A Survey on Energy Conservation Schemes for Present and Next-Generation Passive Optical Networks

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***Abstract*—Due to the massive expansion of the Information and Communication Technology (ICT) sector, the power consumption of this sector is rapidly increasing. Besides greenhouse gas (GHG) emissions, the increase in power consumption also causes these networks to have higher operating costs. Passive Optical networks (PONs) are energy-efficient compared to legacy copper-based access networks and Active Optical Networks (AONs), but still the power consumption of PONs is significant and requires further research. The main cause of the higher power consumption of PONs is the optical network unit (ONU). In this study, we performed a survey on the energy conservation schemes for present and next-generation PONs (TWDM and OFDM PONs), with a focus on ONU-based schemes. The focus of this study is on medium access control (MAC) schemes as they are more economical and can be adapted easily. The review shows that if the cyclic sleep mode (CSM) is efficiently configured, this will be the most economical, efficient, and delay-aware scheme for current as well as next-generation PONs (NG-PONs) for energy conservation with delay guarantees.

***Index Terms*—Energy efficient, Pon, energy conservation, passive optical network, cyclic sleep mode.

I. INTRODUCTION

Today is the era of Information and Communication Technology (ICT). ICT networks have tremendously expanded in the last 20 years, and this trend is still going on. According to the ITU 2016 report, 84% of the world's population today has access to broadband services [1]. This expansion led to increasing power generation requirements in this sector. Around 59% of the generated power in the world is through thermal plants, which result in greenhouse gas (GHG) emissions [2] due to fuel burning. Currently, the ICT sector is estimated to be responsible for 2.5% of GHG emissions [3]. Specifically, the telecom sector is responsible for 21% of these GHG emissions. It has been forecasted that, by 2020, this power consumption will reach up to 40 GW, and in 2025, it is expected to reach 0.13 TW or about 7% of the global electricity supply [4]. Through efficient energy conservation schemes, this carbon footprint can be minimized.

In the telecom sector, 70% of the power consumed is in access networks. The latest development in wired-line access networks is Passive Optical Networks (PONs), which are more energy-efficient than the earlier copper-based networks as well as Active Optical Networks (AONs) due to their passive nature [5]. However, the main problem is that optical network units (ONUs) consume up to 60% of the power of the PON, whereas the Optical Line Terminal (OLT) consumes only 7%. This study shows that energy-aware PON equipment can reduce the power consumption by up to 58% [6]. Therefore, the energy efficiency of PONs is an active research area [7]. However, most of the research focuses on ONU power reduction schemes, and only a few studies have considered OLT energy efficiency [8].

This paper reviews ONU-based energy conservation schemes for the time division multiple access (TDMA) PONs in Section II. In Section III, energy conservation schemes for next-generation PONs (NG-PONs) are reviewed. Finally, Section IV concludes the study. J. I. Kani, S. Shimazu, N. Yoshimoto, and H. Hadama, "Energy-efficient optical access networks: Issues and technologies," IEEE Commun. Mag., vol. 51, no. 2, pp. 22–26, 2013.

II. OLT-BASED ENERGY CONSERVATION SCHEMES

OLT, being the main administrator, has to control and manage the communication between the entire connected ONUs in the PON. Typically, for GPON and XGPON, 32–128 ONUs are connected to a single OLT PON port. Therefore, OLT energy conservation is not simple and requires some special arrangements. To the best of our knowledge, only three schemes have been proposed for OLT energy conservation.

The first solution that was proposed in [9] is based on two OLTs paring in a master–slave configuration using a switch box which comprises 1 × 2 optical switches. Two OLTs (OLT-1 and OLT-2) are electronically connected to an optical switch box which connects one OLT to the network one at a time. When the traffic load of OLT-A is below 10% and that of OLT-2 is below 40%, then OLT-B can take over the load of OLT-1 and let it go to deep

Manuscript received October 5, 2017; revised March 20, 2018.
This work was supported by the Minister of Higher Education Malaysia under FRGS Grant No. XXXXXX.
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doi:10.12720/13.3.129-138

sleep to save energy. OLT-2 continuously works until its traffic load reaches more than 90%, in which case it will brings OLT-1 to the normal mode to take its load back. This scheme requires firmware changes in OLTs and an additional hardware setup to enable pairing between two OLTs.

