

FPGA-based Design and Evaluation of an Energy-Efficient 10G-EPON

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Abstract—This paper presents a hardware design and evaluation of the *Cooperative Cyclic Sleep* (CCS) scheme for saving energy in TDM PONs. The CCS aims at maximizing energy efficiency while guaranteeing end-user QoS requirements for a given system configuration. To obtain that goal, first, a method for maximizing variable sleep time is proposed that considers not only the QoS constraint but also the buffer capacity of both downstream and upstream transmission. Then, two approaches of determining when an ONU is switched to sleep and when a sleeping ONU should wake up, i.e., the *Traffic-based Cooperative Cyclic Sleep* (TCCS) scheme and the *Buffer status-based Cooperative Cyclic Sleep* (BCCS) scheme, are experimentally evaluated in a 10G-EPON FPGA-based testbed. Experimental results show that the BCCS outperforms the TCCS in energy efficiency while guaranteeing the end-user QoS requirements for any DS/US traffic ratio. In addition, the BCCS is more bandwidth efficient than the TCCS because it utilizes less communication overhead for coordination between the OLT and ONU.

Index Terms—IEEE 802.3-2012, IEEE P1904.1, Cyclic Sleep, Energy Efficiency, PONs, FPGA, QoS.

I. INTRODUCTION

It has been widely recognized that reducing power consumption in data communication networks is becoming an important goal for reducing not only CO₂ emissions but also Capital Expenditures (CAPEX). In [1], it is shown that the ONUs consume over 65% of the total PON power consumption. Therefore, most of the studies conducted by research institutions and standardization authorities are targeting solutions for decreasing ONU energy consumption [2], [3]. One of the most popular methods to decrease ONU energy consumption is based on turning off the ONU, or some of its subsystems, in a cyclic manner. This is so-called cyclic sleep/fast sleep and has been first introduced in ITU-T G.Sup45 [4], then standardized for XG-PON [5]. Recently, its standardization is under discussion for EPON and 10G-EPON in IEEE P1904.1 [6].

While standards define guidelines, sleep method implementation details are left to vendors and access providers. The most challenging tasks of a cyclic sleep control are to determine when an ONU is switched to sleep (i.e., *sleep triggering*), for how long the ONU can sleep (i.e., *sleep time computation*), and whether to wake up the ONU during its sleep state (i.e., *wake-up triggering* or *Local Wake-up Indicator* (LWI) as specified in [5]) to maximize energy saving while not violating quality of service (QoS) constraints.

The cyclic sleep was early evaluated as *sleep and periodic wake-up* (SPW) [7]. In SPW, the sleep time and sleep triggering are decided based on downstream (DS) traffic only whereas

the LWI is activated whenever upstream (US) traffic arrives to the ONU. Thus, the SPW can provide very low delay, yet not fully exploiting the potential savings achievable by buffering US traffic as long as QoS constraints are satisfied.

In [8], the authors propose and evaluate two energy management mechanisms, the upstream (US) centric and the downstream (DS) centric scheme. In the US centric scheme, the ONU sleeps outside its assigned US bandwidth allocation and US and DS traffic transmission are locked. Thus, ONU sleep time is highly US traffic dependent. In the DS centric scheme, the ONU must be awake not only during its US bandwidth allocation but also when the OLT schedules DS transmission for it. However, the DS transmission scheduling depends on DS traffic only and it is not synchronized with US scheduling.

The authors in [9] propose two sleep/doze dynamic bandwidth allocation algorithms, just-in-time with varying polling cycle times (JIT) and just-in-time with fixed polling cycle times (J-FIT). The two algorithms schedule ONUs to sleep outside their upstream allocated time slot. The JIT sets ONU sleep time accordingly to the polling cycle time whose length is dependent on upstream traffic load only. Hence, when the upstream traffic load is low, the possible ONU sleep time is short. The J-FIT improves the JIT by fixing the polling cycle time that is independent of the requested bandwidth. Thus, sleep time is fixed and equal among ONUs irrespective of the network load. Furthermore, both schemes assume the symmetric data rate between upstream and downstream transmission.

This paper proposes a *Cooperative Cyclic Sleep* (CCS) scheme that aims at maximizing energy efficiency while guaranteeing QoS requirements. In the CCS, first, the ONU sleep time is maximized by considering not only the end-user QoS constraints, in terms of frame delay and loss rate, but also the system constraints, in terms of buffer capacity, of both DS and US transmission. Then, two approaches of determining sleep triggering and wake-up triggering are evaluated, i.e., *Traffic-based Cooperative Cyclic Sleep* (TCCS) scheme and *Buffer status-based Cooperative Cyclic Sleep* (BCCS) scheme.

