Toward Green Next-Generation Passive Optical Networks

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ABSTRACT

Energy saving in telecom networks in general and in optical IP networks in particular has been a growing field of research. Next-generation passive optical network, which is considered one of the most promising optical access networks, has notably matured in the past few years and is envisioned to massively evolve in the near future. This trend will increase the power requirements of NG-PON and make it no longer coveted. This article first provides a comprehensive survey of the previously reported studies on tackling this problem. A novel solution framework is then introduced, which aims to explore the maximum design dimensions and achieve the best possible power saving while maintaining the QoS requirements for each type of service. Results demonstrate the merits of the proposed framework.

INTRODUCTION

In order to meet the expected global energy demand in 2035, power production must increase by almost 49 percent, which is not feasible [1]. Meanwhile, the bare necessity for ensuring sustainability requires reducing global greenhouse gas (GHG) emissions at large quantities.

Recent studies have revealed shocking facts regarding the energy consumption in modern telecommunications networks. According to Bell Labs, today's networks consume 10,000 times more energy than the absolute minimum required. The Internet currently consumes about 0.4 percent of the total electricity consumption in broadband-enabled countries and is foreseen to reach 1 percent with the data transmission rate increase trend [2]. These appalling numbers have triggered tremendous efforts and collaborations between industry and academia to undertake this challenging problem [3]. Consequently, in 2010, GreenTouch [2], a consortium of leading information and communications technology (ICT) industry, academic, and non-governmental research experts, was launched, aiming to make communications networks, within five years, 1000 times more energy efficient. A joint effort to achieve these theoretical limits would not only reduce the estimated 2 percent of the world's carbon emissions ICT contributes directly, but would also lower the 98 percent contributed by all the other sectors touched directly and indirectly by ICT [2].

Constituting a big portion of modern Internet infrastructure, optical IP networks have been extensively studied, and many strategies have aimed at re-engineering the current optical communication system in order to reduce its energy consumption while maintaining the desired network performance [4].

In recent years, next-generation passive optical network (NG-PON) has been considered one of the most promising broadband access technologies. As illustrated in Fig. 1, NG-PON has massively evolved in the past few years [5]. It is envisioned to support not only higher data rates (up to 10 Gb/s), but also longer reach abilities (up to 100 km) and very high split ratios (up to 1:256), thereby provisioning more users in wider areas.

The term NG-PON became popular with the famous Ethernet PON (EPON) [5], which takes advantage of inexpensive and ubiquitous Ethernet equipment, and offers a transmission speed of 1 Gb/s. However, the proliferation of bandwidth-hungry applications such as voice over Internet Protocol (VoIP), standard and high-definition video (HDTV), videoconferencing (interactive video), and data traffic with strict quality of service (QoS) requirements (e.g., low packet delay and jitter, and bandwidth guarantee) has greatly contributed to the rapid advancement of NG-PON. Consequently, higher-speed versions emerged, such as Gigabit EPON (G-EPON), Gigabit PON (GPON, which also supports asynchronous transfer mode [ATM]), wavelength-division multiplexing PON (WDM-PON), and long-reach PON (LR-PON). LR-PON mainly extends the reach of PONs, and, like WDM-PON, employs multiple wavelengths between the optical line termination (OLT) and optical network units (ONUs). Currently, the term NG-PON1 is used for the *evolutionary growth* of EPON/GPON, which supports coexistence with EPON/GPON on the same optical distribution network (ODN); and the term NG-PON2 represents the *revolutionary change* of NG-PON with

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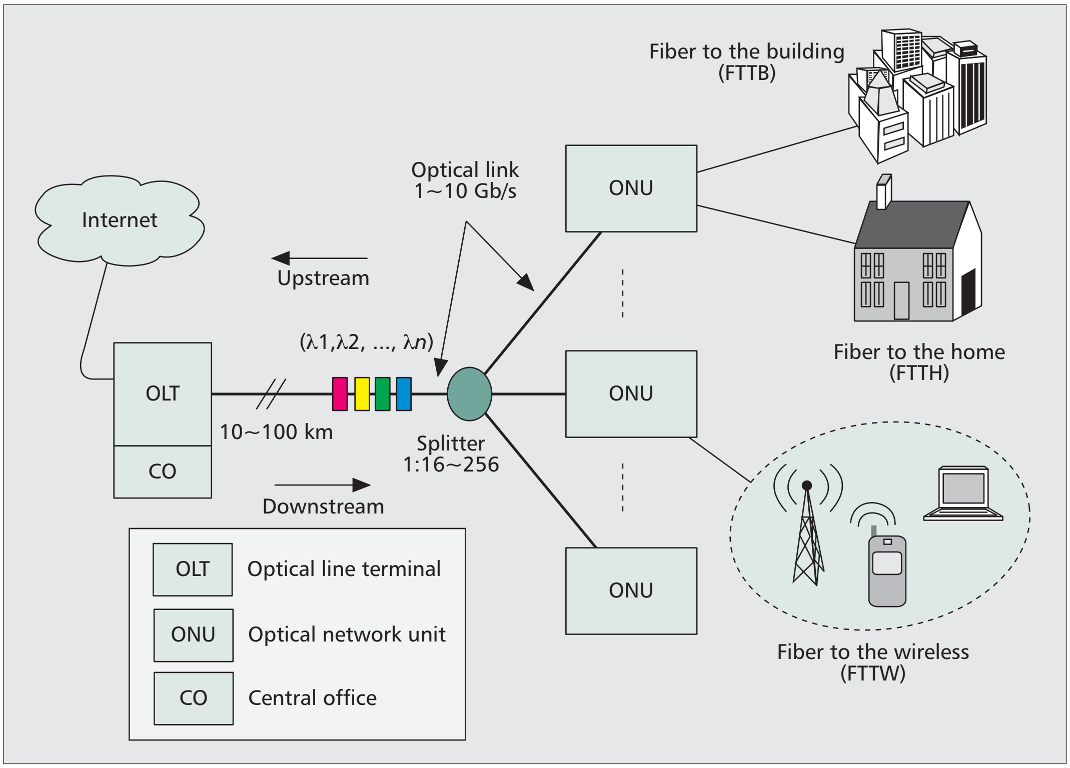