The second scheme that was proposed in [10] is based on the idea of OLT PON line card sharing by multiple PONs using an optical switch. Instead of powering all the OLT line cards serving a group of ONUs, only the minimum "m" line cards required serving and the "n" active ONUs should be turned on. However, this scheme requires a centralized medium access control (MAC) layer controlling all OLT line cards, which could be computationally expensive. A similar idea using a wavelength router at the OLT has been described in [10, 11]. Only the minimum "m" ports are turned on and ONUs are assigned a wavelength corresponding to that port. Other ports are kept in the sleep mode to conserve energy. This scheme is suitable for TWDM PONs and cannot be used in TDM PONs with a single nontunable transceiver at the ONUs.

The third scheme that was proposed in [12] presents the idea of an "elastic OLT" to save optical power by optimizing the transmission distance and split ratio according to the service requirements. The basic idea is to fully utilize the underutilized power budget that would be wasted at the receiving ONU. This scheme can be useful at the time of PON deployment and cannot be applied to an already deployed and functional network.

III. ONU-Based Energy Conservation Schemes

In a GPON network from a single PON port, "r" ONUs are served, where "r" is the split ratio. Typical values of "r" are 32/64/128. So, the power saving scheme that was applied to an ONU saving "m" watts will actually result in an overall power saving of "r" × "m" watts (Fig. 1).

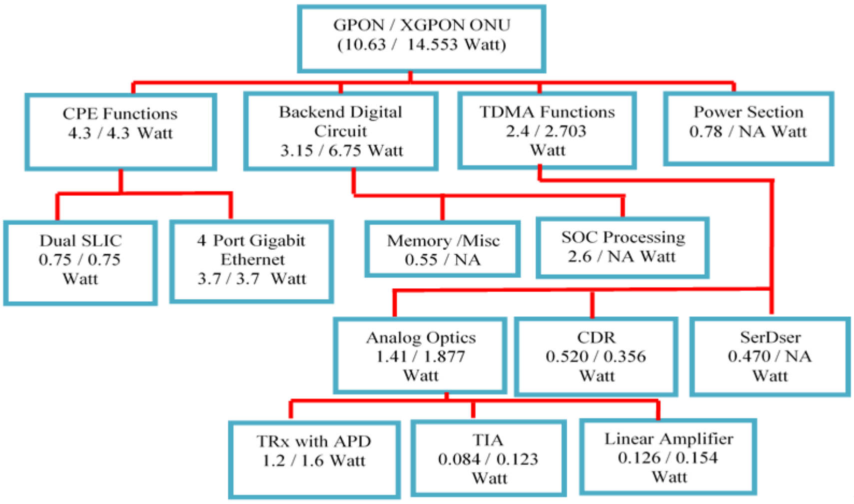

Fig. 1. Power consumption of different GPON/XGPON ONU modules.

In order to understand the power consumption behavior of an ONU, we develop an ONU power model from previous studies [13–16] as shown in Fig. 2. ONUs comprise many optical and electrical function blocks. Based on this model, a GPON ONU consumes 10.6 watts, whereas an XGPON ONU consumes 14.5 watts. The ONU power consumption can be grouped into four major sections as follows:

User section (P_{USER}).
DC–DC power converter (P_{DC}).
TDMA section (P_{TDMA}).
Back end digital circuit (P_{BEDC}).

P_{USER} represents the power consumption of the users' modules and their respective interfaces. Normally, this section comprises the Ethernet and Subscriber Line Interface Card (SLIC) modules. The SLIC module provides basic voice services like ringtones and on-hook and off-hook detection. The DC–DC power, represented by P_{DC}, is consumed by electronic circuits, which are required to convert and regulate the input of DC power to the desired voltage levels. P_{TDMA} represents the power consumption of the whole TDMA section, which includes optical transceivers, a local amplifier (LA), a trans-impedance amplifier (TIA), a clock and data recovery (CDR) circuit, and serializer/deserializer (SerDesr) blocks. Finally, P_{BEDC} represents the MAC layer which performs processing with the incoming frames and buffering in memory banks. P_{DC} remains almost constant when the ONU is turned on, and it can only be fully saved if the ONU is turned off.

Therefore, all ONU-based energy conservation schemes have tried to reduce either P_{USER}, P_{TDMA}, or P_{BEDC}, or all of them. These schemes can be categorized as being physical-layer-based, MAC-layer-based, or a hybrid of both, and they are discussed in the next sections.

