Energy-saving framework for passive optical networks with ONU sleep/doze mode

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Abstract: This paper proposes an energy-saving passive optical network framework (ESPON) that aims to incorporate optical network unit (ONU) sleep/doze mode into dynamic bandwidth allocation (DBA) algorithms to reduce ONU energy consumption. In the ESPON, the optical line terminal (OLT) schedules both downstream (DS) and upstream (US) transmissions in the same slot in an online and dynamic fashion whereas the ONU enters sleep mode outside the slot. The ONU sleep time is maximized based on both DS and US traffic. Moreover, during the slot, the ONU might enter doze mode when only its transmitter is idle to further improve energy efficiency. The scheduling order of data transmission, control message exchange, sleep period, and doze period defines an energy-efficient scheme under the ESPON. Three schemes are designed and evaluated in an extensive FPGA-based evaluation. Results show that whilst all the schemes significantly save ONU energy for different evaluation scenarios, the scheduling order has great impact on their performance. In addition, the ESPON allows for a scheduling order that saves ONU energy independently of the network reach.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks.

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1. Introduction

Passive Optical Networks (PONs) have been widely considered as the most favorable access network architecture to cater for the growing demand of bandwidth-hungry applications. Even though PONs are considered more energy-efficient compared to other wired access technologies, such as xDSL, due to their massive deployment nowadays and even more in the future, it is desirable to further reduce their energy consumption. The research community, network providers, and standardization authorities have been targeting energy-efficient solutions for both current PONs, i.e., EPON, GPON, 10G-EPON, XG-PON [1–9], and next-generation PON, known as NG-PON2 or Time and Wavelength Division Multiplexed (TWDM)-PON [10, 11].

In a PON system, due to the large number of deployed equipment, Optical Network Units (ONUs) are the major energy consumer. However, ONUs represent also the PON components where energy saving potentials are the highest. Indeed, in Time Division Multiplexing (TDM)-PON, the broadcast nature in the downstream (DS) transmission requires an ONU to stay active always for examining all DS frames in order to know whether or not the frames are destined to it. This results in wasting significant energy. In addition, due to the bursty nature of Internet traffic, ONUs usually operate at low average network load. Therefore, most of the energy-efficient solutions for PONs are aimed at reducing the ONU energy consumption. To this end, the ONU cyclic/deep sleep, i.e., turning off the whole ONU transceiver (sleep mode) or only its transmitter (doze mode) in a cyclic fashion, has been chosen in ITU-T recommendations [1, 2] and IEEE standard [3]. This technique is mainly applied to TDM-PONs, yet can also be applied to TWDM-PONs [11].

Even though cyclic sleep has been defined in the standards, how it is incorporated into bandwidth allocation mechanisms is outside the scope of the standards. Due to the fact that a dozing ONU cannot send any upstream (US) traffic and a sleeping ONU cannot receive or send any traffic, the Optical Line Terminal (OLT) must consider not only US transmission but also DS transmission when allocating bandwidth and scheduling sleep/doze periods for ONUs. Thus, new Dynamic Bandwidth Allocation (DBA) algorithms must be designed with awareness of cyclic sleep technique. When redesigning DBA algorithms, one of the challenges is to specify a scheduling order (i.e., a sequence) in which data transmission, control message exchange, sleep period, and/or doze period are scheduled. Moreover, as data frames must be buffered during ONU sleep/doze periods, cyclic sleep brings out a clear trade-off between energy-savings and frame delay and/or frame loss performance. This means that the ONU sleep/doze time should be carefully determined so that energy-savings can be achieved whilst maintaining the required Quality of Service (QoS).

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As an ONU consumes much more energy when operating in doze mode than in sleep mode [12], to maximize energy efficiency, the ONU sleep time should be extended as much as possible. A preferable way is to overlap the DS and US transmissions as much as possible, i.e., locking mode, and schedule the ONU sleep period outside of both DS and US transmission windows. The concept of locking DS transmission to the US timeslot was first proposed in the Upstream Centric Scheme (UCS) [4]. In the UCS, the ONU sleeps outside its US timeslot during which DS traffic is scheduled to be sent. As a result, the ONU sleep time is dependent on US traffic only.

The authors in [5] proposed a Green Bandwidth Allocation framework (GBA) that implements batch-mode US and DS transmissions and an UCS-based DBA algorithm. The GBA performs off-line scheduling where the OLT waits for all the `REPORT` messages from ONUs before computing grants for the next cycle. As a result, the ONU is scheduled to enter sleep mode twice in a polling cycle, i.e., after a `GATE` until the slot start and after a `REPORT` until the next `GATE`. However, sleeping twice implies two times of wake-up overhead [12] that considerably limits the energy saving potentials. Moreover, an off-line scheduling scheme causes extra delay and idle times between successive cycles. Another example of the off-line scheduling paradigm is the Energy-Saving scheme based on DS Packet Scheduling (ESPS) proposed to reduce EPON energy consumption whilst minimizing DS packet delay [6]. In ESPS, independent sleep modes, i.e., either ONU transmitter or receiver or both of them can be switched to sleep, are scheduled based on their respective assigned slot, i.e., US slot and DS slot.

ONU sleep time can be computed in different ways. In [7], a modification of the Interleaved Polling with Adaptive Cycle Time (IPACT) to enable sleep mode was proposed. The ONU is scheduled to sleep when it requests no bandwidth for US traffic. For a given maximum mean US packet delay, ONU sleep time is derived through an analytical model for expected mean US delay. The work therefore limits to consider only US traffic and US delay constraints. On the contrary, the authors in [8] proposed an Adaptive Delay-Aware Energy-Efficient scheme (ADAEE) that aims at maximizing ONU energy-savings based on DS transmission. ONU sleep time is calculated based on delay requirement and estimated data rate of DS transmission only.

