecture (with system optics modification at RN) facilitating both intra-ODN and inter-ODN communication besides supporting conventional PON communication has been introduced in [125]. Similarly, an architecture facilitating inter-ONU communication using a separate wavelength routed through modified RN (added fiber Bragg grating allowing reflection of certain wavelength) to assure direct communication between ONUs co-located edge-computing facilities has been proposed in [111], [113] (see an example illustration in Fig. 7).

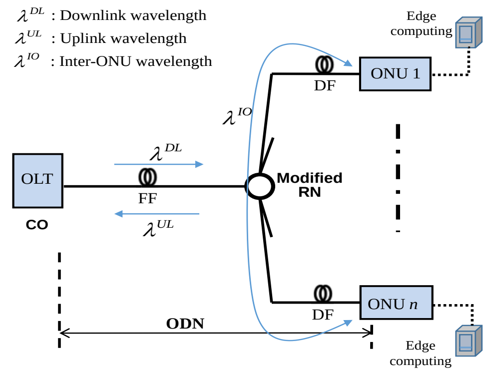

Fig. 7: Intra-ODN communication facilitated by modified RN (reflecting certain wavelength to support inter-ONU communication), allowing direct communication between edge computing facilities.

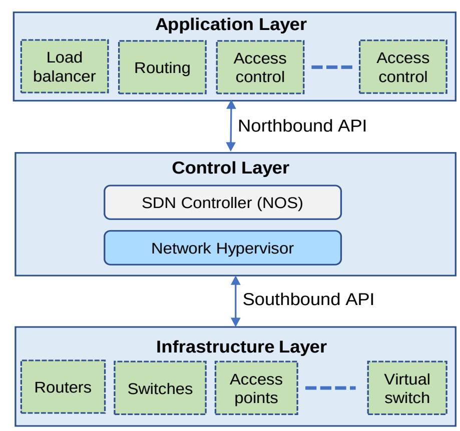

Fig. 8: Illustration of SDN abstraction layers and interfaces: The infrastructure layer, which implements data plane, is controlled by the control layer based on the requirements set by the application layer. The Northbound interface facilitates communication with the SDN controller (e.g., FloodLight and POX [126]) application layer, while the Southbound interface interconnects the control plane and the SDN switches in the infrastructure layer.

III. Software-Defined Networking Assisted Operation in PON: An Overview

This section first provides a background on SDN in Subsection III-A. Next, it discusses the features and opportunities SDN brings to PON in III-B. A summary on SDN controlled photonic devices in Subsection III-C is provided. Finally, in Subsection III-D, a summary of standardization activities related to PON virtualization and SDN-based control is presented.

A. *Software-Defined Networking in Brief*

In general, every computer network can be separated into three planes of functionality: the management, control and data planes [127]. The data plane corresponds to the networking elements such as routers and switches. The control plane represents the protocols utilized to populate the forwarding tables of the data plane elements and, finally, the management plane consists of the software (network) services [127]. In a traditional IP network, a network device (e.g., router) has a tightly coupled control and data plane, making them rigid, and complex to manage and control dynamically. Conversely, in an SDN, the control and data planes are decoupled. The control plane has a logically centralized controller which is a software entity. This software entity is generally referred as Network Operating System (NOS) which runs on a commodity server technology [28], [127], [128]. On the other hand, the data plane in an SDN is represented by interconnected forwarding devices [127]. To leverage the SDN capability, there are several controllers already introduced. They can be categorized based on different features including architecture type, threading and modularity, programming languages used to build them and APIs. For example, ONOS [129], OpenDaylight [130] and ONIX [131] are SDN controllers with a distributed control architecture, whereas NOX [132] and Ryu [133] controllers are centralized. A single-threaded controllers are developed for lightweight SDN deployments, whereas for commercial purposes like 5G, SDN-WAN, and optical networks the multi-threaded controllers are introduced [128]. Majority of controllers are developed using Java, C, C++ and Python. NOX, POX [134], OpenDaylight, ONOS, and Ryu are some of the most well-known controllers [128], which are compared in Table III in terms of their respective architectures and technical features.

1) SDN Architectural Layers: To facilitate efficient control and monitor, an SDN aims at providing a network operator with a simplified view of underlying network through the abstraction of independent network architectural layers [28], [136]: application layer, control layer and infrastructure layer. We briefly explain each of these layers below.

a) Application layer: This layer accommodates several user applications or functions; for example, load balancing, service provisioning, traffic routing, access control and intrusion detection. These hosted applications and services that utilize the control plane to manage the physical or virtual infrastructure in the data plane [28]. To forward the requirements of the applications of this plane and get an abstracted information of the network, an Application Programming Interface (API) is used as a connecting bridge between the management plane and control plane.

TABLE III: Features comparison of some well-known SDN controllers.

Name	Architecture	Northbound API	Southbound API	Prog. language
NOX [132]	Centralized	Ad-hoc API	OpenFlow	C++
POX [134]	Centralized	Ad-hoc API	OpenFlow	Python
ONOS [129]	Distributed (multi-threaded)	RESTful API	OpenFlow	Java
ONIX [131]	Distributed	NVP NBAPI	OpenFlow	Python, C
OpenDaylight [130]	Distributed	REST, RESTCONF	OpenFlow	Java
Ryu [133]	Centralized (multi-threaded)	Ad-hoc API	OpenFlow	Python
FloodLight [135]	Centralized (multi-threaded)	RESTful API	OpenFlow	Java

b) Control layer: This layer is the logically centralized control system in an SDN. The control layer can be broadly viewed as two layers, as shown in Fig. 8: the SDN controller (NOS) layer and Network hypervisor layer. The roles of these two sub-layers are summarized as follows:

- Controller (NOS): Based on the requirements set in the application layer, it manages the whole decision-making process of the network and programs the network devices residing in the infrastructure layer through the southbound interface. Another role of an SDN controller is to provide an abstracted view to the applications in the application layer based on information obtained from the infrastructure layer.
- Network Hypervisor: This sub-layer resides just underneath of the NOS [127]. It is a piece of software that is in charge of abstracting the underlying physical network infrastructure, allowing virtual network(s) to be managed on top of a given physical network infrastructure [28]. Therefore, this hypervisor layer allows multiple coexisting but isolated virtual SDN networks, which are administered by one or more SDN controllers, to share resources from on one or more physical infrastructure providers [28], [127].

  In modern computing, virtualization is a well-known technology where a hypervisor enables sharing resources (e.g., memory, processing power) virtually among distinct Virtual Machines (VMs) that run on top of a host computer (it appears to the applications in each VM as if they are running on a physical computer) [127]. Similarly, in Network Virtualization (NV), network hypervisors abstract the underlying physical network infrastructure, including network resources and control functions [28], [137]. NV facilitates isolated virtual networks to co-exist and run on one or more physical infrastructure providers through abstraction (i.e., each virtual network is a sub-set of the resources of its underlying physical network infrastructure) [137]–[139]. Furthermore, it provides operators with an opportunity for both dynamic scaling and service provisioning as well as creating and deploying network services based on application layer's requirements on-the-fly [140], [141].

c) Infrastructure layer: Infrastructure layer (the lowest layer in the SDN architecture) is made up of various physical or virtual network elements (e.g., switches, routers, and access points). It directly deals with the network elements to facilitate data traffic forwarding (data plane). The network elements in the infrastructure layer are referred to as forwarding devices which are interconnected through a wired or wireless link [127]. Note that these forwarding devices are made of software and hardware components in order to allow communication to the SDN controller, collect and forward traffic management associated statistics, and send packets to the output port following the rules defined by the controller [142]. However, they do not have any control functions (the control functions are moved to an SDN controller). Thus, unlike a node (e.g., router) in a conventional IP network, they are unable to make any decision autonomously.

Therefore, the forwarding devices forward packets in the data plane following the rules defined by the SDN controller. The forwarding devices in this layer communicate with a controller using the southbound API, as shown in Fig. 8.

2) Communication Interfaces: When it comes to facilitating inter-controller, data plane to a controller, and application plane to a controller communication, the control plane relies on a set of well-defined APIs. To allow the SDN controller (NOS) to communicate with the application layer, the northbound interface (API) is used. Through this interface, the controller allows an application in the application layer to express its requirements, which are eventually translated into instructions for the forwarding devices in the data plane [127]. This northbound API is essential to promote application portability and interoperability among the various control platforms. We can compare a northbound API to the POSIX standard [143] in operating systems (i.e., an abstraction that guarantees the independence of programming language and controller). Although the SDN control plane is formed with a physically distributed SDN controller in order to increase scalability and availability of the network, it is logically centralized in most cases [144]. To form such a logically centralized control plane based on distributed SDN controllers, the westbound interface is introduced. Through this interface, physically distributed SDN controllers communicate with each other [28], [144]. Furthermore, to allow the control plane to communicate with a non-SDN domain like Multi-Protocol Label Switching (MPLS) the control plane uses the eastbound interface [28].

3) Packet Forwarding in SDN: When an SDN network element in data plane receives the first packet of a new flow from a sender, it checks for a flow rule for this packet in its flow table. If a matching entry is found in the flow table, the network element runs the instructions associated with the specific flow entry (e.g., update counter, packet/match fields). Next, the packets are then forwarded to the recipient node following the instructions stated in the flow table. Conversely, if the network element cannot find a matching entry in the flow table, it forwards the packet to the controller over a secured channel using the southbound API such as OpenFlow. The controller runs the routing algorithm and adds a new forwarding entry to the flow table in the network element and to each of the relevant network elements along the flow path (the controller has an ability to add, update, and delete flow entries reactively in response to packets or proactively). Finally, the network element sends the packet to its appropriate port to forward the packet to the next hop [145].

It is worth mentioning that besides SDN, the softwarization in a network using NFV is revolutionizing the way networking services are designed and rolled out. In NFV, the network functions are decoupled from the proprietary physical devices, e.g., routers, radio network controller and load balancers [146]. These decoupled functions are packaged as Virtual Machines (VMs) which are placed in general-purpose, off-the-shelf servers, thereby replacing special-purpose, proprietary physical devices [147]. NFV enables the efficient use of ICT infrastructure through softwarization of network functions and offers a freedom to create, deploy and manage network services (with dynamic scaling and service provisioning) without worrying about vendor-specific networking devices configuration. Note that NFV and SDN can be utilized individually. However, using them together can bring significant advantages [148].

B. Features of SDN and Opportunities it Brings to PON

In the legacy PON architectures, OLT and ONU hardware are tightly coupled with the software and they are managed by non-flexible, proprietary network management systems [109], [149], [150]. This results in slowing down operators' network evolution and the development of customized services [109]. To adopt new innovative features or functions, an operator needs to depend on the PON vendors [109]. Therefore, in such a closed and monolithic PON solution, when it comes to any hardware changes or function upgrades, it results not only operational disruption but also impose additional implementation cost [109]. Furthermore, in the legacy PON systems, bandwidth management policy and Operation Administration and Management (OAM) related parameters in an OLT needs to be performed manually [151]. This not only hinders dynamic control and intelligent scheduling of traffic in PON but also increases network operational cost [151].

To overcome these limitations in the legacy PON architectures, in recent years, a growing number of research studies and several industry groups, such as the ONF, the Open Compute Project (OCP), NTT Flexible Access System Architecture (FASA) project, and the Telecom Infra Project (TIP), as well as standardization organizations like the BBF introduced SDN controlled PON architectures [109], [152]. By decoupling control and data plane, the control plane for the OLT can be designed agnostic to the specific hardware platform [109], [152]. The global knowledge of the network state in an SDN controller simplifies introducing more advanced networking functions, services, and applications [127]. The integration of SDN in PON will facilitate cost-efficient, flexible and speed services creation and faster upgrade of any function whenever required such as due to standard evolution and advent of network security threads [152]–[156]. For example, as lighted by Nishimoto *et al.* in [156] that a software form of DBA provides service providers with the opportunity to update the DBA to meet the requirement of new services they wish to deploy.

Furthermore, SDN opens the way for on-the-fly dynamic resource scaling and traffic steering in PON [149], [157]. It is a key enabler for virtualization and slicing [158]. It allows PON to provide with the multi-tenancy capability in a flexible way [159]. This has motivated both standardization bodies (e.g., G Suppl. 74 [160]) and researchers from academia to further investigate in the area of PON slicing (e.g., [161]–[163]).

As SDN provides a global network view to the operator, it allows them to monitor and control a network on-the-fly through APIs, thereby making the network to be more efficient in terms of network availability and capacity [3]. Furthermore, SDN offers a unified control and management platform over different segments of the network [1], [2], [5]. Therefore, with the help of SDN a successful coordination between PON access segment, metro and core network leads to have efficient traffic management [1], [5], [151], [164]. Considering these benefits, a large body of research efforts have attempted to propose SDN based optical-wireless converged architectures. For example, Vardakas *et al.* [157] have proposed a PON integrated beyond-5G/6G cell site architecture with objective of dynamically resource allocation. In their solution, SDN assists to achieve intelligent traffic management and load balancing; thereby ensuring traffic performance requirement and reducing energy conservation by shutting down OLT components during light loads. In [165], the authors have shown that an SDN-based energy saving mechanism is feasible and effective in converged optical-wireless network. Similarly, for such integrated network, Wang *et al.* [163] have demonstrated how the coordination between controllers in different network segments (e.g., 5G core associated controllers) leverages dynamic reconfiguration enabling 5G slicing efficiently. Integrating SDN in PON also results in improving energy conservation in a PON. We will discuss this further in Section IV-H as well as in Section VII we will present an in depth review on the existing solutions that use sleep mode based approach for energy saving in SDN controlled PONs.

Due to the significant benefits of embracing SDN in the access segment, many telecom carriers including Telefónica are promoting commercial deployment of SDN based access-network control and management functions for broadband access [109], [153], [154], [166], [167].

C. SDN Controlled PON

This subsection reviews the SDN controlled PON based infrastructure layer.

1) Transceivers: Advancement in photonics technology has been paving the way for SDN optical transceivers which are capable of transmitting and receiving wide range of optical signal based on instruction received from an SDN controller [168].

In [169], Yeh *et al.* introduced a flexible and highly available 40-Gb/s OFDM downlink TWDM-PON architecture, which is fully controlled by an SDN controller. They eliminate optical transmitter at ONUs by introducing a carrier-distributed continuous-waveform which is transmitted from the SDN-enabled OLT besides the regular downlink signal. The authors proposed to utilize a Reflective Optical Semiconductor Amplifier (RSOA) at each ONU to serve the purpose of a transmitter. To support higher transmission capacity, longer reach and/or a large number of customers with greater network flexibility, coherent PONs appear to be promising candidate for high speed PONs [170]–[172]. Through the use polarisation-time block coding coupled with heterodyne detection, the authors in [173] have implemented coherent ONU transceiver. The results exhibit that their receiver shows very stable performance even under polarisation state fluctuations while offering lower optical complexity and better performance (supports higher transmission rate and longer transmission distance). By utilizing dual-polarized 8-PSK (DP-8PSK) based coherent transceivers,

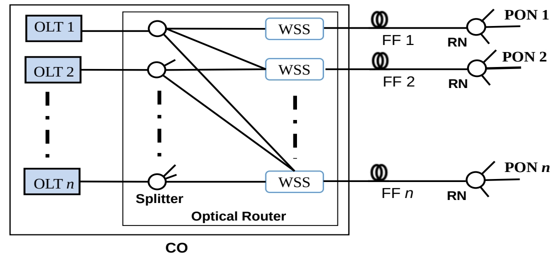

Fig. 9: Flexible central office for TWDM-PONs [58].

Ferreira *et al.* [174] have achieved a 20 channel UDWDM-PON operating at a bit rate of 3.75 Gb/s over 100 km. For a TDM-PON, a Software-Defined coherent transponder has been studied by Vacondio *et al.* [175]. To attain improved burst mode transmissions, their solution digitally process the burst transmissions taking into account distance between an ONU and its OLT. Performance results based on experiment show that their flexible solution improves average capacity per user by more than doubles compared to a static approach.

2) Switching Elements:

a) Wavelength Selective Switch (WSS): Wavelength Selective Switches (WSS) provide the opportunity to rerouting optical signals and bandwidth sharing in optical networks. A dynamic control of traffic switching through an OpenFlow enabled WSS was reported in [176]. The authors in [176] have demonstrated that their WSS can successfully switch any incoming wavelength at any of its input port to any of the output ports in accordance to the instruction received through OpenFlow. In [177], Cvijetic *et al.* introduced an SDN controlled OLT where the receiver is equipped with a software-defined flex-grid WSS, facilitating a software configurable passband selection. Therefore, this makes the performance requirement of the tunable transmitter of an ONU relaxed (i.e., satisfactory uplink reception is still possible in the presence of wavelength drift of an ONU transmitter [178]). To improve flexibility and data security, Das *et al.* [71] have introduced a Wavelength-routed hybrid WDM/TDM PON (Type 2 TWDM PON) system using WSSs in the RN1. Generally, the RN1 equipped with an AWG guides a wavelength to a group on ONUs connected with a splitter in RN2 (see an example illustration in Fig. 2 (d)). However, replacing the AWG of RN1 with a WSS provides the PON system in [71] with the opportunity to steer any wavelength to any of the splitters in RN2, thereby increasing switching flexibility gain. Another useful application of WSS in PON is presented by Dixit *et al.* in [58]. The authors have introduced a flexible CO architecture where the OLTs in a CO are connected with different PON segments through a flexible optical router equipped WSSs and splitters, as illustrated in Fig. 9. This CO allows to share an OLT with multiple PON segments, thereby not only improving network availability and utilization but also providing with the opportunity to reduce energy consumption during low traffic arrival by switching off the unused OLT(s).

b) Optical Add/Drop Multiplexers (OADMs): An Optical Add/Drop Multiplexer (OADMs) is an important photonic switching device generally applied in WDM networks. It

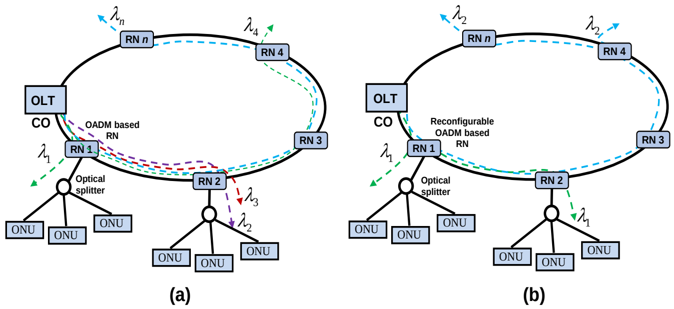

Fig. 10: Wavelength-routed hybrid WDM/TDM PON ring-and-spur topology: (a) fixed wavelength allocation; (b) dynamic wavelength allocation (wavelengths are dynamically assigned to the RNs; in a statistical multiplexing fashion, downlink bandwidth is shared [76]).

is developed to add/drop one or multiple wavelengths at intermediate points of an optical network. An OADM is generally comprised of a multiplex, demultiplexer and an unit that optically adds or drops one or more wavelengths based on instruction. A programmable version of OADM is Reconfigurable OADM (ROADM). WSS is a key element of building commercial ROADMs [179].

ROADM adds the ability to add or drop desired wavelengths through a management control plane on-the-fly, allowing network operators to deploy wavelengths dynamically as needed in the network. It has become an important element in optical core networks. It is also paving the way for deploying flexible, salable, resilient and energy-efficient metro-access networks [180]. Shi *et al.* in [76] have proposed to use ROADMs with "drop-and-continue" capability in a ring-and-spur Long-Reach WDM/TDM PON to facilitate communication with a required number of wavelengths dynamically at a given time, thereby reducing energy consumption by switching off unused OLT-ports at the CO during the off-peak hours, as illustrated in Fig. 10. The recent studies have focused how ROADMs can be managed by SDN control plane dynamically. An SDN controlled ROADM was proposed by Magalhães *et al.* in [3] and Heitor *et al.* in [181]. In [182], Konstantinou *et al.* demonstrated how ROADM can be applied in a ultra-dense WDM-PON ring integrated with a 5G access network infrastructure to facilitate dynamic wavelength routing.

c) Optical White Box: A white box is a network switch which is built using off-the-shelf chips and allows installing of any software for network operation [152], [183]. With the advent of SDN, the white box switching concept is gaining interest. This is because the white box switches are lower-cost alternative to the traditional network hardware and they can be controlled using different southbound APIs (e.g., OpenFlow).

The authors in [139] have developed an optical white box as part of the building-block of a softwareized optical network. They have experimentally demonstrated, a proof-of-concept of the proposed optical white box and SDN abstraction mechanism. To facilitate programmable and flexible interconnections between the node elements of the switch, their proposed optical white box has two-sliver backplanes. Besides, the switch has programmable switching node elements, including programmable interfaces, protocol agnostic switching and digital processing hardware. The programmable interfaces change transmission format, protocol, and bit rate based on SDN instruction. The protocol agnostic switching is responsible for wavelength channel and time slot switching and the digital processing hardware involved in physical layer signal processing and network processing functions. Lopez *et al.* in [183] have introduced an optical white box where wavelength and transmission related parameters can be changed by an SDN controller through an abstraction interface.

In a PON, a white box OLT, where hardware is decoupled from the software, comes with open interfaces for all control and management related functions making it SDN integrable. It has been endorsed by ONF's SDN-Enabled Broadband Access (SEBA) project for further development [117]. White box OLTs are being embraced for commercial deployment. For example, Telefónica has opted to deploy Radisys' white box OLTs to leverage its telco cloud-based networking capabilities, thereby being more efficient, agile, and on-demand elastic serving provisioning capable [184]. Besides white box OLTs, the pluggable OLT (known as microplug OLT) is regarded as an important milestone in the evolution of OLT solutions. It comprises of transceivers integrated with real-time MAC and Transmission Convergence (TC) layer functions of OLT and is pluggable into any switch or router [117].

3) Virtualized PON: When using the OLTs in the current commercial PON systems, the network operators need to modify the configuration of the OLTs through a network management system manually, thereby making the network very inefficient when it comes to applying operational polices dynamically [150], [151]. This has necessitated making the OLTs unified controllable by inclusion of a Southbound API (e.g., OpenFlow) agent and thereby making the OLT remotely controllable on-the-fly.

Lee *et al.* in [185] have proposed a means for abstracting an OLT and ONUs in a GPON system to transform the PON system into a virtual switch which can be controlled by an SDN controller remotely in the same way as handling an OpenFlow switch (entire GPON system is transformed into an SDN virtual switch), as depicted in Fig. 11. The authors have introduced two architectures. The first architecture is designed for the current GPON systems. In this architecture, on behalf of the OLT, an additional agent controller is in charge of communicating with the SDN controller because the OLT does not understand the SDN protocol. The embedded agent processes any instructions coming from the OpenFlow controller, and then translates them into local GPON commands through the ONU Management and Control Interface (OMCI) so as to control the connected ONUs. An OLT generally comes with an embedded Ethernet switch chip which does not support functions defined by OpenFlow. Therefore, to support the functions of an OpenFlow virtual switch, the authors proposed to incorporate an additional add-on OpenFlow switch in the system; see illustration in Fig. 11 (a). The add-on OpenFlow switch reports its switch features to the agent (to this add-on OpenFlow switch the agent acts as a controller). The agent follows the OpenFlow specification to communicate an

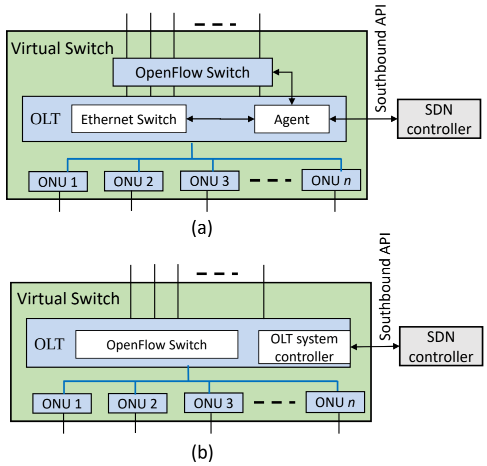

Fig. 11: Illustrates how an entire GPON acts as a virtual switch under an SDN controller: (a) an Openflow switch is collocated with the OLT at the CO; (b) an Openflow switch resides in the OLT itself [185].

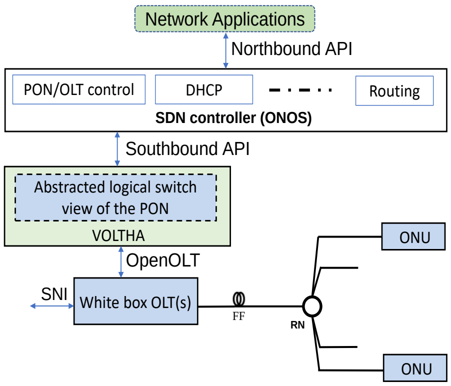

Fig. 12: VOLTHA abstracts the PON network so that the entire PON appears as a programmable Ethernet switch to the SDN controller.

external OpenFlow controller. Aside from facilitating packet forwarding among ONUs, the add-on OpenFlow switch allows statistical data collection of the PON and performs bandwidth control related metering function. In another architecture, the authors have proposed to replace the Ethernet switch with an OpenFlow switch in the OLT, as shown in Fig. 11 (b). This architecture is considered to be simpler in terms of operation and management undoubtedly as the OpenFlow instructions are directly supported by a GPON system without relying on any translation agent as in the earlier case.

D. Standardization Activities for PON Virtualization and SDN Based Control

To make the PON systems to be an integral part of a larger network by establishing a unified control platform and facilitating flexible and faster upgrade of its functions as well as accommodate virtual PONs on shared physical PON infrastructures, the abstraction and softwarization of PON are actively investigated in the standardization bodies like ONF, BBF and ITU-T.

a) Abstraction: To exploit SDN for controlling PON, one important technical challenge is the abstraction of the PON devices (OLT/ONU) [186]. A non-profit organization ONF initiated Central Office Re-architected as a Datacenter (CORD) project with the objective of leveraging SDN, NFV and Cloud technologies. Later, under the CORD platform, the residential CORD (R-CORD) has been launched. With the aim at introducing access system modularization and disaggregation, in 2018, the ONF launched SEBA project to develop a platform (a variant of R-CORD) which can support one or more virtualized access technologies, including PON [187]. Following a similar agent based approach considered in [185], the ONF has introduced open-source PON Abstraction Layer which is referred as Virtual OLT Hardware Abstraction (VOLTHA) [9] so as to facilitate controlling PON using SDN. VOLTHA, which is a software and runs outside-the-box, provides a switch abstraction of the OLTs and their subtending ONUs (their management function is disaggregated from their hardware), thereby allowing an SDN controller to manages the PON system in the same way as it manages any SDN enabled switch [9], [154]. Currently, for a set of white box and vendor-specific PON hardware devices a common vendor agnostic GPON/XG(S)-PON control and management system is provided by VOLTHA. To facilitate interaction with a PON system and an SDN management plane, VOLTHA provides a set of abstract APIs, as shown in Fig. 12. Additionally, on its southbound side (as the intermediary), to communicate with the PON equipment, VOLTHA uses vendor-specific protocols and protocol extensions through adapters [8]. Since an SDN-based architecture is expected to reduce cost compared to use of traditional dedicated OLTs, major telecom operators are strongly promoting the SEBA project [153].

The BBF introduced the Cloud CO reference architecture in TR-384 [40]. It provides guidelines for virtualization in access networks. In particular, it states the guidelines for the disaggregation and virtualization functions of access nodes, i.e., it indicates the criteria to determine the functions that should reside in the physical devices, referred as Physical Network Functions (PNFs), and the ones that can be virtualized (softwarization of functionalities hosted as VNFs on generic hardware (e.g., Commercial Off-The-Shelf hardware). The criteria it incorporated include high processing performance and time sensitiveness. The standard identifies the potential virtualization options for the functions of OLT and ONU, including configuration, reporting and alarming functions. It also recommends that the functions that require real-time processing in PON like DBA can be the candidate to remain as a PNF instead of a VNF due to low processing speed in a virtualized environment. With the performance advancement of hosting general-purpose hardware, the VNF and PNF implementation trade-offs will shift in the coming years [40] and thus it can be expected that this will further push the evolution of OLT and ONU architecture and their capabilities.

The BBF initiated an open source Broadband Access Abstraction (BAA) project which introduces the BAA layer comprising northbound and southbound interfaces and the core components for the functions of virtualized access networks

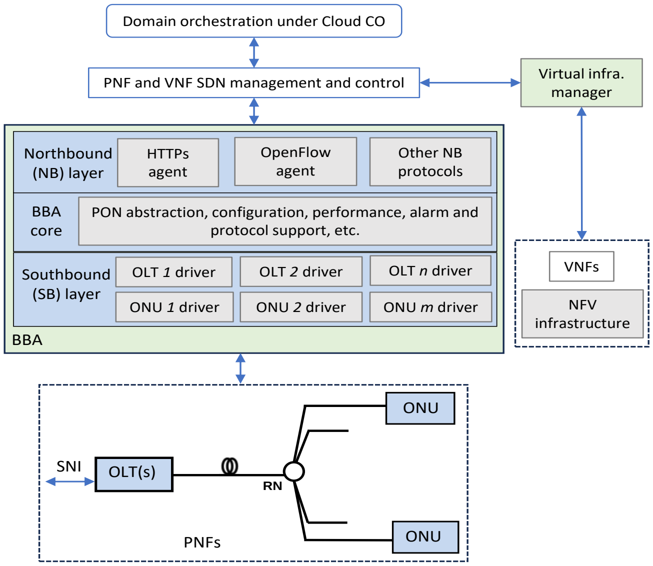

Fig. 13: Cloud-CO's high-level architecture with BAA, SDN, VNF and PNF interactions (simplified).

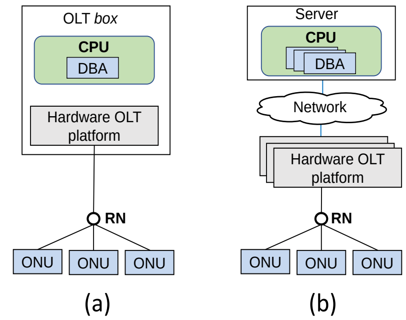

Fig. 14: DBA disaggregation approaches: (a) close DBA placement; (b) remote DBA placement.

devices [188]. The BAA layer facilitates communication with the network devices by means of its southbound device adapters, whereas at the northbound, it maintains communication with one or more management and control systems, including SDN controllers. In the core of the BAA layer, an abstraction function for PON performs conversion of the information exchanged through the BAA layer northbound and southbound interfaces [40] (see simplified illustrations presented in Fig. 13).

b) Softwarization: In doing abstraction, some of the functions of PON are softwarized. Furthermore, to make PON operation in the access segment more flexible to meet various service requirements dynamically, softwarization of PON has been actively explored by researchers.

Flexible Access System Architecture (FASA) project in **2016** was introduced by Japanese operator NTT [117]. The OLT modularization approach NTT introduced in FASA is comprised of three parts: software modules, general-purpose hardware and dedicated optical module with physical chips [117], [189]. The dedicated optical module (not virtualized) equipped with optical transceivers. The software modules are the OLT functions that run as VNFs in a remote location, whereas the time-critical OLT functions run locally in a general-purpose hardware [117]. Motivated by the benefits of modularization and softwarization such as faster policy update and improved energy efficiency and reliability, besides the non-time-critical functions, FASA aims to modularize the time-critical functions (e.g., DBA, ONU sleep control and PON protection) [190]. In the coming years, PON/OLT disaggregation and virtualization with quick response capability will necessitate further the integration of edge computing facilities in PON (e.g., OLT embedded edge computing) [8], [109]. Such convergence of OLT with edge computing will leverage the opportunities cater various applications like content delivery network and wireless network associated NFVs [109].

To enable OLT hardware resources to share among multiple Virtual Network Operators (VNOs), the authors in [191]–[193] have introduced the concept of virtual DBAs (vDBAs). The authors have proposed that each VNO has its own vDBA (it runs on a CPU located near the physical OLT), thereby facilitating sliceable multi-tenancy in a physical PON infrastructure. To meet desired performance requirements (e.g., latency) of vDBAs, Intel's Data Plane Development Kit (DPDK) software packet processing libraries are utilized because of its proven ability to operate with real-time algorithms having precise synchronization requirement [193]. Using a testbed setup, the vDBA concept is demonstrated in [194]. Furthermore, the concept is already ratified in the BBF standard TR-402 (use of interfaces for OLT virtualization) [195]. A remote DBA placement concept is also actively studied by the researchers from NTT (e.g., [196], [197]). An example illustration of close and remote DBA placement is presented in Fig. 14. NTT research aims to realize fully softwarization of PON so as to efficiently manage various access network technologies. Fully softwarized 10G-EPON operated on a general-purpose server is demonstrated by NTT researchers in [198]. In their recent effort in [199], it has been successfully demonstrated that they can achieve a 0.586 *ms* latency for PHY softwarization by using polling-based signal transfer method on Graphic Processing Units (GPUs). We will witness further evolution of OLT hardware (e.g., white-box and microplug OLT solutions) with the advancement of SDN, NFV, and Cloud-related architecture [117].

PON virtualization allows multiple operators, services, and applications to share the common network resources, thereby maximizing resource utilization of the network [162]. In particular, with the advent of 5G and beyond-5G, there has been an increasing interest in designing an SDN assisted PON slicing (e.g., [163], [236]–[238]). In 2021, ITU-T released ITU-T G-Sup.74 [160] stating functional expectation of a PON system to facilitate PON slicing and related functionalities for the control of slicing—OLT, ONU and communication resource (bandwidth) are sliced. From a control plane perspective, a sliced OLT appears as if a group of logically independent OLTs [160]. Similarly, the specification group for the F5G of ETSI is contributing in the area of PON slicing [124]. Current approach for slicing in which network resources are shared among the slices is referred as soft-slicing, as defined by ETSI [51]. The standard also stresses the importance of hard

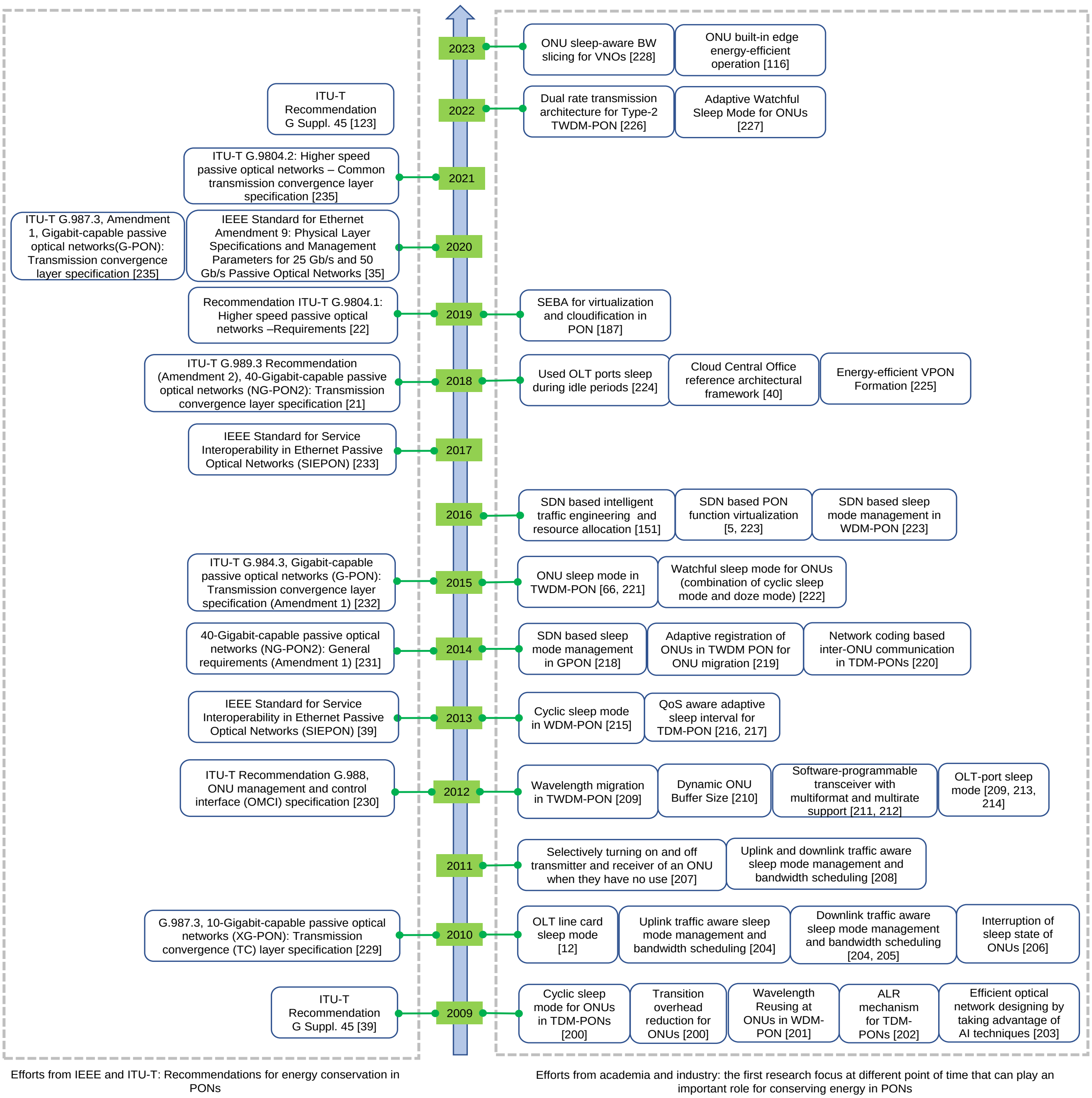

Fig. 15: Timeline infographics: presenting the research efforts by standardization bodies, academia and industries for improving energy saving in PONs.

slicing technology where fixed and independent allocation of network resources (e.g., forwarding queue and CPU computing capabilities) on OLT ports and ONU is reserved to support the services with stringent requirements of delay and jitter [51]. In [110], for an industrial PON deployment scenario, ETSI presented a PON slicing system architecture and identified three granularities of slicing, which are: OLT line card, OLT port and ONU slicing.