A. Physical-Layer-Based Schemes

Studies in this category focus on the energy efficiency of the electronic circuitry of ONUs. The fabrication process of the ONU design is already based on the CMOS technology [12], but still there is ongoing research on new semiconductor materials like TiO_2 (titanium dioxide), and the fabrication technology will focus on more energy-efficient ONU circuit designs in the future. Besides the fabrication process, such schemes basically try to reduce P_{TDMA}. For example, the study in [17] proposed a Vertical-Cavity Surface-Emitting Laser (VCSEL) instead of DFB lasers in optical transmitters and showed that it is relatively more energy-efficient. Another study by Elaine Wong [18] has demonstrated that using VCSEL instead of the DFB laser at the ONU can reduce the transmitter's power from 0.7 W to 0.134 W. Another improvement that was presented in the literature is the CDR design. Burst Mode CDR (BM-CDR) has been shown to be faster and more energy-efficient compared to Continuous Mode CDR (CM-CDR) [19]. Using BM-CDR, an ONU architecture with faster recovery times from the low-power mode has been proposed in [20]. A detailed discussion on ONU hardware design and its limitations can be found in [21]. However, all the physical layer improvements are disruptive and require new investments. These schemes cannot be applied on the currently deployed ONU architectures, and thus these are suitable for future designs only.

B. MAC-Layer-Based and Hybrid Schemes

Some energy conservation schemes require MAC layer changes in addition to architectural changes in the ONU like the Adaptive Link Rate (ALR) [22, 23], Bit Interleaved PON (Bi-PON) [21, 24, 25], and ONU buffer elimination [26]. Such hybrid schemes also have the disadvantage of being disruptive, like physical-layer-based schemes. Therefore, a pure MAC-layer-based energy conservation scheme is the most suitable as it does not require any architectural changes in the ONU and thus can be easily applied to already deployed ONUs as well as in future designs. Such schemes include power shedding [7, 15, 27], ONU doze mode [28–31], ONU sleep mode, an integrated doze–sleep mode [13], and a unifying sleep–doze mode [32–34]. Figure 3 lists all the MAC-layer-based and hybrid ONU energy conservation schemes for PONs. In the following sections, each scheme is reviewed in detail.

1. Power Shedding

This scheme [15] is used to turn off idle users or network interfaces. Basically, it is not a complete energy conservation scheme and is useful as an add-on with other MAC-layer-based schemes. It is typically used during AC power failures so as to prolong the life of backup batteries [7, 27]. The study in [27] shows that a combination of power shedding and sleep mode for a GPON ONU can result in 80% energy saving at a lower traffic intensity. However, when using power shedding, all the traffic frames arriving at the ONU UNI will be lost. Therefore, it is more suitable during long periods of ONU inactivity or when there is an electric power failure.

2. ALR

The dynamic power consumption of any CMOS circuit depends on four factors, namely, load capacitance (*C*), operating voltage (*V*), clock frequency (*F*), and activity factor (*A*), as depicted in Eq. (1). The ALR scheme controls the factor *F*. The study in [30] proposed an adaptive data rate mechanism that can switch between 1 Gbps and 10 Gbps line rates on the basis of a threshold value of the link bandwidth utilization. Due to switching to a lower frequency, significant power saving is achieved. However, the prerequisite for this scheme is the availability of dual rate transceivers with ONTs and OLTs.

$$P_{Dynamic} = ACV^2F \tag{1}$$

3. Processing Efficient Frame Structure

As evident from Eq. (1), the dynamic power also depends on the activity (*A*) factor. The A ∞ processing load, therefore, reducing processing load can actually result in significant power saving of an ONU. This was addressed by the Bi-PON proposal in [21]. The Bi-PON study in [24] revealed that a major cause of energy consumption in GPON and XGPON is their broadcast nature of DS traffic, which leads to continuous wasting of processing power in the ONUs. Therefore, a lot of processing power is wasted in processing and finally discarding these unrelated frames. The Bi-PON scheme enables ONUs to only process the related bits in the DS frames. The starting position and length of the bit stream for each ONU are specified in the control sections. In the control sections, the position of the bits from the start is in accordance with the ONU-ID. By only parsing and processing the bits destined for that ONU, a saving of up to 30% of processing power was demonstrated in [25]. However, Bi-PON requires a decimator unit instead of DEMUX in ONUs. In order to avoid this, the study in [35] proposed a processing efficient frame structure (EGPON) for GPON. However, the study was only based on analysis and was not validated through a simulation or hardware testbed environment.