Figure 1. *Evolution of the NG-PON point-to-multipoint (P2MP) architecture: higher transmission rates, higher split ratios, more ONUs, longer reach, and multiple wavelengths.*

To reduce the impact of long overhead time in GR-ONU-1, it is necessary to design a mechanism that can intelligently manipulate sleep mode operation. The mechanism should be general to possibly be operated on any envisioned ONU architecture in the future.

no requirement of coexistence with EPON/GPON on the same ODN [5].

Although it was shown in [4] that NG-PON consumes the least power among all the reported access network technologies, its evolution is expected to significantly increase its power consumption [5]. To date, only a few techniques have been proposed to address this problem, currently being standardized [6, 7]. Among those, putting the ONU into sleep mode has been considered the most cost-effective and promising method [6–8]. In this article, we first overview the various NG-PON power saving techniques and the little relevant related work. We then propose a new green bandwidth allocation (GBA) framework that leverages the sleep mode feature of the ONU to achieve maximum possible energy saving. The salient feature of GBA is that the delay requirements of all types of services are taken as a constraint when the sleep time is computed for every ONU. Furthermore, due to its novel design in terms of batch-mode transmissions, more energy can be saved with the same amount of sleep time. Our results show that GBA can minimize ONU energy consumption by almost 90 percent without impairing the QoS demands of all types of traffic. We also show that the saving is not much affected by the increased traffic loads, as generally expected.

The rest of the article is organized as follows. We first overview the power saving techniques in NG-PONs and the related work. We then describe our proposed framework. Numerical results that highlight the advantages of our solution are also presented. Finally, we summarize the article and discuss future work.

NG-PON Energy Saving Techniques

As depicted in the taxonomy graph of Fig. 2, NG-PON energy saving techniques can be categorized as either hardware- or software-based. These can be employed under any NG-PON technology, unless specified differently.

Hardware-Based Techniques

Hardware-based techniques can be via either new ONU architectures and/or optical noise reuse.

New ONU Architectures — Legacy IEEE 802.3ah standard ONUs (STD-ONUs) do not support sleep mode. To remedy this deficiency, new ONU architectures were proposed in [9]. Table 1 exhibits these ONUs and highlights the disparity between the attributes of each architecture vs. STD-ONU, which always consumes maximum energy.[1] We briefly describe these architectures as follows:[2]

Green ONU-1 (GR-ONU-1): It basically comprises the same architecture as STD-ONU, yet with enabled sleep mode functionality (using its embedded timer). The advantages of GR-ONU-1 is that it requires no new ONU manufacturing, and can save maximum energy by turning off most of its hardware when going into sleep mode. However, the high overhead time it carries (which is the time spent by the ONU to switch from sleep to active and mainly consists of the laser turn-on time, clock recovery time, and synchronization period), creates a trade-off between maximum energy saving and network performance.