As for the scheduling order, similar to [7], the authors in [9] proposed a Sleep Mode Aware (SMA) algorithm to combine sleep mode with the IPACT. However, in the SMA, the OLT allocates data slot duration as the minimum between US and DS buffer backlogs. The OLT first sends a `GATE` to an ONU. When the ONU receives the `GATE`, it replies with a `REPORT`. After the `REPORT` is sent, both US and DS data transmissions take place. When the data slot duration expires, the ONU enters sleep mode until the scheduled time for the next `GATE` message. The OLT determines the scheduled time for a `GATE` by predicting the total transmission time of all other ONUs. However, such a prediction can result in severe service degradation, e.g., high frame delay and/or frame loss, as well as inefficiency in energy saving performance.

This paper proposes an energy-saving PON (ESPON) framework that aims at saving ONU energy through cyclic sleep. Compared to existing studies on energy-efficient PONs, the ESPON minimizes the wake-up overhead time with at most one sleep period scheduled for every ONU in a cycle. In addition, in ESPON, the OLT takes into account both DS and US transmissions to allocate bandwidth dynamically and schedule ONU sleep/doze periods. The ONU sleep time is maximized based on both DS and US traffic. To further improve energy efficiency, the ONU also enters doze mode whenever possible.

2. Proposed energy-saving PON (ESPON) framework

This section presents the proposed energy-saving PON (ESPON) framework based on the 10G-EPON architecture [13]. The ESPON framework is a set of schemes for allocating bandwidth and at the same time scheduling ONU sleep/doze periods which are all based on the extension

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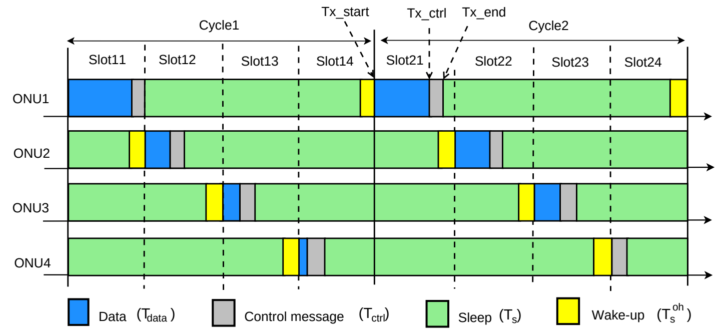

Fig. 1. Illustration of energy-saving PON framework where the number of ONUs is 4.

of 10G-EPON and are different from one another in the timing of `GATE` and `REPORT` messages as well as their grant sizing method.

2.1. *Working principle*

In the ESPON framework, as shown in Fig. 1, for each OLT-ONU transmission pair that comprises data transmission and control message exchange between the OLT and the ONU, a cycle is divided into four parts: a data slot T_{data} during which both DS and US data frames are transmitted and received; a control message slot T_{ctrl} during which a `GATE` and a `REPORT` are exchanged; a sleep period T_s during which the ONU transceiver is switched off whilst all incoming data frames are buffered; and a wake-up period T_s^{oh} during which the ONU performs wake-up procedure from sleep mode [12] and all incoming data frames are buffered.

To guarantee fairness to available resources amongst all ONUs, although potentially incurring into capacity under-utilization, in any given polling cycle, each OLT-ONU pair is assigned the same timeslot $T_{slot} = T_c/N$, where T_c is cycle time, i.e., the time interval between two consecutive timeslots of an OLT-ONU pair, and N is the number of ONUs. However, within a timeslot, depending on traffic conditions and network reach, the OLT-ONU pair utilizes a transmission slot whose duration is $Tx_{len} = T_{data} + T_{ctrl} \leq T_{slot}$ for transmitting and receiving DS and US data traffic and control messages. Outside the transmission slot, the ONU enters sleep mode for saving energy. Moreover, within the transmission slot, if there is any period during which the ONU transmitter is idle, the ONU enters doze mode, i.e., it turns off its transmitter only, for further improving energy efficiency. The OLT allocates bandwidth in an online and dynamic fashion whereby an OLT-ONU pair is assigned Tx_{len} for the next cycle at the end of any current transmission slot based on instantaneous DS and the most recently reported US bandwidth requests.

It is important to note that the ESPON framework first assigns bandwidth to all OLT-ONU pairs equally to avoid the situation whereby an OLT-ONU pair occupies the media for most of the cycle time. This is the same as in fixed bandwidth allocation (FBA). However, the ESPON synchronizes both DS and US transmissions in the same transmission slot, thus allocating bandwidth for the two transmissions rather than only for US one as in the FBA. In addition, the dynamic nature of the framework is that for a given assigned timeslot, it just allocates the minimum transmission slot based on both DS and US traffic conditions in order to maximize ONU sleep time outside the slot in a cycle.

The working principle of the ESPON is applied to TDM-PONs in general. However, this paper implements and evaluates the framework for 10G-EPON only. To facilitate ESPON operation, a frame structure for extended GATE message is defined based on the multi-point control protocol data unit (MPCPDU). As in the legacy 10G-EPON, the extended `GATE` contains the start Tx_start and duration Tx_{len} of a transmission slot. In addition, each extended `GATE` contains RTT that is measured by the OLT for the ONU to compute T_{data} and T_{ctrl} given its assigned

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Tx_{len}. Note that for reporting US bandwidth, the ESPON utilizes the conventional `REPORT` MPCPDU as in legacy 10G-EPON. The ESPON is compatible with current 10G-EPON specification whereby the extended `GATE` messages would only be generated by the ESPON OLT and extracted by the ESPON ONUs. This supports a smooth migration toward energy-efficient 10G-EPONs.

2.2. Scheduling order

In legacy TDM-PONs, a typical upstream scheduling order, i.e., the order implemented in IPACT, is `REPORT-GATE-DATA`: first, the ONU sends a `REPORT` message to request US bandwidth; the OLT then responds with a `GATE` message; and the ONU sends US traffic in the assigned timeslot. The impact of the `REPORT` scheduling, either at the beginning or at the end of an US timeslot for both online and off-line scheduling schemes, on legacy TDM-PON performance has been investigated [14]. However, when incorporating sleep/doze mode into the operations of a PON system, a scheduling scheme must specify where to insert the sleep period and/or doze period into an existing order of data transmission, `REPORT` message, and `GATE` message. Therefore, the scheduling order becomes a challenge. In fact, any combination of a `SLEEP` period and/or a `DOZE` period with the IPACT scheduling order might result in a cyclic sleep protocol. For example, the scheduling order implemented in the SMA [9] is `GATE-REPORT-DATA-SLEEP`.