IV. Energy Saving Approaches in PON

In this section, we familiarize the reader with the commonly applied approaches used in the variants of PON for conserving energy. This will pave the way to understand the remaining sections where we explain the PON energy saving related operational mechanisms that the standardization bodies, like IEEE, and researchers from academia have considered to date. Broadly, we can define energy saving in a PON as development of less energy consuming PON hardware equipment as well as implementing techniques and strategies to operate the PON

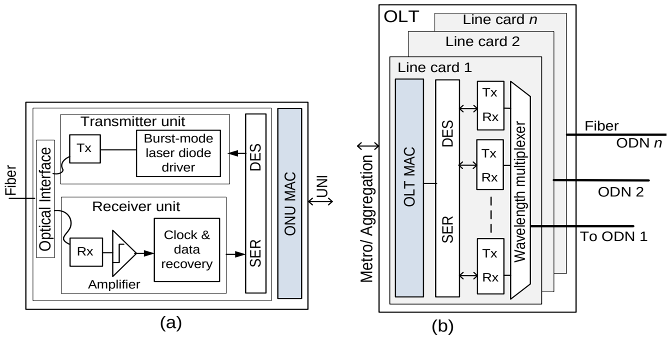

Fig. 16: Functional block-diagram of an OLT and ONU: (a) an ONU block diagram; (b) vertical OLT arrangement with multiple line cards in a TWDM-PON, each connecting an ODN.

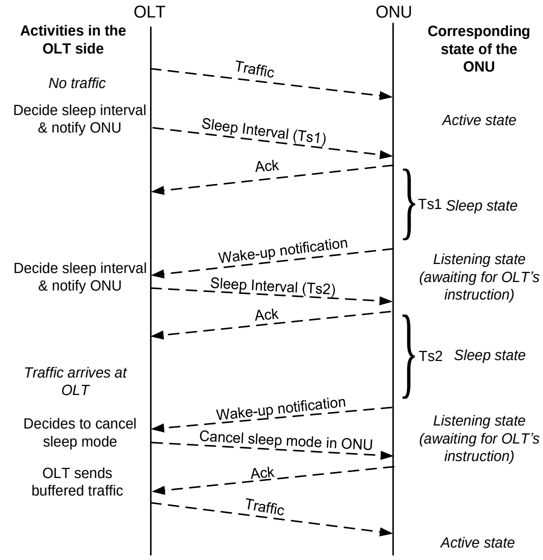

Fig. 17: Three-way handshake between OLT and ONU (after sleep interval, $Ts1$, the ONU switches to *active state* to get the OLT's instruction).

equipment (e.g., ONU) such a way that energy consumption can be minimized. To the best of our knowledge, energy-efficient PON research was initiated around 2009. Among the few notable contributions, in 2009, Wong *et al.* [200] have introduced a sleep mode mechanism for an ONU by turning off its transceivers whenever there no traffic to exchange between the ONU and its serving OLT. In the same year, Kubo *et al.* [202] have proposed a sleep mode and an adaptive link rate control mechanism for the 10G-EPON system. Subsequently, the scientific community in energy-efficient PON research introduced various energy saving approaches which triggered many more research initiatives. The timeline infographics presented in Fig. 15 portraits various important research initiatives (first introduced, to the best of our knowledge) as well as the major IEEE standards and ITU-T Recommendations for PON energy conservation at different point of time since 2009.

A. Sleep Mode

The access network segment has a low utilization (only around 15% [10]) with bursty traffic arrival pattern [207]. Considering this, in academia (e.g., [207], [217], [239], [240]) and standardization efforts (e.g., ITU-T G Suppl. 45 [38] and ITU-T G.988 [230]), different types of sleep modes for the OLT and ONU to date have been proposed. In this article, generally, we refer to the energy saving approach where the transmitter and/or receiver of an ONU and an OLT are turned off for conserving energy as sleep mode. Most of the sleep mode mechanisms discussed in this subsection are considered in the specifications of the standardization bodies, as we will see in Section V.

Generally, both OLT and ONU can be divided into two main parts: frontend analog and backend digital circuitry, where a MAC resides. The frontend analog circuitry of an ONU in a TDM-PON can have a burst mode transmitter, continuous mode receiver, clock and data recovery circuitry, amplifier, and Serializer/De-serializer (SER/DES) [200], [241], [242], as shown in Fig. 16 (a). The analog part of an OLT is also equipped with a similar set of components. However, unlike an ONU, it has a continuous mode transmitter and burst mode receiver. Contrary to an OLT in a TDM-PON, an OLT in a TWDM-PON and WDM-PON can have more than one transmitter and receiver, as depicted in Fig. 16 (b).

To maintain sleep mode in a PON equipment (e.g., an ONU), a sleep control unit (circuit) is required to switch on or off any component(s) in the equipment, as considered in the existing works (e.g., [200], [217], [243]). For example, when an ONU is instructed to initiate the sleep mode by its serving OLT[2] (see an example illustration in Fig. 17), the ONU starts the sleep process. The sleep control unit determines the set of components in the ONU that should be turned off in a power saving state taking into account the factors like allocated sleep duration and transition overhead (time required to change a state). When the sleep duration expires (monitored by a timer), a wake-up signal is triggered to activate the components that were switched off during the *sleep state*.

1) Types of sleep mode: Here, we briefly explain different types of sleep mode that have been introduced in the literature.

- *Deep sleep mode:* In this mode, the transmitter and receiver are switched off completely for a predefined time period when an ONU selects this mode, as stated in ITU-T G-Sup.45 [38].
- *Cyclic sleep mode (TRx sleep mode):* Here, an ONU only switches between an *active* and *sleep state* (i.e., an ONU maintains a sequence of sleep cycles comprised of an active and sleep duration) [38], [230], as shown in Fig. 18 (a). During the *sleep state* in this mode, an ONU turns off its transmitter and receiver; therefore, no communication with the OLT is possible during that time similar to Deep sleep mode. However, as illustrated in Fig. 18 (a), when the ONU is in the *aware state* during T_{aware} duration, the OLT is able to communicate with the ONU.

[2]During an ONU capability discovery stage, the OLT learns the appropriate type of sleep mode for the ONU [39].

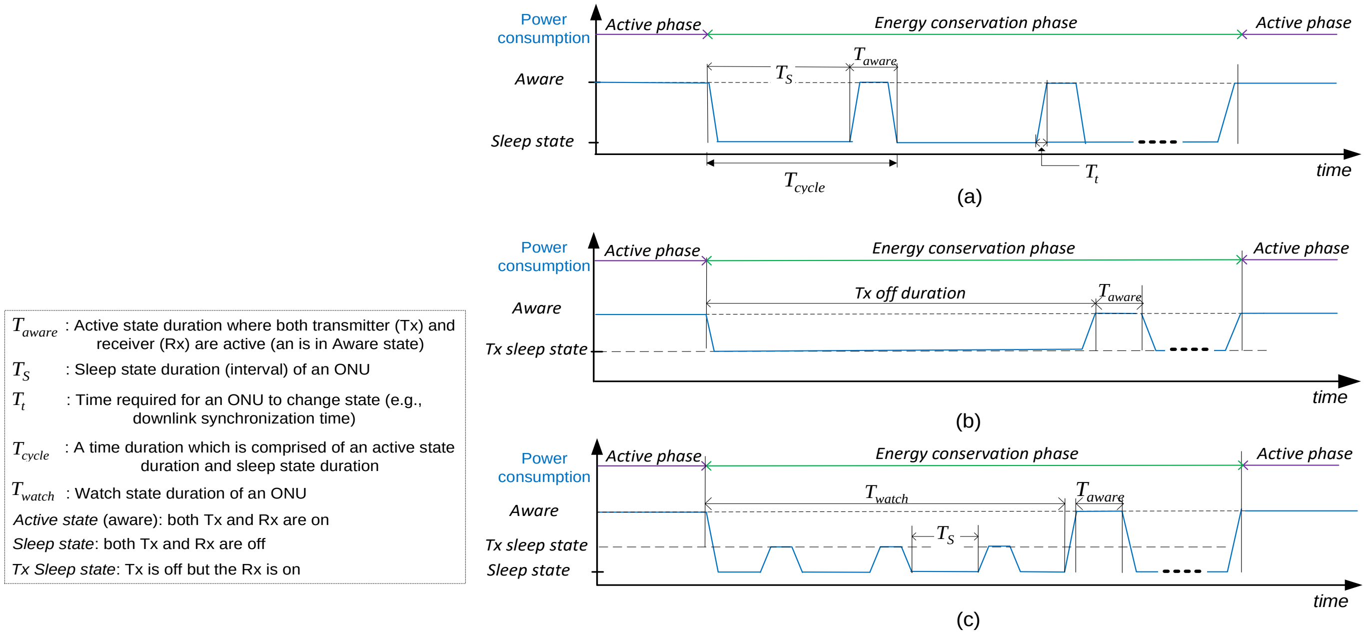

Fig. 18: Sleep mode based power saving techniques for ONUs: (a) cyclic sleep mode (fast sleep) [38]; (b) doze mode [38]; (c) watchful sleep mode [231].

- *Doze mode (Tx sleep mode):* This mode allows an ONU to turn off its transmitter for a predefined time period [38], [207], [217], [230], as shown in Fig. 18 (b). This mode can noticeably reduce energy consumption without affecting downlink traffic performance (ONU's uplink traffic performance might be affected).
- *Rx sleep mode:* In this mode, an ONU turns off its receiver during the *sleep state* while keeping the transmitter active [207].
- *Watchful sleep mode:* Combing doze mode and cyclic sleep mode (fast sleep), Hirafuji *et al.* [222] introduced watchful sleep mode. This mode was amended in the ITU-T G.984 (G-PON) and ITUT G.987 (XG-PON) Recommendations [229], [231]. In particular, similar to cyclic sleep mode and doze mode, an ONU switches between energy conservation and active phase. However, during the energy conservation phase, an ONU remains in the *watch state* in which it periodically turns on the receiver only for a certain duration (say T_w) to receive further instruction from the OLT whether it should leave the sleep mode or not, as shown in Fig. 18 (c).
- *Power shedding:* When power shedding is used, an ONU selectively turns off some of its unused components (e.g., turning off unused UNIs of an ONU) or reduces supplied power to the non-essential functions to conserve energy while keeping the transceivers continuously operational (i.e., the optical link with the OLT remains fully operational) [38], [234], [244].
- *OLT-port sleep mode:* This power saving mode is appropriate for a TWDM-PON (both Type-1 and Type-2) and WDM-PON with tunable ONUs which can be operated on any of the available wavelength channel pairs used in the PON system [22], [219]. When traffic load is low, the OLT needs to calculate the required number of wavelength channels (say, n channels at a given time) taking into account the traffic load. If m is the total number of wavelengths in the PON system, the OLT can turn off its $(m - n)$ wavelengths (ports). When an OLT opts to turn off a port, it first needs to reconfigure the network by migrating the subtending ONU(s) under the port to another one—this mechanism is generally referred as wavelength re-location (migration) [22].
- *OLT-line card sleep mode:* An OLT chassis typically includes several OLT line cards, each of which contains multiple ports (transceivers) for transmission and reception. Similar to the OLT-port sleep, the idea here is to reduce the number of OLT line cards by reconfiguring the network dynamically in a way that allows facilitation of uplink and downlink communication with the active ONUs using a minimum number of OLT line cards at a given time, thereby allowing unused OLT-line cards to be in sleep mode [58], [245]–[247]. A further detail about the research efforts on PON reconfiguration appears in Subsections VI-C and VI-D. It worth noting that long reconfiguration delay can show detrimental effect on QoS performance of network.

2) Synchronization between OLT and ONU for sleep mode management: In sleep mode, communication between the ONU and OLT is disrupted; therefore, an agreement is needed between the OLT and an ONU before moving to a sleep mode. Using the control messages, the OLT and ONU agree upon the sleep mode related parameters, including the duration that the ONU will stay in *sleep state* and the duration that it will stay in *active state* after returning from *sleep state* to listen to further instructions from the OLT.

In case of cyclic sleep mode, as the OLT cannot communicate with an ONU once the ONU moves into *sleep state*, the ONU needs to be periodically available following a schedule provided by the OLT. After leaving the *sleep state*, the ONU gets further instruction from the OLT whether it should leave sleep mode or not. If the OLT has no traffic to forward to the ONU, the OLT instructs the ONU to continue sleep mode. The ONU sends an acknowledgment in response to an instruction from the OLT. These procedures, which is commonly referred as three-way handshake (analogous to the TCP three-way handshaking), allow an ONU to be synchronized with the OLT while maintaining sleep mode. To further elucidate, Fig. 17 illustrates an exemplary negotiation between an OLT and an ONU for sleep mode management in the ONU. It shows that in absence of traffic, the OLT instructs the ONU to move into *sleep state* for *Ts1* duration. The ONU listens to OLT's instruction when the sleep duration expires (this procedure continues until there is traffic to forward). In Section VI-A, we will familiarize the readers with another alternative approach in which an OLT and an ONU do not need a three-way handshake between them to be synchronized while applying sleep mode.

3) Finding optimal sleep interval length: The cyclic sleep mode [38], [230] and Rx sleep mode [207] based energy saving require an ONU to periodically leave *sleep state* after a sleep interval by turning on its transceiver and listen to the OLT's instruction. Although longer sleep intervals lead to reduced energy consumption in a PON by minimizing the number of idle listening[3] of an ONU [248], it necessitates the OLT to buffer all the incoming traffic for that ONU, and consequently increased traffic's delay and drop, thereby deteriorating QoS performance. On the other hand, an ONU may have too many idle listening when a sleep interval length is small, thereby increasing energy consumption of the ONU. Therefore, there is a strong trade-off relationship between these two opposing goals (i.e., energy saving and meeting QoS of the end users) [217], [249]. This foregoing issue has been an increasingly important research area for many researchers in this domain (e.g., [216], [217], [250], [251]).

4) Influence of sleep interval deciding algorithm: A sleep interval deciding algorithm, which is generally implemented as a MAC function in a PON (e.g., as in [217], [252]), determines sleep mode associated parameters (e.g., sleep interval length) of an ONU. It significantly impacts a PON's QoS and energy saving performance, as highlighted in [253], [254]. For instance, Alaelddin *et al.* [253] have shown based on simulations results that different algorithms for determining sleep interval length of an ONU result different delay, energy and throughput performance.

B. Energy-efficient and Fast Response Network Equipment Design

To minimize energy consumption in an OLT and ONU, energy consumption of each component needs to be reduced.

[3]Idle listening represents the scenario during which an ONU moves into *listening state* by turning on its transceiver from *sleep state* to check whether the OLT has downlink frame to forward. However, upon moving into *listening state* the ONU finds that the OLT has no downlink frame for it.

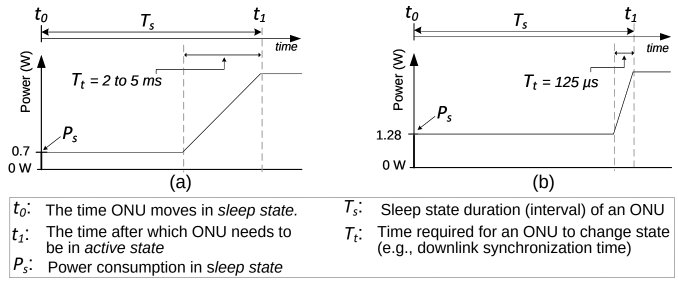

Fig. 19: *Sleep state* to *active state* transition overhead and ONU's power consumption: (a) 2-4 ms transition time; (b) 125 μs transition time.

To attain this goal, a key technology is photonic integration which is paving the way for energy conservation as well as footprint of optical systems [255]. In a Photonic Integrated Circuit (PIC), several photonic functions are integrated into a single tiny chip similar to an electronic integrated circuit using silicon (Si) photonics technology. According to [255], combining electronics and optics would lead to not only improve energy conservation capacity but also performance. Sasaki in [256] has developed a prototype of a TWDM-PON transceiver on a single Si PIC in just within 5mm×3.5mm area. Due to small size, such miniature chips consume low power and the manufacturing cost can be reduced significantly [256]. Yen *et al.* in [257] have proposed a quasi-passive optical and reconfiguration device for the RN of a PON to reduce splitting loss of downlink signal.

The transition overhead (the time required to move from one state to another in a sleep mode) has a significant impact on the energy consumption of PON equipment, as observed in [217], [258]. For example, an ONU takes around 2-5 ms in cyclic sleep mode to switch back into *active state* from *sleep state* (this time is required to make the ONU's receiver synchronized with the OLT's clock) [258]. Therefore, the longer the transition period, the shorter an ONU can stay in *sleep state*, as depicted in Fig. 19. Taking this shortcoming into account, for EPON and GPON, Wong *et al.* [258], [259] have introduced an ONU architecture which takes 125 μs to transit from *sleep* to *active state*. According to the solutions in [258], [259], an ONU turns off fewer numbers of components in the *sleep state*, allowing it to transit to an *active state* in 125 μs. As the ONU turns off fewer components compared to a conventional ONU, which consumes 0.7 W in the *sleep state*, the energy consumption of this ONU accounts 1.28 W. Therefore, we can notice a clear trade-off between energy saving and the transition period. It is worth noting that different types of sleep mode can have different transition periods and energy saving trade-off. For example, in the doze mode of a 1G EPON ONU, the transition period is approximately 1 μs; however, power consumption is 1.7 W [260].

In [261], Valcarenghi *et al.* have suggested that modulation technique has an influence on how fast an ONU tunes to the OLT's clock after leaving its *sleep state*. The research has demonstrated that instead of using non-return-to-zero (NRZ) modulation if Manchester modulation is used for data transmission, an ONU is able to synchronize with the OLT's clock faster. This contributes to reducing transition time when the ONU leaves its *sleep state*. This in turn results in a better energy saving in the ONU as it can sleep longer compared to the case when NRZ is used.

C. Power Gating and Voltage and Frequency Scaling

Dynamic power gating and voltage and frequency scaling are widely applied approaches in control chips and microprocessors for reducing energy consumption [262], [263]. When it comes to Dynamic Voltage and Frequency Scaling (DVFS), the objective is to adjust the applied voltage and frequency in a microprocessor or a control chip in such a way that the energy consumption is reduced while meeting the performance requirement (e.g., delay requirement) [263], [264]. In case of power gating, the objective is to cutting off supplied power of a control chip when it does not have any use [263], [265]. To implement this, an additional hardware (a power gating switch) is required [265]. For energy saving in PONs, the ITU-T has recommended (e.g., ITU-T G Suppl. 45 [38] and ITU-T G.987.3 [234]), to use dynamic voltage scaling and power gating (referred as power shedding) in ONUs.

D. Adaptive Link Rate (ALR) Control

Adaptive Link Rate (ALR), which was considered in IEEE P802.3az Energy-Efficient Ethernet task force, allows dynamic line rate change depending on the requirement [262]. This approach is similar to Dynamic Frequency Scaling (DFS) [241]. A major motivation comes from the fact the most Ethernet links have low utilization and, therefore, operating at a lower link rate energy consumption can be reduced [266] (a low transmission rate generally imposes less energy consumption than transmitting at a higher rate [206], [241]). ALR control function selects link rate in accordance with the traffic load [25], [206], [266]. Therefore, it serves as a potential approach to save energy when high transmission speed is not required. ALR control function has been already investigated in PON research to conserve energy. For example, Kubo *et al.* [206] have proposed ALR mechanism for an EPON having 1G and 10G downlink channels (i.e., an ONU has two receivers for 1G and 10G link). Based on traffic delay and data rate requirement, one of the channels is activated at a given time. Their proposal suggests using 1G link when the downlink traffic arrival is low (below a threshold value). The factors that are likely to play important roles to reduce energy consumption at a lower link rate are: transmitting at a lower rate requires less transmit power (to maintain the desired signal to noise ratio at higher transmission rate, more optical power budget is needed to deal with more transmission impairments and meeting required receiver sensitivity [267], [268]) and operating at slower rate may allow to apply dynamic voltage scaling in the electronics processing part of the equipment, resulting reducing the operating voltage [269]. In [270], Zhang *et al.*, similar to [206], have proposed dynamic link selection for ONUs with 1G and 10G receiver. Note that during the link rate switching period, the communication between an ONU and an OLT is interrupted. Therefore, this mechanism can deteriorate both downlink and uplink traffic performance when the switching time is long.

E. Dynamic ONU Buffer Size Adjustment

The buffer size of an ONU can play an important role in the energy saving performance of the ONU. Uzawa *et al.* in [271] measured that the downlink buffer of a 10G-EPON ONU accounts for 13% of the overall ONU energy consumption. They have introduced an ONU with dual-buffer—an internal and external buffer. The internal buffer is relatively smaller than the external one, which is a large off-chip memory. In case when uplink traffic arrival is low and the ONU finds that the internal buffer is sufficient to hold the incoming uplink traffic, the ONU only keeps the internal buffer active while turning off the external buffer. Undoubtedly an internal small on-chip memory will have smaller energy consumption than the external off-chip memory; therefore, this approach can reduce an ONU's energy consumption significantly. Conversely, if the internal memory is not adequate to hold the uplink traffic, the ONU activates the external memory to avoid any traffic drop.

Sankaran *et al.* [272] have proposed to remove buffer from an ONU so as to reduce ONU's energy consumption. In their solution, the end-user terminals hold the packets as long as an ONU does not request to send the packets, thereby allowing maximizing buffer utilization at end users' terminal and saving energy in ONUs. The ONU instructs to send the buffered packets to its connected terminals before its assigned uplink transmission slot. Therefore, in this solution, an OLT should decide the interval between two consecutive uplink slots and their duration taking into account the buffer capacity of the end-user terminals, traffic arrival rate, average packet size and the maximum delay the uplink packet can tolerate. It is worth highlighting that the sleep mode based energy saving approach requires an ONU to be equipped with a buffer to avoid losses of uplink traffic arrived from the customer premises. Therefore, an ONU introduced in [272] cannot apply sleep mode like cyclic and doze mode. To support long sleep periods, the buffer size needs to be large [210]. However, a larger buffer generally imposes higher energy consumption [273].

F. Downlink Wavelength Reusing at ONUs

Wavelength reusing is another effective strategy to reduce energy consumption in PON. In [201], Uchikata *et al.* have proposed a WDM-PON where the downlink transmitted signal is used for uplink communication (the OLT has light sources only), thereby eliminating the need of transmitters in the ONUs. In their solution, each ONU is provided with a dedicated channel for receiving downlink traffic. For uplink communication, an ONU after retrieving downlink data, first, feeds this downlink signal into a modulator to modulate with uplink data. Next, the ONU forwards the output of the modulator to the OLT. As the ONUs do not need any transmitter and the downlink signal power is effectively utilized, this technique should lead to the reduction of energy consumption in a WDM-PON. Additionally, if there are n numbers of ONUs in a WDM-PON, only n numbers transmitters (light sources) are required instead of $2n$ in their solution, which reduces the deployment cost of a WDM-PON.

Compared to the solution proposed in [201], Šprem *et al.* have introduced in [274] a more advanced solution where a WDM-PON requires only a single light source which is installed at the OLT. A RSOA is utilized in each ONU to serve the purpose of an uplink transmitter. Readers may refer to [274], [275] for a detail explanation of wavelength reuse procedures. It is worth highlighting that some of the approaches involved in realizing wavelength tunable and wavelength reusing in a WDM-PON may lead to high noise in the network [274], which in turn can contribute increasing BER in a WDM-PON. Consequently, network throughput might be deteriorated.

G. Energy-efficient Transmission

At the transmission level, there are opportunities to reduce energy consumption in a PON. The major factors that contribute to signal degradation in optical fiber are: attenuation, splice loss, connector loss, fiber attenuation and splitter loss. To offset such degradation, a PON equipment (e.g., ONU) may need to increase its transmission power, resulting in increased energy consumption. Therefore, continuous efforts have been made by the researchers for designing not only energy-efficient network architectures [276] but also low-attenuation and low-dispersion fibers, energy-efficient amplifiers and transceivers, and low loss splicing [23], [277], [278].

By dynamically adapting the physical transmission parameters, including symbol rate [279] and modulation format [280], the transmission efficiency can be further improved in a PON system [28]. Additionally, the bandwidth requirement can be reduced by adopting the technologies like Network Coding (NC) [220]. In turn, this provides the OLT and ONU with more opportunity to move into low power state as they can complete their transmission faster. For example, Liu *et al.* in [281] have proposed a NC based unicast and multicast traffic sharing among the ONUs in TDM-PONs. The authors have reported that using the NC based transmission, an OLT can reduce up to 50% of its energy consumption as the number of traffic transmission is reduced significantly. Note that, besides the TDM-PON architecture, any PON architectures with a splitter deployed in the RN (e.g., TWDM-PON) can adopt NC technology as an effective means for the inter-ONU communication.

Reducing unnecessary processing in the transmission process and control messages are also other effective means to reduce energy consumption in the OLT and ONU. In [282], the authors have shown how an OLT can become more energy-efficient by avoiding unnecessary packet processing. In a conventional PON, all the uplink traffic is terminated at the OLT before forwarding to the core network regardless of processing requirements at the electrical part at the OLT. In [282], Kani *et al.* have suggested an OLT architecture where an optical switch passes the uplink traffic that do not need any processing at the electrical part of the OLT to the core network directly; thereby, reducing latency and energy consumption at the OLT. In [217], [250], the authors have successfully shown how the control messages associated with the sleep mode management can be reduced in a PON system, thereby saving bandwidth and energy.

H. SDN Enabled Orchestration and Virtualization

Although significant energy saving is possible by simply allowing a PON system to maintain energy saving operations independently (as we will see in Section VI), a centralized orchestration can bring far great opportunities for improving energy conservation and meeting desired QoS requirements. Without centralized orchestration it is not possible to ensure successful flow of packets when some of the hops in their path are unable to process and forward further because they are in power saving mode [287]. Consider that a base station is forwarding traffic to an ONU; however, the ONU is in *sleep state* at that given time. This may result in increasing packet delay and/or packet drop and ONU's sleep interruption. To overcome this, a network-wide control system leveraged by SDN becomes useful as an SDN controller is able to gain global network view [288].

SDN facilitates dynamic programmable PON configuration [152], [289]. It makes a PON system to be an integral part of a larger network by establishing a unified control platform; thereby allowing the PON and its connected networks to dynamically adjust and coordinate their operations to maximize energy conservation and improve traffic forwarding [1], [289], [290]. For example, as demonstrated using a testbed setup in [285], [291] that an SDN controller can provide seamless connectivity to the mobile terminals while maintaining a successful coordination between optical, wireless segment and aggregation network for traffic forwarding and energy conservation. Here, when a base station is turned off, its connected ONU and the corresponding OLT port also move into energy conservation mode following the instruction of the SDN controller. This allows energy conservation as well as reduces the packet delay and packet drop. Similar SDN based such energy saving aware orchestrated operation has been also proposed in several proposals, as we will see in Section VII.

More recently, there has been noticeable advancement in modularization and softwarization in PON (see Sections III and VII). One of the important advantages of this can be improvement in energy conservation. For example, as reported in [5], since the control functions can be detached from the OLT in an SDN controlled PON, OLT's master control board can have reduced energy consumption. Similarly, Nishimoto *et al.* in [147] demonstrated that their proposed solution for virtualization of EPON OLT functions not only provides the network operators with higher degree of freedom for changing/adding OLT functions (e.g., modifying DBA) but also minimizes energy consumption and space requirement.

Table IV summarizes various energy saving approaches in PON variants introduced across standardization bodies and academic research. To enhance energy saving performance, these techniques can be utilized concomitantly as they are mostly independent from each other.

V. Standardization Efforts of IEEE and ITU-T for PON Energy Conservation

The growing awareness on energy conservation in network access segment has propelled standardization activities both in IEEE and ITU-T. The earlier standards of IEEE for EPON

TABLE IV: Summary of energy saving approaches. In the Introduced in column, E, I and A denote an energy saving approach introduced by IEEE, ITU-T, and academia, respectively.

Energy saving approach		Description	Introduced in			Signaling required	Can be used in PON variant:		
							TDM	WDM	TWDM
Sleep mode	Deep sleep mode [38]	ONU turns off both transmitter and receiver		I	A	✓	✓	✓	✓
	Cyclic sleep mode [38], [230]	ONU periodically switches between *active state* and *sleep state* (this mode is referred as TRx sleep mode by the IEEE and cyclic sleep mode by the ITU-T).	E	I	A	✓	✓	✓	✓
	Watchful sleep mode [222], [229], [231]	It combines doze mode and cyclic sleep mode together.		I	A	✓	✓	✓	✓
	Doze mode [38], [207], [217], [230]	ONU turns off transmitter only (this mode is referred as Tx sleep mode by the IEEE and doze mode by the ITU-T).	E	I	A	✓	✓	✓	✓
	Rx sleep mode [207], [217]	ONU turns off its receiver only			A	✓	✓	✓	✓
	OLT-port sleep mode [22], [221]	OLT turns off its downlink wavelengths (ports)	E	I	A	✓	×	×	✓
	OLT-line card sleep mode [58], [245]–[247]	OLT turns off its line card(s)			A	×	✓	✓	✓
Energy-efficient and fast response network equipment design [258], [259], [261]		Several photonic functions are integrated into a single tiny chip. This miniature chips consume low power			A	×	✓	✓	✓
Power Gating and voltage and frequency scaling [263], [265]		Adjusting the applied voltage and frequency in a microprocessor or a control chip to energy consumption and meet performance requirement		I	A	×	✓	✓	✓
Line rate switching [21], [206], [241]		Adjusting transmission link speed dynamically. Lower transmission rate consumes less energy.		I	A	✓	✓	✓	✓
Dynamic ONU buffer size [271], [272]		Reducing or eliminating buffers in the ONU lead to reduce in energy consumption			A	×	✓	✓	✓
Wavelength reusing at ONUs [201], [283]		Reusing the downlink transmitted signal for uplink communication. Therefore, an does not need to have a transmitter.			A	×	×	✓	✓
Energy-efficient transmission [23], [277], [278], [282]		Reducing degradation of signal power, improving spectral efficiency, minimizing control and signaling messages and avoiding unnecessary packet processing, etc.			A	–	✓	✓	✓
SDN enabled orchestration and function virtualization [136], [147], [284], [285]		Unified control and coordination assure better traffic engineering, resource utilization, and orchestrated energy saving operation between network segments, resulting in improved energy saving and QoS performance. On demand flexible and speed services creation and upgrades. Requirement based hardware resource allocation and sharing across the functions can contribute to reduce energy consumption [40], [286]. PON equipment can be smaller, resulting lower space footprint.			A	–	✓	✓	✓

(e.g., IEEE 802.3ah [84] and IEEE 802.3av [87]) did not take into account energy saving issues in PON. Similarly, such consideration was unavailable when first GPON standard was introduced in 2003 [85]. Later on the ITU-T and IEEE introduced ITU-T G-Sup.45 [38] in 2009 and IEEE Std 1904.1 [39] in 2013, respectively to reduce energy consumption in TDM-PONs (GPON and EPON). In Section IV, we have explained different energy saving approaches considered in academic research and standardization efforts. The aim of this section is to provide the readers with a brief understanding about the recommended operational guidelines for the energy saving approaches considered in the IEEE and ITU-T PONs.

A. Energy Saving Approaches and Operational Guidelines for IEEE PONs

The specifications stated in IEEE 1904.1 standard [39] complement IEEE 802.3 and IEEE 802.1 standards to facilitate interoperability at the Physical Layer and MAC Layer of PON. In particular, the management related specifications stated in this standard include the mechanisms for minimizing energy consumption in EPON and supporting service and equipment management. The scope and purpose of IEEE 802.3ca [35] standard is similar to the IEEE Std 1904.1 [292], [293]. Additionally, the IEEE 802.3ca standard incorporated NG-EPON architectures (see Fig. 5) [293].

The IEEE Std 1904.1 defines mainly two modes of an ONU: normal mode and power-saving mode. During the normal mode, an ONU is fully functional, keeping all of its components powered up. Conversely, during the power-saving mode, an ONU moves into a sleep mode. This standard specifies two types of sleep modes for an ONU under the power-saving mode: TRx sleep mode and Tx sleep mode. Each of these modes has two states: *active state* and *sleep state*. Between two normal modes, during which an ONU maintains a power-saving mode, an ONU can have one or more power saving cycles, as shown in Fig. 20. Table V compares between the TRx sleep mode and the Tx Sleep mode as defined in SIEPON standard.

According to the IEEE Std 1904.1 [39], both the OLT and ONU are authorized to initiate an energy saving mode (e.g., cyclic sleep mode). The OLT initiated one is a centralized approach in which the OLT alone makes a decision on putting an ONU into an energy saving mode taking into account traffic arrival for that particular ONU. The OLT learns the appropriate type of sleep mode for an ONU during the device capability discovery stage. In case when an ONU initiates its energy saving mode, it decides based on the observation of its uplink traffic. As an example, Fig. 21 presents the ONU initiated and OLT initiated energy-saving mechanism defined in IEEE Std 1904.1 [39].

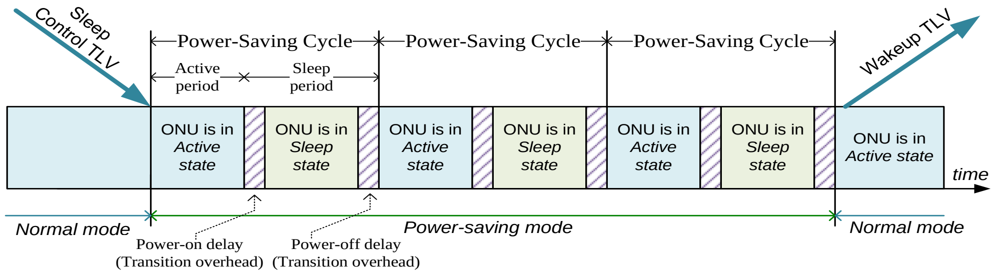

Fig. 20: Power-saving and normal mode of an ONU in IEEE Std 1904.1 (SIEPON) [39]: Between two normal modes, the ONUs maintains power-saving cycle(s). The power-off period and power-on period (both way transition periods) are part of sleep period of the ONU, as suggested in IEEE Std 1904.1 [39].