[1] *The ONU power consumption in active and sleep modes is model-dependent. Some other types might consume differently.*

[2] *For more details on the specific hardware parts that are being turned off in GR-ONU-1, 2, and 3, we refer the reader to [9].*

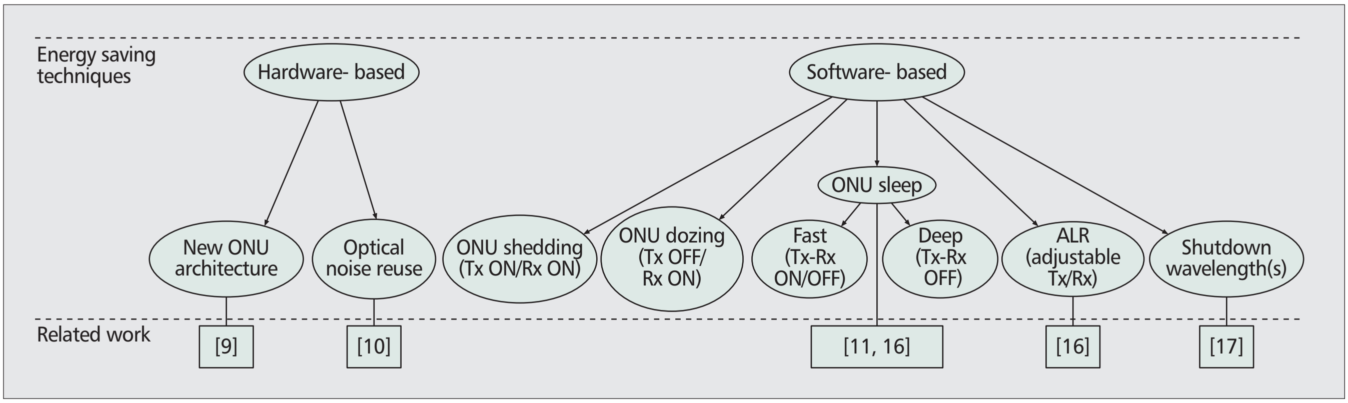

Figure 2. *Taxonomy of energy saving techniques in NG-PONs.*

Green ONU-2 (GR-ONU-2): This ONU basically keeps some of its hardware on, such that a very short overhead time is caused at the expense of slightly higher energy consumption while in sleep mode.

Green ONU-3 (GR-ONU-3): This architecture mainly focuses on eliminating the overhead time by shutting down the minimum hardware required to put the ONU into sleep. However, as expected, the energy consumption in sleep mode will be higher.

These architectures do not work independently. They rely on the existence of software-based protocols that manipulate their sleep functionalities (discussed later). Clearly, GR-ONU-2 is considered to have the best technical merits over the other types of ONUs due to its very short overhead time and slightly higher energy consumption. Nevertheless, the design and installation costs might decelerate its deployment. GR-ONU-1 on the other hand, although subject to longer overhead time and hence possibly impaired QoS levels in power saving mode, has been widely deployed as the mainstream of the NG-PON industry in the past decade [5]. To reduce the impact of long overhead time in GR-ONU-1, it is necessary to design a mechanism that can intelligently manipulate sleep mode operation. The mechanism should be general to possibly be operated on any envisioned ONU architecture in the future.

Optical Noise Reuse — The extension of the network reach in NG-PON (e.g, in LR-PON, NG-PON1, and NG-PON2) may result in significant optical signal losses. Furthermore, the closely adjacent wavelengths are subject to the Rayleigh backscattering effects that can disrupt the feeder fiber of the power splitter, leading to throughput degradation. Equipping the ONU with a semiconductor optical amplifier (SOA) has been the most widely employed solution to this problem so far; however SOA notably increases the power consumption. To resolve this issue, the authors of [10] proposed a new technique that mainly reuses the optical noise of the amplifier as pumping power for all network nodes. This ultimately allows for more simultaneously provisioned users at lower or equal energy costs.

SOFTWARE-BASED TECHNIQUES

Software-based techniques can be via the following five methods.

ONU Power Shedding — With power shedding [6], the ONU simply turns off some of its devices and reduces power usage by engaging in a different mode of services and functions, while leaving the optical link at full function. As such, power shedding can only achieve minimum energy saving, although the best possible system performance can be ensured.

ONU Dozing — ONU dozing only turns off the transmitter for a substantial amount of time (typically during periods where no upstream traffic is available), while the receiver is always on [6]. Although ONU dozing can save the OLT from buffering downstream traffic and from performing downstream bandwidth allocation, it does not exploit the option of turning off the receiver when no downstream traffic is available.

ONU Sleep — ONU sleep reflects the state where both the transmitter and receiver are off for a substantial period of time [6]. This technique is further categorized as follows:

Deep sleep: Under this mode, the ONU's transmitter and receiver are turned off when there is no upstream and downstream traffic. Although this can achieve maximum energy reduction, it might cause performance degradation due to possible dropping of incoming/outgoing packets. This mode can be particularly employed, for example, when the ONU is not in use, or when the loss of some traffic can be tolerated.

Fast/cyclic sleep: Under this mode, the ONU state alternates between sleep state (i.e., when the transceiver is completely turned off) and active state (i.e., when the transceiver is turned on). The active period and the subsequent sleep period form the *sleep cycle*. The system performance of this technique mainly depends on the assigned sleep period and the dynamic bandwidth allocation (DBA) scheme used in the active period.

These three software-based techniques enable the ONU to go into new energy-saving states. The ONU power consumption under different active and energy-saving states is shown in Fig.