This paper implements and evaluates three energy-efficient schemes under ESPON, with each having its own scheduling order in a cycle: i) the sleep-aware DBA (SDBA) scheme with scheduling order `REPORT-GATE-SLEEP-DATA` [15]; ii) the energy-efficient DBA (EDBA) scheme with scheduling order `REPORT-DOZE-GATE-SLEEP-DATA` [16]; and iii) the advanced sleep-aware DBA (ASDBA) scheme with scheduling order `GATE-REPORT-SLEEP-DATA`.

2.3. Grant sizing policy

The ESPON operates under the assumption that all OLT-ONU transmission pairs are always allocated sufficient bandwidth in any polling cycle. This assumption means that T_c is large enough so that $T_{slot} \geq Tx_{len}$ is always be true for any OLT-ONU transmission pair.

Grant sizing specifies a method of determining Tx_{len}. In ESPON, the grant sizing policy is to grant an amount of bandwidth that allows both the OLT and ONU to not only transmit but also receive DS and US data traffic as well as control messages in a cycle. Grant sizing therefore depends not only on traffic conditions but also the scheduling order. It is important to note that in case the bandwidth condition is not met (i.e., $T_{slot} < Tx_{len}$), Tx_{len} must be assigned to T_{slot} to maintain the fairness amongst transmission pairs. If this is the case, the control message exchange has priority over the data traffic transmission.

Whilst both the OLT and the ONU are granted the same grant size Tx_{len}, the actual DS data slot and US data slot in the next cycle are not the same because they depend on the scheduling order and RTT. In ESPON, the grant sizing policy can be based either on the estimated amount of traffic arrived during a cycle as in [15] or based on the actual amount of traffic in data buffers (i.e., buffer backlog) as in [16].

2.4. Cycle time

In ESPON, as the ONU sleeps outside its transmission slot, the longer the cycle time, the longer the ONU sleep time, but also the longer the incurred frame delay. However, a short cycle time might result in insufficient bandwidth for transmission pairs. Thus, choosing a proper cycle time is important. T_c can be computed based on user delay requirements [15]. Whilst the cycle time can be determined different ways, this paper evaluates the three schemes under the ESPON framework with user-defined values of T_c.

Table 1. Summary of energy-efficient schemes under ESPON framework

Feature	**SDBA** [15]	**EDBA** [16]	**ASDBA**
Scheduling order	`REPORT-GATE-SLEEP-DATA`	`REPORT-DOZE-GATE-SLEEP-DATA`	`GATE-REPORT-SLEEP-DATA`
Grant sizing (Tx_{len})	$\max\{B_{ds}, B_{us}\} + RTT + T_{msg}$	$\max\{B_{ds}, B_{us} + RTT\} + T_{msg}$	$\max\{B_{ds}, B_{us}\} + RTT + T_{msg}$
Power saving mode	Sleep	Sleep and Doze	Sleep

3. Energy-efficient schemes under ESPON framework

This section describes the three considered schemes focusing on their protocol operation and grant sizing policy. The main characteristics of the schemes are summarized in Table 1. For illustrative purposes, the protocol operation of each energy-efficient scheme is described for only two ONUs. The OLT maintains a global clock olt_clk, whilst each ONU maintains its local clock onu_clk that is assigned to olt_clk embedded in `GATE` messages for synchronization purposes. Protocol operations are triggered based on the comparison between the clocks and local time variables. For each OLT-ONU pair, the OLT and ONU both maintain the same set of local time variables: Tx_start, Tx_{len}, and $Tx\_end = Tx\_start + Tx_{len}$ indicate the start, duration, and end of a transmission slot, respectively; Tx_ctrl and $T_{ctrl} = Tx\_end - Tx\_ctrl$ indicate the start and duration of the control message slot within the slot, respectively. Whilst Tx_start, Tx_{len}, and Tx_end are the same at the OLT and the ONU, T_{ctrl} and therefore Tx_ctrl at the OLT are different from those at the ONU.

Let B_{ds} and B_{us} be the DS data bandwidth request at the time of a `GATE` generation and the US data bandwidth request at the time of a `REPORT` generation in the same cycle, respectively. Let Len_{ds} and Len_{us} be the actual bandwidth granted to DS and US data traffic in that cycle, i.e., T_{data} at the OLT and at the ONU, respectively. Note that B_{ds}, B_{us}, Len_{ds}, and Len_{us} are expressed in time units (e.g., seconds). Then, Tx_{len} will be a function of B_{ds}, B_{us}, RTT, and T_{msg}. The parameter T_{msg} is the processing time of a `GATE` and a `REPORT` and is assumed to be constant and the same at the OLT and ONUs.

3.1. *Sleep-aware dynamic bandwidth allocation scheme (SDBA)*

Protocol operation: The SDBA protocol operation is illustrated in Fig. 2 comprising an off-line initialization phase and an online phase. During the off-line phase, the OLT measures and informs all ONUs their RTTs, whilst each ONU reports its US data bandwidth request. Once all the initial `REPORT`s are received, the OLT performs off-line scheduling for the first cycle. The online phase operation is as follows:

Step 1: When an ONU receives a `GATE`, it first reassigns its clock onu_clk to olt_clk extracted from the `GATE` for synchronization purposes [15]. It then extracts RTT, Tx_start, and Tx_{len} and updates Tx_end. The ONU enters sleep mode only if its idle time $T_{idle} = Tx\_start - onu\_clk$ is greater than the wake-up time T_s^{oh}. The ONU sleep time is then computed from T_{idle} as $T_s = T_{idle} - T_s^{oh}$. US traffic must be buffered until onu_clk reaches Tx_start.

Step 2: If the ONU decides to sleep, when onu_clk reaches $Tx\_start - T_s^{oh}$, the ONU wakes up and prepares its transceiver for data and control message transmission.