4. Bufferless ONUs

The study in [26] proposed to eliminate buffering at the ONUs to reduce P_{BEDC}. The work in [36] further studied three options—zero buffer, full buffer, and node proportional buffer—for an ONU. The study concluded that careful reduction of buffer sizes at ONUs can reduce 90% of the power leakage. However, this leads to an increase of around 800 μs in communication delays and requires additional buffering at the user terminals/end nodes. Moreover, an ONU with such a scheme will not be able to use low-power mode schemes like ONU sleep/doze mode as these schemes require additional buffering at the ONU. This approach also requires electrooptical switches at the ONU to redirect the data from end nodes to the US link.

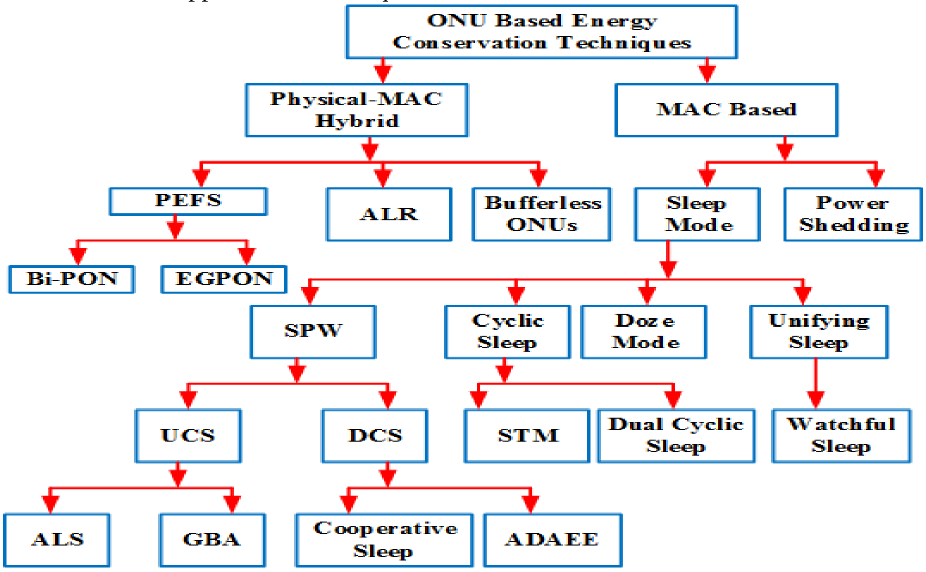

Fig. 2. Classification of ONU-based PON energy conservation techniques.

5. ONU Sleep Mode

ONU sleep mode is the most commonly used energy conservation scheme for all wired and wireless networks. In PONs, it is a very popular scheme and has also been adopted by the PON standardizing bodies [37, 38] as a low-power scheme. The basic idea behind this scheme is to switch off some components like the optical transmitter, photo detector (PD), limiting amplifier (LA), CDR, DEMUX, and CPE functions when there is no available uplink or downlink traffic to/from that ONU to save P_{USER} and P_{TDMA} completely and P_{BEDC} partially as the ONU turns off the optical transceiver and UNI interfaces but the MAC layer processor is working. In general, with the sleep mode, there is a trade-off between the US and DS delays versus power consumption of the network [39]. Many variants of the sleep mode have been proposed in the literature for both IEEE and ITU PONs as shown in Fig. 2.