<table>
<tr><th>ONU architecture</th><th>Laser turn-on time</th><th>Clock recovery time</th><th>Sync. time</th><th>Total overhead</th><th>Active power consumption</th><th>Sleep power consumption</th><th>Doze power consumption</th></tr>
<tr><td>STD-ONU</td><td>600 ns</td><td>N/A</td><td>N/A</td><td>600 ns</td><td>3.85 W</td><td>N/A</td><td>N/A</td></tr>
<tr><td>GR-ONU-1/A</td><td rowspan="2">600 ns</td><td>2 ms (aggressive)</td><td>0.125 ms</td><td>2.125 ms</td><td rowspan="2">3.85 W</td><td rowspan="2">0.75 W</td><td rowspan="2">1.7 W</td></tr>
<tr><td>GR-ONU-1/C</td><td>5 ms (conservative)</td><td>0.125 ms</td><td>5.125 ms</td></tr>
<tr><td>GR-ONU-2</td><td>600 ns</td><td>10 – 50 ns</td><td>0.125 ms</td><td>0.125 ms</td><td>3.85 W</td><td>1.08 W</td><td>1.7 W</td></tr>
<tr><td>GR-ONU-3</td><td>600 ns</td><td>0 ms</td><td>0.125 ms</td><td>0.125 ms</td><td>3.85 W</td><td>1.28 W</td><td>1.7 W</td></tr>
</table>

Table 1. *Comparison between different ONU architectures. Most of the data are collected from [6, 7, 9].*

3. Clearly, ONU sleep mode can save more energy than all other techniques. It has also been considered the most promising energy saving strategy in NG-PONs [8], and has been extensively studied and explored under current research endeavors. The authors of [11] proposed a new energy-aware medium access control (MAC) protocol that performs slotted fixed bandwidth allocation (FBA) for upstream and downstream traffic when the system is operating at low loads. The OLT constantly monitors the system throughput, and turns the system to energy saving mode whenever the traffic load is below a certain threshold. Since the ONU wakes up and sleeps with a predefined period for data transmission/receiving, the scheme cannot handle any possible QoS constraint (e.g., maximum delay requirement). Furthermore, it assumes an infinite ONU buffer that can accommodate all incoming traffic during the sleep period, which may introduce significant packet delay.

As observed in Table 1, the ONU's clock recovery time constitutes the biggest portion of the total overhead time. To alleviate the impact of a long recovery time, the authors of [12] designed a fast clock and data recovery circuit (as of GR-ONU-2 and GR-ONU-3), and proposed a just-in-time sleep control mechanism that can enable the ONU to switch faster from the sleep state to the active state.

The authors of [13] proposed two FBA-based MAC protocols to save energy in EPONs. With the first one, upstream-centric scheme (UCS), the OLT launches the downstream traffic to an ONU whenever the ONU is transmitting in the upstream direction. This forces the OLT to buffer the downstream traffic until there is any allocated upstream slot for the ONU; meanwhile, the ONU can have the maximum sleep time depending on the upstream DBA scheme. With the second one, downstream-centric scheme (DCS), the ONU switches into active mode whenever there is either upstream or downstream scheduled transmission slots, and hence sleep can only occur when both the ONU and OLT are silent. While UCS can achieve larger power saving, it may cause higher packet delay if the overlapped downstream and upstream time slots are not scheduled and/or sized efficiently. Conversely, by waking up every time a transmission is required, DCS can offer better delay performance than UCS at the expense of higher energy consumption.

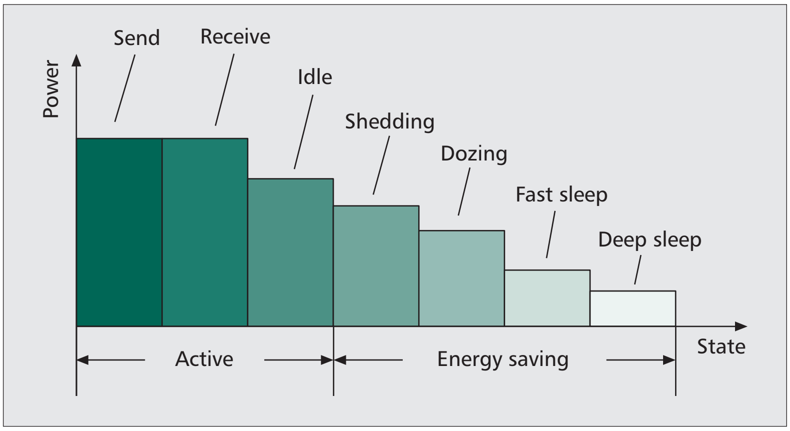

Figure 3. *ONU power consumption under different active and energy-saving states.*

Recently, the authors of [14] proposed a dynamic ONU power saving mechanism, whereby the ONU dynamically switches between burst and continuous modes. With the former, the ONU turns the receiver circuitry off during the power save period, and can be quickly ready for transmission/receiving by recovering the OLT clock using a burst mode receiver. In contrast, the continuous mode keeps the clock recovery circuit active, which requires only trivial circuit control path modifications. Clearly, burst mode sleeping can achieve better energy efficiency and lower overhead time than can continuous mode sleeping at the expense of more complicated circuitry control (similar to GR-ONU-3).