Step 3: When the OLT and ONU local clocks reach Tx_start, both transmit buffered traffic.

Step 4: When onu_clk reaches $Tx\_ctrl = Tx\_end - RTT - T_{msg}$ the ONU stops transmitting US data to send a `REPORT` with an updated value of B_{us}. This ensures that the replying `GATE` is received at the end of the current transmission slot.

Step 5: The OLT stops transmitting DS data traffic when either it receives a `REPORT` or

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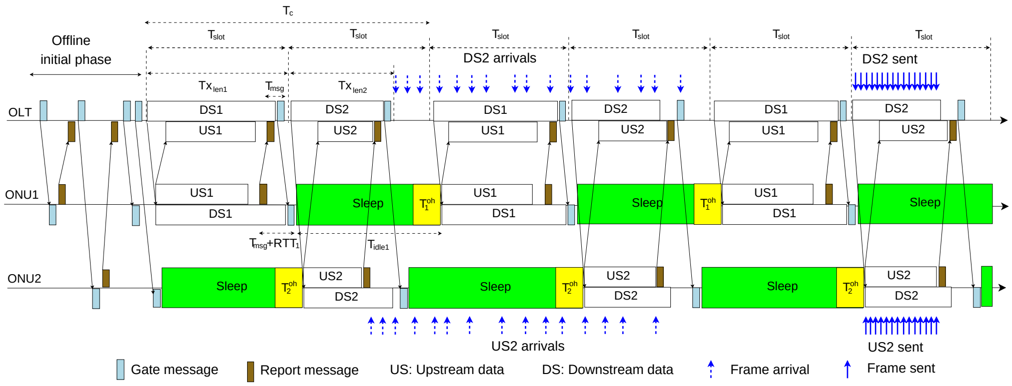

Fig. 2. Illustration of SDBA scheme operation.

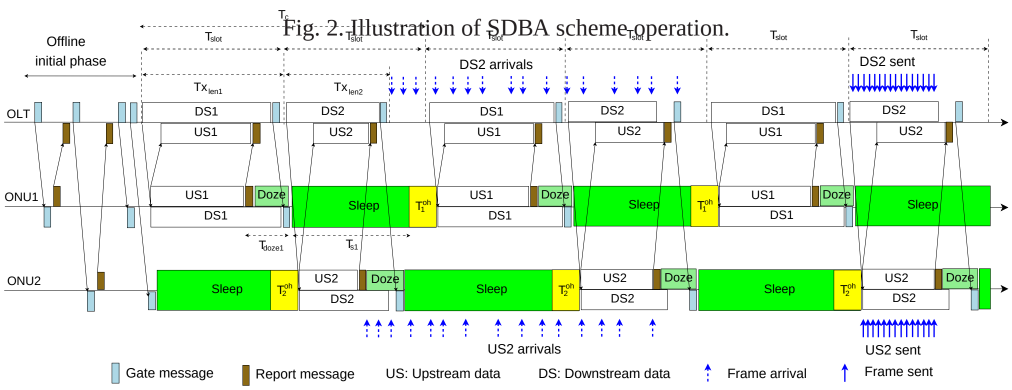

Fig. 3. Illustration of EDBA scheme operation.

olt_clk reaches $Tx\_ctrl = Tx\_end - T_{msg}$. It then recomputes Tx_start and Tx_{len} and sends a new GATE to the ONU. DS traffic is buffered until Tx_start. The protocol repeats with *Step 1*.

Grant sizing policy: In the SDBA scheme, Tx_{len} is computed as:

$$Tx_{len} = \begin{cases} B_{ds} + RTT + T_{msg}, & \text{if } B_{ds} \geq B_{us} \\ B_{us} + RTT + T_{msg}, & \text{otherwise} \end{cases} \tag{1}$$

As shown in Fig. 2, for exchanging messages in a cycle, the OLT needs only T_{msg} time, whereas the ONU needs $RTT + T_{msg}$ time. That is, T_{ctrl} is T_{msg} and $RTT + T_{msg}$ at the OLT and ONU, respectively. Eq. (1) ensures that both OLT and ONU have sufficient bandwidth for both transmission directions. With this grant sizing policy, actual DS and US data bandwidth are:

$$\begin{cases} Len_{ds} &= Tx_{len} - T_{msg} = \max\{B_{ds}, B_{us}\} + RTT \\ Len_{us} &= Tx_{len} - RTT - T_{msg} = \max\{B_{ds}, B_{us}\} \end{cases} \tag{2}$$

From Eq. (2), the DS data slot is always RTT longer the US data slot. Assume that the interval between two consecutive GATEs is equal to T_c, T_{idle} is $T_c - Tx_{len}$ (Fig. 2). In the most common traffic scenario where DS traffic is heavier than US one, i.e., $B_{ds} \geq B_{us}$, T_{idle} becomes $T_c - B_{ds} - RTT - T_{msg}$. Hence, the longer the RTT, the shorter the T_{idle} thereby the shorter the T_s. Therefore, overall energy-savings depends not only on DS traffic load but also on RTT.

3.2. Energy-efficient dynamic bandwidth allocation scheme (EDBA)

The EDBA scheme [16] has been proposed to improve the SDBA performance by implementing doze mode during the REPORT-to-GATE time, i.e., granting time. The doze mode is utilized

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rather than the sleep mode during this time because T_s^{oh} ($\approx$ 2 ms [12]) is usually longer than RTT of a typical PON system ($\approx$ 1 ms for a network reach of 100 km). In addition, the EDBA implements an optimal grant sizing policy compared to the SDBA scheme as will be discussed in the following paragraphs.

Protocol operation: As shown in Fig. 3, the EDBA operation is similar to the SDBA operation except for *Step 4* and *Step 5*. Instead of waiting until $onu\_clk = Tx\_ctrl$ to send a `REPORT`, the ONU sends it as soon as its US data buffer is empty. The ONU then switches off its transmitter, i.e., entering doze mode, whilst leaving its receiver active to receive DS traffic and the replying `GATE`. Once the ONU receives the `GATE`, it switches off also its receiver, i.e., transitioning from doze mode to sleep mode. Whereas, the OLT sends the `GATE` at the end of data slot, i.e., when olt_clk reaches $Tx\_ctrl = Tx\_end - T_{msg}$ regardless of the `REPORT` reception.