The proposed sleep scheme is implemented for a 10G-EPON system on Altera Field Programmable Gate Arrays (FPGAs) [10]. All this will be done while adhering to relevant industry standards including IEEE 802.3-2012 standard section 5 [11] for 10G-EPON, and ITU-T G. Sup45 [4] and IEEE P1904.1 (SIEPON) [6] for cyclic sleep specification. The aim of this work is an FPGA-based design of the energy-aware MAC control sublayer in the IEEE 802.3-2012 layered

architecture for the 10G-EPON system featuring the proposed CCS scheme.

II. COOPERATIVE CYCLIC SLEEP

A. Cooperative Cyclic Sleep Operation

The CCS scheme proposed in this paper is based on the *Cooperative triggering* method in [12] and *Cooperative mechanisms* in [6], [13] with new features introduced. First, the wake-up triggering is considered in the CCS to avoid US frame losses during a sleep period. In addition, the CCS determines the expected sleep time based not only on the traffic load but also on QoS requirements and system constraints.

The operation of the CCS is illustrated in Fig. 1. A sleep request *Sleep req* containing an expected sleep time T_{es} is generated by the OLT and sent to the ONU when the DS sleep triggering condition is met. This condition is indicated by the binary signal *sleep_allow* in Fig. 1. After sending the request, the OLT starts buffering DS traffic and waits for a response from the ONU.

Upon reception of the *Sleep req*, if the US sleep triggering condition is not satisfied, i.e., the signal *sleep_enable* is deasserted, the ONU rejects to sleep by sending a *NACK* message and keeps transmitting US traffic. Otherwise, the ONU sends an *ACK* message, starts buffering US traffic, and switches to sleep.

The reception of a *NACK* at the OLT indicates that the ONU remains active, hence the OLT can transmit the buffered DS traffic, if any. In case of the *ACK* reception, the OLT keeps buffering DS traffic and waits for the ONU to wake up.

The ONU can sleep for whole T_{es} or part of it depending on the occurrence of the wake-up triggering, indicated by the signal *lwi*, during the sleep period. Fig. 1 shows a wake-up triggering example where the actual sleep time $T_s \leq T_{es}$. T_{oh} is the time that the ONU needs for clock recovery and network synchronization when it wakes up from sleeping [2]. When the ONU is totally awake, it sends all US buffered data traffic (in T_d time) followed by a *Confirm* message to ask for another sleep period.

Once the OLT receives the first US data frame during a sleep period of the ONU, it transmits the buffered DS traffic as the ONU is assumed to be already awoken. If the *Confirm* arrives when the DS sleep condition is not met, i.e., *sleep_enable* is deasserted, the OLT responds with an *Awake req* to force the ONU to stay awake for receiving DS traffic. In this case, even there is no traffic in the US buffer, the ONU has to wait a period of time (represented by T_w in Fig. 1) until when the DS sleep condition is met again to start another sleep period. Otherwise, the OLT send a *Sleep req* to allow the ONU another sleep period.

A sleep cycle is defined as an interval of time between the dispatch/reception of two consecutive *ACK* messages at the ONU/OLT. A sleep cycle at the ONU comprises of a sleep period T_s and an active period T_a . T_a comprises of the overhead time T_{oh} , the time for transmitting US buffered traffic T_d , the round-trip delay RTT , and the waiting time T_w . Thus, the sleep cycle duration is variable. In addition, within