Finally, the authors of [15] proposed two sleep mode scenarios for ONUs. The study assumes the availability of multi-power-level ONUs where each level or state corresponds to a specific energy consumption level. In the first scenario, the ONU sleeps for more than one DBA cycle. This is achieved by defining a threshold, *idle_threshold*, to restrict the maximum time in which the ONU stays idle before going to sleep. In the second scenario, the ONU switches to sleep mode based on a threshold estimated through the downstream traffic profiles of all ONUs. Without addressing any performance

ONU sleep-based technique	Complexity	Energy saving	Network performance	Hardware requirements
Energy-aware fixed bandwidth allocation [11]	Low	Medium	Poor	Not investigated
Just-in-time sleep control [12]	Medium	Medium	Medium	GR-ONU-2, GR-ONU-3
Upstream-centric scheme (UCS) [13]	Low	High	DBA-dependent	GR-ONU-2, GR-ONU-3
Downstream-centric scheme (DCS) [13]	Low	Medium	Good	GR-ONU-2, GR-ONU-3
Dynamic ONU power saving [14]	High	High	Good	GR-ONU-2, GR-ONU-3
Energy-aware MAC protocol [15]	High	High	Not investigated	Multi-power-level ONU

Table 2. *Comparison between the ONU sleep-based techniques proposed in the literature.*

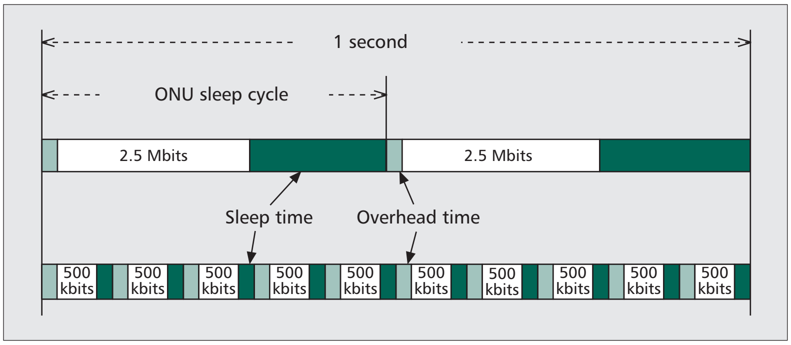

Figure 4. *Transferring 5 Mb/s traffic using batch-mode (upper diagram) and legacy-mode (lower diagram) transmissions.*

issue, the paper leaves some room for further investigation in terms of the impact on users' QoS perception.

Table 2 compares the ONU sleep techniques presented in the literature. As observed, most of the schemes are costly, as they require new ONU architectures to operate. They are also either very complex, or able to attain high energy saving at the cost of sacrificing network performance.

Adaptive Link Rate — Adaptive link rate (ALR) can be achieved due to the ability to select a transmission rate (from a set of available rates) dynamically. With respect to energy efficiency, ALR has been widely employed in wireless networks where most technologies (e.g., WiFi, WiMAX) have multiple transmission rates. The higher the selected rate, the higher the power consumption. Nonetheless, lower transmission rates lead to poorer network performance. This technique can be used in GPONs and G-EPONs where multiple rates are available (1 Gb/s, 2.5 Gb/s, and 10 Gb/s). However, it cannot be implemented in EPONs where typically one rate exists. Furthermore, the application of ALR over NG-PON1 and NG-PON2 has not been yet explored. Using ALR in G-EPONs, the authors of [16] proposed a simple scheme to enable the multirate ONU to set the optical link rate adaptively based on the monitored traffic load. This allows for minimization of the ONU active time and hence extends the sleep period so as to save more energy.

Shutdown Wavelength(s) — Since NG-PON's OLT is the sole controller of the network and is responsible for many more tasks than sending and receiving data, it is not supposed to contribute to any energy reduction plan. Furthermore, since all the ONUs rely on the OLT's clock to synchronize, putting the OLT to sleep will cause a synchronization problem [7]. In some versions of NG-PONs (LR-PONs and WDM-PONs), the OLT can save energy by provisioning the traffic on a subset of wavelengths while shutting down the rest of the wavelengths [17].

In summary, software-based techniques are promising solutions for energy saving in NG-PONs, as they can minimize power consumption at low cost. However, effective mechanisms are required to leverage the advantages of the existing and new ONU architectures in order to build a green NG-PON without breaking the user's service requirements.