TABLE V: Comparison between TRx and Tx sleep mode in IEEE Std 1904.1 (SIEPON) [39].

ONU power saving modes	**Number of states**	**Active communication path**	**Early wake-up function**	**Time required for *Sleep* to *Active state* transition**	**Synchronous wake-up**	**OLT initiated power saving support**	**ONU initiated power saving support**	**Downlink synchronization is required after leaving a *sleep state***
TRx Sleep Mode	*Active state*	Both downlink and uplink	✓(OLT may enable or disable)	✓	✓	✓	✓	✓
	Sleep state	None						
Tx Sleep mode	Active state	Both downlink and uplink	✓(OLT may enable or disable)	✓	✓	✓	✓	×
	Sleep state	Only downlink						

In both sleep modes, *active state* refers to the state of an ONU during which the ONU powers up all the components in order to remain fully functional (i.e., an ONU is able to make both uplink and downlink communication) and the *sleep state* of an ONU refers to the period during which the ONU turns off some of its components to save power while maintaining a particular sleep mode. The components (or subsystems) of an ONU that should be switched off during a *sleep state* under a particular sleep mode is out of scope of the IEEE Std 1904.1. OLT-port sleep mode is an additional power saving mechanism recommend in the IEEE 802.3ca standard for the Nx25G-EPON [35]. To attain aggregated downlink data rate for an ONU, the PON system facilitates bonding of multiple 25Gb/s wavelength channels, as shown in Fig. 5. The standard recommends to turn off wavelength channel(s) at the OLT and/or ONU to conserve energy [35].

The OLT needs to abstain from sending downlink unicast frames when the destination ONU is in *sleep state* under TRx sleep mode. However, according to the SIEPON standard, an ONU may receive downlink traffic while an ONU is in *active state* (the time between two sleep periods). On the other hand, it is expected that regardless of the state of an ONU under Tx sleep mode, the OLT can forward any kind of frames on arrival without waiting for the expiration of sleep period of the ONU. It is possible because in Tx sleep mode, an ONU keeps its reception path powered up while keeping its transmission path powered down. Along with unicast traffic forwarding scenario in an EPON, SIEPON standard takes into consideration how broadcast and multicast traffic can be forwarded to the ONUs that adopt power-saving modes. This standard recommends that the ONUs belonging to the same multicast group should synchronously wake up at the same time to receive the frames of a specific multicast group. Similarly, broadcast frames should be delivered when all the sleeping ONUs wake up.

To avoid delay or packet drop of uplink traffic while an ONU maintains sleep mode, the early wake-up function is introduced in IEEE Std 1904.1 [39]. When the early wake-up function is supported by an ONU, a sleeping ONU (i.e., the ONU which is in *sleep state*) can leave *sleep state* depending on its local situation before expiration of the OLT's assigned sleep period. The early wake-up function of an ONU is supported under both OLT and ONU initiated power saving mechanisms in SIEPON, as stated in IEEE Std 1904.1 [39]. When the OLT allows early wake-up of an ONU, it needs to periodically assign a gratuitous grant (a small uplink grant) to the ONU during each uplink DBA cycle [294]. The OLT uses the GATE MPCPDU message to notify the ONUs periodically regarding uplink transmission grant information, as shown in Fig. 22. An ONU may or may not use the early wake-up function (see the example illustrated Fig. 22 (a) and (b)). The standard identifies some possible reasons that could lead to trigger the early wake-up function of an ONU. The possible reasons are: (i) status of buffered data in an ONU, (ii) user activity detection at any of the UNI ports of the ONU, and (iii) detection of voice port's off-hook condition.

B. Energy Saving Approaches and Operational Guidelines for ITU-T PONs

In 2009, ITU-T G-Sup.45 [38] introduced energy saving mechanisms for GPON, namely, power shedding, fast sleep mode, doze mode and deep sleep mode. Later, in the ITU-T G.984 (G-PON) [231] and ITUT G.987 (XG-PON) [229], [234] incorporated the watchful sleep mode which is a combination of cyclic sleep (fast sleep) and doze mode. In 2019, ITU-T G.9804.1 states the energy saving mechanisms for the PtP WDM and TWDM-PON of NG-PON2. Besides deriving the energy saving mechanism stated in ITU-T G-

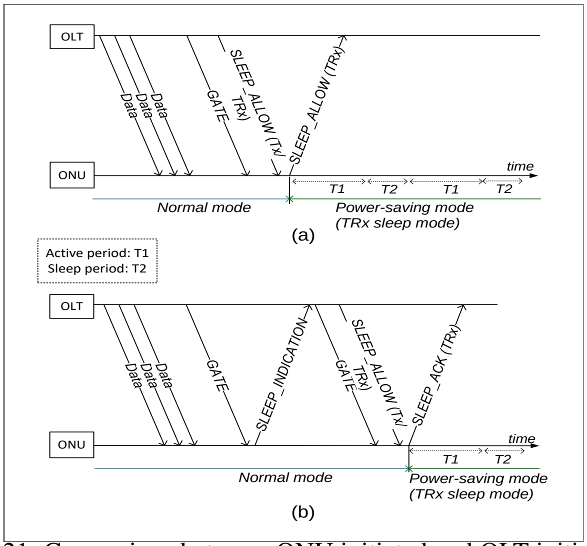

Fig. 21: Comparison between ONU initiated and OLT initiated sleep mode in IEEE Std 1904.1 [39]: (a) OLT initiated; (b) ONU initiated.

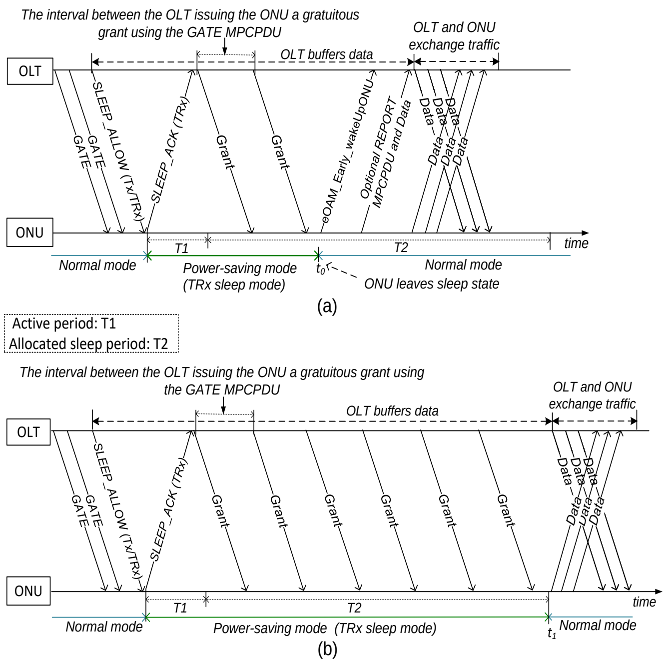

Fig. 22: Early wake-up function for energy saving mode interruption mechanism defined in IEEE Std 1904.1 [39]: (a) ONU uses the early wake-up function (it leaves *sleep state* earlier at time t_0 without spending $T2$ and responds to the issued gratuitous grant by sending *eOAM_Early_wakeUpONU* message and buffered traffic); (b) ONU has no specific condition for triggering the early wake-up function of the ONU; therefore, it abstains from using the gratuitous grants.

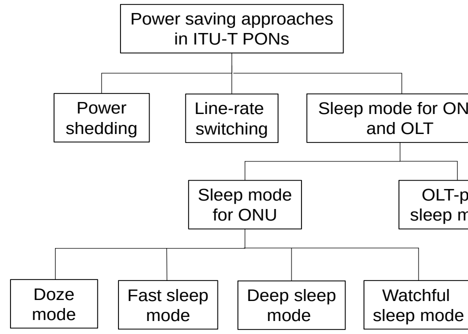

Fig. 23: Taxonomy of the energy saving approaches for PON defined by the ITU-T Recommendations.

Sup.45 [38] and ITU-T G.984 (G-PON) [231], the ITU-T G.9804.1 [22] and ITU-T G.989.3 [21] have incorporated OLT-port sleep mode and Line-rate switching for TWDM-PON and PtP WDM-PON, respectively. To reduce the number of serving OLT-ports in a TWDM-PON, it is required to reallocate wavelengths to the ONUs (tuning the ONUs to a minimal aggregated wavelengths). The mechanism related to ONU's wavelength tuning is specified in the recommendation ITU-T G.9802 [295]. Fig. 23 delineates the taxonomy of energy saving approaches introduced by ITU-T.

According to ITU-T G-Sup.45 [38]), both the OLT and ONU are authorized to initiate a cyclic sleep mode and doze mode. Cyclic sleep mode is same as the TRx sleep mode in IEEE Std 1904.1 (IEEE SIEPON standard) [39], [233]. The OLT needs to maintain different timers to be synchronized with the ONUs using cyclic sleep mode. Upon receiving sleep instruction, an ONU in the cyclic sleep mode moves into *sleep state*. During this state, it maintains a clock which facilitates triggering the reception path of the ONU powered up in advance of the scheduled wake-up frame [38]. In this energy saving mode, the OLT buffers all the incoming traffic when an ONU is in *sleep state* and delivers them when the ONU moves into *active state*.

While an ONU is in doze mode, the OLT does not provide any uplink transmission slot for sending uplink traffic except a short uplink transmission slot (grant) in each DBA cycle which is used by the ONU when it opts to leave doze mode due to uplink traffic arrival. Therefore, doze mode does not have adverse effect on downlink traffic; however, performance of uplink traffic while an ONU is in this mode may depend mainly on transmission grant and uplink transmission cycle length. The ITU-T's proposed doze mode is the same as Tx sleep mode proposed in the IEEE SIEPON standard [39].

As specified in ITU-T recommendations (e.g., [21], [231]), when there is no particular reason to remain fully active for an ONU, it can inform the serving OLT that it wants to exercise watchful sleep mode [21]. During this mode, both the OLT and ONU need to keep their state machines synchronized. The ITU-T recommendations (e.g., [231]), defines T_{aware} (a local time at an ONU) for doze, cyclic and watchful sleep mode. This is dwelling duration of an ONU (after completing the downlink synchronization) upon entering the *aware state* in which both the transmitter and receiver of an ONU remain switched on, as illustrated in Fig. 18. During T_{aware}, an ONU is able to forward downlink frames and respond to bandwidth allocation [231].

Unlike doze, cyclic and watchful sleep mode, power shedding is an one-sided power management technique where an ONU does not require to maintain signalling with the OLT

TABLE VI: Taxonomy of the energy saving mechanisms defined by the ITU-T [21], [22], [38], [229], [234].

		Power shedding	**Doze mode**	**Deep sleep**	**Fast sleep**	**Watchful sleep**	**OLT-port sleep mode**	**Line-rate switching**
ONU's activities		ONU turns off or reduce power to its circuitry associated with non-essential functions or services.	ONU turns off its transmitter only in the energy conservation phase. It can receive downlink traffic in this mode.	ONU turns off its transceivers during the entire sleep sojourn period.	ONU periodically turns on and off its transmitter and receiver (this approach is also referred as cyclic sleep).	Similar to cyclic sleep and doze mode, an ONU in this mode switches between energy conservation and active phase. However, during the energy conservation phase, an ONU periodically turns on receiver only to get instruction from the OLT.	This is a sleep mode has been introduced for the OLTs in a TWDM-PON. The ONUs in a TWDM-PON need to tune into newly assigned wavelength when the OLT decides to turn off their serving wavelengths.	ONU adjusts line-rate to a target level which is set by the OLT when utilization of the link between the OLT and ONU in a PtP WDM-PON is under utilized. During Line-rate switching period, the ONU should defer its transmission.
OLT's activities		none	Periodic notification upon arrival of downlink traffic and may allocate uplink grant to the ONUs in doze mode so as to facilitate uplink traffic transmission.	Target ranging window allocation periodically. The OLT should suppress the PON alarm.	During the active (aware) state duration (T_{aware} in Fig. 18) of an ONU in a sleep cycle, the OLT exchange control messages and traffic with the ONU. The length *active state* and *sleep state* duration (during when transceivers are turned off) are decided after negotiating with the ONU.	The OLT notifies ONUs upon arrival of their downlink traffic during their active state duration. Additionally, the OLT may allocate uplink grant to the ONUs in watchful sleep mode so as to facilitate uplink traffic transmission. The OLT decides on the *sleep state* duration and *active state* duration with the ONUs.	When the OLT decides to turn off its transceiver(s), it instructs the subtending ONU(s) of those transceivers to migrate to other transceiver (wavelength re-location).	OLT measures utilization of optical links and instructs the ONUs that need line-rate readjustment. The role of the OLT is to set a target line-rate for an ONU. During the Line-rate switching period the OLT should defer its transmission to the particular ONUs undergoing the link-rate readjustment process.
Impact on downlink traffic	Delay	none	none	Depend on deep sleep sojourn period.	Depends on active and sleep state duration of a sleep cycle.	Depends on receiver on and off duration during the energy conservation phase.	The longer the time required for wavelength re-location, the higher the traffic delay.	Depends on selected rate and Line-rate switching period.
	Jitter	none	none	none	Depends on active and sleep duration of a sleep cycle, and downlink traffic arrival behaviour.	Depends on receiver on and off duration during the energy conservation phase.	Frequent wavelength re-location may lead to introduce jitter.	Depends on selected rate and Line-rate switching period.
	Packet drop	none	none	All arrived packets are dropped when the OLT's buffer is occupied.	Depends on active and sleep duration of a sleep cycle, and downlink traffic arrival behaviour.	Depends on receiver on and off duration during the energy conservation phase, and traffic arrival rate.	Long wavelength re-location time may cause packet drop.	Depends on selected rate and Line-rate switching period.
Impact on uplink traffic	Delay	none	Depends on uplink transmission grant and uplink transmission cycle length.	Depend on deep sleep sojourn period.	Depends on active and sleep duration of a sleep cycle, and uplink traffic arrival behaviour.	Depends on the size of a uplink grant allocated to an ONU.	The longer the time required for wavelength re-location, the higher the traffic delay.	Depends on selected rate and Line-rate switching period.
	Jitter	none	Depends on uplink transmission grant, uplink transmission cycle length and traffic arrival behavior.	none	Depends on active and sleep duration of a sleep cycle, and uplink traffic arrival behaviour.	Depends on the size of an uplink grant allocated to an ONU and uplink traffic arrival behaviour.	Frequent wavelength re-location may lead to introduce jitter.	Depends on selected rate and Line-rate switching period.
	Packet drop	none	Depends on uplink transmission grant, uplink transmission cycle length, and traffic arrival rate.	All arrived packets are dropped when the ONU's buffer is occupied.	Depends on active and sleep duration of a sleep cycle, and uplink traffic arrival behaviour.	Depends on the size of an uplink grant allocated to an ONU and uplink traffic arrival behaviour.	Long wavelength re-location time may cause packet drop.	Depends on selected rate and Line-rate switching period.

(e.g., three-way handshake in cyclic sleep mode) [222]. As pointed in the recommendation [234] that different operators and customers may not have the same preference on turning off the services of an ONU in power shedding mode. Depending on the amount of power consumption upper bound, an operator may have more than one power shedding class (i.e., different set of services supported under different power shedding classes). Each power shedding class may have static timer during which an ONU stays in that particular power shading class or alternatively an ONU may leave a power shedding class due to an external stimulus. According to the recommendation in [38], to increase service availability, an ONU can have two power sources: battery backup and AC power source. In case when the AC power supply fails, power shedding approach should be applied to prolong battery lifespan. Note that some ONUs may not provide an opportunity to turn off individual ONU ports (service supporting ports); therefore, the power shedding capability may vary in ONUs from different vendors.

As suggested in ITU-T G-Sup.45 [38], an ONU can initiate deep sleep mode. In this mode, an ONU turns off its transmitter and receiver for a predefined time period [38] and during this period the communication between the OLT and ONU is not possible. As suggested in the recommendation [38], the timing and activity detection functions may optionally remain active in an ONU during this mode. For the ONUs in deep sleep mode, the OLT should suppress the PON alarm.

The ITU-T G.989.3 [21] has stated the Line-rate switching mechanism for the ONU and OLT in PtP WDM-PON of NG-PON2 as a mean to reduce power consumption. The PtP WDM-PON allows an ONU to be operated in the continuous mode at multiple levels of line rates with the connected OLT [21]. Once the OLT finds the bandwidth utilization is low for a given line rate of a link (wavelength) between the OLT and an ONU, it would invoke that particular ONU to readjust the line-rate (transmission and reception rate) to a lower level so as to reduce energy consumption on both the OLT and ONU sides [21]. Similar to IEEE, ITU-T has defined sleep mode interruption mechanism. For instance, ITU-T G.987.3 [296] stated Local Wake-up Indication (LWI), which is a local stimulus to prevent an ONU from continuing any energy saving mode and ITU-T G-Sup.45 [38] presented two possible conditions for leaving deep sleep mode for an ONU: local stimuli (internal ONU timer expires) and external stimuli (deliberately it is turned on).

In 2022, ITU-T released another G Suppl. 45 in [123] which focuses on elaborating description of various power saving techniques in ONUs and OLTs recommended in the previous ITU-T standards. It aims at exploring the importance of applying the power saving mechanisms in access network to networks deployed for domestic services (FTTR) or corporate usage. Additionally, centralized powering from the local OLT using Power over Ethernet (PoE) or opposite reverse ONU powering from the connected terminal have also been identified in this recommendation for further investigation.

We provide a summary of energy saving approaches defined by ITU-T in the Recommendations [21], [22], [38], [229], [234] in Table VI. Along with providing a glimpse into the impact of each power saving technique on downlink and uplink traffic performance, the first and second rows of the table state the activities of the OLT and ONU under each power saving

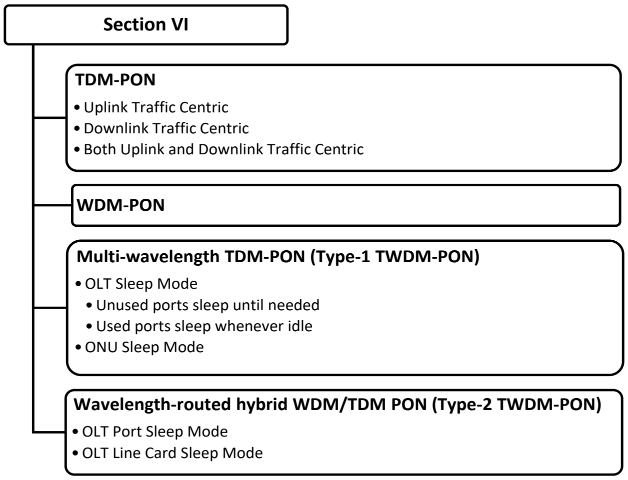

Fig. 24: Structure of Section VI.

technique.

VI. Solutions Applying Sleep Mode Approach in Conventional PONs

This section focuses on an exhaustive review of the sleep mode based solutions proposed for conserving energy in TDM-PON, WDM-PON and TWDM-PON (Type-1 and Type-2), specifically under the respective subsections VI-A, VI-B, VI-C, and VI-D. For each proposed solution, we outline its scope, mechanisms it introduced, and major strengths and/or limitations. Table VII, VIII, IX and X provide a comparison of the main contribution aspects, features, and evaluation methodology of the solutions proposed for each respective PON variant. The overall structure of this section is illustrated in Fig. 24.

A. TDM-PON

A TDM-PON system uses a pair of wavelengths for downlink and uplink communications. It applies a broadcast and select mechanism for downlink transmission, whereas for the uplink communication TDMA is used for sharing a single wavelength among the ONUs in a PON system. In our survey, we found the decision associated with sleep mode operation and bandwidth allocation in the energy-saving solutions in TDM-PONs is generally traffic centric. Some of the solutions make decision based on uplink traffic only, whereas some others make downlink traffic centric decision. There are also a large body of contributions where sleep mode operation and bandwidth allocation related decisions are both uplink and downlink centric.

1) Uplink traffic centric: Yan *et al.* in [204] have proposed an uplink centric bandwidth scheduling in which the OLT in a TDM-PON system determines sleep duration of an ONU based on uplink bandwidth allocation of the ONU. In this approach, the OLT first collects uplink bandwidth demand from each ONU by polling them. Next, taking into consideration the ONUs' bandwidth demand, it decides on uplink transmission slot for each of the ONUs. While an ONU is awake to transmit the buffered uplink traffic during its assigned uplink slot, it also receives downlink traffic from the OLT. An ONU stays in a *sleep state* turning off its transceivers between its two consecutive uplink transmission slots. Therefore, the uplink polling cycle length plays an important role for both QoS and energy saving performance. However, this presented solution does not discuss how to determine a polling cycle under different QoS requirements of traffic.

Dixit *et al.* in [297] have introduced a DBA algorithm to meet jitter, delay requirements, fairness, and throughput performance of traffic. To meet different delay-bound requirements, the authors have proposed a differential polling approach which polls users according to their delay-bound requirements. Based on their research, they drew a conclusion that load fluctuation in a network could lead to increase jitter which in turn could degrade performance of applications such as high-resolution video streaming. In their follow-up work, an uplink traffic centric bandwidth scheduling approach was introduced [298], where transmission slots are determined based on uplink traffic only. In a round-robin manner, the OLT polls the ONUs to know their uplink bandwidth requirement and then notifies them their corresponding transmission slot and sleep period. They have also introduced a sleep period prediction scheme and shown how the grant size of an ONU is determined taking into account uplink and downlink traffic. Based on simulation, the authors have reported that the uplink traffic delay in this proposed solution is similar to IPACT while being able to conserve energy. However, this solution increases downlink traffic delay.

Nikoukar *et al.* [299] have proposed an energy saving solution for the transmitter of an ONU. The solution determines sleep duration of the transmitter and grant size for the uplink transmission taking account the presence of traffic and their priority levels (e.g., best effort). To determine sleep interval duration of the transmitter more appropriately, the OLT in this solution considers an ONU's report message history besides the current one. The authors also have considered the early wake-up function of an ONU, thereby allowing the ONU to leave *sleep state* whenever any high-priority traffic comes from the customer premises. The authors have conducted extensive simulations and have shown that their solution reduces energy consumption while not violating the QoS requirements. However, because of relying on early wake-up function, this solution may yield inefficient energy consumption even when an arrived uplink traffic has relaxed latency requirement.

Similarly, to reduce energy consumption of a transmitter, Yang *et al.* [300] have proposed that an ONU should transit between *active state* and *doze state* to conserve energy. The ONU stays in *doze state* for a longer duration when the uplink traffic has flexible QoS requirement. The maximum amount of time an ONU is allowed to stay in a *doze state* is determined based on arrived traffic priority. When traffic arrival increases rapidly, to avoid buffer overflow at an ONU, the authors have proposed to interrupt *doze state* and request for uplink bandwidth to the OLT in the following cycle(s). Although the solutions proposed in [299], [300] are able to show satisfactory QoS performance, their energy saving performance is undermined because of keeping the receiver of an ONU always switched on.

Even though uplink traffic centric solutions make sleep mode management in the OLT simpler relatively, it has downsides. As the downlink traffic arrival is several folds higher than the arrival rate of uplink traffic [217], [301], deciding an ONU's sleep interval and bandwidth allocation taking into account only uplink traffic would lead to significantly restrict downlink traffic throughput and increase packet drop and delay.

2) Downlink traffic centric: Besides an uplink centric scheduling scheme, Yan *et al.* [204] have introduced downlink centric scheme, where active duration of an ONU is significantly influenced by downlink traffic. An ONU needs to be awake for receiving downlink traffic whenever the OLT has. Therefore, the presence of downlink traffic may force an ONU to revise its preassigned sleep duration. This leads to deteriorate energy conservation performance of an ONU when downlink traffic arrival is high.

Ren *et al.* [205] has proposed a solution where the decision with regard to sleep interval is made using an algorithm. This algorithm restricts the sleep interval length of an ONU within a lower bound (T_{min}) and upper bound (T_{max}). The initial value of sleep interval of an ONU starts with T_{min} and it increases exponentially up to T_{max} as long as there is no traffic arrival for the ONU. (1) shows how *j-th* sleep interval of an ONU is measured in [205]. The authors in [205] have considered that a sleeping ONU should leave *sleep state* immediately on arrival of uplink traffic. One major drawback of this solution is that it keeps the upper and lower limit of sleep interval unchanged regardless of the type of traffic arrival.

$$T_{S,j} = \begin{cases} 2^{j-1}T_{min}, & if\ 2^{j-1}T_{min} < T_{max} \\ T_{max}, & otherwise. \end{cases} \quad (1)$$

In [206], Kubo *et al.* have introduced a hybrid mechanism where both sleep mode and ALR approach are exploited to reduce energy consumption of ONUs in 10G-EPON system. In their solution, the sleep control function for an ONU is activated when traffic is absent for forwarding, whereas the ALR mechanism is triggered in presence of traffic. The presence or absence of traffic is determined based on downlink frame inter-arrival. If the frame inter-arrival period at a given time is above a predefined threshold, an ONU moves into *sleep state* for a predetermined sleep duration. This solution could have been more useful if the authors had determined the predetermined sleep time based on QoS requirement of traffic.

Another work of Kubo *et al.* [302] has proposed that the sleep period of an ONU should be determined according to downlink traffic conditions. The OLT observes downlink frame interval, queue length and traffic priority class. Then, on the basis of the downlink traffic information, the OLT determines whether the ONU should move into sleep mode or not. In their solution, an ONU can have a constant sleep period or variable sleep period while managing its sleep mode operation. In the constant sleep period case, the approach for determining the sleep interval is similar to that of [206]. For variable sleep periods of ONUs, the authors have proposed a function where for an average frame interval value, a sleep period (lies between a minimum and maximum sleep period) is determined. In this solution, an ONU enters into active mode regardless of the sleep instruction of the OLT if the ONU has uplink traffic to forward. Therefore, here, an ONU may experience frequent sleep interruption as the uplink traffic arrival increases, resulting in reduced energy saving opportunity. To avoid frequent sleep interruption, a traffic priority class-based sleep interruption decision could have been considered (as proposed in [294]).

It is worth mentioning that the solutions proposed in [205], [206], [302] require three-way handshake to exchange sleep mode related parameters between an OLT and ONU every time the ONU leaves a *sleep state*, as shown in Fig. 17. When the three-way handshake approach is adopted, a PON system with a large number of ONUs spends a significant portion of its bandwidth for exchanging control messages pertaining to sleep mode. This, in turn, leads to increase packet delay and packet drop [303]. To reduce the number of signaling messages related to sleep mode, Zhang *et al.* in [304] have proposed a solution that eliminates the need for three-way handshake. In their solution, each of the ONUs with downlink traffic is assigned a slot for reception of downlink traffic in a downlink scheduling cycle. If an ONU does not receive any downlink traffic within a certain number of downlink scheduling cycles (say *x*), it moves into *sleep state* for *y* number of downlink scheduling cycles. Therefore, in this solution, *x* is referred to as listening cycles, whereas the *y* number of downlink scheduling cycles are considered as sleeping cycles for the ONU. This sleep mode management policy is also known by the OLT; therefore, the OLT is able to infer the status of each ONUs based on their downlink traffic arrival. As this approach allows the state machines of an OLT and ONU synchronized, a complex handshake protocol for maintaining sleep mode in ONUs is not required in this solution, similar to [207], [217]. Based on a numerical analysis, authors have shown that a 50% of energy saving is obtained using their solution when the network is lightly loaded. However, how uplink traffic should be scheduled when the ONUs maintain sleep mode is beyond the scope of their work.

Similarly, the solution Newaz *et al.* [217] introduced does not require three-way handshake. The authors have proposed that the length of an ONU's sleep interval should be within T_{min} and T_{max}, resembling the authors in [205]. However, here, the value of T_{min} and T_{max} is adjusted dynamically taking into account delay requirements of the downlink traffic. Authors have demonstrated the significance of their proposed solution under constant bit rate, variable bit rate, and real traffic traces. One major limitation of this work is that it does not consider any mechanism for avoiding collision when multiple ONUs leave sleep mode and require to communicate with the OLT simultaneously.

In watchful sleep mode, during a *watch state*, an ONU keep its transmitter off, while it turns on receiver periodically to get an OLT's instruction [222] (see Fig. 18 (c)). The authors in [227], argue that the periodic turning on and off the receiver of an ONU for a certain duration is not an energy-efficient approach. To overcome this limitation, they have proposed an adaptive watchful sleep mode solution, where duration and occurrence of the active period of the receiver during the *watch state* are determined taking account downlink traffic arrival rate. Using simulation, the authors have shown that their solution can reduce a 9% of energy consumption without imposing any additional delay compared to the standard watchful sleep mode. However, this solution can increase an extra layer of implementation complexity due to maintaining additional times associated with different states in the OLT and ONU.

3) Both uplink and downlink traffic centric: In [305], authors have proposed to assign a fixed bandwidth slot for each of the ONUs in a lightly loaded TDM-PON for both uplink and downlink communication. Outside of the assigned slot, an ONU can move into sleep mode by turning off its transmitter and receiver. However, when load is above a threshold, in their proposed solution, the PON system uses DBA for bandwidth allocation. This work does not offer any discussion on how to determine the threshold for switching between these two bandwidth allocation approaches.

Shi *et al.* in [306] have introduced a sleep mode based energy saving solution for a TDM-PON system taking into account the requirement of different traffic priority classes, e.g., expedited forwarding (high-priority class) and best effort (low-priority class) traffic. The authors have proposed to increase sleep duration according to a mix of linear backoff and geometric backoff policy until a maximum value as long as there is no frame to forward in either direction. Their solution also supports early-wake up function on arrival of a high-priority uplink traffic at an ONU (forcing the ONU to leave *sleep state* and send a bandwidth request using a reserved slot). Authors anticipate that the first arrived traffic with high-priority class at a sleeping ONU would experience no more than 5 *ms* extra delay with a cycle time 1 *ms*. However, to reduce this delay further, they have suggested assigning a larger reserved slot which an ONU can use for sending several frames besides the report message after leaving *sleep state*. Note that this approach may lead to wastage of bandwidth during the low traffic arrival periods. The performance of their solution is justified based on simulations. The results indicate that with the increase of traffic with high-priorities, sleep interval length of ONUs reduces.

In [307], Dhaini *et al.* have introduced a bandwidth allocation mechanism which facilitates a batch-mode transmission between the OLT and an ONU to maximize energy saving. The solution allows an ONU to move into *sleep state* even when it has traffic to exchange with the OLT. The decision whether the ONU leaves sleep mode is determined based on maximum delay requirement of traffic instead of presence of uplink and/or downlink traffic. However, any sleep-time measurement mechanism is not specified here. To overcome this limitation, in their follow-up work [216], the authors have introduced a novel sleep-time sizing and scheduling mechanism which can exploit the bandwidth allocation mechanism introduced in [307]. The major role of these two mechanisms is to resize and schedule the sleep times of ONUs so as to avoid any collision of transmission from the ONUs after leaving their sleep mode. However, to accomplish this, an OLT will experience substantial computation load in a network characterized by fluctuating traffic load and frequently changing performance requirements. Results obtained using a simulator show that the proposed solution reduces energy consumption while not impairing the users' requirements.

Two sleep mode scenarios are proposed in [207]. In the first scenario, an ONU remains in *sleep state* more than a DBA cycle. Conversely, in the second one, an ONU is allowed to sleep within a DBA cycle. The authors also proposed an ONU which is able to selectively activate or deactivate its transmitter and receiver based on the presence of uplink and downlink traffic. For the first scenario, they have introduced an algorithm to determine transmitter sleep duration and the condition for moving to other states. This solution does not require a three-way handshaking between the OLT and ONU to be synchronized while maintaining sleep mode because both the ONU and OLT implement the same algorithm to keep their state machines synchronized. In the second sleep mode scenario, an ONU sleeps within a DBA cycle while other ONUs are exchanging traffic with the OLT. Any performance evaluation results to understand the efficacy of the solution have not been reported.

Zhang *et al.* in [240] have proposed downlink and uplink traffic aware sleep mode and bandwidth scheduling solution for a TDM-PON system. Besides cyclic sleep mode, an ONU in their solution supports doze and Rx sleep mode, allowing more energy to be saved. Each ONU needs to send its bandwidth requirement. Then, OLT determines downlink and uplink bandwidth for all ONUs. The contribution of this work stands out especially because it considers both inter-ONU and intra-ONU traffic scheduling in order to meet QoS requirements while saving energy in ONUs. A significant limitation of this solution is that it may experience bandwidth wastage due to the large number of control message exchanges for sleep mode management and bandwidth scheduling, similar to [206].

In [308], Li *et al.* have proposed an energy-efficient DBA algorithm which takes into account both uplink and downlink bandwidth requirements of an ONU. To reduce energy consumption, they have introduced two grant scheduling algorithms for an ONU. Besides finding an optimal sleep duration taking into account traffic arrival of both links, their proposed grant scheduling algorithms make the uplink and downlink transmission window of an ONU overlapping as much as possible, thereby improving energy conservation of the ONU further. Note that, this overlapping approach can be more efficient as the uplink and downlink traffic arrivals become more symmetric. Furthermore, the proposed solution supports dynamic polling cycle length adjustment under different QoS performance requirements. The simulation results demonstrate that the solution enhances energy saving performance significantly with tolerable traffic performance degradation. However, it is not clear how the solution determines the polling cycle length when there exists ONUs with non-identical QoS requirements.

Taking into account the uplink and downlink delay requirements, Helmy *et al.* in [309] have proposed an energy-efficient bandwidth allocation mechanism where the OLT maintains a downlink and uplink transmission cycle for its ONUs. The OLT allocates a single slot to each ONU for both uplink and downlink transmission so as to increase the chance of the ONU's common components to be powered down besides the transmitter and receiver, similar to [308]. To further reduce energy consumption in the ONUs, the authors have proposed to turn off the transmitter of the ONU when the ONU's uplink transmission completes before its downlink reception during the allocated slot. Their proposed solution would have been much more useful if the cycle duration was determined taking uplink and downlink traffic delay requirements.

Hwang *et al.* in [310] have proposed an ONU initiated energy saving mechanism which makes a decision on sleep duration of an ONU based on its current buffer occupancy and maximum tolerable delay of uplink traffic. The ONU measures the sleep duration of its transmitter and notifies the OLT. Next, based on downlink traffic conditions, the OLT determines the sleep duration of the ONU's receiver. Then, it determines whether the ONU moves to Tx sleep mode or cyclic sleep mode. The authors have considered traffic priority classes while determining sleep interval length. Through simulations, the authors have shown that the solution reduces energy consumption significantly while meeting traffic performance requirement in terms of mean traffic delay, packet loss, throughput, and jitter. However, splitting sleep mode related computation load between the OLT and ONU may increase implementation complexity.

A similar distributed sleep mode related decision making has become evident in the work presented in [250]. Similar to [217], the authors in [250] have proposed that the length of an ONU's sleep interval should be within T_{min} and T_{max}, which are dynamically adjusted taking into consideration the imposed delay requirements and traffic arrival rate. First, an ONU determines T_{min} and T_{max} value based on its uplink traffic arrival rate and imposed uplink delay requirement. Similarly, the OLT also measures T_{min} and T_{max} for the downlink traffic arrival rate of the ONU. Next, both the OLT and ONU exchange their measured values to each other and then, select the smallest value of T_{min} and T_{max}, which are used in (1) to measure the ONU's sleep interval. Based on an extensive simulation using real traffic traces, the authors have demonstrated the solution reduces energy consumption in ONU noticeably while meeting the delay requirement of traffic. One limitation of the work, however, it does not explain how to avoid the collision between the transmission bursts from an active ONU and the ONUs leaving *sleep state* at the same time.