Grant sizing policy: In the EDBA scheme, Tx_{len} is computed as:

$$Tx_{len} = \begin{cases} B_{ds} + T_{msg}, & \text{if } B_{ds} \geq B_{us} + RTT \\ B_{us} + RTT + T_{msg}, & \text{otherwise} \end{cases} \tag{3}$$

Eq. (3) ensures that Tx_{len} is the minimal value that satisfies both OLT and ONU data and control message bandwidth requests in a cycle. With this sizing policy, Len_{ds} and Len_{us} are:

$$\begin{cases} Len_{ds} &= Tx_{len} - T_{msg} = \max\{B_{ds}, B_{us} + RTT\} \\ Len_{us} &= Tx_{len} - RTT - T_{msg} = \max\{B_{ds} - RTT, B_{us}\} \end{cases} \tag{4}$$

Based on Eq. (4), the inequality $Len_{ds} \geq Len_{us}$ is always true. In the EDBA scheme, energy-savings results not only from the ONU sleep period (T_s in Fig. 3), but also from the ONU doze period (T_{doze} in Fig. 3). More specifically, the longer the RTT, the shorter the ONU sleep time, but the longer the ONU doze time.

3.3. Advanced sleep-aware dynamic bandwidth allocation scheme (ASDBA)

As the power level of an ONU in sleep state is much lower than that in doze state [12], the ONU would save more energy if the doze period in EDBA can be converted to a sleep period so that T_s can be independent of RTT. In the ASDBA scheme, this is realized by swapping the `GATE` and the `REPORT` and changing the grant sizing policy accordingly (Fig. 4).

Protocol operation: The ASDBA operation during the online phase is as follows:

Step 1: Upon receiving a `GATE`, it first reassigns its clock onu_clk to olt_clk. The ONU then extracts Tx_start and Tx_{len}, updates Tx_end, and sends a `REPORT` to the OLT. The ONU sleeps only if $T_{idle} \geq T_s^{oh}$. US traffic is buffered until Tx_start.

Step 2: If the ONU decides to sleep, when onu_clk reaches $Tx\_start - T_s^{oh}$, it wakes up and prepares its transceiver for data and control message transmission.

Step 3: When the OLT and ONU clock reach Tx_start, they both transmit buffered traffic.

Step 4: When olt_clk reaches $Tx\_ctrl = Tx\_end - RTT - T_{msg}$, the OLT stops transmitting DS data to recompute Tx_start and Tx_{len} and send a new `GATE` to the ONU. After that, DS traffic is buffered until Tx_start.

Step 5: The ONU stops transmitting US traffic when either it receives a `GATE` or onu_clk reaches $Tx\_ctrl = Tx\_end - RTT - T_{msg}$. The protocol repeats.

Grant sizing policy: In the ASDBA scheme, as shown in Fig. 4, the OLT needs $B_{ds} + RTT + T_{msg}$ time for DS data transmission and control message exchange, whereas the ONU needs $B_{us} + T_{msg}$ time for US data transmission and control message exchange. However, due to the new scheduling order, to receive whole US data traffic and the `REPORT` in a transmission slot, the OLT needs $B_{us} + RTT + T_{msg}$ time. Therefore, Tx_{len} is computed as:

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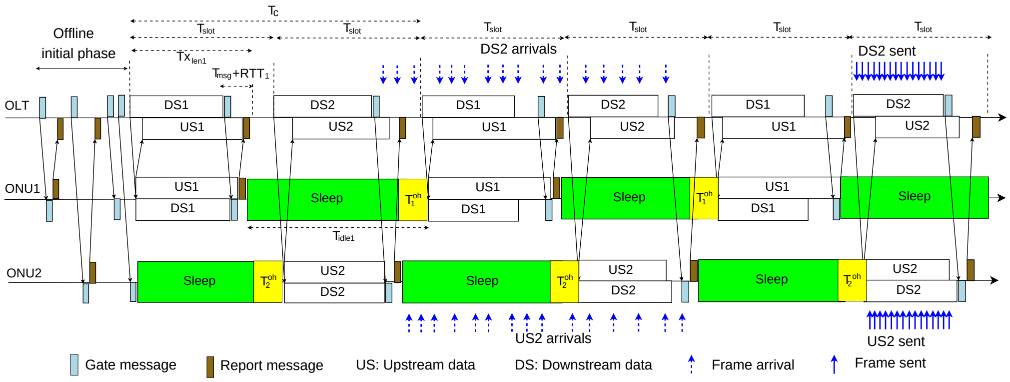

Fig. 4. Illustration of ASDBA scheme operation.

$$Tx_{len} = \begin{cases} B_{ds} + RTT + T_{msg}, & \text{if } B_{ds} \geq B_{us} \\ B_{us} + RTT + T_{msg}, & \text{otherwise} \end{cases} \tag{5}$$

Eq. (5) ensures that Tx_{len} is the optimal grant size that allows both OLT and ONU to transmit and receive all DS and US traffic and control messages in a cycle. Len_{ds} and Len_{us} are:

$$\begin{cases} Len_{ds} &= Tx_{len} - RTT - T_{msg} = \max\{B_{ds}, B_{us}\} \\ Len_{us} &= Tx_{len} - RTT - T_{msg} = \max\{B_{ds}, B_{us}\} \end{cases} \tag{6}$$

Eq. (6) shows that DS and US data slot durations are the same in the ASDBA scheme. From Fig. 4, in ASDBA, the ONU idle time T_{idle} is $T_c - Tx_{len} + RTT$. Thus, when $B_{ds} \geq B_{us}$, T_{idle} becomes $T_c - B_{ds} - T_{msg}$ that is independent of RTT and B_{us}. As a result, the ONU sleep time T_s is independent of RTT as well.