Green Bandwidth Allocation

We propose a new framework for GBA, featuring the following techniques:

- Hybrid cyclic/deep sleep enabled at ONUs
- Batch-mode transmission at OLT and ONUs
- UCS-based DBA

With the proposed GBA, the ONU goes into sleep mode for a certain amount of time before waking up to send/receive a batch of buffered upstream/downstream traffic. The main purpose of this strategy is to extend the ONU sleep time as much as possible so as to reduce the total overhead time that accumulates due to frequent switching of the ONU between active and sleep modes. Figure 4 illustrates the difference between the batch-mode transmission of the proposed GBA (upper diagram) and the legacy transmission strategy (lower diagram). Although the total active time is the same for data transmission (i.e., 5 Mb), the proposed GBA can yield a much longer ONU sleep period in total due to much shorter overhead time, thereby saving more power. Specifically, using the legacy transmission scheme results in a total overhead of $10 \times 5.125 = 51.25$ ms under the GR-ONU-1/C architecture. On the other hand with the proposed batch-mode transmission, the total overhead is reduced to $2 \times 5.125 = 10.25$ ms. The remaining challenge would be to determine the ONU sleep

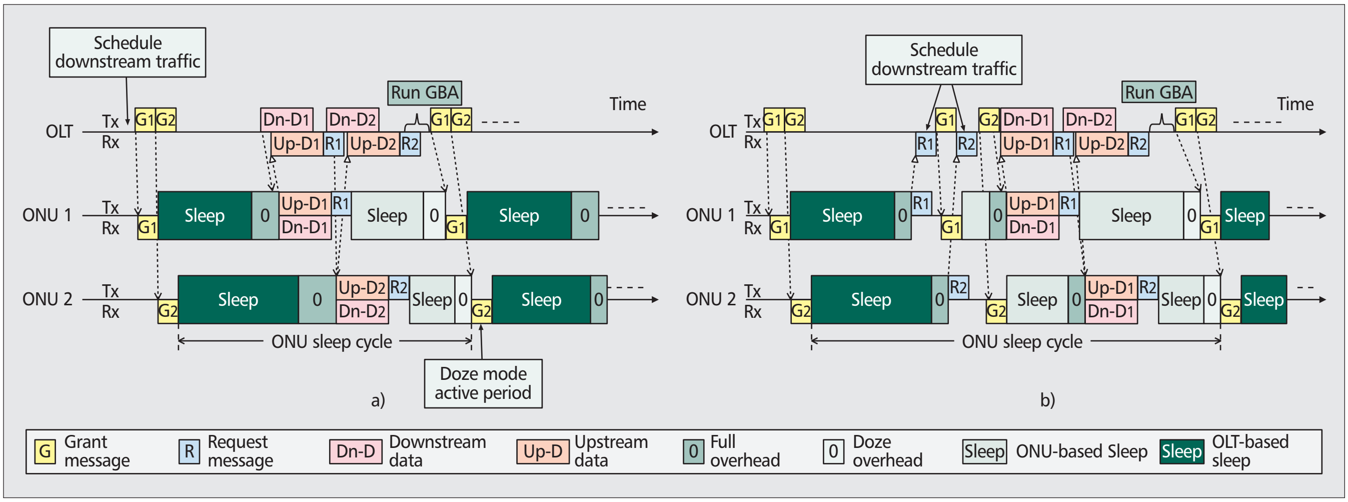

Figure 5. *GBA in TDM-based PONs with a) direct ONU transmission; b) request after sleep.*

time, which should be long enough to possibly save maximum energy, yet short enough to maintain the QoS requirements of all types of traffic, especially for delay-sensitive applications. The expression of sleep time should be dependent on the employed DBA scheme as well as the sleep signaling protocol between the OLT and ONUs. We suggest using a UCS-based DBA scheme because, as discussed earlier, it can ensure maximum saved energy at the ONUs. With these techniques, the proposed framework implements a hybrid deep/cyclic sleep mode at the ONUs.

The rest of the section describes the GBA functions in the OLT and ONUs, respectively. Discussion is provided on how the maximum sleep time could be determined and how the proposed framework can comply with the currently available NG-PON standards.

GBA AT THE OLT

With GBA, the ONU sleeping is initiated by the OLT, where the general procedure's steps are provided as follows:

S1: Wait until all the request messages from all ONUs are received.

S2: Given a per-class maximum delay requirement and a scheduling service discipline (e.g., fixed, gated, limited), compute the expected/approximated sleep time for every ONU.

S3: Schedule the buffered downstream data for the ONUs to be transmitted during the allocated upstream transmission window.

S4: Send grant messages with embedded sleep time values to all ONUs.

GBA AT THE ONU

Upon receiving the grant message, the ONU immediately goes into sleep mode and sets its timer accordingly. In the ONU active period, as illustrated in Fig. 5, the following two scenarios could be applied.