Sleep and Periodic Wakeup (SPW) that was initially proposed in [27] comprises only two ONU power states: active and asleep. The state transitions are negotiated between the OLT and ONU via the messaging channel. The demonstration of the SPW was made on an FPGA-based hardware testbed in [20]; however, the sleep time (T_{AS}) computation was not described. Moreover, traffic generation only comprised fixed packet sizes of 100 and 1000 bytes and did not follow any standard distribution. In SPW schemes, the decision of T_{AS} can be made in two ways [40, 41], resulting in two types of SPW. The first approach, termed Downstream Centric (DCS), suggests that an ONU should be assigned T_{AS} if there is no US and DS traffic pending for the ONU. The second approach, Upstream Centric (UCS), considers US traffic for assigning T_{AS} and the DS traffic which is bound to US only as the ONU will only receive DS when it is active for US transmission and sends a GATE message. They assume a faster ONU architecture: Option-2 or Option-3 presented in [21]. An ONU is only active in its assigned US time slot. A very similar scheme, termed Adaptive Lock Cycle (ALS), was presented in [42], which follows the UCS scheme but is suggested to have both BM-CDR and CM-CDR inside the ONU. The ONU will turn on the BM-CDR during the Asleep (AS) state for a fast transition from the AS to the active state, and thus it is able to awaken quickly during the US time slot assigned by the DBA scheme and sleep otherwise. However, having two CDRs in the ONU is not a practical idea as the ONU can simply use Option-3 architecture. Another improvement for the UCS scheme is presented in [43], termed Green Bandwidth Allocation (GBA). This scheme prolongs T_{AS} and gives the idea of batch mode transmission to reduce the AS to active mode transitions. This increases energy saving but leads to higher queuing delays and buffering requirements. Therefore, it is necessary to compute T_{AS} as a function of delay requirements for a traffic class and target loss probability, which is not discussed in this work. A numerical analysis of GBA with a gated IPACT DBA scheme is presented in [44] with an upper T_{AS} limit of 50 ms as the ONU is required to send a GATE message within this time limit to the OLT to avoid deregistration. The study in [45] combines the UCS scheme with the ALR scheme for an IEEE PON. Overall, the UCS schemes increase the ONU's energy efficiency, but these schemes cannot work with existing ONU architectures and are not good for delay-sensitive applications as DS traffic delays and frame losses increase at higher traffic loads. The DCS [46, 47] schemes with SPW are more suitable as they consider both US and DS traffic for sleep time or transmission time computation.

However, the SPW mechanism suffers from two deficiencies. First, it only has two power levels (AS and active), and there is no observation state in which the ONU checks for the DS and US traffic arrivals to maintain QoS and receive/send any maintenance or signaling messages. The ONU is also required to request the required bandwidth to the OLT for sending such messages. Second, ONUs are able to wake up during the AS state. These features are incorporated into the modified SPW scheme presented by L. Valcarengh et al. in [48, 49]. The observation state, named SleepAware state, is added to the sleep cycle. A similar proposal was presented in [50], and two observation states (sleep and awake) were added for the same purpose. However, there is still a deficiency that the ONU cannot be awakened early during the AS state. Moreover, sleep decisions only consider DS traffic and is based in COS filed of Ethernet frames as in [51]. Francesco Zanini et al. improved this work further in [52] and added the missing feature of early wakeup of ONUs during the AS state. The authors presented the idea of a sleep buffer at the ONU. An ONU can sleep as long as the buffer is not full. Therefore, the size "N" of the sleep buffer determines the length of the AS state.

Compared to the SPW, a sleep process with four ONU power states like the cyclic sleep mode (CSM) is a far better choice. Although there are some SPW proposals with four power levels like ADAEE [53] and the sleep proposal in [54], there is still no single observation state to monitor both US and DS traffic arrivals. The state transitions are also not clearly defined. Therefore, the CSM is the most comprehensive four-power-level sleep process, which has also been adopted as a standard energy conservation scheme by both ITU [55] and IEEE [56] for their respective PONs. It should be noted that the IEEE standard calls this scheme Trx Sleep. In this scheme, an ONU can wake up during sleep by a Local Wakeup Indication (LWI) event at the ONU or OLT. The information of the LWI at the OLT is communicated to the ONU using an SA_OFF message or a Forced Wakeup Indication (FWI) indication in the BWmap field of DS frames.

An ONU using CSM switches between four power states, namely, ActiveHeld (AH), ActiveFree (AF), SleepAware (SLA), and AS. The corresponding power states of OLT are AwakeForced (AWF), AwakeFree (AFR), AlertedSleep (ASP), and LowPowerSleep (LPS). The state transitions mainly depend on LWI events at the OLT and ONU. These events indicate crossing of the DS/US traffic queue threshold for an ONU during the AS state. Figures 3 and 4 show the ONU and OLT state diagrams for the CSM operation for GPON/XGPON. The OLT maintains a separate CSM process for each ONU.

Fig. 3. ONU cyclic sleep state diagram.