4. Performance evaluation

An energy-efficient 10G-EPON system with 4 ONUs and one OLT featuring either the SDBA, EDBA, or ASDBA schemes is designed in Verilog hardware description language (HDL) and evaluated using ModelSim as a HDL simulator. The experimental evaluation of the SDBA in an FPGA testbed with negligible RTTs was previously presented in [15]. Due to hardware limitation, this paper performs the pre-synthesis evaluation. However, when related hardware resources are available, hardware evaluation of the current HDL designs is possible.

4.1. Pre-synthesis functional verification

Fig. 5 shows the functional verification of the EDBA and ASDBA schemes in ModelSim. Fig. 5(a) shows the behavior of major signals of an OLT-ONU pair in the energy-efficient 10G-EPON system with EDBA enabled. The communication between the OLT and the ONU verifies the correctness of the EDBA HDL design. DS and US data frame arrivals (indicated by signals `ds_frame_arrival` and `us_frame_arrival`) are buffered and sent in bursts (`ds_frame_sent` and `us_frame_sent`) during their dedicated data slots (`ds_data_slot` and `us_data_slot`). The ONU starts US data transmission once it receives the first DS frame, verifying the locking mode transmission. At the end of each US data slot, a `REPORT` is sent (`report_sent`) by the ONU. A `GATE` is generated and sent (`gate_sent`) immediately after the OLT receives the `REPORT` (`report_rcvd`), confirming online scheduling. After sending the `REPORT` (`report_sent`), the ONU enters S_DOZE state. When the `GATE` is received, the ONU transitions from S_DOZE state to S_SLEEP state. The ONU wakes up during S_POST_SLEEP state then transitions to S_ACTIVE state for DS and US transmissions.

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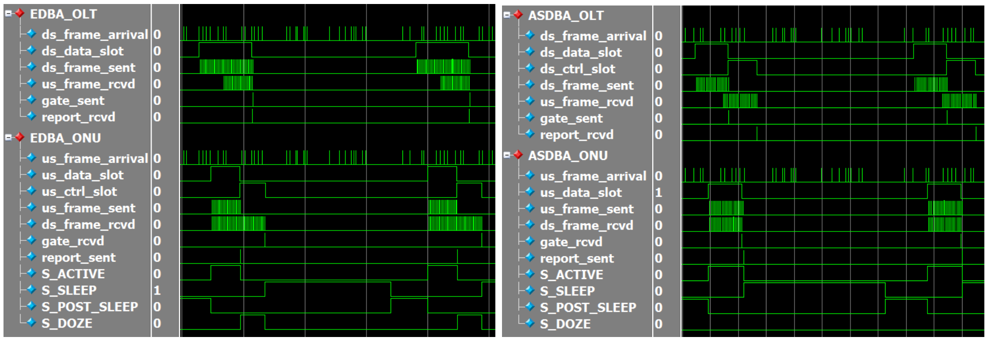

(a) Behavior of an OLT-ONU pair with EDBA enabled. (b) Behavior of an OLT-ONU pair with ASDBA enabled.

Fig. 5. Waveform demonstration of 10G-EPON featuring ESPON schemes in ModelSim.

The behavior of an OLT-ONU pair shown in Fig. 5(b) also match the ASDBA protocol description in Section 3.3. The exchange order of the `GATE` and the `REPORT` is swapped and the control message exchanging time is converted at the OLT rather than at the ONU, i.e., T_{ctrl} at OLT is RTT longer that at the ONU. Thus, the ONU is released from the granting time, maximizing its sleep time. Furthermore, in the ASDBA, the ONU sleeps continuously rather than dozing during the granting time as in the case of the EDBA scheme. It is worth emphasizing that in Fig. 5, the ONU enters sleep mode once per cycle in both EDBA and ASDBA schemes, verifying one of the advantages of the proposed online scheduling framework.

4.2. Performance metrics and parameters

The performance metrics used in the evaluation are average energy-savings, average DS frame delay, and average US frame delay. The frame delay is measured as the interval from the time the frame arrives at the data buffer until the time it departs the buffer. The energy-savings arising from implementing an energy-efficient scheme over an always-active ONU is calculated using:

$$\eta = 1 - \frac{P_a T_a + P_s T_s + P_d T_d}{P_a (T_a + T_s + T_d)} = \frac{(P_a - P_s) T_s + (P_a - P_d) T_d}{P_a T_c}, \tag{7}$$

where P_a, P_s, and P_d are the ONU power consumption in active, sleep, and doze states; and T_a, T_s, and T_d are the average time an ONU sojourns in each state within a cycle. Note that T_a also includes T_s^{oh} and T_d^{oh} [12] because ONUs are assumed to be fully powered during these states.

Table 2 summarizes the values of evaluation parameters. The simulation time is set to 50 times of T_c to have consistent and converged results. The frame arrival process is Poisson with constant frame size. DS and US data frames are internally generated inside the OLT and ONU HDL designs. All four ONUs are configured to have the same network reach, which is varied from 10 km to 100 km, corresponding to the RTT value from 0.1 ms to 1 ms, respectively. For illustrative purposes, three values of T_c, namely 7.5 ms, 10 ms, or 15 ms, are chosen.

Two evaluation scenarios are performed. In *Scenario 1*, three schemes are compared with varying network reach. Both traffic profiles, i.e., symmetric and asymmetric are considered. For the symmetric traffic case, each ONU is configured to have the same DS and US normalized load of 0.15, i.e., 1.5 Gb/s, thereby resulting an aggregate network load is 0.6 for both DS and US transmissions. This paper evaluates the most common asymmetric traffic case where DS traffic is heavier than US traffic. This is similar to the asymmetric configuration supported in PON standards (e.g., 10G-EPON [13]). In particular, each ONU is configured to have a DS normalized load of 0.15 and an US normalized load of 0.1. T_c is fixed to 10 ms. Results of one ONU as a function of network reach are reported. In *Scenario 2*, the impact of T_c on the performance of three schemes is investigated with asymmetric traffic case. Results of the EDBA

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Table 2. Values of evaluation parameters

Parameter	**Value**
Downstream and upstream line rate	10 Gb/s
Number of ONUs (N)	4
Data frame size	1250 bytes
Message time (T_{msg})	0.0256 ms
Data buffer size (all transmissions)	4 MB
Sleep/Doze overhead time (T_s^{oh}/T_s^{oh})	2 ms/ 760 ns
ONU power consumption ($P_a/P_d/P_s$)	5.052 W/3.85 W/0.75 W [12]
Downstream data rate (each ONU)	1.5 Gb/s
Upstream data rate (each ONU)	1.0 Gb/s or 1.5 Gb/s
Cycle time (T_c)	7.5 ms, 10 ms, or 15 ms
Network reach/Round-trip time (RTT)	10 km - 100 km/0.1 ms - 1 ms

and ASDBA are reported.