Butt *et al.* in [11] have introduced a cyclic sleep mode control framework taking into consideration of uplink and downlink delay requirement of different class-of-service in a PON system. In this solution, the required buffer size is measured for the imposed delay requirement for the uplink and downlink traffic. An ONU remains in *sleep state* until the OLT assigned sleep interval expires or its buffer or the corresponding downlink buffer at the OLT is full. Therefore, during high traffic arrival, the sleep interruption would be due to a buffer full. Conversely, when traffic arrival is very low, the sleep interruption would be triggered because of assigned sleep time expiration. However, it is not clear how the traffic forwarding takes place in this solution in case when sleep interruption happens due to buffer full as well as how this solution deals with the collision in case when multiple ONUs start transmission directly after leaving sleep mode.

Bang *et al.* in [311] have formulated a mathematical model to find an optimal sleep interval length for an ONU in cyclic sleep mode. Using simulation results, the authors have demonstrated the significance of their contribution. In [312], Zeng *et al.* aim at finding optimal sleep interval length for an ONU in watchful sleep mode. The authors have shown using simulation results that the solution can successfully determine an optimal sleep interval length for a target delay requirement. They have also demonstrated that the watchful sleep mode is more effective than the cyclic sleep mode. It has been assumed in [311], [312] that the ONUs have unlimited buffer capacity; however, in a commercial PON system, this assumption does not hold true.

In [113], Helmy *et al.* introduced a decentralized bandwidth allocation solution in a long-reach TDM-PON as opposed to the centralized OLT based bandwidth allocation decision. Furthermore, the authors have considered a co-located (standalone) edge computing facility integration with the PON system using a separate wavelength facilitating inter-ONU communications. To incorporate the additional wavelength, the authors have proposed to include an additional transceiver in an ONU. To offer energy efficiency, the primary transceiver of the ONUs can stay in the sleep mode until no downstream traffic waiting in the queue while the secondary transceiver operates when inter-ONU communication is needed.

Ahmad *et al.* in [116] have introduced a PON system where each ONU has a built-in edge computing unit to cater various applications at the customer premises. The authors have proposed to manage energy saving operation both in edge computing unit and ONU transceivers. To measure sleep interval duration of the ONU transceivers, the deadline for task completion to edge computing unit has been taken into account. Additionally, the authors have introduced a solution to reduce the number of active edge computing unit at a given time in the PON system taking consideration overall task request arrival rate, thereby minimize energy consumption. The work is limited by the lack of information, including how the task allocation is coordinated between the edge computing units and how both downlink and uplink bandwidth allocation is facilitated taking account task completion coordination and conventional PON traffic QoS requirements.

B. WDM-PON

In a WDM-PON, unlike a TDM-PON, both an ONU and OLT can apply sleep mode by turning off their unused transceivers when traffic arrival is low.

In [201], Uchikata *et al.* have proposed a WDM-PON solution that needs only transmitters at the OLT (centralized light sources). The ONUs at the customer premises reuse the downlink wavelength to transmit the uplink traffic. To do this, an ONU needs to have a SOA and a modulator. The OLT employs a transceiver for each ONU. Additionally, the OLT requires a supervisor transceiver which includes a tunable laser for transmission and a tunable optical filter with the receiver

TABLE VII: Summary of sleep mode based solutions in TDM-PONs. In the major contributions aspects column, ✓indicates the criterion is met. In the evaluation method column, S is simulation, N is numerical analysis, E is experimentation and X indicates no evaluation is conducted.

Scope	Reference	Major contribution aspects: Determining ONU sleep duration	Major contribution aspects: Proposing energy saving aware Bandwidth (BW) allocation, enabling efficient sleep mode operation — DL BW	Major contribution aspects: Proposing energy saving aware Bandwidth (BW) allocation, enabling efficient sleep mode operation — UL BW	Evaluation method	Main features	Advantages and/or drawbacks
Uplink (UL) traffic	[204]	✓		✓	S	OLT transmits DL traffic during the UL allocation of the ONU. An ONU stays in *sleep state* between two consecutive UL transmission slots.	DL traffic performance of an ONU may not be satisfactory due to relying on UL transmission slot and UL polling sequence.
	[299]	✓		✓	S	Considers transmitter power saving mechanisms. Optimal sleep cycle for an ONU is measured considering QoS requirements of different classes of service. Considers ONU's report message history to determine sleep interval.	ONUs support Early Wakeup Function (EWF); however, no clear explanation related to the operational policy when the ONUs support EWF.
	[8]	✓		✓	S	In a round-robin manner, the OLT polls the ONUs to know their UL BW requirement and then notifies the ONUs their corresponding transmission slot and sleep duration. Introduces a sleep duration prediction scheme.	DL traffic may experience delay significantly as sleep interval is determined based on UL traffic only.
	[300]	✓		✓	S	Categories traffic into three priority classes. Uses a support vector regression model to predict the presence of high priority traffic and determines the amount of time an ONU can stay in *doze state*.	Receiver of an ONU remains always turned on regardless of the presence of DL traffic.
Downlink (DL) traffic centric	[304]	✓	✓		N	Defines DL traffic scheduling and sleep mode management policy, which allows the state machines of an OLT and an ONU to be synchronized.	How UL traffic should be scheduled in the proposed solution is not discussed.
	[227]	✓	✓	✓	S	During *watch state* in watchful sleep mode, the receiver of an ONU has dynamic duration and occurrence of active period unlike the standard watchful sleep mode.	No significant improvement in energy saving. May add operational complexity compared to the standard watchful sleep mode.
	[206]	✓			S & E	The presence or absence of traffic is determined based on DL frame inter-arrival. When traffic inter-arrival time surpasses a predefined threshold, an ONU moves into *sleep state* for a certain duration. OLT provides a minimum UL bandwidth in every DBA cycle, i.e., supports (EWF).	These solutions require three-way handshake to maintain sleep mode in an ONU, resulting in increasing wastage of bandwidth when a large number ONUs need to move into sleep mode. Although, leaving *sleep state* on arrival UL traffic immediately may improve UL traffic QoS performance, the ONU may experience frequent sleep interruption as the UL traffic arrival increases, resulting in increasing energy consumption of the ONU.
	[302]	✓			S	OLT measures sleep duration, which can be constant or variable. EWF is supported.	
	[205]	✓			N	Sleep duration of an ONU is determined using (1). In absence of DL and UL traffic arrival, the sleep interval increase exponentially. A sleep interval can have initial value T_{min} and it increases up to T_{max}, which are predefined. A sleeping ONU wakes up on an UL traffic arrival immediately.	
	[217]	✓			S	Uses the same algorithm as [205]; however, the T_{min} and T_{max} value are adjusted dynamically taking DL traffic delay requirement. ONU's sleep interval increases exponentially if no traffic arrival. EWF is supported.	No consideration on how to resolve the issue when multiple ONUs leave *sleep state* and start transmission directly. Buffer capacity of an OLT and an ONU is not considered to measure sleep period.
	[204]	✓	✓	✓	S	The awake periods are assigned for exchanging both UL and DL traffic.	Presence of DL traffic may force an ONU to cut short its sleep sojourn period, resulting degrading energy saving performance. However, a better delay performance can be achieved.
UL and DL traffic centric	[207]	✓	✓	✓	X	The maximum sleep interval length is determined taking account periodic report sending interval in a PON system. A common algorithm is implemented in both the OLT and ONU to keep their state machines for sleep mode management synchronized. ONU's sleep interval increases exponentially when no traffic arrival.	Transmitter and receiver of an ONU are turned off independently, allowing more energy saving than the solution where transmitter and receiver are turned on and off together. Performance evaluation results are not provided.
	[307]		✓	✓	N	BW allocation mechanism facilitates a batch-mode transmission between an OLT and an ONU. Maximum delay requirement of traffic influences sojourn period at sleep mode of any ONU instead of presence of UL and/or DL traffic.	An ONU can have longer sleep period, thereby increasing energy saving. A detailed operational procedures and performance evaluation results are not presented.
	[216]	✓	✓	✓	S	Proposes sleep-time sizing and scheduling scheme to avoid any collision in case when multiple ONUs start transmission directly after leaving sleep mode. The scheme sorts and shifts the sleep time of the collided ONUs as long as the chance of collision of transmission is obliterated.	Maximizes energy saving while meeting delay requirement of traffic.
	[240]	✓	✓	✓	S	Transmitter and receiver of an ONU are turned off independently whenever they do not have any use. An OLT takes traffic priority level into account while making scheduling decision.	Traffic priority level is broadly categorized into real-time and non-real-time which is not realistic.
	[311]	✓	✓	✓	S	Determines an optimal sleep period for ONU's cyclic sleep mode to balance the performance tradeoff between energy conservation and traffic delay. A single delay requirement is considered for both UL and DL traffic.	Does not show how to determine optimal sleep interval when UL and DL have different delay requirement. Detailed traffic scheduling mechanism is missing. Considers that OLT and ONU have unlimited buffer capacity, which is not realistic.
	[312]	✓	✓	✓	S	Finds optimal sleep period for the ONUs using watchful sleep mode.	Considers a single delay requirement constrain for both UL and DL communication and the ONUs have unlimited buffer capacity which is unlike a real-world scenario in a PON system.
	[310]	✓	✓	✓	S	An ONU can initiate sleep mode. Presence of the most stringent QoS requirement traffic influences the overall sleep duration of an ONU significantly. Transmitter and receiver of an ONU are turned off independently.	Minimizes energy consumption significantly while meeting QoS requirement.
	[11]	✓	✓	✓	S	Considers UL and DL delay requirement of different traffic classes in a PON system when determining sleep interval and buffer size. ONU may leave sleep mode due to buffer overflow or sleep time expiration.	It is not clear how it deals with the collision in case when multiple ONUs start transmission directly after leaving sleep mode.
	[306]	✓	✓	✓	S	Packets are categorized into high-priority class and low-priority class traffic. An ONU with no traffic can have sleep duration increment until a maximum sleep period. Low-priority class traffic is forwarded when sleep time expires but for the high-priority class ONU uses EWF.	EWF reduces UL high-priority traffic delay; however, DL high-priority traffic may still need to wait until the ONU leaves *sleep state*, resulting DL high-priority traffic to experience more delay.
	[309]	✓	✓	✓	S	Locking DL and UL transmissions for each ONU in a slot while allocating bandwidth. An ONU turns off its transmitter when its UL transmission completes before its DL reception to conserve energy further.	No consideration traffic delay requirement. Locking both UL and DL transmission would be a challenge in case when the delay requirement for UL and DL traffic is not the same.
	[250]	✓			S	(1) is used to determine sleep duration. However, T_{min} and T_{max} are adjusted dynamically taking both UL and DL traffic requirement. Both OLT and ONU take part in determining T_{min} and T_{max}.	There is no consideration on how to resolve the issue when multiple ONUs leave *sleep state* and start transmission directly. No consideration of buffer capacity to determine ONU's sleep interval.
	[305]	✓	✓	✓	S	Assigns a fixed bandwidth (slot) for each ONU when traffic load is low. When traffic load is above a threshold, it uses DBA for bandwidth allocation.	No explanation for how the threshold for switching between fixed and DBA based allocation. No consideration of QoS requirement for measuring cycle duration and bandwidth.
	[308]	✓	✓	✓	S	Scheduling algorithms aims to overlap the UL and DL transmission slot as much as possible for an ONU. The polling cycle length of ONUs is adjustable based on QoS requirement.	Improves energy saving performance significantly with tolerable performance degradation.

unit. After a threshold time, if there is no uplink or downlink transmission for an ONU, the corresponding transceiver at the OLT enters sleep mode. To allow the ONU to communicate for uplink transmission with the OLT while its corresponding OLT transceiver is in sleep mode, the supervisor transceiver periodically polls it by transmitting at the corresponding wavelength for the ONU (using the corresponding wavelength, the supervisor transceiver is polling each ONU one by one). Therefore, the polling interval of the supervisor transceiver can have significant impact on uplink traffic delay in this network. This is obviously a cost-efficient and energy-efficient approach. However, the authors in their work have offered no explanation on how the threshold time and polling interval can be determined. An extensive performance evaluation is also missing in this work.

A Centralized Light Source (CLS) based WDM-PON architecture is proposed by Tse *et al.* in [313]. The downlink signals are routed by an AWG at a RN and forward to the corresponding ONUs. At the ONU side, the half of the received downlink signal is fed into receiver to retrieve downlink traffic, whereas the other part of the signal is re-modulated with uplink (data) traffic using the RSOA of the ONU and send to the OLT. In absence of downlink and uplink traffic for a certain time threshold, the ONU and the corresponding transceiver at the OLT move into sleep mode to conserve energy. On arrival uplink traffic, the RSOA's Amplified Spontaneous Emission (ASE) signal triggers the respective transceiver at the OLT to be activated. Based on an experiment, it is demonstrated that the solution is able detect the wake-up signals sent from different ONUs. However, it is not explained how the solution tackles downlink traffic when an ONU is in sleep mode.

The proposed solution by Zhu *et al.* in [283] also relies on the centralized light sources at the OLT for the ONUs' uplink communication. Additionally, here, depending on absence of uplink and/or downlink traffic, an ONU uses cyclic sleep or doze mode, whereas the corresponding transmitter for the ONU at the OLT is turned off only if and only if when the ONU has neither uplink nor downlink traffic for a threshold time value. However, the corresponding receiver at the OLT of the ONU remains always active to allow the ONU to terminate sleep mode on arrival of an uplink traffic. The ONU is equipped with a RSOA, which acts as a transmitter. It produces uplink ASE light power as a wake-up indication signal to the OLT to activate the associated transceiver at the OLT. Therefore, this solution eliminates the modulation operation of any sleep termination request, as in [201]. Based on simulation results the authors demonstrate the importance of their solution. One significant limitation of this work is that the OLT in this solution discards the arrived traffic when the ONU is in *sleep state*, turning off both transmitter and receiver.

Lee *et al.* in [314] have proposed a solution where an ONU turns off both of its transmitter and receiver in absence of downlink and uplink traffic and notifies the OLT about sleep mode initiation. Next, the OLT also moves into sleep mode by turning off its transmitter only, thereby allowing the ONU to send any uplink traffic immediately upon arrival from the customer premises. Additionally, the authors have proposed that the ONU and OLT should periodically wake-up and exchange control messages while maintaining sleep mode to avoid any communication fault. The major limitation of this study is that the OLT needs to buffer downlink traffic as long as the ONU returns from *sleep state*. Thus, in this solution, the downlink traffic may experience higher delay and packet drop compared to uplink traffic.

Using a prototype, Lee *et al.* in [215] have developed and evaluated two energy saving approaches for a WDM-PON, namely: partial sleep mode and full sleep mode. In the former case, an ONU powers off its I/O ports (e.g., Ethernet ports) in absence of traffic. In the latter case, both the OLT and ONU turn off their transmitter (doze mode) when there is no traffic to transmit. In this sleep mode, in particular, when the ONU does not receive any traffic from the customer premises, it notifies the OLT by sending a message about the initiation of its energy saving operation by turning off its transmitter only. Upon receiving this message, the OLT also moves into sleep mode by turning off its transmitter if there is no downlink traffic to transmit. As the receiver of the OLT and ONU is active during the sleep mode, it is possible for both OLT and ONU to initiate transmission after leaving sleep mode immediately. Although, in this solution, the PON traffic experience negligible delay, both an OLT and ONU spend energy unnecessarily by keeping their receiver active regardless of the presence of traffic. Authors have reported that an ONU in their solution can reduce its energy consumption up to a 60%.

In [315], Kim *et al.* have introduced a WDM-PON architecture which can be operated in a PMP mode and PtP mode at the same time. That is, in the PON architecture, besides having a pair of dedicated channels for facilitating communication between an ONU and OLT (PtP mode), a broadcast channel is deployed for downlink broadcast transmission (PMP mode). Therefore, each ONU has two receivers for extracting frames from its unicast and the shared broadcast channels. Newaz *et al.* in [214] went a step further by introducing an energy-efficient operational procedure for the WDM-PON architecture that Kim *et al.* introduced in [315]. Newaz *et al.* in [214] have proposed an operational procedure where the PON system switches from the normal mode, in which both PMP and PtP mode are functional, to an energy saving mode when traffic arrival is below a predefined threshold. During the energy saving mode, the PON system is operated using only PMP mode (it acts as a TDM-PON system), thereby allowing an ONU's transmitter and receiver that are used for the PtP communication to be powered off. This work does not justify how to determine the predefined threshold. An extensive performance evaluation is also missing to understand the efficacy of the solution.

C. Multi-wavelength TDM-PON (Type-1 TWDM-PON)

Reducing the number of active transceivers (ports) is an effective means for saving energy in an OLT of a Type-1 TWDM-PON. As we will see in this subsection, a very large body of literature (e.g., [209], [316], [317]) has explored to date how to facilitate communication over a minimum number of wavelengths by migrating the ONU(s) under an under-utilized port to other ones which have sufficient bandwidth

TABLE VIII: Summary of sleep mode based solutions in WDM-PONs. In the major contributions aspects column, ✓indicates the criterion is met. In the evaluation method column, S is simulation, N is numerical analysis, and E is experimentation. In the main features column, ✓indicates the criterion is met.

Reference	Major contribution aspects		Evaluation method	Main features			Advantages and/or drawbacks
	Proposing PON architecture enabling sleep mode in OLT and/or ONU without service interruption	Proposing a solution to find required number of serving Wavelengths (WLs)		Allows sleep mode in: OLT	ONU	Others	
[201]	✓	✓	N	✓		OLT has transmitters only, i.e., CLS. ONUs reuse the OLT's Downlink (DL) transmitted signal for Uplink (UL) communication. If there is no DL and UL traffic for a threshold time value, the OLT turns off the corresponding wavelength. A supervisor transceiver, periodically polls the ONU by transmitting at the corresponding wavelength of the ONU, allowing the ONU to communicate with the OLT by sending recovery request on any uplink traffic arrival.	No guideline is provided to determine the threshold time and polling interval for the supervisor transceiver.
[313]	✓	✓	E	✓	✓	It is a CLS based solution. In absence of traffic for an ONU, the ONU and corresponding transceiver move into sleep mode. The ASE signal from the ONU's RSOA triggers the OLT to activate the corresponding transceiver (port) of the ONU.	For UL traffic, ASE based triggering can activate uplink communication path. Does not offer any explanation of how DL traffic is managed for a sleeping ONU.
[283]	✓	✓	S	✓	✓	The light sources are at the OLT (CLS). ONUs move into doze mode or cyclic sleep mode (both RSOA and receiver are turned off) depending on presence or absence of traffic. The OLT can turn off its transmitter if and only if when the ONU is in cyclic sleep mode. In other modes of ONUs, the OLT keeps its transceiver active.	When an ONU is in a state where its transmitter and receiver are off, the OLT is unable to communicate with the ONU. Hence, in such case, the DL traffic for the ONU is discarded, which can significantly degrade QoS performance.
[214]		✓	N	✓	✓	PON system is operated PMP mode and PtP mode. An ONU is equipped with two receivers for traffic reception in both modes. PON system is operated PMP and PtP mode at the same time when traffic arrival rate is above a traffic load threshold value. When the load is below that threshold, the PON system is operated in PMP mode. This allows an ONU to turn off its receiver associated with the PtP traffic reception and the OLT to turn the off the corresponding PtP transmitter of the ONU.	No detailed explanation for how to determine traffic load threshold value. An extensive performance evaluation is missing.
[314]		✓	N	✓	✓	ONU turns off both of its transmitter and receiver in absence of DL and UL traffic. However, the OLT turns off its transmitter only during its sleep mode. An ONU can send any UL traffic immediately upon arrival.	DL traffic experiences more delay than UL traffic. No extensive performance evaluation conducted.
[215]		✓	E	✓	✓	An ONU powers off its I/O ports in absence of traffic. When there is no traffic to exchange, the OLT and ONU turn off their transmitter. As the receiver of the OLT and ONU is active during the sleep mode, the OLT and ONU can initiate transmission immediately after switching on the transmitter whenever there is traffic to exchange.	Receiver of an OLT and an ONU remains always functional regardless of presence of traffic.

to serve those ONUs, thereby allowing the OLT to switch off those underutilized ports. Additionally, to reduce energy consumption in the ONUs in a TWDM-PON, a significant body of literature (e.g., [318]–[320]) have studied how cyclic sleep mode and doze mode can be effectively utilized.

1) OLT sleep mode:

a) Unused ports sleep until needed: In a related study, to conserve energy, Yang *et al.* [321] have proposed to reduce the number of active ports of an OLT by migrating its ONUs to a minimum number of wavelengths when the PON system is underutilized. They have outlined ONU migration procedures and investigated how PON traffic performance is influenced under different migration delays. In their follow-up work [276], the authors have presented a PON architecture with a shared transceiver pool at an OLT to increase network resource sharing among the multiple PONs connected with the OLT. They have also explained how energy consumption and network deployment cost can be minimized through wavelength migration among the TWDM-PONs. The authors have imparted that frequent wavelength migration contributes to reducing available bandwidth and increasing traffic delay in the network. Therefore, an interesting research question is how to reduce the adverse effect of wavelength migration and how to decide on appropriate condition for migration (reconfiguration) triggering. Some of the existing literature has attempted to explore these questions. In [322], Dixit *et al.* have also pointed out the downside of frequent ONU migration (wavelength switching). Taking into consideration the occupancy of channels and the required tuning time with a new channel (tuning time overhead), the authors in [322] have developed an algorithm to adapt with the frequency of wavelength migration. Authors have not provided any detailed performance evaluation to demonstrate the efficacy of the solution.

In another follow-up work, Dixit *et al.* [221] have proposed a solution where after a predefined time (referred as reconfiguration period), depending on traffic load, the number of required wavelengths for serving the active ONUs and ONUs under each wavelength are determined with the objective to minimize the number of active wavelengths in the PON system. Additionally, their proposed wavelength allocation algorithm aims at ensuring wavelength migration fairness among the ONUs by assigning them to the wavelengths in a round robin manner. After the reconfiguration period, an ONU is assigned the same wavelength pair or other wavelength pair based on the traffic load of the network. It is worth mentioning that the reconfiguration period has a pivotal role to the overall performance of the TWDM-PON. A longer value of the reconfiguration period will lead to reduced number of migrations of ONUs among different wavelengths. Conversely, a shorter value of this will improve energy saving while increasing the number of wavelength switching for the ONUs. One limitation of the work, however, it does not explain how to determine optimal migration interval. Additionally, the round robin manner approach for improving fairness for wavelength migration may potentially hinder an ONU serving latency stringent traffic to meet the performance requirements.

Wang *et al.* in [323] have introduced an energy saving solution via wavelength sharing in a TWDM-PON. In their solution, a grouped of ONUs share the bandwidth of a wavelength form a Virtual PON (VPON) slice. The ONUs can migrate from one VPON to another VPON depending on wavelength aggregation requirement in a TWDM-PON. The decision procedures for wavelength aggregation take into account how to maximize energy saving, maintain load balancing, reduce frequent ONU migration and meet SLA in the network. The migration procedure of an ONU from a VPON to another VPON is the same, as stated in [219]. Each VPON is operated independently using a pair of separate wavelengths. As a TWDM-PON uses a passive splitter at the RN, only the ONUs tuned to the VPON's wavelength can decode the downlink signal. Therefore, each VPON appears as if a separate TDM-PON within a TWDM-PON system, allowing it to be operated using the GPON/EPON protocol suite [323]. Note that, to facilitate migration, the native TDM-PON protocol requires modification, which has not been investigated in this work. The authors have considered a historical traffic load patterns while forming and reforming (ONU migration) the VPONs. Furthermore, they have taken into account the type of traffic each ONU is serving to make migration decision. By exploiting such information into a multi-objective optimization problem, their solution successfully reduces energy consumption and maintains optimal load balancing with a minimum ONU migration. Similarly, Tinini *et al.* in [225] have introduced an energy-efficient VPON slice formation mechanism with the objective of serving maximum number of PON connected 5G base stations with the minimum number wavelengths, thereby reducing energy consumption in the OLT side.

Taking into account the delay requirements of the traffic in a TWDM-PON system, Dias *et al.* [319], [320] numerically analyzed the number of wavelengths that the OLT needs to keep active taking account bandwidth demand from the ONUs. It is observed that as the delay constraint becomes stringent, the number of active wavelengths increases [320]. In another follow-up work, Dias *et al.* in [324] have aimed at optimizing the number of wavelengths of a TWDM-PON and increasing energy saving at ONUs using sleep and doze mode. Unlike [319], [320], where an offline wavelength and bandwidth allocation algorithm is used, in [324] the authors have presented both offline and online schemes for dynamic wavelength and bandwidth allocation. Their results show that the online scheme produces a better energy saving performance compared to the offline one. In [325], Garg *et al.* have used an offline bin-packing algorithm based traffic scheduling to determine the number of active wavelengths at a given time in a TWDM-PON. The solution may increase traffic delay compared to the online scheduling solutions as the traffic arrived during a scheduling cycle can be forwarded in the following cycle(s).

In [326], Valcarenghi has presented a simple solution to decide reconfiguration triggering of the ONUs in a TWDM-PON system. The author considered that a transmission cycle of a channel comprises several slots each of which is equivalent to a frame transmission duration. At the beginning of a cycle, the OLT polls all the ONUs. The number of slots allocated to an ONU in a transmission cycle depends on the number of queued packets in the ONU's buffer. Then, at the beginning of a cycle, the network load (ratio between traffic arrival and service rate of the network), ρ, is measured based on the response of the OLT's polling. Then, considering there are four downlink channels available in a TWDM-PON, the number of active channels at the OLT is determined using the expression in (2). The performance of the proposed solution is presented based on a time-driven simulator.

$$\omega = \begin{cases} 1, & when\ \rho < 0.25 \\ 2, & when\ 0.25 \leq \rho < 0.5 \\ 3, & when\ 0.5 \leq \rho < 0.75 \\ 4, & otherwise, \end{cases} \tag{2}$$

where, ω is the number of active wavelengths at the OLT at a given time.

In [327], Valcarenghi *et al.* have studied migration delay fairness among the ONUs in a TWDM-PON which requires wavelength switching among the ONUs to balance traffic load and reduce energy consumption at the OLT. When ONUs are forced to migrate from one wavelength to another, the traffic destined to/originated by the ONUs need to be buffered during the entire wavelength migration time. The amount of delay those traffic experience is significantly high compared to the ones that are destined to/originated by the ONUs that are not instructed to switch wavelengths. Such unfairness in delay is generally observed when the number of active ONUs is small, as reported in [327]. However, during peak hours such delay unfairness may not be noticed as the opportunity of wavelength aggregation reduces with the increment of traffic load. The authors have proposed a novel algorithm aiming at reducing delay unfairness problem when the number of active ONUs are less in a TWDM-PON. Additionally, to determine the required active wavelengths, their solutions uses the expression in (2), similar to [326]. Note that, this mechanism to determine active wavelengths tends to increase the average traffic delay noticeably when the network traffic load is close to the maximum load that the active channels can support. The findings in [327] impart that the solution can balance delay experienced by the connected ONUs. Furthermore, it is also demonstrated that as the migration interval increases, the average traffic delay decreases in the PON system. This happens because with a longer migration interval, the ONUs go through less number of times the migration related procedures, resulting less interruptions for traffic exchange.

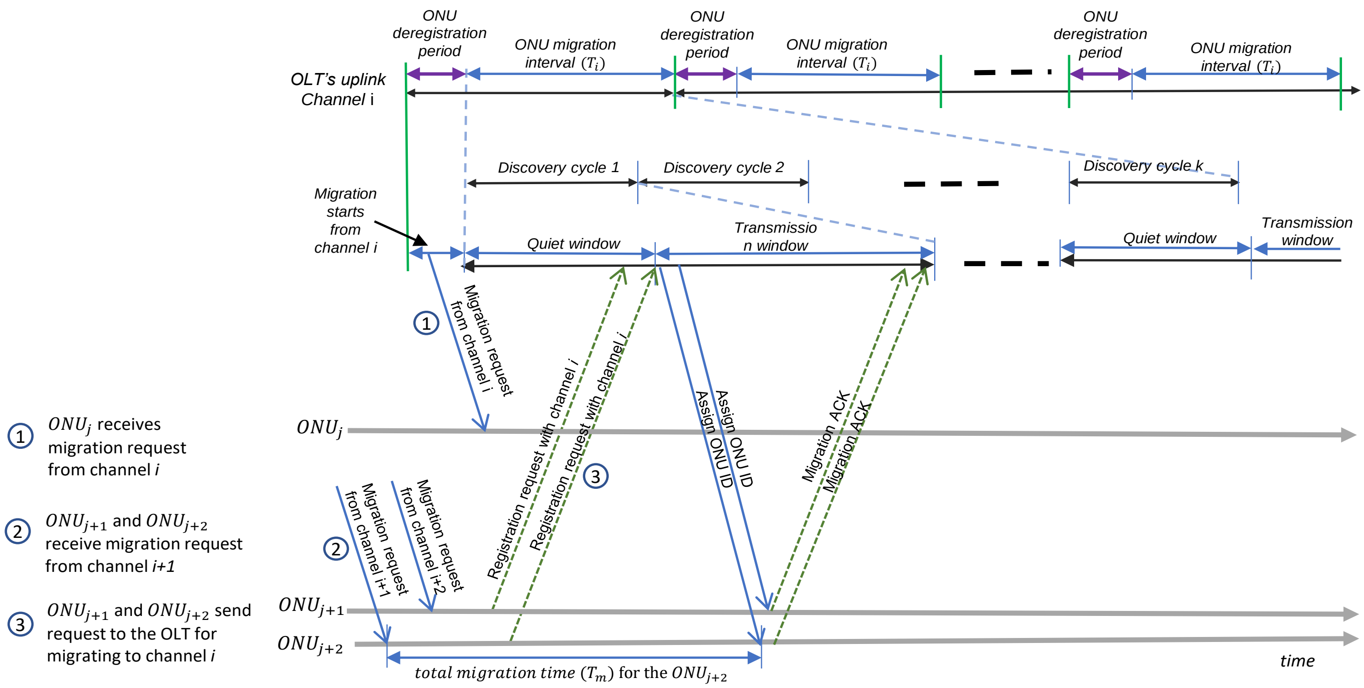

Fig. 25: Overall ONU migration procedures: an ONU first deregisters from a wavelength and registers itself with another wavelength by sending registration request during the Quiet window [219].

The time required to complete the migration related procedures, can significantly influence overall migration delay performance of a TWDM-PON system, as pointed in [219], [328]. Once migration process of an ONU is triggered, the ONU needs to first deregister from the previously allocated wavelength(s) and then register itself[4] with the OLT for the target wavelength within a given time window which is allocated by the OLT so as to complete migration process [219], [321]. This time window is referred to as a Quite window during which the OLT does not allocate any bandwidth to the in-service (registered) ONUs so as to avoid any collision between the transmission bursts from the in-service ONUs and the control messages from the ONUs that are undergoing activation process (registration) [231]. An ONU gets a deregistration opportunity after every migration interval (say, T_i). During each T_i, there are k number of discovery cycles, each of which consists of a Quite window and transmission window [219], as shown in Fig. 25. Then, the migration delay (T_m) is measured using the expression in (3).

$$T_m = T_e + T_{rr}^{onu} + 2T_{pro} + T_{rr}^{olt}, \quad (3)$$

where, T_e is the ONU tuning time with newly assigned wavelength, T_{rr}^{onu} is the time required for the ONU to transmit the registration request with the newly assigned wavelength, T_{rr}^{olt} is the time the OLT takes to transmit the response to the ONU's registration request and T_{pro} is the one-way propagation delay from the ONU to OLT. When the Quite window size is too small, a newly joining ONU that requires deregistration and registration to the target wavelengths needs to compete more with others ONUs requiring to complete migration process compared to the case when window size is larger. On the other hand, the longer the length of a discovery cycle, the higher the waiting time for an ONU to get an opportunity for sending a registration request. Therefore, their value should be decided carefully to meet desired performance requirements, especially when the number of serving ONUs in a TWDM-PON is large. In [219], to increase chances for an ONU to make a successful registration, and therefore reduce migration delay, Li *et al.* have proposed adaptive Quite window and discovery cycle size taking into account the number of involved ONUs requiring registration and SLA requirement. Their findings state that their solution can successfully reduce the blocking in the registration process even for a large number of involved ONUs. The authors have not stated how their solution adjusts the Quiet window size when the round-trip propagation delay between OLT and ONUs are not uniform. Furthermore, the solution can impose additional signaling and increase implementation complexity compared to the static approach when there is a large number of connected ONUs and traffic load shows frequent fluctuating behavior.

b) Used ports sleep whenever idle: Existing proposals reviewed in Subsection VI-C1a aim at facilitating communication with minimum number of wavelengths, while keeping the unused wavelengths (ports) switched off as long as they are not needed. To further improve energy saving performance of an OLT, there are works that propose to put the used OLT ports into sleep mode during their idle periods.

Dutta *et al.* in [224] have focused on reducing energy consumption of receivers at the OLT in a TWDM-PON while meeting uplink traffic delay constraints. They have proposed to utilize all available wavelengths of an OLT. While scheduling in the active wavelengths for uplink transmission, the OLT may

[4] As stated in ITU-T G.984.3 [231], registering an ONU with its connected OLT is necessary in PON due to its downlink point-to-multipoint topology.

TABLE IX: Summary of sleep mode based solutions in Type-1 TWDM-PONs. In the major contribution aspects column, ✓indicates the criterion is met. In the evaluation method column, S is simulation, N is numerical analysis, E is experimentation and X indicates no evaluation is conducted.

Reference	Major contribution aspects: For unused OLT ports: turn them off (until required)				Major contribution aspects: For used OLT ports: turn them off whenever idle	Evaluation method	Main features	Advantages and/or drawbacks
	Finding number of serving WLs	Reducing migration delay	Reducing frequent ONU migration	Increasing ONU migration fairness	Finding transmitter and receiver idle duration and clubbing the idle durations			
[321]	✓				Not applicable	S	Aims at rearranges active ONUs under minimum number of Wavelengths (WLs). Introduces ONU migration procedures.	No analysis is provided to find appropriate migration interval.
[276]	✓				Not applicable	S	Transceivers are shared among the multiple PONs connected to the OLT, thereby reducing active transceivers.	Besides improving energy saving, increases scalability and interoperability among multiple PONs. No clear guideline for determining optimal serving WL and the condition for migration triggering.
[221]	✓			✓	Not applicable	S	The number of WLs are determined after a certain time interval. Proposed algorithm seeks to maintain migration fairness.	No analysis is provided to find appropriate migration interval. Some ONUs may experience more migrations than others, causing migration unfairness.
[323]	✓		✓		Not applicable	N	The ONUs sharing the same WL forms a VPON. At every migration interval, it determines required active VPONs (WL) and then, it readjusts load of WLs while ensuring the least number of ONU migration.	No detailed discussion on what modifications are required in a native TDM-PON protocol to facilitate migration procedures in VPONs, each of which is operated independently using a pair of separate wavelengths.
[319]	✓				Not applicable	S	Offline WL and Bandwidth (BW) allocation approach. Considering delay constraint, the number of active WLs are determined. Both OLT port sleep and ONU cyclic sleep/doze mode have been considered.	As sleep mode in both OLT and ONUs is jointly considered, energy saving can be increased compared to the solutions where only OLT port sleep mode is considered. However, it may increase the sleep mode and migration operation more complex.
[320]	✓				Not applicable	S	Offline WL and BW allocation approach. Number of active WLs are determined first based on BW demand. The delay constraints play an important role in determining the length of ONU polling cycle. Both OLT and ONU sleep mode has been considered.	No detailed discussion on migration procedures. DL traffic delay requirement is not considered.
[324]	✓				Not applicable	N & S	Present both offline and online WL and BW allocation approach. Under the proposed online scheme, an ONU estimates the average inter-arrival time of packets based on Bayesian estimation. This estimation helps OLT to predict future BW demand.	Online scheme shows better energy saving performance.
[325]	✓				Not applicable	S	Offline bin-packing algorithm for determining number of required active WLs.	Can increase traffic delay compared to the online scheduling algorithms because the traffic arrive during a cycle can be forwarded during the following ones.
[326]	✓				Not applicable	S	The OLT performs an offline WL and BW allocation for the ONUs at the end of a cycle. Reconfiguration is triggered based on two main factors: load threshold and triggering time. Switching on or off of WLs depends on predefined traffic load threshold.	No clear justification on the network load thresholds for activating or deactivating a WL. Similar to binPckAlgoTWDMgrg2019, the solution can increase traffic delay as it uses an offline WL and BW allocation mechanism.
[327]	✓			✓	Not applicable	S & E	Decision to switching on/off of WLs replies on the same approach applied in WhDoRenTWDM2015. For slot allocation to ONUs, largest the remainder method is applied.	Delay fairness is balanced between the ONUs in the PON system where ONUs are invoked to switch WLs.
[219]		✓			Not applicable	S	Quite window and discovery cycle size are determined adaptively to reduce migration delay and improve BW utilization.	Increases implementation complexity and signaling in network.
[224]	Not applicable				✓	S	Finds OLT receiver idle period. Utilizes all available wavelengths of an OLT. Proposes to club several small idle transmission periods together to avoid frequent transition overheads. If the idle duration of the OLT receiver is more than a transition overhead, the OLT is able to turn off the port during that idle duration.	Algorithm considers a single class of traffic which is unlike a real-world scenario in a PON system.
[329]	Not applicable				✓	S	Finds OLT transmitter idle period. Aims at reducing energy consumption of the active transmitters and receivers. OLT uses the algorithm introduced in idletimeofOLTrxOFdutta2018 for receiver energy consumption.	Effect of clubbing on energy saving performance of this solution may not be very effective when transition overhead for the OLT ports become negligible.

find some of its receivers do not have any traffic to receive. The occurrence of such an idle period (voids) may frequently be noticed during the off-peak hours of a day. Dutta *et al.* have proposed to turn off a receiver of the OLT in a TWDM-PON during those idle periods if the idle duration of the receiver is more than a receiver's transition time (transition overhead). To avoid frequent transition between *sleep* and *active state* of an OLT port, the authors have proposed to club several small idle transmission periods together. Taking into account delay requirements, they have also developed an online uplink-traffic scheduling algorithm. One major drawback of their solution is that their proposed algorithm considers a single class of traffic which is unlike a real-world scenario in a PON system.