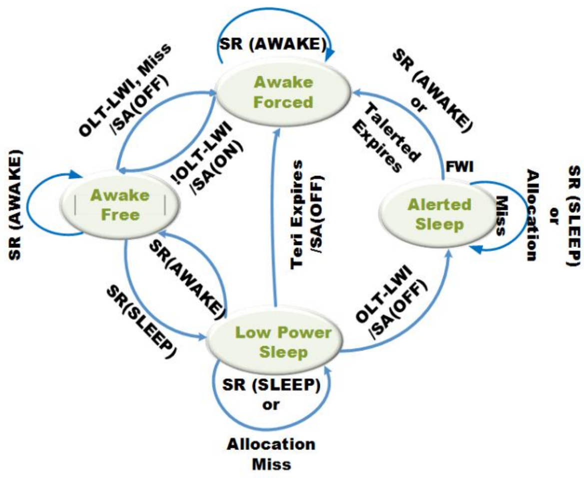

Fig. 4. OLT cyclic sleep state diagram.

Like in the SPW scheme, the length of T_{AS} also impacts the energy saving and QoS of the CSM scheme [57]. Like in other sleep mode schemes, for the CSM also, T_{AS} can also be configured in two ways: fixed or dynamic. In the first approach, it remains fixed during the entire sleep cycle (FCSM) unless interrupted by LWI or FWI events. The studies in [58–61] show that higher values of T_{AS} lead to reduced power consumption of ONU and thus provide higher energy saving. However, delays and buffering requirements also increase because of more traffic queuing during the AS state. A value of 20–50 ms has been shown to be a suitable choice for T_{AS} in [60], whereas in [61], 50 ms has been shown to be the most optimum value to maximize ONU energy saving and minimize delays. The dynamic cyclic sleep (DCSM) approach increases T_{AS} according to some function as in [37, 62] or based on traffic type as in [52, 63]. A dynamic sleep period calculation method based on the OLT queue length using a feedback controller has been presented in [64, 65]. Although all of these schemes have been demonstrated for IEEE PONs, they can also be used for ITU-based PONs as demonstrated in [66]. However, all DCSM-based schemes increase the computation load of OLTs and require the reconfiguration of all sleep mode timers at the OLT and ONU every time, before starting a sleep cycle. They also increase the messaging overhead between OLTs and ONUs and show a higher latency [67].

The study in [68] shows that the DCSM is suitable for point-to-point optical systems, but for a TDM PON, the FCSM approach shows a better energy saving performance and is a more suitable choice.

In addition to the CSM, the standards also provide an option of partial CSM mode that only turns off the optical transmitter of the ONU, which is termed doze mode or Tx Sleep in respective ITU and IEEE standards. A comprehensive demonstration of cyclic sleep/doze mode for XGPON was presented by Skubic et al. in [13]. However, a proper DBA scheme [69, 70] as well as its processing impact was not considered in this work. The LWI event is raised as soon as a single frame arrives during the AS state. The disadvantage of this early wakeup is the energy saving for only very low traffic loads, as it is evident from the results of this study that the performance was tested for only very low loads of 0.001, 0.01, and 0.1. In the CSM scheme, the ratio of AS to SA states is very important and impacts the energy saving. SA should be as minimum as possible, but it is subject to the ONU sleep to active wakeup time. It was shown by the same authors in [71] that the finite wakeup time of ONU modules and components significantly reduces the energy saving of the CS scheme.

Since the DS link has a fourfold higher link rate compared to the US, therefore the DS delay is more affected by the CSM. The doze mode can reduce this impact, but it also reduces energy saving. Therefore, watchful sleep has also been introduced by the ITU for GPON and XGPON as a combination of cyclic sleep and doze modes that provide a middle solution. The studies in [33, 72] show that this scheme has better energy saving compared to the CSM. However, our previous work in [34] showed opposite results, but still a comprehensive comparative study of both of these schemes is necessary.

TABLE I: PROS AND CONS OF ONU-BASED PON ENERGY CONSERVATION TECHNIQUES.