4.3. Performance results

Fig. 6 shows the average energy-savings for *Scenario 1*. All three schemes achieve significant ONU energy-savings for all network reaches. In most cases, the ASDBA outperforms the other two schemes. Moreover, its energy-savings is independent of RTT for both traffic cases. The SDBA saves less energy when RTT increases because the ONU must stay active longer during the granting time, resulting in shorter sleep time. The EDBA saves more energy compared to the SDBA due to the doze mode. The longer the RTT, the more energy the EDBA saves compared to the SDBA because of the longer doze time. However, the EDBA behaves differently in the two traffic cases. In the symmetric case, like the SDBA, the EDBA energy-savings decreases when RTT increases. In the asymmetric case, the EDBA energy-savings increases for a range of RTT (0.2 ms - 0.6 ms) and even exceeds the ASDBA energy-savings. This is because for given DS and US data rates, in this range, $B_{ds} \geq B_{us} + RTT$ resulting in constant T_{idle} (Eq. (3) and Eq. (4)) whilst ONU doze time increases. However, with larger network reaches, the EDBA saves less energy because Tx_{len} increases and T_{idle} decreases as a result.

Fig. 7 shows the DS average frame delays for *Scenario 1*. The ASDBA incurs higher DS delays compared to the SDBA and the EDBA. Each DS frame has to wait an average of 14 ms to be sent, an acceptable delay considering the delay requirement for access segments of typical Internet applications [17]. The ASDBA DS delay is independent of RTT because of the constant Len_{ds} (Eq. (6)). The SDBA DS delay decreases when RTT increases because the OLT has more bandwidth for DS traffic (Eq. (2)). As for the EDBA, for symmetric traffic, similar to the SDBA, DS traffic is granted RTT time more than US one resulting a lower DS delay when RTT increases. In the asymmetric case, when RTT is small, the DS actual data bandwidth is constant resulting in a constant EDBA DS delay. However, when RTT is larger, Len_{ds} becomes $B_{us} + RTT$ (Eq. (4)) resulting in a decrease in DS delay when RTT increases.

Fig. 8 shows the US average frame delays for *Scenario 1*. It is important to note that US delay in the asymmetric traffic case is lower than that in the symmetric one. This is because the ONU is always granted no more than its request in the symmetric case (Eq. (2, 4, 6)). This also explains the independency of US delay on RTT for all the schemes. In the asymmetric case, as Len_{us} is constant for both SDBA and ASDBA schemes, their US delays are also constant. Interestingly enough, even though the EDBA saves less energy than the ASDBA does for most of the network reaches, it incurs much higher US frame delays. When $RTT \leq 0.5$ ms (50 km of network reach), EDBA US delay increases because Len_{us} is RTT dependent (Eq. (4)). However, when RTT is larger, Len_{us} is constant, and therefore US delay is independent of RTT.

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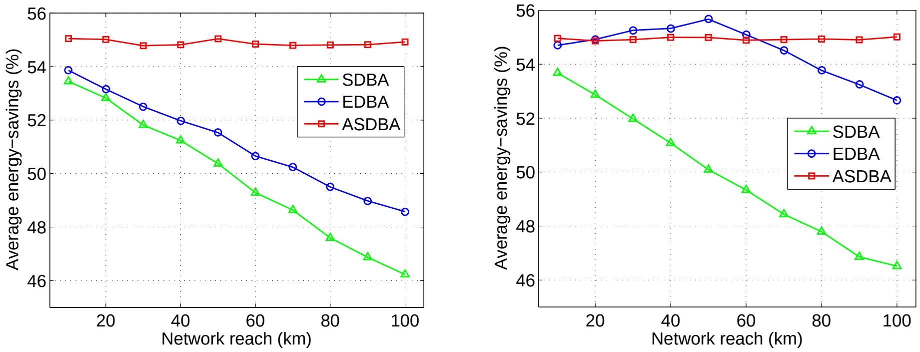
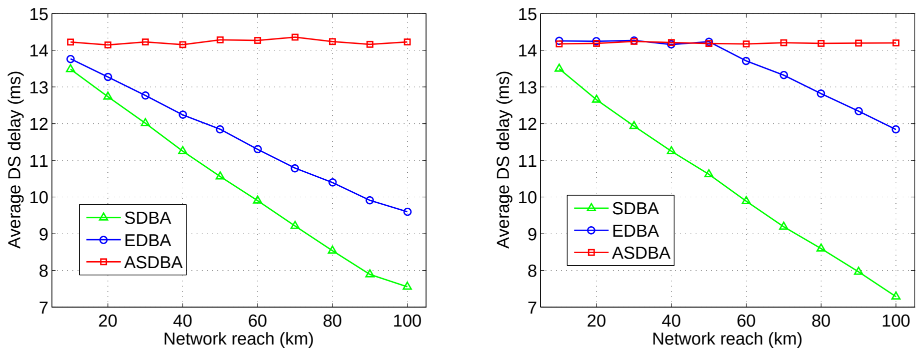


(a) Symmetric traffic (US aggr. load = 0.6). (b) Asymmetric traffic (US aggr. load = 0.4).

Fig. 6. Energy-savings with varying network reach (T_c = 10 ms, DS aggr. load = 0.6).



(a) Symmetric traffic (US aggr. load = 0.6). (b) Asymmetric traffic (US aggr. load = 0.4).