Direct ONU transmission: In this scenario, upon waking up, the ONU starts sending/receiving the buffered data directly. As shown in Fig. 5, the total overhead exhibited in every ONU sleep cycle will be low without any wasted idle time. However, in time-division multiplexing (TDM)-based PONs, the OLT will be required to sort/synchronize the sleep time periods of all ONUs to avoid any possible collision in case two or more ONUs access the shared channel simultaneously.

Request after sleep: Upon waking up, the ONU has to issue a request in the upstream direction and wait for an OLT grant. Compared to the first scenario, where the request-grant procedure right after sleeping is eliminated, this scenario does not require high precision of OLT synchronization among the ONUs. Such a request-grant procedure certainly causes additional delay, as shown in the figure, and should be included in the computation of the sleep time, thereby making it more complex and possibly less energy efficient.

With either scenario, after sending the request message to the OLT, each ONU will remain idle until receiving a grant message from the OLT. In TDM-based PONs, this idle time might be lengthy if other ONUs have large amounts of data to be transmitted and/or received. Hence, the ONU can meanwhile switch to sleep mode in order to save energy. As a result, the OLT will be required to specify in the grant message two sleep times:

- OLT-based, which represents the time the ONU spends in sleep mode upon receiving the grant message
- ONU-based, which represents the time the ONU spends in sleep mode directly after sending a request message and until receiving a grant message

The sum of both times should not exceed the computed maximum sleep time to preserve the desired QoS performance.

The case of a "short" sleep time might be problematic for slow recovering ONUs (e.g., GR-ONU-1). To resolve this issue, the OLT can allow the ONU to sleep (in either OLT-based or ONU-based mode) only if the respective sleep time is greater than its overhead time. Furthermore, since the ONU goes directly into OLT-based sleep mode once it receives a grant message, it can spend the time receiving the grant message in doze mode (or alternatively sleep-aware mode [8]). With all these methods, GBA can achieve the maximum possible energy reduction.

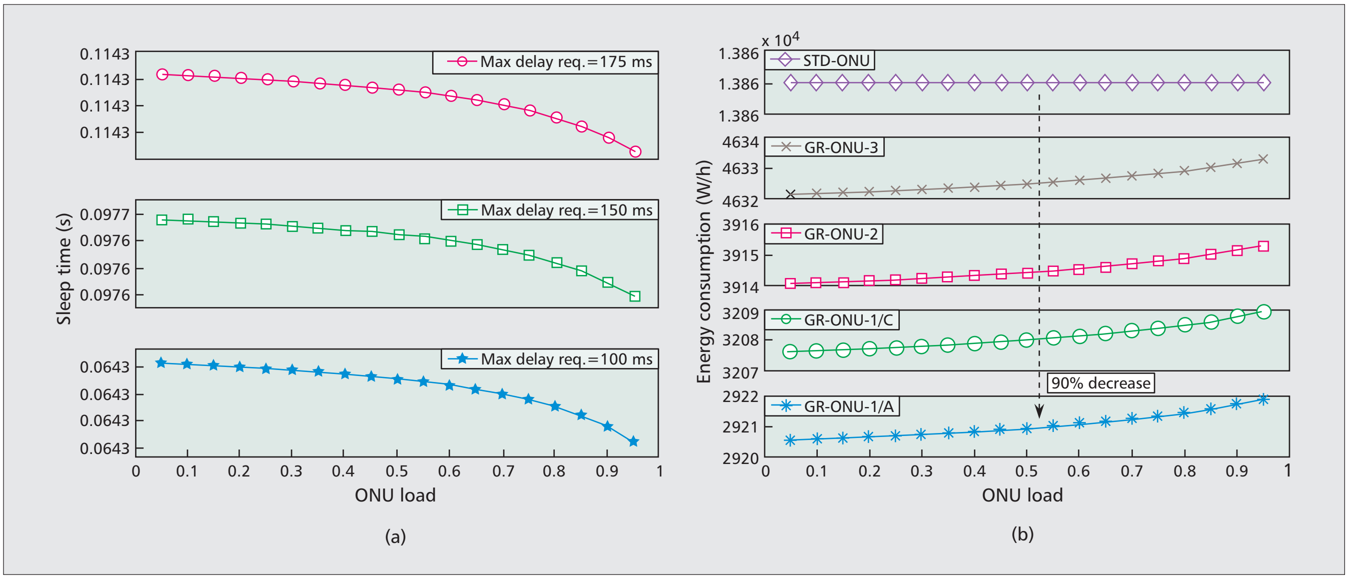

Figure 6. *a) Sleep time under GR-ONU-1/A; b) energy consumption of different ONU architectures.*

GBA FOR WDM-BASED NG-PONS

The operation of GBA over WDM-based NG-PONs is straightforward and requires no amendment. Since every ONU connects to the OLT through a separate wavelength, instead of having the OLT wait for all the requests of all ONUs, it can send the sleep time grant (with the OLT-based sleep time value only) for every ONU directly upon receiving the request message. In addition, sleep time synchronization is not required under the direct ONU transmission scenario.