In a follow-up work [329], Dutta *et al.* aim at reducing energy consumption of the active transmitters of an OLT by switching those off during the idle periods. The proposed algorithm aims at minimizing the idle duration as much as possible while not violating the SLA requirement. To reduce energy consumption at the receivers' side, the authors have assumed to use the solution they proposed earlier in [224]. Performance obtained based on extensive simulations indicate that a 45% energy saving can be achieved compared existing DBA protocols.

2) ONU sleep mode: Besides proposing OLT port sleep mode, Dias *et al.* in [319], [320], [324] aim at reducing energy consumption in ONUs using sleep mode. To determine the sleep duration in [319], [320], the OLT requires the ONUs to send periodically their uplink packet arrival information (e.g., inter-packet arrival time, packet size) and the amount of uplink bandwidth they require. After collecting these information, the OLT runs an off-line scheduling algorithm and then informs the ONUs the amount of bandwidth allocated in the next cycle, duration of sleep interval and the uplink wavelength the ONU should transmit on. The results show that the proposed solution reduces energy consumption of the PON system while meeting the delay requirement.

To identify the amount of time an ONU can move to any of the power saving modes, in [324], the maximum polling cycle length and transmission slot of each ONU were identified taking into account QoS requirement of traffic and bandwidth demand of all active ONUs. Then depending on the idle duration, an ONU uses one of the power saving modes. Furthermore, to maximize idle duration, authors have suggested to keep the downlink and uplink transmission related activities synchronized. Additionally, they have introduced both online and offline scheduling of the uplink traffic. Their online scheduling approach relies on a prediction mechanism, allowing ONUs to get an opportunity to transmit traffic in the current cycle instead of waiting for the following cycles. This in turn contributes in reducing uplink traffic delay. Although, applying sleep mode both OLT and ONU side at the same time can increase energy saving undoubtedly in [319], [320], [324], it can increase implementation complexity. Additionally, the solutions would require a large number of signaling to keep the OLT and ONU synchronized.

In [330], Rayapati *et al.* have proposed an adaptive polling solution and sleep mode management mechanisms for a ring TWDM-PON. The procedures introduced by the authors to save energy in a TWDM-PON using sleep mode is almost identical to the uplink centric scheduling for saving energy in TDM-PONs proposed in [204]. In [63], Alaelddin *et al.* have proposed a solution to save energy in TWDM-PON ONUs in an integrated PON and 5G Heterogeneous Networks (HetNets). The prime objective of their solution is to meet the latency requirements of the latency stringent applications in 5G while reducing energy consumption in a TWDM-PON based backhaul using sleep mode. While measuring the sleep duration for an ONU, their solution takes into account the delay requirements imposed by each based station connected with an ONU and the forwarding delay between the base stations and the ONU. Based on this, the solution measures an optimal cycle time comprised of the ONU sleep and active duration. The solution considers only a single ONU under a wavelength. However, in a real-world scenario, there can be multiple ONUs under a single wavelength.

D. Wavelength-routed hybrid WDM/TDM PON (Type-2 TWDM-PON)

Wavelength-routed hybrid WDM/TDM PON with at least two RNs is another implementation of a TWDM-PON system. We refer to this PON system as Type-2 TWDM-PON (see section II-A3b for its architecture and operational procedures). This type of PON mainly aims at increasing transmission coverage and split size so as to accommodate a large number of users using a single PON infrastructure as well as consolidate network resources (e.g., OLTs) in a CO (i.e., replacing many active central offices) [76], [213]. Similar to the sleep mode based solutions for Type-1 TWDM-PON, a large body research efforts aim at reducing the number of active transceivers at the OLT of a PON for minimizing energy consumption in Type-2 TWDM-PON. Additionally, we have found that an extensive research effort for designing flexible CO and RN to manage dynamic connection between the OLTs in a CO and the ODNs, thereby allowing turning off an unused OLT line cards during the off-peak hours.

1) OLT port sleep mode: Dixit *et al.* [213] have introduced an energy-efficient two tiers of RN based Type-2 TWDM-PON architecture. In their architecture, the first remote node (RN1) deploys WSSs, amplifiers and cyclic AWGs, whereas the second set of remote nodes use a passive splitter. WSSs and AWGs are configured in cascaded manner in RN1. One WSS feeds downlink signal to multiple AWGs. Then, the output port of each AWG connects to a passive splitter residing in the second RN (RN2). The purpose of keeping the RN1 active using WSSs, which consumes 5.5 W [213], is to make the network re-configurable depending on traffic load. As per the solution, when a network is less loaded, the unused wavelengths at the OLT are turned off while the remaining wavelengths are guided through the RNs to serve the customers. The authors do not explain in their work how the optimal number of required wavelengths are decided considering the traffic load at a given time. Despite the fact that they use an active remote node, the authors have reported that their solution outperforms a passive remote node based TWDM-PON architecture in terms of energy consumption.

In another follow-up work [58], Dixit *et al.* have introduced a Type-2 TWDM-PON architecture with two RNs. To facilitate flexible wavelength routing, they have proposed to use WSSs and AWGs in the RN1. This architecture also supports traffic aggregation to reduce the number of active transceivers at the OLT. Additionally, to conserve OLT energy consumption, the authors have proposed a DBA algorithm which aims at optimizing the grouping of ONU under a minimum number of wavelengths taking account data rate requirements of ONUs and their distance from the OLT. However, a detailed procedure about how an ONU migrates to another wavelength and how the required optimal number of wavelengths is measured are not available in their work.

In [331], Cheng *et al.* have proposed a flexible TWDM-PON architecture with load balancing and energy saving capability. The authors have introduced a two tiers of RN based PON system, similar to [213]. To increase reach and splitting ratio of the network, optical amplifiers are deployed in the CO and a hybrid AWG (cyclic with 200GHz channel spacing) and splitter are placed in the RN1. Then, this RN1 connects four ODNs each of which connects 64 ONUs using a passive splitter. An OLT transceiver module has four pairs of wavelengths for communicating with all connected ONUs. When traffic load is small, the authors have proposed to turn off light sources at the OLT to conserve energy. In a very low traffic load situation, only one wavelength is kept on for all four ODNs. This wavelength is forwarded through the splitter in RN1 so that it can reach all ONUs under each ODN. Besides load balancing and energy saving, the authors claim that their flexible T WDM-PON can coexist with all the legacy PON systems as well as provide high availability of the network. The efficacy of their proposed solution is demonstrated using an experimental testbed. However, the authors do not provide any explanation on how the optimal number of required wavelengths are determined in their proposed solution.

Shi *et al.* in [76] have developed a dynamic wavelength allocation scheme for a ring-and-spur Long-Reach WDM/TDM PON. Their purpose is to facilitate wavelength sharing among multiple RNs in a statistical multiplexing fashion. Their proposed solution taking account traffic load determines required number of wavelengths for serving end users and the remaining unused wavelengths are turned off. After each scheduling cycle, based on two threshold values, say L and H, their proposed wavelength allocation scheme determines whether to deploy one less wavelength or activate one more wavelength, respectively. To facilitate dynamic wavelength sharing feature among multiple RNs, the authors have suggested to use reconfigurable "drop-and-continue" OADMs, instead of "drop-and-add" OADMs in the RNs. The authors demonstrate that 30% of energy can be reduced using their proposed dynamic wavelength allocation scheme. This work does not offer any explanations how wavelength migration procedures take place in this solution.

Tadokoro *et al.* in [332] have proposed a two-RN based WDM-TDM PON architecture that supports both PtP and PMP broadcast transmission (dual rate transmission). Depending on downlink traffic load, their proposed network changes its operational procedures dynamically to maximize its energy savings. The OLT is equipped with multiple 10G transceivers and a 1G transceiver, which outputs a narrowband wavelength. This narrowband wavelength is a shared wavelength for transmitting broadcast traffic to all the ONUs under the OLT, similar to the one proposed in [315]. Each ONU is equipped with a 1G/10G dual rate receiver, allowing the ONUs to tune into one of the reception modes. The RN1 is comprised of an AWG and a coupler. Each downlink 10G wavelength is forwarded by the AWG to the respective PON brunch. Similar to the 10G wavelengths, the narrowband wavelength reaches one of the output ports of the AWG at the RN1. However, unlike the other wavelengths, first, from the AWG output port this narrowband signal is fed into the coupler of the RN1. Next, the coupler uniformly distributes the input signal to its output ports which again feed the signal into the input ports of the AWG residing in the same RN. Then, the AWG passes the signal to all the PON brunches. During a low traffic arrival scenario, the narrowband wavelength producing transceiver remains active, while other transceivers at the OLT are turned off to conserve energy. The decision to switch into this energy saving mode by turning off transceivers relies on a traffic arrival rate threshold. The authors in [332] do not provide any detailed explanation on how this threshold is measured in their solution.

A similar architecture supporting dual rate transmission as [332] has been proposed by Garg *et al.* for a WDM-TDM PON system in [333], where the authors also have confirmed that switching to lower transmission rate (narrowband signal) when traffic load is low leads to reduce energy consumption in a PON significantly. The architecture is designed such that it can be resilient to OLT port and line card failure. Another dual rate transmission architecture is proposed by Garg *et al.* in [226] (i.e., supporting both PtP and PMP). However, unlike their proposed architecture in [333] where the RN1 is based on AWG and splitter, to reduce power penalty, the RN1 in [226] is based on pure Fiber Bragg Grating (FBG) array instead. When there is no broadcasting traffic for the ONUs, the respective transceiver for broadcast wavelength is switched off as proposed in [226]. This broadcast wavelength is also used when any transceivers for PtP wavelength fails, thereby increasing availability of the network. The decision related to broadcasting wavelength activation or deactivation as well as transmission rate control in [226], [333] depends on traffic load thresholds which have not been clearly discussed in these works.

In [334], Garfias *et al.* have proposed an uplink traffic demand aware OLT's energy conservation mechanism. In this solution, when low channel utilization is noticed during a predefined observation period, one or more receivers of the OLT is put into sleep mode, similar to [71]. Similarly, when there is high utilization of an uplink channel, which is measured based on the number of uplink transmission requests arriving at the OLT, the sleeping receivers at the OLT are switched to active mode. In this work, the authors have offered no explanation on how the predefined observation period is set and how an ONU is migrated to another wavelength when the serving wavelength is found under utilized.

2) OLT line card sleep mode: Feng *et al.* in [247] have proposed a LR WDM/TDM PON system where they consider the CO has several OLT cards, each of which are connected with a group of ONUs. To increase energy saving, reduce cost and operational flexibility, Feng *et al.* in [247] have proposed remote Channel Combine/Split (CCS) module, which can be controlled using a out-of-band communication channel. The proposed CCS combined with remotely controllable tunable laser diodes is installed at the RN1. The role of the CCS is to facilitate active control and selective aggregation of uplink signal from the active ONUs and split of downlink signals thereby allowing communication with minimum number of OLTs located in the CO. Besides using controllable CCS at the RN, the tunable lasers are employed to tune the uplink wavelengths from different active ONUs to a minimum number of wavelengths that are sufficient to meet the bandwidth demand of those active ONUs. Similarly, their proposed CCS along with the tunable laser diodes allows the CO to maintain downlink transmission with a minimum number of wavelengths. The DBA modules in this solution decides on the required number of active OLT cards in the CO at a given time taking account number of active ONUs. Feng *et al.* have reported that a 35% of power consumption saving is possible using their solution during the off-peak hours.

In their follow-up work, Feng *et al.* [335] have developed a seamless migration mechanism for assigning an ONU from an OLT to another OLT in a LR WDM/TDM PON. In this solution, when an OLT finds that only a small portion of its ONUs are active and the other OLT(s) have room to accommodate those ONUs, the OLT initiates the process for migration of those ONUs so that it can switch to sleep mode. The CCS at RN1 establishes a physical link to switch (migrate) an ONU from an OLT to another OLT. Additionally, an ONU migration process requires de-registering the ONU from the serving OLT and then, re-registering it with the target OLT. Based on simulation, the authors have shown that the migration delay in their proposal is well below the delay bound of 10 *ms*. However, their solution would have been much more useful if the buffer capacity requirement was considered for the downlink and uplink traffic while migrating a group of ONUs from an OLT to another.

In [12], Chowdhury *et al.* have highlighted that in a ring PON system, there can be several OLTs (line cards). The authors have suggested to put the low-load OLTs in sleep while other OLTs in the CO remain active to exchange traffic with the ONUs. To reduce excessive energy consumption of the unused OLTs in a CO that serves a large number of customers, Dixit *et al.* in [58] also have introduced a flexible CO architecture which facilitates sharing OLTs. They have explained how a flexible CO architecture leads to reduce energy consumption by activating the OLTs according to PON traffic load (the active OLTs serve all the ONUs under different PON brunches). To attain this flexibility, in a CO, the OLTs are connected with an optical router which consists of a number of WSSs and power splitters. The optical router combines the OLTs in such a way they can be utilized depending on aggregated network traffic load. However, it lacks detailed explanation on how inter-OLT migration of ONUs takes place.

E. Summary and Discussion

The solutions applying sleep mode based energy saving approach introduced for TDM-PON, WDM-PON and TWDM-PON are reviewed in Section VI-A, VI-B and VI-C.

In Table VII, we summarize key contributions aspects of all the reviewed solutions in Subsection VI-A. As we can notice that a large body research focused on finding sleep interval length of ONUs in a TDM-PON, while considering how the bandwidth should be scheduled in a PON system taking traffic priority into account. Another observation is that in the most downlink traffic centric solutions (e.g., [206], [207], [217], [302]) that we reviewed, consider the ONUs need to support early wake-up function. Note that although early wake-up function can help to reduce uplink traffic delay, it can contribute to reducing bandwidth utilization as in every uplink cycle the OLT needs to leave a small amount of uplink bandwidth for each sleeping ONU (the bandwidth utilization can noticeably drop for the networks with large number of ONUs). Future research needs to investigate further this challenge. Due to inherent broadcasting characteristics of the downlink transmission, TDM-PON and TWDM-PON are an ideal choice for broadcast and multicast transmission. However, none of the surveyed articles has investigated how sleep interval and bandwidth can be scheduled when the ONUs in a PON have unicast, multicast and broadcast traffic.

In case of TDM-PON, the ONU sleep mode is only considered as the OLT needs to be always active (a single pair of wavelength is shared among all the connected ONUs, thereby making the OLT busy most of the time). Unlike, a TDM-PON, multiple wavelength pairs for the communication between an OLT and ONUs are used in WDM-PON and TWDM-PON. Therefore, as we have found in VI-B, VI-C and VI-D, the existing solutions focusing on improving energy saving in WDM-PON and TWDM-PON also shed light on how energy conservation can be improved in the OLTs using sleep mode when they do not have any use.

In a WDM-PON, to reduce energy consumption both in an OLT and an ONU using sleep mode, solutions for facilitating synchronization of energy saving related state information between them have been developed in the existing studies, as we have seen in VI-B. Additionally, a CLS based approach (the OLT has the transmitters only) is proposed in several works (e.g., [283]) as a potential solution to reduce the number of transmitters in a WDM-PON system. In these works, specifically, to facilitate energy saving while resuming communication on traffic arrival, introducing architectures for OLT and ONU have been central to research efforts. It is worth mentioning that an in-depth performance analysis is missing in most of the reviewed works in VI-B.

We have summarized the solutions applying sleep mode approach for Type-1 and Type-2 TWDM-PON variants in Table IX and X, respectively. Generally speaking, how the number of serving wavelengths can be reduced by aggregating traffic flows of ONUs so that OLT port can be switched off is the major contribution aspect in most of the existing Type-1 TWDM-PON based solutions, as one can observe from the presented summary in Table IX. On the other hand, there are few research works (e.g., [320], [324]) have attempted to consider sleep mode both OLT and ONU side at the same time. However, such approach may add additional implementation complexity to maintain the precise synchronization requirement between OLT and ONU, increase signaling overhead and deteriorate traffic perform.

Introducing a PON architecture that can facilitate energy saving by turning off an OLT's port and line card while delivering services at the customer premises and determining optimal number of serving wavelength have been central to the sleep mode approach based research in Type-2 TWDM-PON generally, as can be noticed from the summary presented in Table X.

Frequent ONU migration has a detrimental effect on PON traffic performance, particularly it can increase delay and jitter (and may introduce packet drop). Although ONU migration in TWDM-PON has been extensively studied in academia (e.g., [219], [323]), there is still no clear guideline with regard to the appropriate migration triggering condition in the existing research. Further research is warranted to investigate how to trigger ONU migration taking performance requirement different applications and how to avoid frequent ONU migration. Buffer capacity for the OLT and ONU side is mostly overlooked while making migration decision in the

TABLE X: Summary of sleep mode based solutions in wavelength-routed hybrid WDM/TDM PON (Type-2 TWDM-PON). In the contribution aspects column, ✓indicates the criterion is met. In the evaluation method column, S is simulation, N is numerical analysis, E is experimentation and X indicates no evaluation is conducted. In the main features column, ✓indicates the criterion is met and X represents not applicable.

OLT Sleep mode	Reference	Major contribution aspects		Evaluation method	Main features			Advantages and/or drawbacks
		Proposing PON architecture enabling port /line card sleep without service interruption	Proposing a solution to find required number of serving WLs		Routing & reach: Flexible WL routing capability	Routing & reach: Long reach	Others	
OLT port sleep	[213]	✓		N	✓	✓	RN1 uses active equipment like WSS, whereas RN2 deploys a passive splitter. Turns off unused OLT ports when traffic arrival is low.	No explanation on how to determine optimal serving WLs and the WL migration procedures for the ONUs.
	[331]	✓		E	✓		Architecture with pay-as-you-grow in capacity facilitates load balancing and energy saving. When low traffic arrival, a pair of WL for DL and UL traffic from all ODNs is used, whereas other WLs (ports) are switched off.	
	[76]		✓	N	✓	✓	Whether to deploy one less WL or activate one more WL is determined by two threshold values.	WL allocation at different RNs is scheduled after a scheduling cycle (interval). No clear explanation how an optimal value of this can be measured.
	[332]	✓	✓	N	✓		In a low traffic scenario, the PtP WLs are turned off, while a PMP WL facilitates DL transmission to ONUs. Three mechanisms with different thresholds for determining DL rate under a low traffic scenario have been proposed.	No clear explanation for determining the threshold values used for making port sleep related decision. A detailed traffic performance evaluation is not conducted.
	[333]	✓	✓	S	✓		Proposes a PON architecture that supports PtP and PMP transmission. Additionally, the OLT supports both 10Gbps and 1 Gbps link rate for PtP communication. To conserve energy, below a certain traffic load 10 Gbps ports are turned off, while keeping 1 Gbps ports active.	
	[334]		✓	S	X	X	Proposes an energy-efficient bandwidth and WL allocation mechanism. During low traffic arrival, UL traffic is aggregated to serve with minimum number of WLs, thereby saving energy at the OLT.	Sleep mode for OLT's transmitter is not considered.
	[58]	✓	✓	S	✓	✓	Increases number of ONUs served by a WL, thereby reducing number of active transceivers at a given time. A DBA groups ONUs based on their distances from the OLT while meeting their data rate requirements.	Does not provide detailed procedures related to ONU migration and measuring the optimal number of serving WLs.
	[226]	✓	✓	S	✓		Uses pure FBG array in RN1 to support both PtP and PMP transmission. Broadcast transmission rate can be controlled depending on traffic load and it is turned off when there is no broadcast traffic to forward.	No explanation for determining the threshold value used for switching between 1 Gbps and 10 Gbps transmission rates.
OLT line card sleep	[247]	✓	✓	S	✓	✓	Facilitates serving all ONUs with a minimum number of OLT cards. Establishes a physical link to switch an ONU from an OLT to another OLT. DBA output determines required active OLT cards.	Architecture has gradual capacity scale up (as the customer grows) and energy saving capability by turning off unused OLTs. Migration procedures of an ONU from an OLT to another OLT is not presented.
	[335]			S	✓	✓	A seamless ONU migration mechanism between OLTs is presented.	No consideration of buffer capacity and delay requirement in migration related decision.
	[58]	✓		X	✓	✓	Flexible CO facilitates connection between the OLTs and the PON segments (sharing the OLTs in CO with PON segments). Energy saving is achieved by turning off unused OLTs in CO. The OLTs are activated depending on traffic load in the customer premises at a given time.	Although energy consumption in the CO can be reduced, the architecture may have inability to counter potential security attacks as each WL is routed to all ONUs.

existing literature. When a large number of ONUs migrating to other wavelengths, there needs to have sufficient buffer space to accommodate those incoming packets in the OLT and migrating ONU(s). Future research needs to investigate optimal discovery cycle and Quiet window length and the number of ONUs that should be instructed to migrate to a target wavelength taking into consideration the maximum tolerable migration delay, ONU wavelength tuning time and available buffer capacity in both OLT and ONU sides.

VII. Solutions Applying Sleep Mode Approach in Software-defined PONs

To date, there have been several research efforts showing how different variants of PON can be managed using SDN. This section reviews the existing works for energy saving using sleep mode in SDN controlled TDM-PON, WDM-PON and TWDM-PON, specifically under the respective subsections VII-A, VII-B, and VII-C. Similar to previous section, for each reviewed work, we outline its scope, mechanisms it introduced, and major strengths and limitations. A comparison of the main contribution aspects, evaluation methodology, and features of the solutions proposed for each respective PON variant is

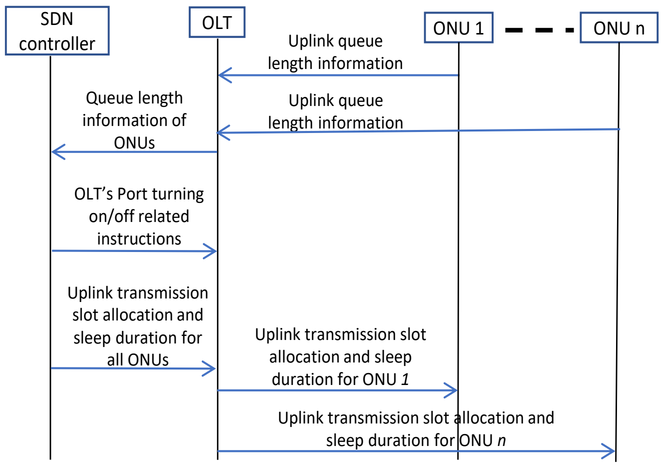

Fig. 26: Illustration of control message exchange between an SDN controller, OLT and ONUs to facilitate SDN based energy saving and network resource allocation [5], [218].

presented in Table XI.

A. SDN Controlled TDM-PONs

In [336], Li *et al.* have highlighted that a hard-coded DBA algorithm in a specific hardware does not offer flexibility during runtime. For a single algorithm may not be able to meet desired traffic performance when traffic profiles and network state are highly dynamic. The hard-coded IPACT DBA is unable to reschedule the ONU orders, resulting in an inability to reduce delay for the ONUs with high-priority [336]. To overcome this, the authors have proposed a SDN managed EPON architecture which replaces the hardware based DBA algorithm with a programmable DBA. They have proposed to implement an SDN controller at the CO. The SDN controller connects multiple OLT line cards at the CO and runs in parallel. Here, the controller having a global view of the networks can optimize different aspects of the network, including QoS and energy saving improvement. The controller applies different DBA algorithms to meet the traffic requirements of the ONUs adaptability. It executes a bandwidth management scheme taking into account traffic priority and queue status at each port in OLTs and ONUs. The scheme gets optimal polling cycle length dynamically and modifies traffic scheduling rules with the objective of reducing traffic delays and supporting differentiated traffic classes in the network. A DBA module runs in the OLT for processing bandwidth request and grant related message processing, whereas the SDN controller running over the top of the OLT makes decisions about bandwidth grant for the ONUs. With an extensive simulation, the authors have demonstrated that their proposed SDN managed EPON has lower delay compared to IPACT. Although, the solution is claimed to optimize energy consumption in the network, a detailed operation appears to be beyond the scope of their work.

Yan *et al.* in [218] have introduced SDN based sleep mode management in an EPON system. In the solution, an OLT uses port sleep and board sleep mode, whereas an ONU uses cyclic sleep mode for its transceivers in the absence of traffic to conserve energy. The ONUs send their uplink queue length information to their corresponding OLT. Next, the OLT sends queue length information of each OLT port and each ONU uplink queue length to the SDN controller. Finally, based on the received information, the controller notifies the appropriate ONUs and the ports of the OLT that need to move into energy saving mode (an illustration for the aforesaid procedures is presented in Fig. 26). Once the controller's assigned sleep duration elapses, the ONU and its corresponding OLT port wake up. The ONU notifies its queue length of its buffer to the OLT, which then relays this information to the controller along with its own state information. Based on the received information, the controller decides whether an ONU or an OLT port should further stay in *sleep state* or move to active mode. The major limitation of this work is the lack of explanations on how OLT port sleep and ONU cyclic sleep can be managed under different QoS requirements. The solution assumes a PON system with two ONUs only, however, in a real-world scenario, an OLT in a TDM-PON is very likely to have several ONUs, thereby it would be barely able to turn off its port. Furthermore, no detailed performance evaluation is provided to demonstrate the efficacy of the solution.

Zhao *et al.* [5] have introduced an SDN based EPON architecture with the objective is to manage (monitor and control) multiple PON domains remotely and implement large-scale resource optimization. Similar to [218], the OLT in [5] uses port sleep and board sleep mode. In this solution, an OpenFlow agent is placed with the OLTs at the CO, whereas the SDN controller is located in the central side. Based on the information obtained from the ONUs through the OLT, the controller decides the sleep mode and duration for the OLT and the ONUs. In this method, the SDN controller determines the sleep duration of an ONU taking into account the traffic arrival of both uplink and downlink. If the controller finds any inactive board (where all ports are not active), it turns off the board and disconnects the connection between the board and backplane. The solution also introduced new OpenFlow messages which are exchanged between OLTs and the controller to facilitate energy saving operations in OLTs and ONUs. Through an experimental setup, where two TDM-PON systems are connected through a ROADM based metro network and governed by SDN, the work demonstrated the unified controllability of the proposed architecture. However, it lacks a detailed performance evaluation in terms of energy savings.

In [337], Khalili *et al.* have introduced a framework where an SDN controlled EPON serves as the backhaul for 5G Radio Access Networks (RANs). Similar to [185], the authors have considered an OpenFlow switch embedded at the OLT and the SDN controller is located in a data-center of the access provider or a dedicated server in the network backbone. Additionally, they have proposed to migrate (relocate) some of the functions of a conventional OLT in the SDN controller, including management of bandwidth, MAC based flow and energy saving operation management. Therefore, the OLT in this solution is partially virtualized similar to [338]. The

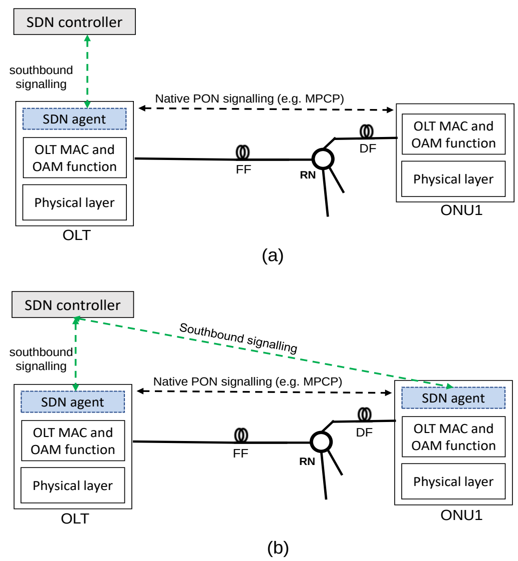

Fig. 27: Illustration of two different SDN agent based setups in PON: (a) the OLT only is equipped with an SDN agent (an OLT and ONU communicate using the native PON signalling messages) [5], [185], [338]; (b) both the OLT and ONU have SDN agents, allowing them to communicate through southbound signaling besides the native PON messages [223], [340], [341].

authors also considered to migrate some of the RAN functions to the SDN controller. In particular, the energy management function in the controller manages energy saving operations in access network equipment, specifically the ONUs and their serving RANs. However, the method has not provided any detailed operation on how sleep mode cycles are decided for those network entities. Furthermore, there are no results presented to demonstrate the effectiveness of the proposed solution. In their follow-up work, Khalili *et al.* [339] have used Artificial Intelligence (AI) techniques for the PON operation related decision, including optimizing energy consumption and automating the configuration and management services. Note that introducing a sleep mode based energy saving solution is not the central to the focus of this work.

Pakpahan *et al.* [341] have introduced an adaptive solution where an ONU in a TDM-PON conserves its energy by turning off transmitter and receiver independently depending on presence or absence of traffic. In their architecture, both OLT and ONUs are equipped with an OpenFlow agent (see an example illustration in Fig. 27 (b)), allowing the network to be controlled as per requirement by a centralized SDN controller which may reside in a dedicated server in the network backbone or edge of metro network and possess a global network view. The SDN controller orchestrates sleep mode operation in the ONUs and it decides on sleep duration of the receiver and wake-up threshold of the transmitter based on traffic arrival statistics of an ONU. As both the OLT and ONUs have an OpenFlow agent, the controller uses OpenFlow messages to communicate with these PON equipment. The authors have highlighted that, unlike their proposed SDN-agent equipped ONU, the conventional ONU does not allow any change of energy saving configuration a daptively once they are deployed in the customer premises. Their simulation results have demonstrated that the solution reduces energy consumption in the PON system while meeting QoS requirements. However, the authors have not shed any light on how their solution outperforms in terms of cost and performance compared to the architectures like VOLTHA [9] where only the white box OLT only is be able to communicate with an SDN controller.

Previous studies (e.g., [225], [323]) have focused on reducing energy saving in the OLT side in a PON slicing environment. By contrast, the authors in [228] have developed an ONU sleep-aware bandwidth scheduler to facilitate sliced bandwidth allocation to multiple VNOs operating individual vDBA, while reducing energy consumption in ONUs. The solution takes into account bandwidth and QoS demand of each operator and accordingly determine optimal bandwidth allocation and sleep cycle of each ONU. Based on simulation results the authors have imparted the solution improves energy saving performance while satisfying VNO delay performance. This work would have been more interesting if the authors could demonstrate more detailed results including how the different VNOs experience jitter performance in their solution.

B. *SDN Controlled WDM-PONs*

To facilitate direct communication with an SDN controller, Ren *et al.* [223] have proposed to equip both the OLT and ONUs with an OpenFlow switch (i.e., the OLT and ONUs become directly part of the data plane of an SDN). The controller makes optimal operational choices so as to maximize energy saving while meeting QoS requirements in the PON system. All the communication between the entities in the data plane and a controller is facilitated by the southbound interface, thereby eliminating the need of MPCP GATE and REPORT messages in the PON system. The controller houses functions like wavelength management unit and sleep control unit, which makes a decision with regard to sleep mode of ONUs taking into account network conditions. The network coding technology is also used in this solution to increase resource utilization. The sleep control unit gathers uplink buffer status of an ONU and allocates wavelength resources for the ONU. If there is no traffic to forward, the transmitter of the ONU moves into sleep mode. Similarly, taking downlink buffer information at the OLT, the wake-up time of the receiver at the ONU is determined by the sleep control unit. However, the decision procedures on how the sleep control unit determines sleep duration for the transmitter and receiver of an ONU lack a detailed explanation.

PON is considered to be an attractive fronthaul solution for the Cloud/centralized RAN (C-RAN) which is one of the main architectures proposed for 5G [15], [342]. In a C-RAN architecture, at a cell site, which is referred as Radio Remote Head (RRH) or Radio Unit (RU), only antennas are placed and a pool of centralized Base Band Unit (BBU) is collocated at the CO typically [15]. When functional split is implemented in C-RAN, it is increasingly important to ensure seamless connectivity between the cell sites and VNFs

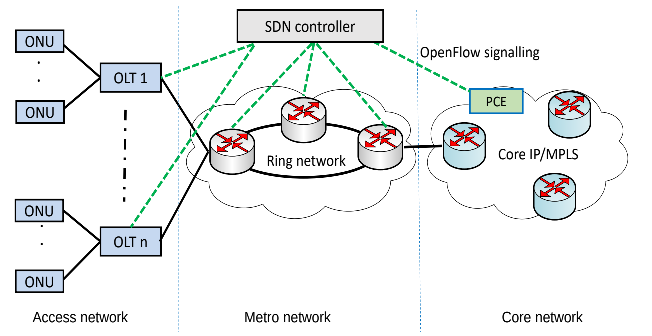

Fig. 28: Illustration of an SDN based unified control platform for controlling and monitoring the network equipment in core, metro and access network segment for a global traffic engineering [164]).

which are located in remote servers. Kondepu *et al.* in [285] have proposed an orchestrated energy saving operation in an SDN managed converged optical-wireless network where such functional splitting approach is supported. Here, the SDN controller(s) aims at dynamically configuring the WDM-PON based mobile fronthaul and aggregation network to maintain VNFs connectivity with the mobile terminals seamlessly when their serving cells and ONUs move to sleep mode. The authors aim at keeping reconfiguration time within a few milliseconds when cell on/off takes place. In the architecture, the base stations (cells) are connected with the ONUs. The OLT is connected with an OpenFlow switch which establishes a connection with the metro aggregation network. There is a light version of an SDN controller (say, *Controller-1*) placed in the CO (aggregation node) and it is used for controlling the OpenFlow switch. The aggregation network is also managed by an SDN controller (say, *Controller-2*). When an ONU and its corresponding port at the OLT are switched off, the OLT notifies *Controller-1* which, in turn, initiates the reconfiguration at OpenFlow switch. The *Controller-1* also instructs *Controller-2* to reconfigure the switches in the aggregation network such that the mobile terminals, which are served by a new cell as their previously serving base station is turned off, can have service continuity seamlessly. Their findings based on an experimental testbed show that the imposed delay due to reconfiguration remains within a few tens of milliseconds. Further research effort is required to reduce this reconfiguration time because such delay would not be acceptable to many latency stringent applications such as Smart traffic control (latency requirement 10 *ms* [343]) and Haptics and robotics (1 *ms* [42]).