Method	Energy saving	US delay	DS delay	Requires a new investment	Changes required	Complexity level	Compatibility (GPON/XGPON/TWDM PON/OFDM PON/IEEE PON)
ALR	High	Low	Low	Yes	Dual rate transceivers	High	All
ALR with sleep	Higher	High	High	Yes	Dual rate transceivers	High	All
Bi-PON	Medium	Not impacted	Not impacted	Yes	New MAC layer and hardware	High	GPON/XGPON/TWDM PON
Bi-PON with sleep	Highest	High	High	Yes	New MAC layer and hardware	Highest	GPON/XGPON/TWDM PON
EGPON	Medium	Not impacted	Not impacted	No	New MAC layer	Low	GPON/XGPON/TWDM PON
UCS	Highest	High	Highest	Yes	ONU Option-2 or Option-3	Higher	IEEE PON
DCS	Higher	High	High	No	No	Low	IEEE PON
Doze mode	Low	High	Low	No	No	Low	All
Cyclic sleep	Highest	High	High	No	No	Low	All
Watchful sleep	Higher	High	High	No	No	High	All
DWA	High	Low	Low	No	No	Higher	TWDM PON

Based on the detailed review above and the comparative studies especially in [7, 16, 73, 74], a comparison of all the above discussed schemes has been made in Table 1 on the basis of energy saving, US/DS delays, new investment requirements, and computational complexity. It is clear that CSM and watchful sleep modes seem to be the best choices based on our comparison criteria, as they do not require any hardware changes or new investments. As shown in [34], CSM is actually more energy-efficient than watchful sleep, but it has higher delays compared to it. Therefore, there should be a comprehensive framework to configure the CSM to obtain maximum saving while still not exceeding the maximum delay limits to ensure QoS. Such a framework has been presented in [75] for ITU PONs and in [76] for IEEE PONs. These studies show that by preconfiguring the

IV. Energy Conservation in NG-PONs

In order to cope with the increasing bandwidth demands in the future, TWDM PONs with an initial capacity of 40 Gbps DS and 10 Gbps US, later upgraded to 80 Gbps DS, have been standardized by the ITU [77, 78]. All the energy conservation schemes discussed above for GPON/XGPON are also applicable on TWDM and OFDM-based PONs.

An energy-efficient TWDM architecture with an ALR-like concept was proposed in [79]. Like earlier PON standards, the CSM scheme is also included in the TWDM G.987.3 recommendations as a standard low-power energy conservation scheme. It has been demonstrated to work efficiently for TWDM PONs in [33]. A specific widely studied scheme for energy conservation in TWDM PONs is the dynamic allocation of wavelengths to ONUs and only turning on the necessary OLT PON ports and turning off the unused ports to conserve energy [79–84].

Similarly, for future capacity upgrades in PONs, OFDM PONs are an attractive candidate [85, 86] for NG-PONs. However, the main drawback of OFDM PONs is the computationally expensive processing operations like FFT, IFFT, ADC, DAC, and OFDM symbol generation, which increase the energy consumption of ONUs and OLTs [87]. In order to cope with these issues, there are many energy-efficient OFDM implementations, for example, rate adaptive transceiver design [88], energy-efficient DSP operation by controlling the calculation precision of FFT and IFFT operations [89], and a modular DSP design to turn off the unused computational resources [90], and an almost similar idea was also presented in [91]. In addition to specific energy conservation schemes, the sleep mode has also been demonstrated to be an effective energy conservation scheme for OFDM PONs [92, 93].

V. Conclusions

In this study, we reviewed the energy conservation schemes for GPON/XGPON and IEEE PONs with an outlook at NG-PONs, that is, TWDM and OFDM PONs. The review was narrowed toward MAC-layer-based schemes as they only require firmware changes and are applicable to presently deployed networks through firmware upgrades and do not require new investments. The applicability of the present energy conservation schemes on NG-PONs was also discussed, and specific additional schemes for TWDM and OFDM PONs were also reviewed. The CSM mode was found to be the most effective economical energy conservation scheme for both present PONs and NG-PONs as well. However, CSM also increases the US and DS delays, and a comprehensive CSM framework to optimize its performance according to the desired delay is still needed. A further thorough study of watchful sleep and its comparative performance with the CSM is also needed. In the long term with the new ONU architecture, Bi-PON is also an attractive option for saving ONU active mode energy consumption.

For TWDM and OFDM PON architecture, specific schemes can be used to efficiently improve the network energy, but the sleep mode can also be used for these PONs to significantly reduce the energy consumption of the network. However, the performance of the CSM mode with TWDM PONs and specifically OFDM PONs is still an open research avenue.

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