MAXIMUM ONU SLEEP TIME

Taking the maximum ONU sleep time without violating the user's QoS requirements is the core theme of GBA. This should be jointly determined by the idle statuses of the ONUs (or whether or not they have traffic to transmit) and by their expected traffic patterns. Computing the sleep time for each ONU in advance without relying on conventional polling mechanisms can effectively reduce the control messaging overhead needed to learn about every ONU's status.

To demonstrate the operation of the proposed framework, we developed in [18] the first analytical model for multiclass EPONs, which provides a closed-form expression of the ONU sleep time under the gated service discipline and the direct ONU transmission scenario. Each ONU is modeled as an M/G/1 system with vacations, where the sleep time and the control messaging period are considered vacation times for the ONU server. Specifically, the sleep time for every ONU is approximated via the ONU traffic pattern and the maximum upstream delay requirement.

Due to its design flexibility, GBA can utilize any other selected sleep time value (e.g., from [15]), but may require further DBA considerations. Other analytical models may further be developed to measure the sleep time based on the expected downstream packet latency and its respective QoS requirement (if any). The OLT will then set the ONU sleep time to be the minimum between upstream-based and downstream-based values.

GBA COMPLIANCE WITH MPCP AND PLOAM

EPON's Multi-Point Control Protocol (MPCP) defines three timeout mechanisms for the interconnection between OLT and ONUs:

- *mpcp_timeout*, which forces the ONU to send a REPORT message at least once every second in order to maintain registration
- *gate_timeout*, which forces the OLT to generate a (possibly empty) GATE message for a particular ONU at least once every 50 ms
- *report_timeout*, which specifies a 50 ms timeout between two consecutive REPORT messages of the same ONU

Similarly, GPON's Physical Layer Operations and Maintenance (PLOAM) defines a timeout period of 100 ms, after which an ONU will fully deactivate [6].

To comply with MPCP and PLOAM, an ONU should wake up by 50 ms. Alternately, MPCP and PLOAM can be amended to enable a dynamic timeout setting so as to allow the sleep time to exceed 50 ms or possibly 1 s, and thus maximize energy saving in NG-PON.

RESULTS

To demonstrate the effectiveness of our proposed framework, we consider an EPON network of 16 ONUs and 1 Gb/s speed.

We first plot in Fig. 6a the computed sleep time of GR-ONU-1/A using the proposed analytical model in [18] vs. multiple maximum delay requirement values. It is observed that GR-ONU-1/A can sleep up to 64.3 ms, 97.6 ms, and 114.3 ms for a delay requirement of 100 ms, 150 ms (which is the typical voice/video maximum delay requirement), and 175 ms, respectively. These numbers highlight the advantages of the proposed batch-mode transmission, which can keep the ONU in sleep mode for the longest possible time (and thus enables maximum energy saving) while statistically maintaining the delay requirements for all types of traffic. It is also noted that the sleep time does not vary much as the load increases. This is due to the fact that the sleep time approximation is DBA-dependent (in the case of [18], a gated service). Thus, other DBA schemes may be employed and analyzed, resulting in possibly different sleep time behavior at various loads.

We then plot in Fig. 6b the energy consumption of different types of ONUs. As expected, STD-ONU always consumes maximum power as it never sleeps. With efficient sleep time management employing maximum ONU sleep time approximation [18], GR-ONU-1 can achieve much lower energy consumption than GR-ONU-2 and GR-ONU-3, although it carries the longer overhead time disadvantage. In comparison with the legacy transmission mode (i.e., under STD-ONU), the figure also shows that GBA can achieve almost 90 percent energy reduction. This proves that the design of a robust sleep control protocol can foster the availability and low-cost deployment of legacy ONUs and alleviate their long overhead time to build a "greener" NG-PON.

Conclusion and Future Work

Energy saving in telecom IP networks has been gaining massive attention in both the industry and academia. In this article, we first review the previously reported power saving techniques and research efforts that aim at reducing energy consumption in NG-PONs. We then introduce a green bandwidth allocation framework, which is characterized by a novel batch-mode transmission mechanism that can incorporate any ONU sleep time computation scheme. Our results show that the proposed framework can take advantage of the sleep mode functionality at the ONUs to achieve maximum energy saving while maintaining the users' requirements.

Due to the uncertainty of Internet traffic, bound analysis on the sleep time for ONUs is critical in pushing the proposed framework into practical deployment. A suite of closed-form expressions can be formulated for the upper and lower bounds on the possible ONU sleep time while statistically meeting the users' requirements. Such bounds can provide a design guideline for the ONU sleep time selection, in order to take advantage of the advances in ONU architectures and explore the user's QoS tolerance while achieving maximum power efficiency.

Our results show that the proposed framework can take advantage of the sleep mode functionality at the ONUs to achieve maximum energy saving while maintaining the users' requirements.

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