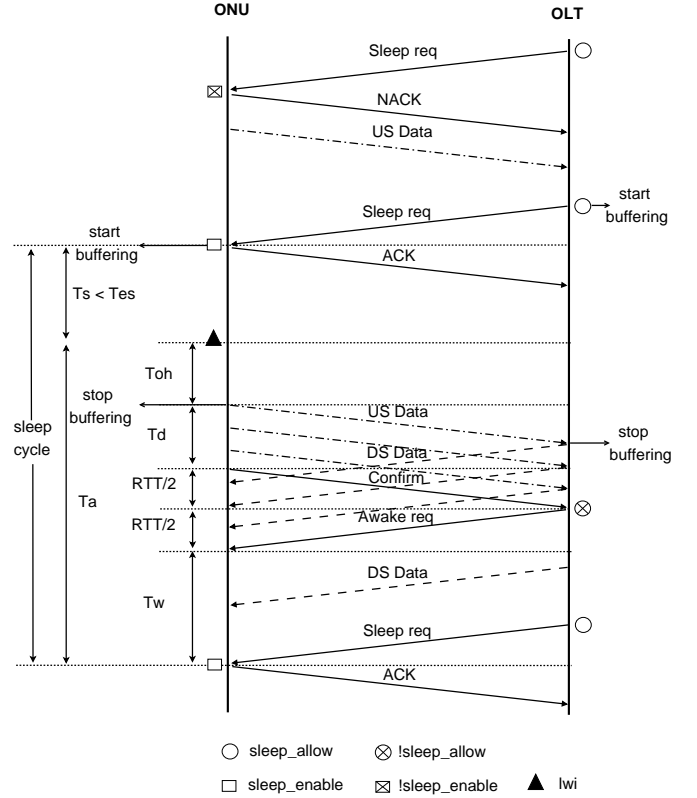


Figure 1. Cooperative Cyclic Sleep Protocol

a sleep cycle, the OLT buffers DS traffic RTT time longer than the ONU does for US traffic as seen in Fig. 1.

B. Maximum Variable Sleep Time

Obviously, the longer the ONU sleeps, the more energy it saves. However, there is a trade-off between energy efficiency and network performance, in terms of incurred frame delays and possibly frame losses. Thus, the core idea is to find an optimal point in the trade-off where the ONU sleep time is determined as long as the system conditions and end-user constraints are not violated.

To compute the maximum expected sleep time T_{es} , the OLT computes in runtime four variable sleep times T_{us}^{qos} , T_{ds}^{qos} , T_{us}^{cap} , and T_{ds}^{cap} , then set T_{es} to the minimum of these four values. T_{us}^{qos} and T_{ds}^{qos} are defined as two sleep times that limit the average frame delay experienced by US and DS traffic to the corresponding maximum allowable delay, respectively. These are inferred from the instantaneous end-user average frame delay constraint of US and DS traffic, respectively. T_{us}^{cap} and T_{ds}^{cap} are defined as two maximum allowable sleep times that avoid US and DS frame losses, respectively. These are computed based on the estimated data rate and buffer size of US and DS transmission, respectively.

T_{us}^{qos} and T_{ds}^{qos} are computed as follows. Let D_{us}^{max} and D_{ds}^{max} be the maximum average frame delay required by US and DS end-user application, \bar{I}_{us} and \bar{I}_{ds} be the time-averaged frame inter-arrival time of US and DS traffic, respectively.

Assume that the US buffer can accommodate all incoming US data frames during a sleep cycle, i.e., $T_s + T_{oh}$ (Fig. 1). Let N_{us} be the number of US data frames that arrive at the US buffer within $T_s + T_{oh}$ time. It is possible to write:

$$T_s + T_{oh} = N_{us} \bar{I}_{us}. \quad (1)$$

Then, the N_{us}^{th} frame arriving at the buffer when the ONU wakes up waits 0 second in the buffer. The $N_{us} - 1^{th}$ frame arriving at the buffer \bar{I}_{us} seconds before the N_{us}^{th} frame has to wait \bar{I}_{us} seconds, and so on. Thus, the average US frame delay \bar{D}_{us} is computed as:

$$\bar{D}_{us} = \frac{\bar{I}_{us} + 2\bar{I}_{us} \dots + (N_{us} - 1)\bar{I}_{us}}{N_{us}} = \frac{N_{us} - 1}{2} \bar{I}_{us}. \quad (2)$$

From Eq.(1) and Eq.(2), T_s is derived as:

$$T_s = 2\bar{D}_{us} + \bar{I}_{us} - T_{oh} \leq 2D_{us}^{max} + \bar{I}_{us} - T_{oh}. \quad (3)$$