C. SDN Controlled TWDM-PONs

Pakpahan *et al.* in [290] have proposed a SDN managed TWDM-PON system to make the PON system programmable and an integral part of a larger metro area network, thereby allowing to make any modification of its operation when there is any change in other parts of the network. In their proposed architecture, the ONUs are equipped with a tunable transceiver and they support ALR control. The proposed solution considers that OLT is enhanced by integrating OpenFlow-based SDN controller and an ONU equipped with an OpenFlow switch. In particular, in this solution, an ONU's link-rate and wavelength tuning related instructions are forwarded to the ONUs using OpenFLow message, whereas ONU discovery and registration related processes require low-level native PON and OpenFlow based messaging. The SDN controller gathers periodically statistical information of the OLT ports and average buffer status of the connected ONUs. It determines the required number of active wavelengths and selects the appropriate link-rates taking into account the traffic condition at a given time to reduce energy consumption while not compromising with QoS requirements. The controller instructs an ONU if there is any need for changing link-rates or wavelength for the ONU. The IPACT DBA function resides in the OLT and it assigns uplink slots to the ONUs based on the requests received from the ONUs. The simulation results show that the proposed SDN controlled TWDM-PON is able to reduce energy consumption by 75% compared to a solution without energy conservation consideration. However, this work does not discuss how the DBA cycle length adapts as with the QoS requirements different ONUs. In a real-world scenario, the ONUs in a PON need to cater diverse range of customers, including residential users and infrastructure of mobile operators.

In [289], Pakpahan *et al.* have introduced an SDN controlled TWDM-PON with the objective of facilitating software-defined programmable operation in the PON system so as to improve energy saving in an OLT and ONU using sleep mode and ALR while still meeting QoS requirements. In this solution, both the OLT and ONUs are equipped with an SDN agent. The controller has an energy management related function (EM function) which orchestrates resource provisioning and sets energy saving related decision based on its global knowledge about the status of network equipment (e.g., ONU) and traffic conditions. It also has a QoS management function which defines the QoS requirement in the PON system. Unlike [337], here the DBA resides in the OLT, thereby providing short timescale execution time and ultra-responsiveness to the requests locally within the PON system. The QoS management function collaborates with the EM function and OLT's DBA to set important policies related to PON performance (e.g., energy saving boundaries). The EM function measures sleep duration of the receiver and wake-up threshold of the transmitter of an ONU taking into account the information obtained from the QoS management function and traffic condition. The authors have shown how these are measured under the delay requirements of different traffic types. To reduce energy consumption in the OLT side, the unused transceivers at the OLT are turned off after determining required serving wavelengths in the PON system at a given time. It is also shown with simulation results that the proposed solution is able to reduce energy consumption while meeting the QoS requirements. However, it is not clear how the proposals in [289], [290] handle interactions with other parts of the network, such as the metro network segment.

In [344], Damit *et al.* have proposed a cognition driven framework, where decision about power saving mode in ONUs and sleep mode associated parameters are decided considering a number of factors that include traffic arrival behavior, energy

TABLE XI: Summary of solutions applying energy conservation approaches in software-defined PONs. In the contribution aspects column, ✓indicates the criterion is met. In the evaluation method column, S is simulation, N is numerical analysis, E is experimentation and ⋆ indicates no evaluation is conducted. In the major architectural features column, ✓indicates the criterion is met, X represents not specified, and O indicates the SDN controller is located outside of the CO (e.g., central side).

PON variant	Reference	Major contribution aspects				Evaluation method	Major architectural features				Advantages and/or drawbacks
		Proposing sleep mode management for OLT and/or ONU: OLT	Proposing sleep mode management for OLT and/or ONU: ONU	Proposing an energy saving aware orchestrated operation of interconnected domains	Proposing on-the-fly the optimal physical transmission parameters selection (e.g., modulation scheme, link rate) to save energy		SDN controller is in	SDN agent is in	OLT functions are partially virtualized at an SDN controller	Energy saving function reside in the SDN control plane	
TDM	[218]	✓	✓			S	X	X	✓	✓	Assumes only two ONUs are served by an OLT, which is unrealistic. No detailed performance evaluation related to energy saving and QoS.
TDM	[5]	✓	✓	✓		N & E	O	OLT	✓	✓	Facilitates the integration of access and metro networks. No explanation on how sleep durations are adjusted based on performance requirements.
TDM	[337]	✓	✓	✓		*	O	OLT	✓	✓	Not adequately explained how sleep mode operation is managed in OLT and ONU. Performance evaluation results are not provided.
TDM	[341]		✓			S	X	OLT & ONU	✓	X	No evaluation for the added benefits of including SDN agent in ONUs.
WDM	[223]		✓			S	X	OLT & ONU	✓	✓	QoS requirement of traffic is not considered for sleep mode related decisions.
WDM	[285]	✓	✓	✓		E	CO	OLT	X	X	A few tens of *ms* are required for reconfiguration when sleep mode is applied in base stations and PON equipment. This delay may not be tolerable for some very latency stringent applications running at user equipment.
TWDM	[290]	✓			✓	S	CO	ONU	✓	✓	A detailed operation related to migration of ONUs is missing. No consideration is given to buffer requirement in OLT and ONU depending on the number of ONUs migrating at a given time and time required for migration.
TWDM	[289]	✓	✓		✓	S	X	OLT & ONU	✓	✓	OLT port sleep mode and ONU cyclic sleep mode are used. Thus, an ONU migration procedure to another wavelength can be more complex compared to the solutions where only OLT port sleep mode is proposed.
TWDM	[1]	✓		✓		E	CO	OLT	X	X	No consideration has been given to the buffer capacity requirements in OLT for ONU migration.
TWDM	[344]		✓			S	CO	OLT	✓	✓	Lacks adequate explanation on how appropriate sleep mode and its associate parameters are selected.

saving features of an ONU and operational contexts like human presence, number of online devices and network usage behavior of the end users. The authors have also proposed that an ONU also collects different statistics including its performance (e.g., delay, packet drop, and jitter) and provides as feedback so that the energy saving operation in the PON system can be revised accordingly to maximize energy saving. The study does not present any technique on how the optimal sleep mode associated parameters can be determined. A detailed performance evaluation to demonstrate the efficacy of the solution is also missing in this work (it considers only a single ONU in the performance evaluation).

To obtain a unified control and monitoring of the access, metro, and core networks, an SDN based solution has been introduced by Sgambelluri *et al.* in [164], as illustrated in Fig. 28. In this solution, based on the information obtained from the PON segment, the SDN controller communicates with the Path Computation Elements (PCEs) of a MPLS based core network to improve traffic routing performance.

Similarly, Kondepu *et al.* in [1] have proposed an SDN controller based coordination mechanism between a TWDM-PON (access network), aggregation node and metro segments to reduce energy consumption and meet the end-to-end latency requirement of traffic. The OLT is connected with an SDN OpenFlow switch which assists it to exchange traffic with the metro network. The OLT moves into sleep mode in absence of traffic by turning off its port(s). Depending on traffic load, the PON system selects either the operational procedures of a TWDM-PON or a TDM-PON. That is, while using a TWDM-PON operational procedure, the OLT uses all the wavelengths for the uplink and downlink communication. However, when traffic load is less than a predefined threshold, the OLT keeps active one of the transmitter and receiver pair only, thereby forcing the network to be operated using a TDM-PON operation mode. A full discussion on how this threshold value is set for selecting between these two operational modes was not covered in this work. To meet the end-to-end delay requirements of traffic flows, the solution relies on the coordination between a lightweight SDN controller, TWDM-PON OLT and the metro/aggregation node controller. When the PON system decides to be operated as a TDM-PON system to conserve energy, the OLT instructs the ONUs that require migration to the target wavelength. It also communicates with the lightweight SDN controller requesting for a reconfiguration. This request triggers update of the OpenFlow switch. The switch scheduling priorities, forwarding table and traffic balancing toward connected metro network are reconfigured to adapt to the changes in the operation mode of the PON system. Additionally, for a possible flow reconfiguration (e.g., prioritization of the TWDM-PON traffic), the metro network controller is instructed. This allows the proposed solution to offset the delay experienced by traffic due to port sleep mode in the OLT. Performance measurements of this work using a testbed network setup indicate that it is possible to satisfy the end-to-end latency requirement when the OLT's sleep mode management and traffic shaping in the aggregation and the metro network nodes have coordination using SDN.

D. Summary and Discussion

The solutions we reviewed in this section payed no attention to scalability, reliability, and availability aspects of the SDN based PON architecture. A single physically centralized SDN controller is mostly considered in the existing studies (majority assumed it is outside of the PON CO or at the CO, as indicated in Table XI), which may lead to have bottle neck (slow processing may affect scalability and performance of a network) and single point of failure. Furthermore, most of the solutions we reviewed in this section consider function virtualization (see summarized information in Table XI). Virtualizing PON can have several benefits as we have discussed previously in Section III-B; however, there are several challenges that need to overcome to fully realize the benefits of SDN in PON. One of the important challenges is that the some of the functions in PON require very short timescale execution that might be problematic for the controller due to low processing speed of softwarization of various network functions. Also note that moving a function from PON physical equipment as virtualized function which run at Could/edge node, may reduce energy consumption in PON, as claimed in some research (e.g., [5]). However, it does not void the PON energy consumption footprint from a global perspective.

A major application of PON is the fronthaul of C-RAN. Since the wireless signal processing is performed at a remotely located BBU, C-RAN demands a large bandwidth capacity and stringent latency requirement in the PON fronthaul. There are ten different functional splits have been considered and each of the them can have different bandwidth requirement at the optical fronthaul [15]. Therefore, PON can have different energy conservation performance under different C-RAN functional splitting (a fully centralized C-RAN architecture may impose the highest amount of energy consumption). Therefore, as we have found, a number of research efforts (e.g., [285], [337], [345]) attempted SDN based convergence between the optical and wireless domains to improve energy saving and resource utilization while meeting traffic performance requirement.

There are also some research efforts (e.g., [285], [337]) to make SDN based coordination between metro and PON segment to improve energy saving and QoS performance, as we have reviewed in this section. Most of these reviewed studies attempting coordination between network segments fall short of providing details on how sleep mode operation related parameters (e.g., sleep duration) are determined and how to abstract key characteristics related to energy saving capability (e.g., types of energy saving approaches supported, state transition delay), supported QoS classes, and available network resources etc. of each connected segments. Abstracting such important characteristics, feeding those information into the orchestration process and optimizing the key operational parameters in real-time as well as understanding various performance trade-offs are some of the important issues that future research should shed further light on.

Overall performance evaluation aspects of SDN integrated PON in this section is limited in terms of detailed analysis. Furthermore, there is no provided insights into the energy saving gain of the SDN controlled PON compared to the conventional ones (without SDN and softwarization).

VIII. Lesson Learned, Challenges and Future Research Directions

As illustrated in the previous sections, PON is continuously evolving to cope with the demand for better experiences and performances at customer premises. Therefore, although energy saving in PON has been well investigated in the past years, research needs to be continued with the evolution of PON and performance requirements concurrently as the societal demands shifts. In this section, we present insightful lessons we learned from the previous sections and identify specific challenges that demand future research exploration.

A. AI Powered Optimal Operation Supporting Sleep Mode

The performance of the existing sleep mode based solutions is well understood under far more relaxed requirements than that of the emerging applications (refer to Sections VI and VII). The upcoming 6G of which PON is a promising candidate as backhaul infrastructure, is expected to support unprecedented demand for high-bandwidth capacities (>1 *Tbps*) and ultra-low latency (<1 *ms*) for applications requiring stringent latency and high bandwidth [17], [41], [346]. Similarly, in an industrial setting, PON aims to provide time sensitive service connectivity, such as latency between 100 μs to 2 ms and jitter 1 μs to 2 ms [110], [347]. Current solutions may face challenges to meet such stringent performance requirements. This warrants further investigation of sleep mode operation. Therefore, introducing novel solutions for sleep mode management and refinement of the currently available ones remain open research issues. To meet performance demand while saving energy is a challenge as network traffic condition may change dynamically, requiring continuous monitoring and optimal PON operation adaptively. Another challenge is how to decide efficiently which PON equipment is eligible to move into sleep mode. Otherwise, it may lead to degradation of traffic performance. Another issue is how to interrupt a sleeping equipment to leave *sleep state* and re-allocate network resource seamlessly. In the following subsections, we discuss aforesaid issues in further details.

1) Optimal PON Operation: Satisfying customers' demand while saving energy using sleep mode has been the key focus of the existing research works we reviewed in Sections VI and

VII. To attain this objective, besides finding sleep mode related parameters like sleep cycle and type of sleep mode, bandwidth allocation and dynamic network reconfiguration have been the major contributory aspects of the existing research to support sleep mode operation cohesively in different PON variants, as one can notice from Table VII, VIII, IX and X. These proposed solutions rely primarily on optimization algorithms and pre-established rules.

As we observed, one common limitation of the current energy saving PON research is that the traffic and energy models are usually over simplified and some assumptions are too rigid. These includes: uniform traffic arrival pattern in all ONUs, same QoS requirement by all ONUs, all ONU having identical energy saving behavior, fixed length frame size, network only with unicast traffic, and analog part of the OLT and ONU only having traffic dependent energy consumption. Such optimization model may fail to capture complexity of network and pose a significant challenge to ensure desired performance as the network situation changes and ONUs are most likely to demonstrate non-identical behavior. To handle more realistic and dynamic scenarios and gain insights into how different variables interplay to each other, advanced optimization techniques are needed which may require a combinatorial problem with large number of variables. However, this may pose significant computational complexity challenge. Conversely, training of supervised and/or unsupervised Machine Learning (ML) methods can yield better results for selecting appropriate parameters that can not only improve transmission efficiency but also reduce energy consumption in the network. Therefore, we believe that ML based optimized decision and prediction will be extremely effective in real-time estimation of different input variables, including traffic arrival and performance requirements patterns of customers, leading to more optimized energy aware and well-coordinated PON operation. For example, in an industrial PON setting, AI based analysis can facilitate understanding the behavior of packet generation cycle of different equipment connected with an ONU and based on that intelligent actions can be taken for dynamically adjusting DBA cycle and suitable slot size and its location within a cycle for the ONU.

2) Employing Dynamic Criteria for Sleep Activation: In Sections VI and VII, we observed that traffic arrival rate and bandwidth demand are the two commonly used criteria to determine a threshold value to trigger an ONU and OLT line/port sleep, respectively. These threshold values are generally static, which often lead to degraded performance as the network condition and performance requirements changes. Additionally, threshold selection based on these two parameters only may not be a realistic solution. This needs to be coupled with target performance requirements of the connected ONUs. Advanced AI techniques, particularly deep learning, can be applied to understand traffic arrival pattern and application QoS requirements of customers and adjust the these thresholds dynamically.

3) Proactive Sleep Interruption and Resource Allocation: In addition to dynamic nature of network condition, exceptional situation can always occur. Therefore, sleep interruption has been considered in academic research and standardization efforts. At present, we observed that most PON energy saving studies reviewed in Sections VI and VII rely on rule-based reactive approaches for sleep interruption in OLT and ONU. These approaches include scheduled sleep timer expiration, bandwidth demand threshold based OLT port and line card sleep interruption and uplink packet arrival at UNI based interruption and often results in introducing delay, jitter and packet drop to the flows. We believe that to meet performance demand of the emerging applications while conserving energy in PON, it is important to introduce *proactive* sleep mode interruption techniques. Future research needs to explore how ML based learning techniques can be used to learn appropriate conditions for proactively interrupt sleep mode of OLT and ONU and allocate required resources beforehand. For example, based on bandwidth demand pattern of each ONU, an OLT in a TWDM-PON system can determine how many wavelengths (ports) need to be activated at given time and proactively trigger ONU migration to other wavelengths to balance load and assign bandwidth for the migrated ONUs in advance.

Building comprehensive training datasets and selecting suitable AI techniques/architectures for a given PON system for administering optimal sleep mode supported PON operation should be a new area for further investigation. The AI models that can be useful in this case include Linear Regression, Decision Trees, Random Forest, Support Vector Machines, Artificial Neural Networks, Long Short-Term Memory (LSTM), and deep learning [348]. LSTMs can capture long-term dependencies in data and, in combination with recently proposed attention mechanisms, have demonstrated promising results in some studies [349], and can build effective models usable in PON Systems. Research has also produced compact ML models which can deployed without consuming much resources [350]. Additionally, an ensemble of models can increase estimation accuracy while being more robust to noisy data [351]. Similarly, transfer learning [352] is a powerful technique in ML that can also be exploited when only a limited labelled dataset is available on some PON aspects. Note that training and running the AI models incur computational and communication overhead in a network [353]. Thus, this can also impose additional energy consumption. In this regard, an important research challenge lies in achieving a balance between lightweight and yet effective PON intelligentization, ensuring that the associated overhead and implementation complexity do not become excessive.

Note that, in some certain sleep mode approaches (refer to Section IV-B), the transition between *sleep* to *active state* can impose milliseconds of additional delay for state transition, thereby impeding meeting performance of application with stringent latency demand. Therefore, application QoS requirements and traffic load profile aware sleep mode should be selected to reduce energy consumption opportunistically in the realm of emerging applications with string performance requirements. Furthermore, future research should target building low response network equipment to allow fast power state transition without increasing their energy consumption.

B. Energy Aware Disaggregation and Virtualization in PON

As observed in our review, most of the works in literature on software-defined energy saving PON research (in Section VII) consider virtualization of energy saving control function. This function (resides in the SDN control plane and is operated centrally) makes optimal decision related to energy saving operation in the OLT and ONU. Note that imposed latency due to the low processing speed of softwarization of various network functions is still a challenge. Furthermore, physical isolation of such functions from the data plane can add additional communication latency (e.g., delay due to processing at different hops) [40], resulting PON response to any particular event slow. In the current literature, PON energy saving related decision relies on real-time (online) optimization algorithms, which require various live data from OLT and ONU (e.g., downlink traffic load, uplink buffer status, number of registered ONUs) as inputs. Therefore, besides slow responsiveness, centralized energy saving decision at the control plane will lead to increase communication overhead between the planes. We believe, a viable solution is to adopt a distributed approach. Future research needs to investigate distributed energy saving decision in an orchestrated manner in a software-defined PONs to provide fast response with less communication overhead. For example, a long-term and optimal energy-efficient operational strategy can be set by an algorithm(s), which can be encapsulated as a VNF in Cloud stratum, makes the optimal decision for a PON with global view of the network and historical knowledge and coordinate with distributed localized energy saving algorithms. These localized algorithms may run as a PNF in the PON data plane (facilitating fast response) with relevant instructions and optimized parameters. Then, one important challenge that future study needs to address is how global policy and local actionable decisions can be harmonized to meet QoS, reliability, and availability while reducing energy consumption in PON.

As elucidated in Sections III and VII, the integration of SDN and NFV advances traditional PON to offer dynamic programmable fine-grained control and management of computing and network resources. This integration is embodying a multi-plane network infrastructure (e.g., control plane and user plane) where some functions reside in the OLT and ONU as PNFs, while others are virtualized functions residing in different plane(s), e.g., as stated in [40] a DBA function can be a PNF, while a higher level function like configuration and reporting can be a VNF. To ensure desired QoS, reliability and availability requirements of the PON customers, this multi-plane network infrastructure should require robust vertical and horizontal service chaining among the functions. Therefore, future research needs to investigate how to determine energy saving, QoS and resiliency aware optimal placement and computational resource for VNFs as well as facilitate appropriate interactions among the VNFs, PNFs and PON equipment using SDN. As the knowledge as we know, this important area has not been carefully investigated in current literature.

Furthermore, the interactions between the components residing in different planes need to be secured to combat against potential security attacks and sensitive information leakage. Therefore, the functions, equipment and forwarding paths planes need to be protected from cyberattacks and confidential information disclosure. Additionally, VNFs and SDN controllers may run in a common infrastructure but owned by different organizations [40]. This indicates importance of applying a robust security mechanism to facilitate a secured PON operation in the realm of SDN and NFV. Again, this will result in increasing communication overhead and node level processing (e.g., encryption/decryption, authentication), thereby increasing energy consumption. Therefore, future research needs to concentrate on how this additional energy consumption can be reduced without compromising the level of required security.

C. Granular Energy Saving Control for PON Slicing

Current energy efficient PON slicing solutions basically embody soft slicing in which PON resources are shared by the slices, as observed in Sections VI and VII. Generally speaking, energy saving research in a PON slicing environment is still limited and the current ones focus on almost entirely OLT side energy saving by packing multiple VNOs within minimum number of wavelengths (e.g., [225], [323]). On the other hand, ONU side energy saving in a sliced PON barely received any attention. In a PON slicing environment, ONU side energy saving becomes even more challenging as multiple VNOs' bandwidth need to be accommodated within the assigned wavelength while ensuring their individual slice consistent performance requirements, including delay, jitter, throughput, packet loss and availability, and thus should be addressed in future research. A potential future research direction here is to explore how the performance requirements of different network slices can be collected efficiently and use that information in real-time to determine appropriate traffic prioritization and optimally allocate PON resources (e.g., bandwidth, forwarding buffer space) while reducing energy consumption both at OLT and ONU sides. To improve scalability of the PON slices, AI techniques should also be leveraged to predict traffic and understand performance requirement patterns of each VNO slice to facilitate efficient resource allocation.

D. Energy-efficient Built-in PON Edge Computing

From previous sections (see Sections II-B and III-D), we observe that edge computing is becoming an integral part of PON with the growing needs of disaggregation and virtualization of functions and AI assisted service demand at the customer premises. Although earlier edge computing was considered as an OLT/ONU co-located independent computing and storage entities (e.g., [112]–[114]), presently it is being regarded as a part of OLT and ONU (e.g., in [8], [109], [110], [117]). This built in computing platform in PON may need to coordinate with each other as well as with the Cloud to facilitate cooperative computing to support customer applications efficiently and can leverage PON energy saving capability, e.g., by reducing volume of uplink data through local processing [110]. With this setting, this built-in edge module in OLT and ONU needs to be operated in an energy-efficient manner as it will affect overall energy consumption of a PON segment. However, in the current literature, we noticed still very limited efforts (e.g., [116]) on this. Future research should therefore need to explore how energy-efficient operation can be facilitated not only in OLT/ONU communication related interfaces but also in their built-in edge computing module. The communication and computing capabilities in PON need to be well-coordinated and cohesive to gain synergy. For example, the built-in computing module can be switched off when there is no use (or the clock speed be adjusted as per the processing need), and OLT needs to facilitate optimal bandwidth allocation that promotes energy conservation while allowing seamless communication among the participating computing modules while processing the tasks cooperatively as well as ensuring consistent QoS performance requirement of conventional traffic flows. Furthermore, an important challenge is how to ensure uninterrupted power supply to ONUs to facilitate flawless computing operation. Another issue needs to be tackled in built-in PON edge computing is security and privacy protection (this has been an important research challenge in the domain of edge computing [16]).

E. Comprehensive Performance Evaluation of Evolving PONs Including Energy Consumption Aspects

The energy saving works in software-defined PON reviewed in Section VII lack comprehensive performance evaluation. In particular, they do not impart any clear insights into complexity and performance gain on various aspects like QoS, energy saving, reliability and availability trade-off under different levels of virtualized/disaggregated functions as VNF or PNF, new types of OLT solutions (e.g., microplug OLTs [117]) and SDN controller architectures (e.g., centralized, distributed, flat and hierarchical organization) along with their inter-plane interactions. This unexplored area requires further in-depth performance testing to gain insightful understanding for real-world software-defined PON deployment decision making. This is particularly important when it comes to catering emerging bandwidth intensive, ultra-responsiveness and ultra-reliability demanding applications. Such investigation will also proliferate further advancement of more inspiring research in this domain. Furthermore, defining a performance evaluation framework for the software-defined PON systems should be useful to assess the effectiveness and efficiency of various architectural and operational aspects.

Current energy saving PON solutions reviewed in Section VI and VII are basically tree and ring-and-spur topology based solutions which are generally developed targeting public access network deployment. However, PON is evolving to reach further deeper into the customer premises (tailored to be operated end user specific use cases) to support more bandwidth intensive and deterministic performance demanding applications at office and residential users [118], [122], [123] and industrial production and manufacturing facilities [110]. All these are geared to propel further evolution of PON architecture (e.g., intra-ODN communication [125]), equipment (e.g., OLT/ONU with built-in edge computing [110], [116], [117] and ONU with industrial equipment specific interfaces [110]) and protocol operation (e.g., proactive and cyclic bandwidth allocation [8], [347]), as discussed in the last part of Section II-B. To the best of our knowledge, current research does not shed adequate light on understanding the operational efficiency in terms of energy consumption of these evolving solutions. Evaluating the performance of these solutions and introducing new solutions to meet stringent performance requirements while conserving energy should be a pivotal focus for future research.

IX. Conclusion

To keep pace with the bandwidth demand and latency stringent requirements of applications in the access network segment, PON technologies have been evolving. Recently, we have witnessed the integration of PON with SDN and NFV, which presents a major paradigm shift in the operation of communication networks. This paper takes the reader on a journey through the energy-efficient PON research starting from conventional PON to the current SDN based PON solutions. To provide an in-depth understanding of the energy saving mechanisms in PON solutions, this paper has presented readers the variants and evolution of PON systems, including their SDN based operation and control as well as their virtualization and disaggregation of functions. In our survey, we covered the major energy saving approaches used in PON, particularly sleep mode approach based solutions under both conventional and SDN controlled PON. This survey also presents standardization efforts on PON systems, their variants and energy saving approaches by various bodies including the IEEE, ITU-T and BBF.

Our analyses suggest that the currently available sleep mode based solutions may face challenges to satisfy the stringent performance requirements of emerging applications which 6G envisions to offer. We infer that existing SDN managed centralized energy saving solutions will lead to reduce responsiveness and increase communication overhead. To reduce overall PON energy footprint, in such softwarized PON should require energy-efficient operation both in PON infrastructure (OLT/ONU hardware) as well as in its virtualized functions hosting facilities. The technological development trends as observed in recent standards and research indicate that the SDN based PON will leverage the virtualization and disaggregation of PON functions and integration of PON with edge computing is imminent. We stress that, with the shifts in societal demands and advances in technology, PON will continue to evolve in terms of architecture, equipment, capacity, reach and protocol operations, requiring new breakthrough energy saving approaches and enhancement of the existing ones to be continually explored. To conclude, based on the inferences in this review, several future research challenges are identified, and how those challenges can be tackled for further advancement of energy-efficient PON are discussed.

References

[1] K. Kondepu, A. Sgambelluri, L. Valcarenghi, F. Cugini, and P. Castoldi, "Exploiting sdn for integrating green twdm-pons and metro networks preserving end-to-end delay," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. 67–74, 2017.

[2] M. Channegowda, R. Nejabati, and D. Simeonidou, "Software-defined optical networks technology and infrastructure: Enabling software-defined optical network operations," *Journal of Optical Communications and Networking*, vol. 5, no. 10, pp. A274–A282, 2013.

[3] E. Magalhães, M. Garrich, H. Carvalho, M. Magalhães, N. González, J. Oliveira, A. Bordonalli, and J. Oliveira, "Global wss-based equalization strategies for sdn metropolitan mesh optical networks," in *2014 The European Conference on Optical Communication (ECOC)*. IEEE, 2014, pp. 1–3.

[4] A. Amokrane, J. Hwang, J. Xiao, and N. Anerousis, "Software defined enterprise passive optical network," in *10th International Conference on Network and Service Management (CNSM) and Workshop*. IEEE, 2014, pp. 406–411.

[5] Y. Zhao, B. Yan, and J. Zhang, "Software defined passive optical networks with energy-efficient control strategy," *Optik*, vol. 127, no. 23, pp. 11 211–11 219, 2016.

[6] L. Guan, M. Zhang, D. Wang, and S. Xu, "Qot-aware adaptive modulation format-based resource provisioning for clustered lr-pon," *Optical Fiber Technology*, vol. 57, p. 102204, 2020.

[7] E. Niknia, M. Toycan, and S. D. Walker, "Energy efficient operation for a reconfigurable and self-interleaved optical access network," *Computers & Electrical Engineering*, vol. 66, pp. 189–199, 2018.

[8] T. Hatano, J.-I. Kani, and Y. Maeda, "Standardization and technology trends in optical, wireless and virtualized access systems," *IEICE Transactions on Communications*, vol. 102, no. 7, pp. 1263–1269, 2019.

[9] S. Das, "From cord to sdn enabled broadband access (seba)[invited tutorial]," *Journal of Optical Communications and Networking*, vol. 13, no. 1, pp. A88–A99, 2021.

[10] G. Auer, V. Giannini, I. Gódor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, C. Desset, and O. Blume, "Cellular energy efficiency evaluation framework," in *2011 IEEE 73rd vehicular technology conference (VTC Spring)*. IEEE, 2011, pp. 1–6.

[11] 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," *Optical Switching and Networking*, vol. 27, pp. 7–17, 2018.

[12] P. Chowdhury, M. Tornatore, S. Sarkar, and B. Mukherjee, "Building a green wireless-optical broadband access network (WOBAN)," *Journal of Lightwave Technology*, vol. 28, no. 16, pp. 2219–2229, 2010.

[13] Y. Luo, A. Shen, and F. Effenberger, "Pon coexistence interference avoidance with cross-layer design," in *2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC)*. IEEE, 2022, pp. 01–03.

[14] J. A. Hernández, R. Sánchez, I. Martín, and D. Larrabeiti, "Meeting the traffic requirements of residential users in the next decade with current ftth standards: How much? how long?" *IEEE Communications Magazine*, vol. 57, no. 6, pp. 120–125, 2019.

[15] C. Ranaweera, J. Kua, I. Dias, E. Wong, C. Lim, and A. Nirmalathas, "4g to 6g: disruptions and drivers for optical access," *Journal of Optical Communications and Networking*, vol. 14, no. 2, pp. A143–A153, 2022.

[16] Q. Duan, J. Huang, S. Hu, R. Deng, Z. Lu, and S. Yu, "Combining federated learning and edge computing toward ubiquitous intelligence in 6g network: Challenges, recent advances, and future directions," *IEEE Communications Surveys & Tutorials*, 2023.

[17] E. Wong, "Towards 6g: the evolution of passive optical networks," in *2022 IEEE Photonics Conference (IPC)*. IEEE, 2022, pp. 1–2.

[18] R. Tucker, "Green Optical Communications;Part II: Energy Limitations in Networks," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 17, no. 2, pp. 261–274, 2011.

[19] S. Dutta, D. Roy, and G. Das, "Protocol design for energy efficient olt in twdm-epon supporting diverse delay bounds," *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 3, pp. 1438–1450, 2021.

[20] Z. Zhang, Y. Chen, S. Cai, B. Zhang, M. Zhang, and X. Chen, "Colorless-light and tunable-light-source schemes for twdm and wdm pons," *IEEE Communications Magazine*, vol. 56, no. 8, pp. 120–128, 2018.

[21] *ITU-T G.989.3 Recommendation (Amendment 2), 40-Gigabit-capable passive optical networks (NG-PON2): Transmission convergence layer specification*, Std., Nov. 2018.

[22] *Recommendation ITU-T G.9804.1: Higher speed passive optical networks –Requirements*, Std., Nov. 2019.

[23] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy efficiency in telecom optical networks," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 4, pp. 441–458, 2010.

[24] B. Kantarci and H. T. Mouftah, "Bandwidth distribution solutions for performance enhancement in long-reach passive optical networks," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 3, pp. 714–733, 2011.

[25] J.-i. Kani, "Power saving techniques and mechanisms for optical access networks systems," *Journal of Lightwave Technology*, vol. 31, no. 4, pp. 563–570, 2012.

[26] J. Liu, H. Guo, H. Nishiyama, H. Ujikawa, K. Suzuki, and N. Kato, "New perspectives on future smart fiwi networks: scalability, reliability, and energy efficiency," *IEEE Communications surveys & tutorials*, vol. 18, no. 2, pp. 1045–1072, 2016.

[27] H. S. Abbas and M. A. Gregory, "The next generation of passive optical networks: A review," *Journal of network and computer applications*, vol. 67, pp. 53–74, 2016.

[28] A. S. Thyagaturu, A. Mercian, M. P. McGarry, M. Reisslein, and W. Kellerer, "Software defined optical networks (sdons): A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2738–2786, 2016.

[29] R. A. Butt, S. M. Idrus, N. Zulkifli, and M. W. Ashraf, "A survey of energy conservation schemes for present and next generation passive optical networks." *JCM*, vol. 13, no. 3, pp. 129–138, 2018.

[30] M. Kumari, R. Sharma, and A. Sheetal, "Passive optical network evolution to next generation passive optical network: A review," in *2018 6th Edition of International Conference on Wireless Networks & Embedded Systems (WECON)*. IEEE, 2018, pp. 102–107.

[31] *ITU-T G.9806 Corrigendum 1, Higher speed bidirectional, single fibre, point-to-point optical access system (HS-PtP)*, Std., Feb 2022.

[32] N. Lingas, M. R. Uddin, S. Newaz, and H. Hashim, "Energy efficient approaches in passive optical network: a review," 2018.

[33] T. Horvath, P. Munster, V. Oujezsky, and N.-H. Bao, "Passive optical networks progress: a tutorial," *Electronics*, vol. 9, no. 7, p. 1081, 2020.

[34] *IEEE P802.3cp Bidirectional 10 Gb/s, 25 Gb/s, and 50 Gb/s Optica Access PHYs Task Force*, Std., 2018.

[35] "Ieee standard for ethernet amendment 9: Physical layer specifications and management parameters for 25 gb/s and 50 gb/s passive optical networks," *IEEE Std 802.3ca-2020 (Amendment to IEEE Std 802.3-2018 as amended by IEEE 802.3cb-2018, IEEE 802.3bt-2018, IEEE 802.3cd-2018, IEEE 802.3cn-2019, IEEE 802.3cg-2019, IEEE 802.3cq-2020, IEEE 802.3cm-2020, and IEEE 802.3ch-2020)*, pp. 1–267, 2020.

[36] J. S. Wey, "The outlook for pon standardization: a tutorial," *Journal of Lightwave Technology*, vol. 38, no. 1, pp. 31–42, 2020.

[37] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future internet: a survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 2, pp. 223–244, 2010.

[38] *ITU-T Recommendation G Suppl. 45*, Std., May 2009.

[39] *IEEE Standard for Service Interoperability in Ethernet Passive Optical Networks (SIEPON)*, Std., 2013.

[40] B. F. (BBF). (2018) Cloud Central Office reference architectural framework. [Online]. Available: https://www.broadband-forum.org/download/TR-384.pdf

[41] Y. Shi, L. Lian, Y. Shi, Z. Wang, Y. Zhou, L. Fu, L. Bai, J. Zhang, and W. Zhang, "Machine learning for large-scale optimization in 6g wireless networks," *IEEE Communications Surveys & Tutorials*, 2023.

[42] C. C. Byers, "Architectural imperatives for fog computing: Use cases, requirements, and architectural techniques for fog-enabled iot networks," *IEEE Communications Magazine*, vol. 55, no. 8, pp. 14–20, 2017.

[43] J. Angelopoulos, H. C. Leligou, T. Argyriou, S. Zontos, E. Ringoot, and T. Van Caenegem, "Efficient transport of packets with QoS in an FSAN-aligned GPON," *Communications Magazine, IEEE*, vol. 42, no. 2, pp. 92–98, 2004.

[44] I.-S. 802.3ah 2004, "Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications," 2004, pp. –.

[45] J.-i. Kani and D. van Veen, "Current tdm-pon technologies," *Springer Handbook of Optical Networks*, pp. 849–870, 2020.

[46] H.-C. Leligou, C. Linardakis, K. Kanonakis, J. D. Angelopoulos, and T. Orphanoudakis, "Efficient medium arbitration of fsan-compliant gpons," *international journal of communication systems*, vol. 19, no. 5, pp. 603–617, 2006.