Fig. 7. DS frame delay with varying network reach (T_c = 10 ms, DS aggr. load = 0.6).

Fig. 9(a) shows the energy-savings for *Scenario 2*. Both EDBA and ASDBA schemes achieve significant energy-savings for all the cycle times and RTTs. The longer the cycle time, the higher the energy-savings as a result of longer T_{idle}. For a given T_c, when RTT is large, ASDBA outperforms EDBA because its scheduling order helps extend T_{idle}. Moreover, the ASDBA's energy-savings is independent of RTT for most of the cases except when T_c is 7.5 ms and $RTT \geq 0.8$ ms. This is because with this value of T_c and such a long RTT, the light US traffic (asymmetric) enables the ONU to extend its sleep time (see Section 3.2).

Fig. 9(b) shows the DS frame delays for *Scenario 2*. For all the cases, the longer the T_c, the longer delay the DS and US data frames experience. In the ASDBA, the delays are independent of RTT for most of the cases. However, its DS delay increases rapidly when T_c is 7.5 ms and $RTT \geq 0.8$ ms because a small assigned timeslot together with a long RTT lead to the insufficiency of bandwidth for DS traffic in this case. The EDBA incurs lower DS delays compared to the ASDBA when RTT is large because during the granting time, whilst the ASDBA OLT only waits for the `REPORT`, the EDBA OLT keeps transmitting DS traffic (Fig. 5).

4.4. Discussion

The results shown in Fig. 9(b) reveal that when T_c is too short (7.5 ms), the ASDBA DS delay increases rapidly. This is because of the violation of the bandwidth condition ($T_{slot} \geq Tx_{len}$ always). In fact, if a lower value of T_c is chosen, the ASDBA US delay as well as the delays of other schemes would behave the same. Even though the ESPON framework dynamically allocates bandwidth within a timeslot, assigning equal and fixed timeslots to all the OLT-ONU

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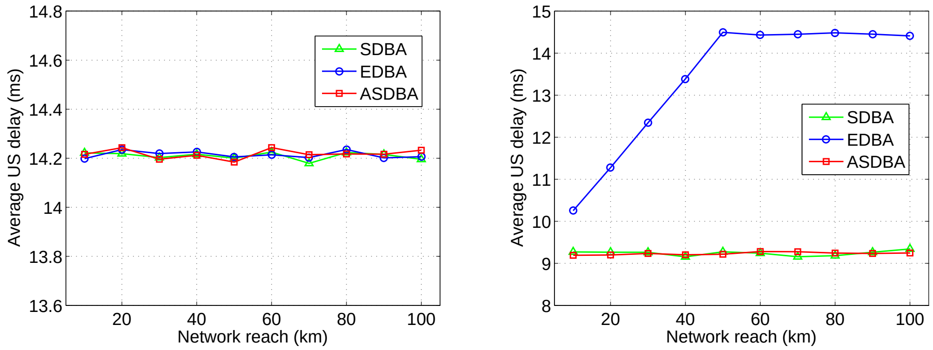
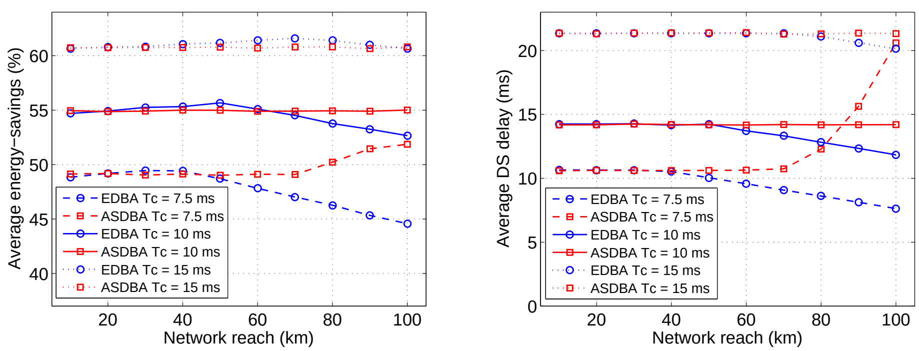


(a) Symmetric traffic (US aggr. load = 0.6).
(b) Asymmetric traffic (US aggr. load = 0.4).

Fig. 8. US frame delay with varying network reach (T_c = 10 ms, DS aggr. load = 0.6).



(a) Average energy-savings with asymmetric traffic.
(b) Average DS frame delay with asymmetric traffic.

Fig. 9. EDBA vs ASDBA with varying T_c (DS aggr. load = 0.6, US aggr. load = 0.4).

transmission pairs in any polling cycle might result in violations of bandwidth condition even with a large cycle time. This occurs when network load is unevenly distributed so that some ONUs have not enough bandwidth whilst other timeslots are under-utilized. In such a scenario, however, the issue could be solved by incorporating an excess bandwidth distribution (EBD) mechanism into the ESPON. This means that the OLT transfers excess bandwidth from some lightly-load OLT-ONU pairs to heavily-load OLT-ONU pairs in ESPON. EBD in both online and off-line scheduling paradigms has been investigated for conventional PONs [18]. The comparison between the online cyclic sleep-aware DBA schemes without EBD (e.g., schemes under the ESPON) and the off-line scheduling schemes with EBD is an interesting topic that warrants future investigation.

5. Conclusions

This paper proposes the ESPON, an online and dynamic scheduling framework for energy-efficient 10G-EPONs that aims at reducing ONU energy consumption with cyclic sleep. ONU sleep time and doze time are maximized for any given network condition to maximize energy efficiency. Three different energy-efficient schemes under the ESPON are designed and evaluated in HDL simulation. Pre-synthesis verification confirms functionality of the HDL designs. Whilst all considered schemes significantly save ONU energy for different test scenarios, the scheduling order has great impact on their performance. By swapping the order of the `GATE` and the `REPORT`, the ASDBA outperforms the SDBA and the EDBA with energy-savings and frame delays independent of the network reach. However, the polling cycle time must be care-

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fully chosen to avoid violation of the bandwidth condition that causes high frame delays.