From Eq.(3), the maximum sleep time based on US delay constrain T_{us}^{qos} is computed as:

$$T_{us}^{qos} = 2D_{us}^{max} + \bar{I}_{us} - T_{oh}. \quad (4)$$

As mentioned earlier, within one sleep cycle, the US buffering time of US data buffer is RTT less than that of the DS buffer. By the same derivation, T_{ds}^{qos} is computed as:

$$T_{ds}^{qos} = 2D_{ds}^{max} + \bar{I}_{ds} - T_{oh} - RTT. \quad (5)$$

T_{us}^{cap} and T_{ds}^{cap} are computed as follows. Let B_{us} and B_{ds} be the implemented US and DS data buffer capacity in bit, \bar{R}_{us} and \bar{R}_{ds} be the time-averaged US and DS data rate in bit/s, respectively. Then, B_{us}/\bar{R}_{us} and B_{ds}/\bar{R}_{ds} are the US and DS buffer capacity in second, respectively. T_{us}^{cap} is computed by forcing the maximum US buffering time within one sleep cycle, i.e., $T_{es} + T_{oh}$ (Fig. 1), to be less than or equal to B_{us}/\bar{R}_{us} . Thus, T_{us}^{cap} is:

$$T_{us}^{cap} = \frac{B_{us}}{\bar{R}_{us}} - T_{oh} - C_{us}, \quad (6)$$

where C_{us} is a safety margin (in second) used to limit the US frame losses that might occur as result of an underestimation of the real US data rate. Similarly, let C_{ds} be the safety margin for the DS buffer, T_{ds}^{cap} is computed as:

$$T_{ds}^{cap} = \frac{B_{ds}}{\bar{R}_{ds}} - T_{oh} - RTT - C_{ds}. \quad (7)$$

Thus, the final equation for computing T_{es} is:

$$T_{es} = \min\{T_{us}^{qos}, T_{ds}^{qos}, T_{us}^{cap}, T_{ds}^{cap}\}. \quad (8)$$

III. SLEEP AND WAKE-UP TRIGGERING

This paper implements and evaluates in hardware two approaches of determining sleep triggering and wake-up triggering for the CCS sleep, i.e., the TCCS and BCCS scheme. Indeed, the two approaches differ from one another in the way the the three binary signals *sleep_allow*, *sleep_enable*, and *lwi* in Fig. 1 are implemented.

A. Sleep Triggering

In the TCCS scheme, the two triggering signals *sleep_allow* and *sleep_enable* are determined based on the estimated DS and US traffic load, respectively. More specifically, the sleep triggering condition at the OLT and ONU are met if the corresponding estimated traffic load is low. To determine whether the traffic load is low or not, two estimated frame inter-arrival time I_{ds}^{est} and I_{us}^{est} are updated in runtime and compared with two predefined thresholds Th_{ds} and Th_{us} for the DS and US traffic, respectively. The estimation is obtained through a smoothing average function as in [7] that takes into account the new frame inter-arrival time and the current average value. For example, let I_{ds}^{new} and \bar{I}_{ds} be the new frame inter-arrival time and the current time-averaged frame inter-arrival time of DS traffic, respectively. I_{ds}^{est} is computed as:

$$I_{ds}^{est} = \alpha \bar{I}_{ds} + (1 - \alpha) I_{ds}^{new}, \quad (9)$$

where α denotes the smoothing factor which varies from zero to one. Thus, the DS traffic is considered as low load, i.e., the signal *sleep_allow* is asserted, if $I_{ds}^{est} \geq Th_{ds}$. Similarly, the signal *sleep_enable* is asserted if $I_{us}^{est} \geq Th_{us}$.

Differently from the TCCS scheme, the BCCS scheme considers the buffer status of the two buffers utilized for storing DS and US data traffic during ONU inactive time to determine the sleep triggering. In particular, the signal *sleep_allow* is asserted at the OLT if the DS data buffer is empty, whereas the signal *sleep_enable* is asserted at the ONU if the US data buffer is empty.

B. Wake-up Triggering

This paper also evaluates two methods for wake-up triggering corresponding to the two CCS schemes. The condition for waking up the ONU during a sleep period is based on either the observed US traffic load or the US buffer status. More concretely, in the TCCS scheme, the ONU wakes up if the estimated frame inter time is lower than a predefined threshold Th_{lwi} , i.e., the signal *lwi* is asserted if $I_{us}^{est} \leq Th_{lwi}$. Whereas, in the BCCS, the ONU wakes up during a sleep period if the US buffer is almost-full. The buffer is considered as being almost-full if the available US buffer space is not enough for storing the estimated amount of US traffic coming during the overhead time T_{oh} .