[47] K. A. Memon, K. H. Mohammadani, A. A. Laghari, R. Yadav, B. Das, W. U. K. Tareen, X. Xin *et al.*, "Dynamic bandwidth allocation algorithm with demand forecasting mechanism for bandwidth allocations in 10-gigabit-capable passive optical network," *Optik*, vol. 183, pp. 1032–1042, 2019.

[48] B. Skubic, J. Chen, J. Ahmed, L. Wosinska, and B. Mukherjee, "A comparison of dynamic bandwidth allocation for epon, gpon, and next-generation tdm pon," *IEEE Communications Magazine*, vol. 47, no. 3, pp. S40–S48, 2009.

[49] S.-i. Choi and J. Park, "Sla-aware dynamic bandwidth allocation for qos in epons," *Journal of Optical Communications and Networking*, vol. 2, no. 9, pp. 773–781, 2010.

[50] E. Wong and L. Ruan, "Towards 6g: Machine learning driven resource allocation in next generation optical access networks," in *European Conference and Exhibition on Optical Communication*. Optica Publishing Group, 2022, pp. Mo3C–5.

[51] ETSI. (2023) Fifth generation fixed network (F5G); F5G technology landscape release 2. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/F5G/001_099/013/01.01.01_60/gs_F5G013v010101p.pdf

[52] G. Talli and P. D. Townsend, "Hybrid dwdm-tdm long-reach pon for next-generation optical access," *Journal of lightwave technology*, vol. 24, no. 7, p. 2827, 2006.

[53] M. S. Ahsan, M. S. Lee, S. S. Newaz, and S. M. Asif, "Migration to the next generation optical access networks using hybrid wdm/tdm-pon," *Journal of Networks*, vol. 6, no. 1, p. 18, 2011.

[54] M. Maier, "WDM passive optical networks and beyond: the road ahead," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 1, no. 4, pp. C1–C16, 2009.

[55] Y. Zhang, N. Deng, C.-K. Chan, and L.-K. Chen, "A Multicast WDM-PON Architecture Using DPSK/NRZ Orthogonal Modulation," *Photonics Technology Letters, IEEE*, vol. 20, no. 17, pp. 1479–1481, 2008.

[56] N. Ansari and J. Zhang, *Media access control and resource allocation: For next generation passive optical networks*. Springer Science & Business Media, 2013.

[57] Z. Zhang, Y. Chen, S. Cai, B. Zhang, M. Zhang, and X. Chen, "Colorless-light and tunable-light-source schemes for twdm and wdm pons," *IEEE Communications Magazine*, vol. 56, no. 8, pp. 120–128, 2018.

[58] A. Dixit, B. Lannoo, G. Das, D. Colle, M. Pickavet, and P. Demeester, "Flexible TDMA/WDMA passive optical network: Energy efficient next-generation optical access solution," *Optical Switching and Networking*, vol. 10, no. 4, pp. 491–506, 2013.

[59] "40-gigabit-capable Passive Optical Networks (NG-PON2)," *ITU-T Recommendation G.989*, 2015.

[60] *ITU-T G.989.2 Recommendation, 40-Gigabit-capable passive optical networks (NG-PON2): Physical Media Dependent Layer Specification*, Std., Jan. 2016.

[61] *ITU-T G.989.2 Recommendation, 40-Gigabit-capable passive optical networks (NG-PON2): Physical Media Dependent Layer Specification*, Std., Feb. 2019.

[62] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time-and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NG-PON2)," *Journal of lightwave technology*, vol. 31, no. 4, pp. 587–593, 2012.

[63] A. F. Y. Mohammed, S. S. Newaz, D. Sankar, M. S. Ahsan, and T.-W. Um, "A green converged TWDM-PON and 5G hetnet catering applications demanding low latency," *Optical Fiber Technology*, vol. 58, p. 102261, 2020.

[64] J. S. Wey, D. Nesset, M. Valvo, K. Grobe, H. Roberts, Y. Luo, and J. Smith, "Physical layer aspects of ng-pon2 standards—part 1: Optical link design," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 8, no. 1, pp. 33–42, 2016.

[65] Y. Xiong, P. Sun, C. Liu, and J. Guan, "Traffic-aware energy saving scheme with modularization supporting in TWDM-PON," *Optical Fiber Technology*, vol. 33, pp. 7–15, 2017.

[66] K. Kondepu, L. Valcarenghi, D. P. Van, and P. Castoldi, "Trading energy savings and network performance in reconfigurable TWDM-PONs," *Journal of Optical Communications and Networking*, vol. 7, no. 5, pp. 470–479, 2015.

[67] R. P. Davey, D. B. Grossman, M. Rasztovits-Wiech, D. B. Payne, D. Nesset, A. Kelly, A. Rafel, S. Appathurai, and S.-H. Yang, "Long-reach passive optical networks," *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 273–291, 2009.

[68] M. Ruffini, D. Mehta, B. O'Sullivan, L. Quesada, L. Doyle, and D. Payne, "Deployment strategies for protected long-reach pon," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 4, no. 2, pp. 118–129, 2012.

[69] H. Feng, C.-J. Chae, and A. V. Tran, "Cost-effective and power-efficient extended-reach wdm/tdm pon systems," in *2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*. IEEE, 2011, pp. 1–3.

[70] R. Q. Shaddad, A. Mohammad, S. M. Idrus, A. M. Al-hetar, and N. A. Al-geelani, "Emerging optical broadband access networks from tdm pon to ofdm pon," in *PIERS Proceedings*, 2012.

[71] G. Das, B. Lannoo, A. Dixit, D. Colle, M. Pickavet, and P. Demeester, "Flexible hybrid wdm/tdm pon architectures using wavelength selective switches," *Optical Switching and Networking*, vol. 9, no. 2, pp. 156–169, 2012.

[72] R. Bushra, M. Hossen, and M. M. Rahman, "Online multi-thread polling algorithm with predicted window size for dba in long reach pon," in *2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT)*. IEEE, 2016, pp. 1–5.

[73] A. Emsia, Q. Le, M. Malekizandi, D. Briggmann, I. Djordjevic, and F. Küppers, "Wdm–tdm ng-pon power budget extension by utilizing soa in the remote node," *IEEE Photonics Journal*, vol. 6, no. 2, pp. 1–10, 2014.

[74] L. Shi, S.-S. Lee, H. Song, and B. Mukherjee, "Energy-Efficient Long-Reach Passive Optical Network: A Network Planning Approach Based on User Behaviors," *Systems Journal, IEEE*, vol. 4, no. 4, pp. 449–457, 2010.

[75] A. Kanungoe, A. Mukhopadhyay, G. Das, R. Banerjee, and R. Das, "A new protection scheme for a combined ring-star based hybrid wdm/tdm pon architecture," *Optical Switching and Networking*, vol. 18, pp. 153–168, 2015.

[76] L. Shi, S.-S. Lee, and B. Mukherjee, "Energy-efficient long-reach passive optical network: A dynamic wavelength allocation scheme," in *Photonics in Switching*. Optica Publishing Group, 2010, p. PTuB1.

[77] L. B. Du, X. Zhao, S. Yin, T. Zhang, A. E. Barratt, J. Jiang, D. Wang, J. Geng, C. DeSanti, and C. F. Lam, "Long-reach wavelength-routed twdm pon: Technology and deployment," *Journal of Lightwave Technology*, vol. 37, no. 3, pp. 688–697, 2018.

[78] L. Shi, P. Chowdhury, and B. Mukherjee, "Saving energy in long-reach broadband access networks: architectural approaches," *IEEE Communications Magazine*, vol. 51, no. 2, pp. S16–S21, 2013.

[79] H. Song, B.-W. Kim, and B. Mukherjee, "Long-reach optical access networks: A survey of research challenges, demonstrations, and bandwidth assignment mechanisms," *IEEE communications surveys & tutorials*, vol. 12, no. 1, pp. 112–123, 2010.

[80] K.-I. Suzuki, Y. Fukada, D. Nesset, and R. Davey, "Amplified gigabit pon systems," *Journal of Optical Networking*, vol. 6, no. 5, pp. 422–433, 2007.

[81] FSAN. (2016, November) Fsan standards roadmap 2.0. [Online]. Available: https://www.fsan.org/roadmap/

[82] K. S. Kim, "On the evolution of pon-based ftth solutions," *Information sciences*, vol. 149, no. 1-3, pp. 21–30, 2003.

[83] T. Horvath, P. Munster, V. Oujezsky, and N.-H. Bao, "Passive optical networks progress: a tutorial," *Electronics*, vol. 9, no. 7, p. 1081, 2020.

[84] IEEE, *802.3ah-2004 - Standard for Information technology– Local and metropolitan area networks– Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment: Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks*, Std., 2004.

[85] *ITU-T G.984.1 Recommendation: Gigabit-capable passive optical networks (GPON): General characteristics*, Std., May 2008.

[86] J. C. Velásquez Micolta, "Next generation optical access networks and coexistence with legacy pons," 2019.

[87] IEEE, *802.3av-2009 - Physical Layers Pacification and Management Parameters for 10 Gb/s Passive Optical Networks*, Std., Oct. 2009.

[88] *ITU-T G.987 Recommendation: 10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms*, Std., Jan. 2012.

[89] *ITU-T G.9807.1 Recommendation: 10-Gigabit-capable symmetric passive optical network (XGS-PON)*, Std., June 2016.

[90] G. Kramer, L. Khermosh, F. Daido, A. Brown, H. Yoon, K.-I. Suzuki, and W. Bo, "The IEEE 1904.1 standard: SIEPON architecture and model," *Communications Magazine, IEEE*, vol. 50, no. 9, pp. 98–108, September 2012.

[91] IEEE. (2014, may) P1904.1 working group standard for Service Interoperability in Ethernet Passive Optical Networks (SIEPON). [Online]. Available: http://grouper.ieee.org/groups/1904/1/

[92] K. Asaka and J.-i. Kani, "Standardization trends for next-generation passive optical network stage 2 (ng-pon2)," *NTT Technical Review*, vol. 13, no. 3, pp. 80–84, 2015.

[93] W. Wang, W. Guo, and W. Hu, "A fair and flexible dynamic wavelength and bandwidth allocation algorithm for ieee 100g-epon," in *2017 19th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2017, pp. 1–4.

[94] C. Knittle, "Ieee 50 gb/s epon (50g-epon)," in *2020 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2020, pp. 1–3.

[95] R. Koma, J. Kani, K. Asaka, and K. Suzuki, "Standardization trends for future high-speed passive optical networks," *NTT Tech. Rev.*, vol. 15, pp. 1–5, 2017.

[96] W. Wang, W. Guo, and W. Hu, "Mechanism design and performance analysis of coordinated registration protocol for ng-epon," *Journal of Optical Communications and Networking*, vol. 11, no. 3, pp. 107–117, 2019.

[97] D. Nesset, "Pon roadmap," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. A71–A76, 2017.

[98] V. Houtsma, D. van Veen, and E. Harstead, "Recent progress on standardization of next-generation 25, 50, and 100g epon," *Journal of Lightwave Technology*, vol. 35, no. 6, pp. 1228–1234, 2017.

[99] *ITU-T G.983.1 (10/98) Recommendation, Broadband optical access systems based on Passive Optical Networks (PON)*, Std., Oct. 1998.

[100] *ITU-T G.983.1 (01/05) Recommendation, Broadband optical access systems based on Passive Optical Networks (PON)*, Std., Jan. 2005.

[101] J. Prat, I. N. Cano, M. Presi, I. Tomkos, D. Klonidis, G. Vall-llosera, R. Brenot, R. Pous, G. Papastergiou, A. Rafel *et al.*, "Technologies for cost-effective udwdm-pons," *Journal of Lightwave Technology*, vol. 34, no. 2, pp. 783–791, 2015.

[102] "Ieee standard for ethernet – amendment 14: Bidirectional 10 gb/s, 25 gb/s, and 50 gb/s optical access phys," *IEEE Std 802.3cp-2021 (Amendment to IEEE 802.3-2018)*, pp. 1–142, 2021.

[103] V. Houtsma, D. van Veen, and E. Harstead, "Recent progress on standardization of next-generation 25, 50, and 100g epon," *Journal of Lightwave Technology*, vol. 35, no. 6, pp. 1228–1234, 2017.

[104] "Ieee standard for ethernet - amendment 11: Physical layers and management parameters for 100 gb/s and 400 gb/s operation over single-mode fiber at 100 gb/s per wavelength," *IEEE Std 802.3cu-2021 (Amendment to IEEE Std 802.3-2018 and its approved amendments)*, pp. 1–87, 2021.

[105] H. Roberts, "Status of ITU-T Q2/15: New higher speed pon projects," *IEEE Communications Standards Magazine*, vol. 4, no. 1, pp. 57–59, 2020.

[106] *ITU-T G.9806 Amendment 3, Higher speed bidirectional, single fibre, point-to-point optical access system (HS-PtP)*, Std., Jan 2024.

[107] J. A. Hernández, R. Sánchez, I. Martín, and D. Larrabeiti, "Meeting the traffic requirements of residential users in the next decade with current ftth standards: how much? how long?" *IEEE Communications Magazine*, vol. 57, no. 6, pp. 120–125, 2019.

[108] S. S. Newaz, G. M. Lee, M. R. Uddin, A. F. Y. Mohammed, J. K. Choi *et al.*, "Towards realizing the importance of placing fog computing facilities at the central office of a pon," in *2017 19th International Conference on Advanced Communication Technology (ICACT)*. IEEE, 2017, pp. 152–157.

[109] J. Montalvo, J. Torrijos, D. Cortes, R. Chundury, and M. S. Peter, "Journey toward software-defined passive optical networks with multi-pon technology: an industry view," *Journal of Optical Communications and Networking*, vol. 13, no. 8, pp. D22–D31, 2021.

[110] ETSI. (2023) Fifth generation fixed network (F5G); F5G industrial PON. [Online]. Available: https://www.etsi.org/deliver/etsi_gr/F5G/001_099/007/01.01.01_60/gr_F5G007v010101p.pdf

[111] A. Helmy and A. Nayak, "Fog integration with optical access networks from an energy efficiency perspective," in *IEEE INFOCOM 2020-IEEE Conference on Computer Communications*. IEEE, 2020, pp. 2639–2647.

[112] D. Roy, S. Dutta, A. Datta, and G. Das, "A cost effective architecture and throughput efficient dynamic bandwidth allocation protocol for fog computing over epon," *IEEE Transactions on Green Communications and Networking*, vol. 4, no. 4, pp. 998–1009, 2020.

[113] A. Helmy and A. Nayak, "Decentralized bandwidth allocation framework for energy-efficiency and fog integration in pons," in *2020 International Conference on Computing, Networking and Communications (ICNC)*. IEEE, 2020, pp. 1026–1030.

[114] S. Mondal, G. Das, and E. Wong, "Ccompassion: A hybrid cloudlet placement framework over passive optical access networks," in *IEEE INFOCOM 2018-IEEE Conference on Computer Communications*. IEEE, 2018, pp. 216–224.

[115] B. P. Rimal, M. Maier, and M. Satyanarayanan, "Experimental testbed for edge computing in fiber-wireless broadband access networks," *IEEE Communications Magazine*, vol. 56, no. 8, pp. 160–167, 2018.

[116] F. H. Ahmad, S. S. Newaz, D. Sankar, R. Ramlie, and N. S. Nafi, "Fog computing in optical access networks: An energy-efficient and deadline-aware task scheduling mechanism," in *2023 13th International Conference on Information Technology in Asia (CITA)*. IEEE, 2023, pp. 66–69.

[117] G. Simon, P. Chanclou, M. Wang, D. Abgrall, and D. Minodier, "Optical access evolutions towards sdn and disaggregated hardware: an operator perspective," *Journal of Optical Communications and Networking*, vol. 14, no. 6, pp. C57–C69, 2022.

[118] L. Pesando, J. K. Fischer, B. Shariati, R. Freund, J. Cananao, H. Li, Y. Lin, O. Ferveur, M. Jiang, J. Jin *et al.*, "Standardization of the 5th generation fixed network for enabling end-to-end network slicing and quality-assured services," *IEEE Communications Standards Magazine*, vol. 6, no. 4, pp. 96–103, 2022.

[119] ETSI. (2021) Fifth generation fixed network (F5G); F5G technology landscape. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/F5G/001_099/003/01.01.01_60/gs_F5G003v010101p.pdf

[120] ——. (2020) The fifth generation fixed network (F5G): Bringing fibre to everywhere and everything. ISBN: 979-10-92620-36-5. [Online]. Available: https://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp_41_FSG_ed1.pdf

[121] M. Philpott and S. Wilson. (2022) FTTR's role in optimizing the future connected home. [Online]. Available: https://carrier.huawei.com/~/media/CNBGV2/download/products/networks/FTTR-Role-in-Optimizing-the-Future-Connected-Home-en.pdf

[122] *GSTP-FTTR Use cases and requirements of fibre-to-the-room (FTTR)*, Std., April 2021.

[123] *ITU-T Recommendation G Suppl. 45: Power conservation in optical access systems*, Std., Sept. 2022.

[124] ETSI. (2022) Fifth generation fixed network (F5G); F5G network architecture. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/F5G/001_099/004/01.01.01_60/gs_F5G004v010101p.pdf

[125] T. Pfeiffer, P. Dom, S. Bidkar, F. Fredricx, K. Christodoulopoulos, and R. Bonk, "PON going beyond FTTH [invited tutorial]," *Journal of Optical Communications and Networking*, vol. 14, no. 1, pp. A31–A40, 2022.

[126] B. A. M. Haidi, T. W. Au, and S. S. Newaz, "Single cluster load balancing using sdn: Performance comparison between floodlight and pox," in *2019 IEEE 19th International Conference on Communication Technology (ICCT)*. IEEE, 2019, pp. 1332–1336.

[127] D. Kreutz, F. M. Ramos, P. E. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," *Proceedings of the IEEE*, vol. 103, no. 1, pp. 14–76, 2014.

[128] L. Zhu, M. M. Karim, K. Sharif, C. Xu, F. Li, X. Du, and M. Guizani, "Sdn controllers: A comprehensive analysis and performance evaluation study," *ACM Computing Surveys (CSUR)*, vol. 53, no. 6, pp. 1–40, 2020.

[129] J. H. M. K. P. R. T. L. R. S. S. Z. W. S. U. Krishnaswamy, P. Berde and G. Parulkar. (2013) Onos: An open source distributed SDN OS. [Online]. Available: https://www.slideshare.net/umeshkrishnaswamy/open-network-operating-system

[130] "Opendaylight: A linux foundation collaborative project," 2013. [Online]. Available: http://www.opendaylight.org

[131] T. Koponen, M. Casado, N. Gude, J. Stribling, L. Poutievski, M. Zhu, R. Ramanathan, Y. Iwata, H. Inoue, T. Hama *et al.*, "Onix: A distributed control platform for large-scale production networks." in *OSDI*, vol. 10, 2010, pp. 1–6.

[132] N. Gude, T. Koponen, J. Pettit, B. Pfaff, M. Casado, N. McKeown, and S. Shenker, "Nox: towards an operating system for networks," *ACM SIGCOMM Computer Communication Review*, vol. 38, no. 3, pp. 105–110, 2008.

[133] "Ryu SDN framework," 2013. [Online]. Available: https://ryu-sdn.org/

[134] "Pox controller manual," 2018. [Online]. Available: https://noxrepo.github.io/pox-doc/html/

[135] Atlassian, "Floodlight is a java-based openflow controller," 2016. [Online]. Available: https://floodlight.atlassian.net/wiki/spaces/floodlightcontroller/pages/1343542/Getting+Started

[136] D. B. Rawat and S. R. Reddy, "Software defined networking architecture, security and energy efficiency: A survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 325–346, 2016.

[137] A. Blenk, A. Basta, M. Reisslein, and W. Kellerer, "Survey on network virtualization hypervisors for software defined networking," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 655–685, 2015.

[138] N. M. K. Chowdhury and R. Boutaba, "A survey of network virtualization," *Computer Networks*, vol. 54, no. 5, pp. 862–876, 2010.

[139] R. Nejabati, S. Peng, B. Gou, M. Channegowda, and D. Simeonidou, "Toward a completely softwareized optical network," *Journal of Optical Communications and Networking*, vol. 7, no. 12, pp. B222–B231, 2015.

[140] N. operators, "Network functions virtualisation: An introduction, benefits, enablers, challenges and call for action," in *SDN and OpenFlow World Congress*, 2012, pp. 1—-6.

[141] A. Rehman, R. L. Aguiar, and J. P. Barraca, "Network functions virtualization: The long road to commercial deployments," *IEEE Access*, vol. 7, pp. 60 439–60 464, 2019.

[142] E. Kaljic, A. Maric, P. Njemcevic, and M. Hadzialic, "A survey on data plane flexibility and programmability in software-defined networking," *IEEE Access*, vol. 7, pp. 47 804–47 840, 2019.

[143] H. K. Andreas Voellmy and N. Feamster, "Procera: a language for high-level reactive network control," in *the first workshop on Hot topics in software defined networks*, 2012, pp. 43–48.

[144] F. Bannour, S. Souihi, and A. Mellouk, "Distributed sdn control: Survey, taxonomy, and challenges," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 333–354, 2017.

[145] S. Sezer, S. Scott-Hayward, P. K. Chouhan, B. Fraser, D. Lake, J. Finnegan, N. Viljoen, M. Miller, and N. Rao, "Are we ready for sdn? implementation challenges for software-defined networks," *IEEE Communications Magazine*, vol. 51, no. 7, pp. 36–43, 2013.

[146] B. Yi, X. Wang, K. Li, M. Huang *et al.*, "A comprehensive survey of network function virtualization," *Computer Networks*, vol. 133, pp. 212–262, 2018.

[147] K. Nishimoto, M. Tadokoro, T. Mochida, A. Takeda, T. Tanaka, and T. Inoue, "Virtualization of epon olt functions and collision suppression techniques for multi-point mac control," in *2016 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2016, pp. 1–3.

[148] K. L. D. Michel S. Bonfim and S. F. L. Fernandes, "Integrated NFV/SDN architectures: A systematic literature review," *ACM Computing Surveys*, vol. 51, no. 6, 2019.

[149] H. Khalili, D. Rincón, S. Sallent, and J. R. Piney, "An integrated sdn-based architecture for passive optical networks," *Broadband Communications Networks: Recent Advances and Lessons from Practice*, vol. 215, 2018.

[150] T. Suzuki, S.-Y. Kim, J.-i. Kani, and T. Yoshida, "Virtualized pon based on abstraction, softwarization, and service chaining for flexible and agile service creations," *Journal of Optical Communications and Networking*, vol. 15, no. 1, pp. A39–A48, 2023.

[151] H. Yang, J. Zhang, Y. Zhao, J. Wu, Y. Ji, Y. Lin, J. Han, and Y. Lee, "Experimental demonstration of remote unified control for openflow-based software-defined optical access networks," *Photonic Network Communications*, vol. 31, no. 3, pp. 568–577, 2016.

[152] J. Montalvo, J. A. Torrijos, and D. Cortés, "New approaches in optical access networks to increase network flexibility and achieve 5g targets: an operator's view," in *2020 European Conference on Optical Communications (ECOC)*. IEEE, 2020, pp. 1–4.

[153] T. Suzuki, Y. Koyasako, K. Nishimoto, K. Asaka, T. Yamada, J.-i. Kani, T. Shimada, and T. Yoshida, "Demonstration of ieee pon abstraction for sdn enabled broadband access (seba)," *Journal of Lightwave Technology*, vol. 39, no. 20, pp. 6434–6442, 2021.

[154] K. Nishimoto, T. Suzuki, K. Asaka, J.-i. Kani, and J. Terada, "Softwarized and open olt architecture for flexible optical access network," in *Optical Fiber Communication Conference*. Optical Society of America, 2020, pp. M1K–4.

[155] K. Asaka, H. Ujikawa, J.-i. Kani, and A. Otaka, "Flexible access system architecture (fasa)," in *2018 Optical Fiber Communications Conference and Exposition (OFC)*. IEEE, 2018, pp. 1–3.

[156] K. Nishimoto, K. Asaka, J.-i. Kani, and J. Terada, "Dba dis-aggregation in pon-olt with scalability enhancement by report/gate compression," *Journal of Optical Communications and Networking*, vol. 13, no. 1, pp. A13–A20, 2021.

[157] J. S. Vardakas, K. Ramantas, E. Vinogradov, M. A. Rahman, A. Girycki, S. Pollin, S. Pryor, P. Chanclou, and C. Verikoukis, "Machine learning-based cell-free support in the o-ran architecture: An innovative converged optical-wireless solution toward 6g networks," *IEEE Wireless Communications*, vol. 29, no. 5, pp. 20–26, 2022.

[158] B. Ojaghi, F. Adelantado, A. Antonopoulos, and C. Verikoukis, "Slicedran: Service-aware network slicing framework for 5g radio access networks," *IEEE Systems Journal*, vol. 16, no. 2, pp. 2556–2567, 2021.

[159] A. F. Pakpahan and I.-S. Hwang, "Flexible access network multi-tenancy using nfv/sdn in twdm-pon," *IEEE Access*, 2023.

[160] Series G Supplement 74, "Network slicing in a passive optical network context," 12/2021. [Online]. Available: https://www.itu.int/rec/T-REC-G.Sup74-202112-I

[161] H. Uzawa, K. Honda, H. Nakamura, Y. Hirano, K.-i. Nakura, S. Kozaki, and J. Terada, "Dynamic bandwidth allocation scheme for network-slicing-based tdm-pon toward the beyond-5g era," *Journal of Optical Communications and Networking*, vol. 12, no. 2, pp. A135–A143, 2020.

[162] K. H. Mohammadani, R. A. Butt, K. A. Memon, N. N. Hussaini, and A. Shaikh, "Load adaptive merging algorithm for multi-tenant pon environments," *Optical Switching and Networking*, vol. 47, p. 100712, 2023.

[163] M. Wang, G. Simon, L. A. Neto, I. Amigo, L. Nuaymi, and P. Chanclou, "Sdn east–west cooperation in a converged fixed-mobile optical access network: enabling 5g slicing capabilities," *Journal of Optical Communications and Networking*, vol. 14, no. 7, pp. 540–549, 2022.

[164] A. Sgambelluri, F. Paolucci, F. Cugini, L. Valcarenghi, and P. Castoldi, "Generalized sdn control for access/metro/core integration in the framework of the interface to the routing system (i2rs)," in *2013 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2013, pp. 1216–1220.

[165] S. Li, G. Shou, Y. Hu, and Z. Guo, "Sdn-based energy-saving scheme for fiber-wireless network," in *11th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2015)*. IET, 2015, pp. 1–4.

[166] A. Morris. (June 2021) Telefónica flags fixed access evolution with open broadband project. [Online]. Available: https://www.telcotitans.com/telefonicawatch/telefonica-flags-fixed-access-evolution-with-open-broadband-project/3293.article(Dateaccessed:31.07.2022).

[167] R. Cantó. (May 2022) Strategy towards open broadband: ONF Berlin meet up meeting. [Online]. Available: https://opennetworking.org/wp-content/uploads/2022/05/Telefonica-ONF-Broadband_v1.1_20220520_Berlin_TEF.pdf(Dateaccessed:31.07.2022).

[168] D. Hillerkuss and J. Leuthold, "Software-defined transceivers in dynamic access networks," *Journal of Lightwave Technology*, vol. 34, no. 2, pp. 792–797, 2016.

[169] C.-H. Yeh, C.-W. Chow, M.-H. Yang, and D.-Z. Hsu, "A flexible and reliable 40-gb/s ofdm downstream twdm-pon architecture," *IEEE Photonics Journal*, vol. 7, no. 6, pp. 1–9, 2015.

[170] J. Zhang and Z. Jia, "Coherent passive optical networks for 100g/λ-and-beyond fiber access: Recent progress and outlook," *IEEE Network*, vol. 36, no. 2, pp. 116–123, 2022.

[171] J. Zhang, G. Li, S. Xing, and N. Chi, "Flexible and adaptive coherent pon for next-generation optical access network," *Optical Fiber Technology*, vol. 75, p. 103190, 2023.

[172] V. Sales, J. Segarra, V. Polo, J. C. Velásquez, and J. Prat, "Udwdm-pon using low-cost coherent transceivers with limited tunability and heuristic dwa," *Journal of Optical Communications and Networking*, vol. 8, no. 8, pp. 582–599, 2016.

[173] M. Erkılınç, D. Lavery, K. Shi, B. Thomsen, R. Killey, S. Savory, and P. Bayvel, "Bidirectional wavelength-division multiplexing transmission over installed fibre using a simplified optical coherent access transceiver," *Nature communications*, vol. 8, no. 1, p. 1043, 2017.

[174] R. M. Ferreira, A. Shahpari, J. D. Reis, and A. L. Teixeira, "Coherent udwdm-pon with dual-polarization transceivers in real-time," *IEEE Photonics Technology Letters*, vol. 29, no. 11, pp. 909–912, 2017.

[175] F. Vacondio, O. Bertran-Pardo, Y. Pointurier, J. Fickers, A. Ghazisaeidi, G. de Valicourt, J.-C. Antona, P. Chanclou, and S. Bigo, "Flexible tdma access optical networks enabled by burst-mode software defined coherent transponders," in *39th European Conference and Exhibition on Optical Communication (ECOC 2013)*. IET, 2013, pp. 1–3.

[176] V. Gudla, S. Das, A. Shastri, G. Parulkar, N. McKeown, L. Kazovsky, and S. Yamashita, "Experimental demonstration of openflow control of packet and circuit switches," in *Optical Fiber Communication Conference*. Optical Society of America, 2010, p. OTuG2.

[177] N. Cvijetic, A. Tanaka, P. N. Ji, S. Murakami, K. Sethuraman, and T. Wang, "First openflow-based software-defined λ-flow architecture for flex-grid ofdma mobile backhaul over passive optical networks with filterless direct detection onus," in *National Fiber Optic Engineers Conference*. Optica Publishing Group, 2013, pp. PDP5B–2.

[178] N. Cvijetic and T. Wang, "Systems challenges for sdn in fiber wireless networks," *Fiber-Wireless Convergence in Next-Generation Communication Networks: Systems, Architectures, and Management*, pp. 189–209, 2017.

[179] Y. Ma, L. Stewart, J. Armstrong, I. G. Clarke, and G. Baxter, "Recent progress of wavelength selective switch," *Journal of Lightwave Technology*, vol. 39, no. 4, pp. 896–903, 2020.

[180] S. Sarmiento, J. A. Altabas, D. Izquierdo, I. Garces, S. Spadaro, and J. A. Lazaro, "Cost-effective dwdm roadm design for flexible sustainable optical metro–access networks," *Journal of Optical Communications and Networking*, vol. 9, no. 12, pp. 1116–1124, 2017.

[181] H. Carvalho, E. Magalhães, M. Garrich, N. Gonzalez, M. Nascimento, F. Margarido, L. Mariote, A. Bordonalli, and J. Oliveira, "Sdn dual-

optimization application for edfas and wss-based roadms," in *2015 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2015, pp. 1–3.

[182] D. Konstantinou, T. A. Bressner, S. Rommel, U. Johannsen, M. N. Johansson, M. V. Ivashina, A. B. Smolders, and I. T. Monroy, "5g ran architecture based on analog radio-over-fiber fronthaul over udwdm-pon and phased array fed reflector antennas," *Optics Communications*, vol. 454, p. 124464, 2020.

[183] V. Lopez, W. Ishida, A. Mayoral, T. Tanaka, O. G. de Dios, and J. P. Fernandez-Palacios, "Enabling fully programmable transponder white boxes," *Journal of Optical Communications and Networking*, vol. 12, no. 2, pp. A214–A223, 2020.

[184] Radisy, "Telefónica partners with radisys to add flexibility and programmability to its network with radisys' connect open broadband," 2022. [Online]. Available: https://www.telefonica.com/en/wp-content/uploads/sites/5/2022/10/pr-radisys-telefonica.pdf

[185] S. S. Lee, K.-Y. Li, and M.-S. Wu, "Design and implementation of a gpon-based virtual openflow-enabled sdn switch," *Journal of Lightwave Technology*, vol. 34, no. 10, pp. 2552–2561, 2016.

[186] K. Nishimoto, K. Asaka, J.-i. Kani, and J. Terada, "Automated provisioning method for a modular pon-olt device toward plug & provision," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 12, no. 9, pp. D9–D16, 2020.

[187] *ONF TS-100 (version 1.0): SDN Enabled Broadband Access (SEBA)*, Std., March, 2019.

[188] "Open Broadband - Broadband Access Abstraction (OB-BAA)." [Online]. Available: https://obbaa.broadband-forum.org/overview/

[189] T. Suzuki, S.-Y. Kim, J.-i. Kani, and J. Terada, "Software implementation of 10g-epon upstream physical-layer processing for flexible access systems," *Journal of Lightwave Technology*, vol. 37, no. 6, pp. 1631–1637, 2018.

[190] J.-i. Kani, M. Yoshino, K. Asaka, H. Ujikawa, T. Yamada, K. Nishimoto, K.-I. Suzuki, and A. Otaka, "Flexible access system architecture (fasa) to support diverse requirements and agile service creation," *Journal of Lightwave Technology*, vol. 36, no. 8, pp. 1510–1515, 2018.

[191] F. Slyne, D. Coyle, J. Singh, R. Sexton, B. Ryan, R. Giller, M. O'Hanlon, and M. Ruffini, "Experimental demonstration of multiple disaggregated olts with virtualised multi tenant dba, over general purpose processor," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2020, pp. M3Z–11.

[192] F. Slyne, R. Giller, J. Singh, and M. Ruffini, "Experimental demonstration of dpdk optimised vnf implementation of virtual dba in a multi-tenant pon," in *2018 European Conference on Optical Communication (ECOC)*. IEEE, 2018, pp. 1–3.

[193] 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," *Journal of Optical Communications and Networking*, vol. 12, no. 4, pp. B63–B73, 2020.

[194] F. Slyne, A. Elrasad, C. Bluemm, and M. Ruffini, "Demonstration of real time vnf implementation of olt with virtual dba for sliceable multi-tenant pons," in *2018 Optical Fiber Communications Conference and Exposition (OFC)*. IEEE, 2018, pp. 1–3.

[195] B. F. (BBF). (2018) Functional model for PON abstraction interface. [Online]. Available: https://www.broadband-forum.org/download/TR-402.pdf

[196] K. Nishimoto, T. Tochino, T. Hatano, K. Asaka, J.-i. Kani, and J. Terada, "Mini-pon: disaggregated module-type pon architecture for realizing various pon deployments," *Journal of Optical Communications and Networking*, vol. 12, no. 5, pp. 89–98, 2020.

[197] K. Nishimoto, K. Asaka, J.-i. Kani, and J. Terada, "Automated provisioning method for a modular pon-olt device toward plug & provision," *Journal of Optical Communications and Networking*, vol. 12, no. 9, pp. D9–D16, 2020.

[198] T. Suzuki, S.-Y. Kim, J.-i. Kani, and J. Terada, "Demonstration of fully softwarized 10g-epon phy processing on a general-purpose server for flexible access systems," *Journal of Lightwave Technology*, vol. 38, no. 4, pp. 777–783, 2020.

[199] T. Suzuki, S.-Y. Kim, J.-i. Kani, and T. Yoshida, "Low-latency pon phy implementation on gpus for fully software-defined access networks," *IEEE Network*, vol. 36, no. 2, pp. 108–114, 2022.

[200] S.-W. Wong, L. Valcarenghi, S.-H. Yen, D. Campelo, S. Yamashita, and L. Kazovsky, "Sleep mode for energy saving pons: Advantages and drawbacks," in *GLOBECOM Workshops, 2009 IEEE*, 2009, pp. 1–6.

[201] T. Uchikata and A. Tajima, "A novel power saving scheme for WDM-PON with centralized light sources," in *2009 14th OptoElectronics and Communications Conference*. IEEE, 2009, pp. 1–2.