IV. HARDWARE IMPLEMENTATION

A. System Architecture

Fig. 2 shows the system architecture of the energy-efficient 10G-EPON system composed of one OLT implemented in

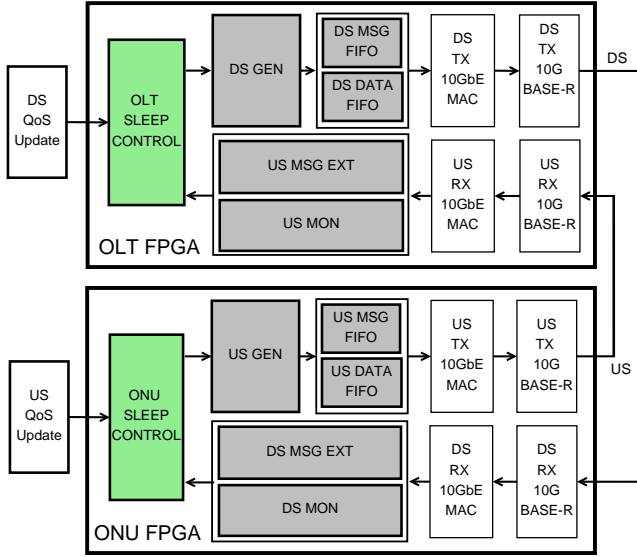


Figure 2. System Architecture

one Altera FPGA board and one ONU implemented in another board. The OLT and ONU functions partly use Altera Intellectual Property (IP) cores, such as Altera 10GbE MAC and Altera 10G BASE-R PHY IP cores, corresponding to the MAC and physical layer in the IEEE 802.3-2012 layered architecture [11], respectively. This section focuses on describing the major blocks supporting the sleep schemes, whereas functionalities of the two lower layers (i.e., MAC and physical layer) are out of scope of this description.

The block diagrams of the OLT design and the ONU design are similar. The main difference consists in the two SLEEP CONTROL blocks. At the OLT SLEEP CONTROL, a sleep-related decision can be a request to generate a control message, i.e., either a `Sleep req`, or a `Awake req`, or a request to drive the DS DATA FIFO, i.e., either storing or forwarding data frames. To make a sleep-related decision, it takes relevant inputs including the traffic load, buffer information, and instantaneous maximum tolerable average frame delay of both DS and US transmission. The DS information is provided by the DS QoS Update, the DS frame generator DS GEN, and the DS data buffer DS DATA FIFO. Meanwhile, the US information is provided by the extractor US MSG EXT through analyzing the US control messages.

Similarly, the ONU SLEEP CONTROL module considers both DS control messages, i.e., `Sleep req` or `Awake req` message, and US information, i.e., traffic load or buffer status, to make a sleep-related decision such as a request to generate a control message or a request to drive the DS DATA FIFO. In this paper, because the experiments aim at verifying the sleep mode functions, the ONU transceiver is not physically switched off during sleep state. Instead, the energy saving of the ONU is inferred from the amount of time it sojourns in active state and sleep state. Thus, the ONU SLEEP CONTROL monitors the transition among ONU states without requesting the 10G BASE-R block to power down.

In the transmission direction, the DS/US GEN generates

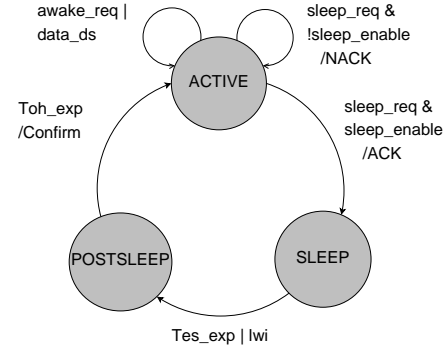


Figure 3. ONU SLEEP CONTROL Finite State Machine

both data frames (Ethernet frames) and control messages (MAC control frames). Data frames are generated based upon the embedded traffic model, whereas control message generation is triggered by the SLEEP CONTROLS. Data frames are forwarded to the DATA FIFO whereas control messages are forwarded to the MSG FIFO. The GEN also provides the SLEEP CONTROL with the estimated traffic load. The MSG FIFO and the DATA FIFO store control messages and data frames, respectively. The MSG FIFO has priority over the DATA FIFO. The operation of the two FIFOs, i.e., storing or forwarding a frame/message, is controlled by the SLEEP CONTROL finite state machine (FSM). The DATA FIFO provides the SLEEP CONTROL with its occupancy level for determining sleep triggering and wake-up triggering. Both data frames and control messages are sent to the TX 10GbE MAC and the TX 10G BASE-R for further processing before being transmitted.

In the reception direction, the RX 10G BASE-R and the RX 10GbE MAC process the received frames and pass them to the MON and the MSG EXT. The MSG EXT checks incoming bit stream from the RX MAC and informs the SLEEP CONTROL when a control message is received. In case of control message reception, the MSG EXT passes the control message content to the SLEEP CONTROL for taking sleep-related decisions.

While the transmission statistics are registered in the GEN, MSG FIFO, and DATA FIFO, the reception statistics are registered in the MON and MSG EXT. Statistics related to sleep mode are registered in the SLEEP CONTROL.

B. ONU Sleep Finite State Machine

Each module shown in Fig. 2 is implemented in hardware with a finite state machine (FSM). Because of the space limitation, only ONU Sleep FSM is described in this section.

The ONU SLEEP CONTROL module is driven based on a sleep FSM as depicted in Fig. 3. Three states are devised: ACTIVE, SLEEP, and POST_SLEEP. Triggering events include binary signals: `sleep_enable`, `sleep_req`, `awake_req`, `Tes_exp`, `Toh_exp`, `lwi`, and `data_ds`.

In the ACTIVE state, when the ONU receives a `Sleep req` message, i.e., `sleep_req = 1`, it decides whether to transit to the SLEEP state or not depending on the implemented sleep triggering method. If the sleep condition is met, i.e.,

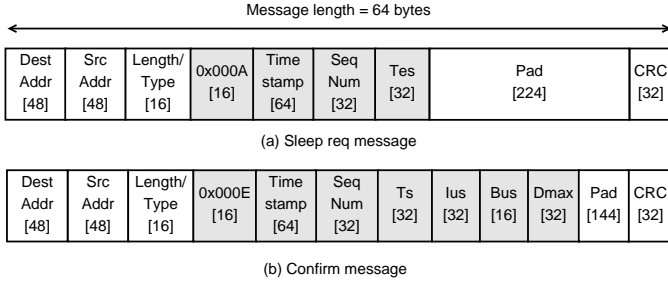


Figure 4. Control Message Structure

$sleep_enable = 1$, the ONU sends an `ACK` to notify the OLT that it is switching to sleep mode, then transits to SLEEP state. During the SLEEP state, if a LWI is triggered, i.e., $lwi = 1$, the ONU wakes up by transiting to POST_SLEEP state. Otherwise, it sleeps for whole expected time, i.e., only transiting to POST_SLEEP state upon expiration of T_{es} ($Tes_exp = 1$). After T_{oh} , i.e., $Toh_exp = 1$, the ONU returns to the ACTIVE state and transmits all buffered US traffic followed by a `Confirm` message to ask for another sleep period. If the ONU receives an `Awake req` during the ACTIVE state, i.e., $awake_req = 1$, it must stay active for receiving DS traffic and transmitting US traffic if there is any. Otherwise, the ONU can start another sleep period.

C. Control Message Structure

The control messages are based on the 64-byte MPCP messages defined in IEEE 802.3-2012 section 5 [11] with some extensions in the `Opcode` field and some additional fields carried in the padding bits. The four control messages have similar format. The `Opcode` field has a value from 0x000A to 0x000E to identify a `Sleep req`, an `Awake req`, an `ACK`, a `NACK`, and a `Confirm` message, respectively.

Fig. 4 shows the structure of the `Sleep req` and `Confirm` message. Except the MPCP header fields including MAC destination and source address and length/type, the message structure and content are different from one another accordingly to their purposes. For example, the `Sleep req` message contains a 32-bit T_{es} field indicating the expected sleep time specified by the OLT. Meanwhile, the `Confirm` message contains a 32-bit T_s field indicating the actual sleep time of the ONU, a 32-bit I_{us} field indicating the time-averaged US frame inter-arrival time, a 16-bit B_{us} field indicating the US data buffer capacity, and a 32-bit D_{max} indicating the maximum allowable US frame delay. All of these values are used for the OLT to determine the sleep-related decisions. In addition, each message has a 64-bit time-stamp field `Timestamp` and a 32-bit sequence number field `Seq Num` used for statistic collection purpose.