[202] R. Kubo, J.-I. Kani, Y. Fujimoto, N. Yoshimoto, and K. Kumozaki, "Sleep and adaptive link rate control for power saving in 10g-epon systems," in *GLOBECOM 2009-2009 IEEE Global Telecommunications Conference*. IEEE, 2009, pp. 1–6.

[203] T. V. y Villalba, S. M. Rossi, M. P. Mokarzel, M. R. Salvador, H. M. A. Neto, A. C. Cesar, M. A. Romero, and M. d. L. Rocha, "Design of passive optical networks using genetic algorithm," in *2009 SBMO/IEEE MTT-S international microwave and optoelectronics conference (IMOC)*. IEEE, 2009, pp. 682–686.

[204] Y. Yan and L. Dittmann, "Energy efficient ethernet passive optical networks (epons) in access networks," in *WSEAS International Conference on Applied Informatics and Communication*, 2010.

[205] D. Ren, H. Li, and Y. Ji, "Power saving mechanism and performance analysis for 10 Gigabit-class passive optical network systems," in *Network Infrastructure and Digital Content, 2010 2nd IEEE International Conference on*, sept. 2010, pp. 920 –924.

[206] R. Kubo, J.-i. Kani, H. Ujikawa, T. Sakamoto, Y. Fujimoto, N. Yoshimoto, and H. Hadama, "Study and Demonstration of Sleep and Adaptive Link Rate Control Mechanisms for Energy Efficient 10G-EPON," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 2, no. 9, pp. 716–729, 2010.

[207] J. Zhang and N. Ansari, "Toward energy-efficient 1G-EPON and 10G-EPON with sleep-aware MAC control and scheduling," *Communications Magazine, IEEE*, vol. 49, no. 2, pp. s33–s38, 2011.

[208] L. Shi, S. S. Lee, and B. Mukherjee, "An SLA-based energy-efficient scheduling scheme for EPON with sleep-mode ONU," in *Optical Fiber Communication Conference*. Optical Society of America, 2011, p. OThB4.

[209] Y. Luo, M. Sui, and F. Effenberger, "Wavelength management in time and wavelength division multiplexed passive optical networks (TWDM-PONs)," in *2012 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2012, pp. 2971–2976.

[210] H. Bang, J. Kim, Y. Shin, and C.-S. Park, "Analysis of ont buffer and power management performances for XG-PON cyclic sleep mode," in *2012 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2012, pp. 3116–3121.

[211] H. Y. Choi, L. Liu, T. Tsuritani, and I. Morita, "Demonstration of ber-adaptive wson employing flexible transmitter/receiver with an extended openflow-based control plane," *IEEE Photonics Technology Letters*, vol. 25, no. 2, pp. 119–121, 2012.

[212] J.-P. Elbers and A. Autenrieth, "From static to software-defined optical networks," in *2012 16th International Conference on Optical Network Design and Modelling (ONDM)*. IEEE, 2012, pp. 1–4.

[213] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Wavelength switched hybrid tdma/wdm (twdm) pon: A flexible next-generation optical access solution," in *2012 14th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2012, pp. 1–5.

[214] S. H. S. Newaz, K. Laghari, G. M. Lee, N. Crespi, and J. Choi, "Energy efficient shared WDM-PON," in *2012 14th International Conference on Advanced Communication Technology (ICACT)*. IEEE, 2012, pp. 1017–1020.

[215] H. H. Lee, K. Kim, J. Lee, and S. Lee, "Efficient power-saving 10-gb/s onu using uplink usage-dependent sleep mode control algorithm in wdm-pon," *ETRI Journal*, vol. 35, no. 2, pp. 253–258, 2013.

[216] A. R. Dhaini, P.-H. Ho, G. Shen, and B. Shihada, "Energy efficiency in tdma-based next-generation passive optical access networks," *IEEE/ACM transactions on networking*, vol. 22, no. 3, pp. 850–863, 2013.

[217] S. S. Newaz, Á. Cuevas, G. M. Lee, N. Crespi, and J. K. Choi, "Adaptive delay-aware energy efficient TDM-PON," *Computer Networks*, vol. 57, no. 7, pp. 1577 – 1596, 2013.

[218] B. Yan, J. Zhou, J. Wu, and Y. Zhao, "Poster: Sdn based energy management system for optical access network," in *9th International Conference on Communications and Networking in China*. IEEE, 2014, pp. 658–659.

[219] J. Li, W. Sun, H. Yang, and W. Hu, "Adaptive registration in TWDM-PON with ONU migrations," *Journal of Optical Communications and Networking*, vol. 6, no. 11, pp. 943–951, 2014.

[220] J. Zhao, N. Feng, X. Liu, W. Bai, and M. Maier, "Implementing network coding in service interoperability ethernet passive optical network (ieee p1904. 1 siepon)," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 6, no. 5, pp. 510–522, 2014.

[221] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Energy efficient DBA algorithms for TWDM-PONs," in *2015 17th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2015, pp. 1–5.

[222] R. O. 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 Communications Magazine*, vol. 53, no. 8, pp. 150–157, 2015.

[223] D. Ren, S. Wu, and L. Zhang, "A new wavelength optimization and energy-saving scheme based on network coding in software-defined wdm-pon networks," *Journal of Optical Communications*, vol. 37, no. 3, pp. 265–269, 2016.

[224] S. Dutta, D. Roy, C. Bhar, and G. Das, "Online scheduling protocol design for energy-efficient TWDM-OLT," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 10, no. 3, pp. 260–271, 2018.

[225] 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 *2018 IEEE Symposium on Computers and Communications (ISCC)*. IEEE, 2018, pp. 521–526.

[226] A. K. Garg, "Fully flexible remote node based energy-efficient and scalable hybrid wdm-tdm optical access network with broadcasting capability," *Optical and Quantum Electronics*, vol. 54, no. 5, pp. 1–23, 2022.

[227] R. A. Butt, A. Akhunzada, M. Faheem, and B. Raza, "Enhanced energy savings with adaptive watchful sleep mode for next generation passive optical network," *Energies*, vol. 15, no. 5, p. 1639, 2022.

[228] K. H. Mohammadani, R. A. Butt, W. Nawaz, S. Faizullah, and Z. A. Dayo, "Energy-efficient sleep-aware slicing-based scheduler (sa-sbs) for multi-operators virtualized passive optical networks," *IEEE Access*, 2023.

[229] *10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification*, Std., 2010.

[230] ITU-T Recommendation G.988, "ONU management and control interface (OMCI) specification," 2012. [Online]. Available: https://www.itu.int/rec/T-REC-G.988/en

[231] *ITU-T G.984.3, Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification, year = Jan. 2014, url = https://www.itu.int/rec/T-REC-G.984.3-201401-I.,*, Std.

[232] *40-Gigabit-capable passive optical networks (NG-PON2): General requirements (Amendment 1)*, Std., Aug. 2015.

[233] "Ieee standard for service interoperability in ethernet passive optical networks (siepon)," *IEEE Std 1904.1-2017 (Revision of IEEE Std 1904.1-2013)*, pp. 1–893, 2017.

[234] *ITU-T G.987.3, Amendment 1, Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification, year = Jan. 2020, url = https://www.itu.int/rec/T-REC-G.987.3-202003-P!Amd1.* ,, Std.

[235] *Recommendation ITU-T G.9804.2: Higher speed passive optical networks – Common transmission convergence layer specification*, Std., Sep. 2021.

[236] E. Kosmatos, C. Matrakidis, D. Uzunidis, A. Stavdas, S. Horlitz, T. Pfeiffer, A. Lord, and E. Riccardi, "Real-time orchestration of qos-aware end-to-end slices across a converged metro and access network exploiting burst-mode technology," *Journal of Optical Communications and Networking*, vol. 15, no. 1, pp. 1–15, 2023.

[237] C. Centofanti, A. Marotta, D. Cassioli, F. Graziosi, N. Sambo, L. Valcarenghi, C. Bernard, and H. Roberts, "Slice management in sdn pon supporting low-latency services," in *European Conference and Exhibition on Optical Communication*. Optica Publishing Group, 2022, pp. Tu5–64.

[238] 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 Transactions on Green Communications and Networking*, vol. 5, no. 1, pp. 18–28, 2020.

[239] J.Zhang and N. Ansari, "Standards-compliant EPON sleep control for energy efficiency: design and analysis," in *Communications (ICC), 2012 IEEE International Conference on*, 2012, pp. 2994–2998.

[240] L. Zhang, Y. Liu, L. Guo, and X. Gong, "Energy-saving scheme based on downstream packet scheduling in ethernet passive optical networks," *Optical Fiber Technology*, vol. 19, no. 2, pp. 169–178, 2013.

[241] L. Valcarenghi, D. P. Van, P. G. Raponi, P. Castoldi, D. R. Campelo, S.-W. Wong, S.-H. Yen, L. G. Kazovsky, and S. Yamashita, "Energy efficiency in passive optical networks: where, when, and how?" *IEEE Network*, vol. 26, no. 6, pp. 61–68, 2012.

[242] A. Lovrić and S. Aleksić, "Power efficiency of extended reach 10g-epon and tdm/wdm pon," in *2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference*. IEEE, 2010, pp. 1–3.

[243] J. Sugawa, H. Ikeda, and T. Kazawa, "Method of recovery from sleep state of an onu in a pon system capable of power saving," Apr. 22 2014, U.S. Patent 8705965.

[244] H. Khalili, D. Rincón, S. Sallent, and J. R. Piney, "An energy-efficient distributed dynamic bandwidth allocation algorithm for passive optical access networks," *Sustainability*, vol. 12, no. 6, p. 2264, 2020.

[245] J. Zhang, T. Wang, and N. Ansari, "Designing energy-efficient optical line terminal for TDM passive optical networks," in *34th IEEE sarnoff Symposium*. IEEE, 2011, pp. 1–5.

[246] M. Taheri, J. Zhang, and N. Ansari, "Design and analysis of green optical line terminals for TDM passive optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 8, no. 4, pp. 221–228, 2016.

[247] H. Feng, C.-J. Chae, A. V. Tran, and A. Nirmalathas, "Cost-effective introduction and energy-efficient operation of long-reach wdm/tdm pon systems," *Journal of Lightwave Technology*, vol. 29, no. 21, pp. 3135–3143, 2011.

[248] S. S. Newaz, A. Cuevas, G. M. Lee, N. Crespi, and J. Choi, "A novel approach for making energy efficient pon," in *Proceedings of the ACM SIGCOMM 2011 conference*, 2011, pp. 428–429.

[249] S. Petridou, S. Basagiannis, and L. Mamatas, "Formal methods for energy-efficient epons," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 1, pp. 246–259, 2017.

[250] S. S. Newaz, M. S. Jang, F. Y. M. Alaelddin, G. M. Lee, and J. K. Choi, "Building an energy-efficient uplink and downlink delay aware TDM-PON system," *Optical Fiber Technology*, vol. 29, pp. 34–52, 2016.

[251] L. Shi, S.-S. Lee, and B. Mukherjee, "An SLA-based energy-efficient scheduling scheme for EPON with sleep-mode ONU," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference*, March 2011, pp. 1–3.

[252] Y. Yan and L. Dittmann, "Enhanced sleep mode mac control for epon," in *16th Opto-Electronics and Communications Conference*. IEEE, 2011, pp. 545–546.

[253] F. Y. M. Alaelddin, S. S. Newaz, J. Lee, M. R. Uddin, G. M. Lee, and J. K. Choi, "Performance analysis of TCP traffic and its influence on ONU's energy saving in energy efficient TDM-PON," *Optical Fiber Technology*, vol. 26, Part B, pp. 190 – 200, 2015.

[254] S. S. Newaz, A. Cuevas, G. M. Lee, N. Crespi, and J. K. Choi, "Evaluating energy efficiency of ONUs having multiple power levels in TDM-PONs," *IEEE communications letters*, vol. 17, no. 6, pp. 1248–1251, 2013.

[255] D. C. Kilper and H. Rastegarfar, "Energy challenges in optical access and aggregation networks," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374, no. 2062, p. 20140435, 2016.

[256] H. Sasaki, "Development of silicon photonics integrated circuits for next generation optical access networks," in *2019 2nd International Symposium on Devices, Circuits and Systems (ISDCS)*. IEEE, 2019, pp. 1–4.

[257] S.-H. Yen, S.-W. Wong, S. Das, N. Cheng, J. Cho, S. Yamashita, O. Solgaard, and L. G. Kazovsky, "Photonic components for future fiber access networks," *Selected Areas in Communications, IEEE Journal on*, vol. 28, no. 6, pp. 928–935, 2010.

[258] S.-W. Wong, L. Valcarenghi, S.-H. Yen, D. Campelo, S. Yamashita, and L. Kazovsky, "Sleep Mode for Energy Saving PONs: Advantages and Drawbacks," in *GLOBECOM Workshops, 2009 IEEE*, 2009, pp. 1–6.

[259] S.-W. Wong, S.-H. Yen, P. Afshar, S. Yamashita, and L. G. Kazovsky, "Demonstration of energy conserving TDM-PON with sleep mode ONU using fast clock recovery circuit," in *Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference, 2010 Conference on (OFC/NFOEC)*, 2010, pp. 1–3.

[260] Y. Lv, M. Bi, Y. Zhai, H. Chi, and Y. Wang, "Study on the solutions to heterogeneous onu propagation delays for energy-efficient and low-latency epons," *IEEE Access*, vol. 8, pp. 193 665–193 680, 2020.

[261] L. Valcarenghi, M. Presi, G. Contestabile, P. Castoldi, and E. Ciaramella, "Impact of modulation formats on ONU energy saving," in *Optical Communication (ECOC), 2010 36th European Conference and Exhibition on*, 2010, pp. 1–3.

[262] S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall, "Reducing network energy consumption via sleeping and rate-adaptation," *NSDI'08 Proceedings of the 5th USENIX Symposium on Networked Systems Design and Implementation*, vol. 20, pp. 323–336, 2008.

[263] A. Kanduri, A. M. Rahmani, P. Liljeberg, A. Hemani, A. Jantsch, and H. Tenhunen, "A perspective on dark silicon," in *The Dark Side of Silicon*. Springer, 2017, pp. 3–20.

[264] D. Kliazovich, S. T. Arzo, F. Granelli, P. Bouvry, and S. U. Khan, "Accounting for load variation in energy-efficient data centers," in *Com-*

munications (ICC), 2013 IEEE International Conference on. IEEE, 2013, pp. 2561–2566.

[265] B. Calhoun, J. Kao, and A. Chandrakasan, "Power gating and dynamic voltage scaling," in *Leakage in Nanometer CMOS Technologies*. Springer, 2006, pp. 41–75.

[266] C. Gunaratne, K. Christensen, B. Nordman, and S. Suen, "Reducing the energy consumption of ethernet with adaptive link rate (alr)," *IEEE Transactions on Computers*, vol. 57, no. 4, pp. 448–461, 2008.

[267] T. Kodama, R. Matsumoto, T. Inoue, S. Namiki, and M. Jinno, "Baud-rate-adaptive olt integrated-coherent transceiver for nyquist spectral shaped/channel spaced wdm-pon," in *2020 Opto-Electronics and Communications Conference (OECC)*. IEEE, 2020, pp. 1–3.

[268] P. Sun, M. M. Hayat, B. E. Saleh, and M. C. Teich, "Statistical correlation of gain and buildup time in apds and its effects on receiver performance," *Journal of Lightwave Technology*, vol. 24, no. 2, p. 755, 2006.

[269] S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall, "Reducing network energy consumption via sleeping and rate-adaptation." in *NsDI*, vol. 8, 2008, pp. 323–336.

[270] L. Zhang, L. Guo, and Y. Liu, "Energy saving mechanism based on sleep mode and dynamic double-threshold link selection in EPON," in *2012 1st IEEE International Conference on Communications in China (ICCC)*. IEEE, 2012, pp. 291–296.

[271] H. Uzawa, K. Terada, N. Ikeda, A. Miyazaki, M. Urano, and T. Shibata, "Energy-efficient frame-buffer architecture and it's control schemes for ONU power reduction," in *2011 IEEE Global Telecommunications Conference-GLOBECOM 2011*. IEEE, 2011, pp. 1–5.

[272] G. C. Sankaran and K. M. Sivalingam, "Onu buffer elimination for power savings in passive optical networks," in *2011 IEEE International Conference on Communications (ICC)*. IEEE, 2011, pp. 1–5.

[273] W. Qadeer, T. S. Rosing, J. Ankcorn, V. Krishnan, and G. De Micheli, "Heterogeneous wireless network management," in *Power-Aware Computer Systems: Third International Workshop, PACS 2003, San Diego, CA, USA, December 1, 2003 Revised Papers 3*. Springer, 2005, pp. 86–100.

[274] M. Šprem and D. Babić, "Wavelength reuse wdm-pon using rsoa and modulation averaging," *Optics Communications*, vol. 451, pp. 1–5, 2019.

[275] M. Zhu, W.-D. Zhong, Z. Zhang, and F. Luan, "A cls-based survivable and energy-saving wdm-pon architecture," *Optics Communications*, vol. 308, pp. 293–303, 2013.

[276] H. Yang, W. Sun, J. Li, and W. Hu, "Energy efficient TWDM multi-PON system with wavelength relocation," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 6, no. 6, pp. 571–577, 2014.

[277] R. S. Tucker, "Green optical communications—part ii: Energy limitations in networks," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 17, no. 2, pp. 261–274, 2010.

[278] P. Yin, J. R. Serafini, Z. Su, R.-J. Shiue, E. Timurdogan, M. L. Fanto, and S. Preble, "Low connector-to-connector loss through silicon photonic chips using ultra-low loss splicing of smf-28 to high numerical aperture fibers," *Optics express*, vol. 27, no. 17, pp. 24 188–24 193, 2019.

[279] N. Kaneda, R. Zhang, Y. Lefevre, A. Mahadevan, D. van Veen, and V. Houtsma, "First experimental demonstration of flexible rate pon beyond 100gb/s with probabilistic and geometric shaping," in *2021 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2021, pp. 1–3.

[280] M. C. Yuang, D.-Z. Hsu, P.-L. Tien, H.-Y. Chen, C.-C. Wei, S.-H. Chen, and J. Chen, "An energy and cost efficient wdm/ofdma pon system: design and demonstration," *Journal of Lightwave Technology*, vol. 31, no. 16, pp. 2809–2816, 2013.

[281] X. Liu, K. Fouli, R. Kang, and M. Maier, "Network-coding-based energy management for next-generation passive optical networks," *Journal of lightwave technology*, vol. 30, no. 6, pp. 864–875, 2012.

[282] J.-i. Kani, J. Terada, T. Hatano, S.-Y. Kim, K. Asaka, and T. Yamada, "Future optical access network enabled by modularization and softwarization of access and transmission functions," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 12, no. 9, pp. D48–D56, 2020.

[283] M. Zhu, W.-D. Zhong, Z. Zhang, and F. Luan, "An efficient energy-saving scheme incorporating dozing and sleep modes for cls-based wdm-pons with colorless onus," *Optics Express*, vol. 20, no. 28, pp. 29 931–29 939, 2012.

[284] J. H. Cox, J. Chung, S. Donovan, J. Ivey, R. J. Clark, G. Riley, and H. L. Owen, "Advancing software-defined networks: A survey," *IEEE Access*, vol. 5, pp. 25 487–25 526, 2017.

[285] K. Kondepu, A. Sgambelluri, F. Cugini, P. Castoldi, R. A. Morenilla, D. Larrabeiti, B. Vermeulen, and L. Valcarenghi, "Performance evaluation of sdn-controlled green mobile fronthaul using a federation of experimental network testbeds," *Photonic Network Communications*, vol. 37, no. 3, pp. 399–408, 2019.

[286] I. A. Alimi, A. L. Teixeira, and P. P. Monteiro, "Toward an efficient c-ran optical fronthaul for the future networks: A tutorial on technologies, requirements, challenges, and solutions," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 708–769, 2018.

[287] R. Bolla, R. Bruschi, F. Davoli, and C. Lombardo, "Fine-grained energy-efficient consolidation in sdn networks and devices," *IEEE Transactions on Network and Service Management*, vol. 12, no. 2, pp. 132–145, 2015.

[288] K. Wang, A. Gavler, C. M. Machuca, L. Wosinska, K. Brunnström, and J. Chen, "Migration strategies for fttx solutions based on active optical networks," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 78–85, 2016.

[289] A. F. Pakpahan and I.-S. Hwang, "Enabling flexible software-defined energy-efficient orchestration in twdm-pon," *Journal of Internet Technology*, vol. 21, no. 2, pp. 365–374, 2020.

[290] A. F. Pakpahan, I.-S. Hwang, and A. Nikoukar, "Olt energy savings via software-defined dynamic resource provisioning in TWDM-PONs," *Journal of Optical Communications and Networking*, vol. 9, no. 11, pp. 1019–1029, 2017.

[291] L. Valcarenghi, K. Kondepu, A. Sgambelluri, F. Cugini, P. Castoldi, R. A. Morenilla, D. Larrabeiti, and B. Vermeulen, "Sdn-controlled energy-efficient mobile fronthaul: An experimental evaluation in federated testbeds," in *2016 European Conference on Networks and Communications (EuCNC)*. IEEE, 2016, pp. 298–301.

[292] G. Kramer. (2020) Ieee 1904 access networks working group: Opening report. [Online]. Available: https://grouper.ieee.org/groups/1904/meeting_archive/2020/06/anwg_2006_opening.pdf

[293] I. . T. Force. (2020) Ieee 1904.4 task force:standard for service interoperability in 25 gb/s and 50 gb/s ethernet passive optical networks. [Online]. Available: https://grouper.ieee.org/groups/1904/4/tf4_home.shtml

[294] A. F. Y. Mohammed, S. S. Newaz, M. R. Uddin, G. M. Lee, and J. K. Choi, "Early wake-up decision algorithm for onus in tdm-pons with sleep mode," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 8, no. 5, pp. 308–319, 2016.

[295] *Multiple-wavelength passive optical networks (MW-PONs)*, Std., Apr. 2015.

[296] *10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification*, Std., Jan. 2014. [Online]. Available: https://www.itu.int/rec/T-REC-G.987.3-201401-I/en.

[297] A. Dixit, B. Lannoo, G. Das, D. Colle, M. Pickavet, and P. Demeester, "Dynamic bandwidth allocation with SLA awareness for QoS in ethernet passive optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 3, pp. 240–253, 2013.

[298] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Energy efficient dynamic bandwidth allocation for ethernet passive optical networks: Overview, challenges, and solutions," *Optical Switching and Networking*, vol. 18, pp. 169–179, 2015.

[299] A. Nikoukar, I.-S. Hwang, C.-J. Wang, M. S. Ab-Rahman, and A. T. Liem, "A SIEPON based transmitter sleep mode energy-efficient mechanism in EPON," *Optical Fiber Technology*, vol. 23, pp. 78–89, 2015.

[300] C.-Z. Yang, M. A. Lotfolahi, I.-S. Hwang, M. S. Ab-Rahman, A. Nikoukar, A. T. Liem, and E. Ganesan, "Enhancing energy efficiency of the doze mode mechanism in ethernet passive optical networks using support vector regression," in *Photonics*, vol. 9, no. 3. MDPI, 2022, p. 180.

[301] S. Nishihara, N. Miura, N. Tanaka, K.-I. Suzuki, and N. Yoshimoto, "Effectiveness of SIEPON package B compliant ONU sleep technique and impact on latency and transmission efficiency from a theoretical point of view," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 6, no. 4, pp. 362–370, April 2014.

[302] R. Kubo, J. ichi Kani, Y. Fujimoto, N. Yoshimoto, and K. Kumozaki, "Adaptive power saving mechanism for 10 gigabit class PON systems," *IEICE Transactions on Communications*, vol. E93.B, no. 2, pp. 280–288, 2010.

[303] P. G. Sarigiannidis, V. D. Pechlivanidou, M. D. Louta, and P. Angelidis, "Towards an effective energy efficient passive optical network," in *2011 IEEE Symposium on Computers and Communications (ISCC)*. IEEE, 2011, pp. 391–396.

[304] J. Zhang, M. T. Hosseinabadi, and N. Ansari, "Standards-compliant EPON sleep control for energy efficiency: Design and analysis,"

IEEE/OSA Journal of Optical Communications and Networking, vol. 5, no. 7, pp. 677–685, 2013.

[305] S. Lee and A. Chen, “Design and Analysis of a Novel Energy Efficient Ethernet Passive Optical Network,” in *Networks (ICN), 2010 Ninth International Conference on*, 2010, pp. 6–9.

[306] L. Shi, B. Mukherjee, and S.-S. Lee, “Energy-efficient pon with sleep-mode onu: progress, challenges, and solutions,” *IEEE Network*, vol. 26, no. 2, pp. 36–41, 2012.

[307] A. R. Dhaini, P.-H. Ho, and G. Shen, “Toward green next-generation passive optical networks,” *IEEE Communications Magazine*, vol. 49, no. 11, pp. 94–101, 2011.

[308] C. Li, W. Guo, W. Hu, and M. Xia, “Energy-efficient dynamic bandwidth allocation for epon networks with sleep mode onus,” *Optical Switching and Networking*, vol. 15, pp. 121–133, 2015.

[309] A. Helmy and A. Nayak, “Towards more dynamic energy-efficient bandwidth allocation in EPONs,” in *2018 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2018, pp. 1–6.

[310] I.-S. Hwang, A. Nikoukar, Y.-M. Su, and A. T. Liem, “Decentralized siepon-based onu-initiated tx/trx energy-efficiency mechanism in epon,” *Journal of Optical Communications and Networking*, vol. 8, no. 4, pp. 238–248, 2016.

[311] H. Bang, J. Kim, S.-S. Lee, and C.-S. Park, “Determination of sleep period for cyclic sleep mode in XG-PON power management,” *IEEE communications letters*, vol. 16, no. 1, pp. 98–100, 2011.

[312] X. Zeng, M. Zhu, L. Wang, and X. Sun, “Optimization of sleep period in watchful sleep mode for power-efficient passive optical networks,” *Photonic Network Communications*, vol. 35, no. 3, pp. 300–308, 2018.

[313] K.-H. Tse, W. Jia, and C.-K. Chan, “A cost-effective pilot-tone-based monitoring technique for power saving in rsoa-based wdm-pon,” in *Optical Fiber Communication Conference*. Optical Society of America, 2011, p. OThB6.

[314] H. H. Lee, K.-O. Kim, J. H. Lee, and S. S. Lee, “Power saved olt and onu with cyclic sleep mode operating in WDM-PON,” in *2012 International Conference on ICT Convergence (ICTC)*. IEEE, 2012, pp. 217–218.

[315] N. Kim and M. Kang, “Traffic share-based multicast scheduling for broadcast video delivery in shared-wdm-pons,” *Journal of lightwave technology*, vol. 25, no. 9, pp. 2814–2827, 2007.

[316] W. Wang, W. Guo, C. Li, W. Hu, and M. Xia, “ONU aggregation schemes for TWDM PONs with multiple tuning ranges,” *Journal of Optical Communications and Networking*, vol. 9, no. 4, pp. 319–326, 2017.

[317] H. Yang, W. Sun, J. Li, and W. Hu, “User migration in time and wavelength division multiplexed pon (twdm-pon),” in *2013 15th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2013, pp. 1–4.

[318] K. Kondepu, L. Valcarenghi, and P. Castoldi, “Dynamic wavelength and bandwidth allocation versus osu-onu cyclic sleep in twdm-pons: An experimental evaluation,” in *2015 International Conference on Optical Network Design and Modeling (ONDM)*. IEEE, 2015, pp. 162–167.

[319] M. P. I. Dias, D. P. Van, L. Valcarenghi, and E. Wong, “Energy-efficient dynamic wavelength and bandwidth allocation algorithm for twdm-pons with tunable vcsel onus,” in *2014 OptoElectronics and Communication Conference and Australian Conference on Optical Fibre Technology*. IEEE, 2014, pp. 1007–1009.

[320] M. P. I. Dias, E. Wong, D. P. Van, and L. Valcarenghi, “Offline energy-efficient dynamic wavelength and bandwidth allocation algorithm for twdm-pons,” in *2015 IEEE International Conference on Communications (ICC)*. IEEE, 2015, pp. 5018–5023.

[321] H. Yang, W. Sun, W. Hu, and J. Li, “Onu migration in dynamic time and wavelength division multiplexed passive optical network (TWDM-PON),” *Optics express*, vol. 21, no. 18, pp. 21 491–21 499, 2013.

[322] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, “Dynamic bandwidth allocation with optimal wavelength switching in twdm-pons,” in *2013 15th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2013, pp. 1–4.

[323] R. Wang, H. H. Lee, S. S. Lee, and B. Mukherjee, “Energy saving via dynamic wavelength sharing in TWDM-PON,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 8, pp. 1566–1574, 2014.

[324] M. P. I. Dias, D. P. Van, L. Valcarenghi, and E. Wong, “Energy-efficient framework for time and wavelength division multiplexed passive optical networks,” *Journal of Optical Communications and Networking*, vol. 7, no. 6, pp. 496–504, 2015.

[325] S. Garg and A. Dixit, “Novel dynamic bandwidth and wavelength allocation algorithm for energy efficiency in TWDM-PON,” in *2019 21st International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2019, pp. 1–4.

[326] L. Valcarenghi, “Where do we stand and where are we heading in making NG-PONs more energy efficient?” in *2015 International Conference on Optical Network Design and Modeling (ONDM)*. IEEE, 2015, pp. 210–215.

[327] L. Valcarenghi, K. Kondepu, and P. Castoldi, “Delay fairness in reconfigurable and energy efficient twdm pon,” *Computer Networks*, vol. 110, pp. 223–231, 2016.

[328] D. M. Dourado, R. J. L. Ferreira, M. de Lacerda Rocha, and U. R. Duarte, “Strategies to increase spectral efficiency and energy saving with quality metric assurance in TWDM-PON,” *Optical Switching and Networking*, vol. 36, p. 100550, 2020.

[329] S. Dutta, D. Roy, and G. Das, “Sla-aware protocol design for energy-efficient olt transmitter in twdm-epon,” *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 4, pp. 1961–1973, 2021.

[330] B. R. Rayapati and N. Rangaswamy, “Ring topologies with energy efficient scheduling of onus in twdm pon,” in *2019 TEQIP III Sponsored International Conference on Microwave Integrated Circuits, Photonics and Wireless Networks (IMICPW)*. IEEE, 2019, pp. 255–259.

[331] N. Cheng, L. Wang, D. Liu, B. Gao, J. Gao, X. Zhou, H. Lin, and F. Effenberger, “Flexible TWDM-PON with load balancing and power saving,” in *39th European Conference and Exhibition on Optical Communication (ECOC 2013)*. IET, 2013, pp. 1–3.

[332] M. Tadokoro, R. Kubo, S. Nishihara, T. Yamada, and H. Nakamura, “Adaptive bandwidth aggregation mechanisms using a shared wavelength for energy-efficient wdm/tdm-pon,” in *The 10th International Conference on Optical Internet (COIN2012)*. IEEE, 2012, pp. 87–88.

[333] A. K. Garg and V. Janyani, “Adaptive bandwidth mechanism using dual rate olt for energy efficient wdm-tdm passive optical network,” *Telecommunication Systems*, vol. 66, no. 4, pp. 657–670, 2017.

[334] P. Garfias, M. De Andrade, M. Tornatore, A. Buttaboni, S. Sallent, and L. Gutiérrez, “Energy-saving mechanism in wdm/tdm-pon based on upstream network traffic,” in *Photonics*, vol. 1, no. 3. Multidisciplinary Digital Publishing Institute, 2014, pp. 235–250.

[335] H. Feng, C.-J. Chae, and A. Nirmalathas, “Seamless handover scheme in energy-efficient long reach wdm/tdm pon systems,” in *2012 17th Opto-Electronics and Communications Conference*. IEEE, 2012, pp. 711–712.

[336] C. Li, W. Guo, W. Wang, W. Hu, and M. Xia, “Programmable bandwidth management in software-defined epon architecture,” *Optics Communications*, vol. 370, pp. 43–48, 2016.

[337] H. Khalili, P. S. Khodashenas, D. Rincon, S. Siddiqui, J. R. Piney, and S. Sallent, “Design considerations for an energy-aware SDN-based architecture in 5G EPON nodes,” in *2018 20th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2018, pp. 1–4.

[338] H. Khalili, S. Sallent, J. R. Piney, and D. Rincón, “A proposal for an sdn-based SIEPON architecture,” *Optics Communications*, vol. 403, pp. 9–21, 2017.

[339] H. Khalili, P. S. Khodashenas, and M. S. Siddiqui, “Study on softwarization of management wavelength allocation in epon networks,” in *2020 22nd International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2020, pp. 1–4.

[340] A. F. Pakpahan, I.-S. Hwang, Y.-M. Yu, W.-H. Hsu, A. T. Liem, and A. Nikoukar, “Novel elastic protection against ddf failures in an enhanced software-defined siepon,” *Optical Fiber Technology*, vol. 36, pp. 51–62, 2017.

[341] A. F. Pakpahan and I.-S. Hwang, “Adaptive onu energy-saving via software-defined mechanisms in tdma-pon,” in *2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN)*. IEEE, 2018, pp. 137–142.

[342] G. Hasegawa, M. Murata, Y. Nakahira, M. Kashima, and S. Ata, “Optimizing functional split of baseband processing on twdm-pon based fronthaul network,” in *2020 16th International Conference on Mobility, Sensing and Networking (MSN)*. IEEE, 2020, pp. 330–336.

[343] ITU-Report. (2014) The tactile internet. [Online]. Available: https: http://www.itu.int/oth/T2301000023/en(Dateaccessed:25.04.2019).

[344] D. S. N. A. B. Pg, S. H. S. Newaz, F. H. Rahman, T.-W. Au, N. S. Nafi, R. K. Patchmuthu, F. Al-Hazemi *et al.*, “Digital-twin-assisted software-defined pon: A cognition-driven framework for energy conservation,” in *2021 31st International Telecommunication Networks and Applications Conference (ITNAC)*. IEEE, 2021, pp. 166–177.

[345] F. Slyne, R. S. Guimaraes, Y. Zhang, M. Martinello, R. Nejabati, M. Ruffini, and L. A. DaSilva, “Coordinated fibre and wireless spectrum allocation in sdn-controlled wireless-optical-cloud converged

[346] H. Guo, Y. Wang, J. Liu, and N. Kato, "Super-broadband optical access networks in 6g: Vision, architecture, and key technologies," *IEEE Wireless Communications*, vol. 29, no. 6, pp. 152–159, 2022.

[347] C. Su, J. Zhang, and Y. Ji, "Cyclic transmission window-based bandwidth allocation scheme for asynchronous time-sensitive industrial applications in tdm-pon," *Journal of Optical Communications and Networking*, vol. 15, no. 11, pp. 820–829, 2023.

[348] Y. Anzai, *Pattern recognition and machine learning*. Elsevier, 2012.

[349] H. Huang, R. Du, Z. Wang, X. Li, and G. Yuan, "A malicious code detection method based on stacked depthwise separable convolutions and attention mechanism," *Sensors*, vol. 23, no. 16, p. 7084, 2023.

[350] S. S. Shafin, G. Karmakar, and I. Mareels, "Obfuscated memory malware detection in resource-constrained iot devices for smart city applications," *Sensors*, vol. 23, no. 11, p. 5348, 2023.

[351] M. Rashid, J. Kamruzzaman, T. Imam, S. Wibowo, and S. Gordon, "A tree-based stacking ensemble technique with feature selection for network intrusion detection," *Applied Intelligence*, vol. 52, no. 9, pp. 9768–9781, 2022.

[352] F. Zhuang, Z. Qi, K. Duan, D. Xi, Y. Zhu, H. Zhu, H. Xiong, and Q. He, "A comprehensive survey on transfer learning," *Proceedings of the IEEE*, vol. 109, no. 1, pp. 43–76, 2020.

[353] N. Kato, B. Mao, F. Tang, Y. Kawamoto, and J. Liu, "Ten challenges in advancing machine learning technologies toward 6g," *IEEE Wireless Communications*, vol. 27, no. 3, pp. 96–103, 2020.

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