V. EXPERIMENTAL EVALUATION

The two proposed CCS schemes are experimentally evaluated and compared using the same configured test parameters. The energy-efficient 10G-EPON system is implemented in two Altera Transceiver Signal Integrity Development Kits equipped with Stratix IV GT edition FPGA and capable of supporting

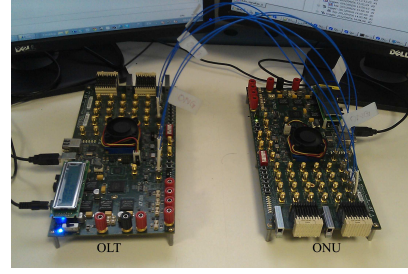


Figure 5. Energy-Efficient 10G-EPON Testbed

up to 10 Gb/s. The Electronic Design Automation (EDA) tool used for synthesizing and configuring the FPGAs is Quartus II. The testbed configuration is illustrated as in Fig. 5. The Optical Distribution Network (ODN) is not implemented because the experiments aim at testing the sleep mode functions that are independent from the ODN and implemented in electronics. Thus, the SMA inputs and outputs of the OLT and the ONU are directly interconnected by means of coaxial cables capable of supporting transmission rate higher than 10 Gb/s. One OLT and one ONU are considered in the system.

The considered performance metrics include the expected sleep time T_{es} , average energy saving η , average frame loss rate, and average frame delay of both DS and US traffic. Also, the considered sleep schemes are compared in terms of control message overhead utilized for sleep related communication.

A. Energy Saving Upper Bound

Energy saving is computed as the relative energy consumption decrease with respect to the energy consumption of an ONU without sleep scheme implemented:

$$\eta = 1 - \frac{P_a T_{active} + P_s T_{sleep}}{P_a (T_{active} + T_{sleep})} = \frac{(P_a - P_s) T_{sleep}}{P_a (T_{active} + T_{sleep})}, \quad (10)$$

where P_a and P_s are the power consumption of ONU in active and sleep state; T_{active} and T_{sleep} are the total time the ONU sojourns in active and sleep state, respectively. Note that T_{active} includes also overhead times because the ONU is assumed to be fully powered during the POST_SLEEP state.

In the considered schemes, it is possible to find an energy saving upper bound η_{max} . From Fig. 1, η_{max} is achieved when the system consists of a sequence of sleep cycles where all sleep requests are accepted, the ONU sleeps for whole expected sleep time (i.e., $T_s = T_{es}$) and the active time T_a is minimal (i.e., $T_d = T_w = 0$ and $T_a = T_{oh} + RTT$). In this case, η_{max} can be computed within one sleep cycle, i.e., $T_{sleep} = T_{es}$ and $T_{active} = T_a$. Hence, η_{max} is:

$$\eta_{max} = \frac{(P_a - P_s) T_{es}}{P_a (T_{oh} + RTT + T_{es})}. \quad (11)$$

B. Constants and Parameters

Several constants and parameters, summarized in Tab. I, are defined in the experiments. The data traffic is transmitted in frames with a fixed size of 1250 bytes. The frame arrival

Table I
HARDWARE TEST CONSTANTS AND PARAMETERS

Name	Variable	Value	Unit
Number of transmission frames	N_{frame}	10000	frame
DS and US data frame size	F_s	1250	byte
DS data buffer size	B_{ds}	256	kB
US data buffer size	B_{us}	256	kB
DS buffer safety margin	C_{ds}	$5\bar{I}_{ds}$	ms
US buffer safety margin	C_{us}	$5\bar{I}_{us}$	ms
Round-trip transmission delay	RTT	0.06	ms
Wake-up overhead time	T_{oh}	2	ms
ONU active power consumption	P_a	10	Watt
ONU sleep power consumption	P_s	1	Watt
Minimum of maximum delays	D_{max}	25	ms
Timeout for ACK/NACK message	T_{ACK}	0.12	ms
Smoothing factor	α	0.5	
DS inter-arrival threshold	Th_{ds}	\bar{I}_{ds}	ms
US inter-arrival threshold	Th_{us}	\bar{I}_{us}	ms
Local wake-up threshold	Th_{lwi}	$0.3\bar{I}_{us}$	ms

process is Poisson in both DS and US transmission. OLT and ONU are programmed to generate and transmit the same number of frames. \bar{R}_{us} is fixed at 10 Mb/s, whereas \bar{R}_{ds} is varied from 1 Mb/s to 200 Mb/s. C_{us} is set to $5\bar{I}_{us}$ and C_{ds} is set to $5\bar{I}_{ds}$. This means that the two buffers leave five frame inter arrival times in attempt to avoid the corresponding frame losses. The minimum of the DS and US required maximum delay D_{max} is set to 25 ms. RTT is 0.06 ms in the testbed. T_{ACK} is set to 0.12 ms (full-way round-trip delay). T_{oh} is set to 2 ms. ONU power consumption in active state and sleep state are assumed to be 10 Watts and 1 Watt, respectively [2].

C. Experimental Results

For each DS and US data rate pair, the experiments are run with multiple random seeds for traffic generation and various number of transmission frames. The obtained results are within a relative confidence interval of 93% at the 95% confidence level for all the performance metrics. Both CCS schemes are capable of providing no frame losses for both DS and US traffic. This is due to the determination of the expected sleep time and the wake-up triggering as well.

Fig. 6 shows the average energy saving η obtained by each scheme together with the upper bound saving η_{max} (Eq.(11)). The BCCS closely approximates η_{max} because only few sleep requests are refused at the ONU due to the presence of US traffic. Moreover, the ONU sleeps for whole expected sleep time because the LWI does not occur (i.e., US buffer is not full) as a result of the sleep time computation. The TCCS saves significantly less than the BCCS because the sleep triggering conditions are based on the DS and US traffic load resulting in fewer sleep requests generated at the OLT and fewer sleep requests accepted at the ONU. Also, in the TCCS, the wake-up triggering condition is more strict causing the ONU wake up from sleeping often during sleep state. When the $\bar{R}_{ds} \geq 20$ Mb/s, the energy savings decrease in both schemes. This is because when \bar{R}_{ds} increases, T_{ds}^{cap} decreases resulting in lower expected sleep time T_{es} (Eq.(7) and Eq.(8)).

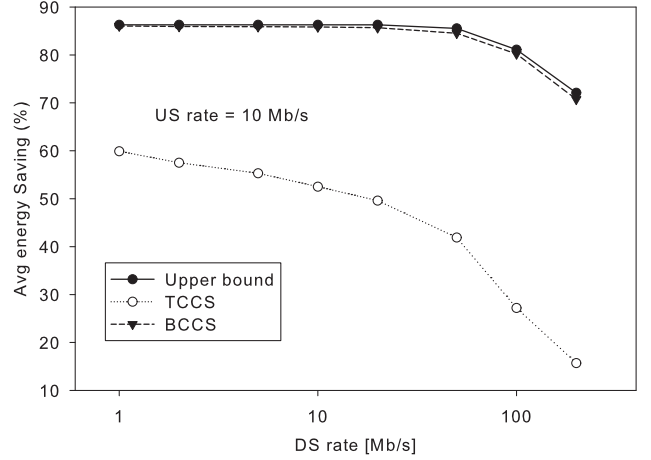


Figure 6. Average energy saving with different DS/US traffic ratio

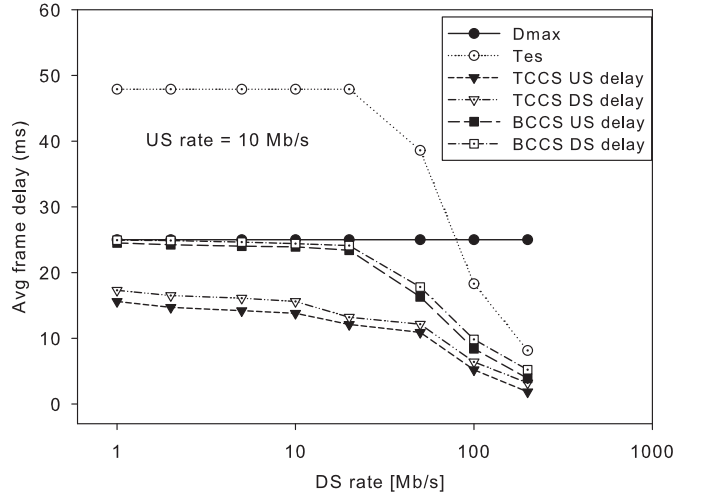


Figure 7. Average frame delays experienced by DS/US traffic

Fig. 7 reports the minimum constrained delay D_{max} , expected sleep time T_{es} , and average frame delay incurred in US and DS traffic for the two schemes. As discussed earlier, when the DS data rate increases, T_{es} decreases resulting in lower delays experienced by US and DS traffic. The DS and US delay in each scheme are quite similar. This is because of the cooperative nature of the CCS sleep that provides balanced frame delay for the two transmission directions. As seen in the figure, the BCCS scheme is capable of producing DS and US frame delays that are close to the allowable QoS delay to take advantage of the allowable frame delay to maximize energy saving.

Fig. 8 shows the overhead of sleep-related control messages utilized in the two sleep schemes. This is the ratio between the bandwidth utilized for both DS and US messages and the bandwidth for DS and US data traffic. Note that a control message has size of 64 bytes, whereas a data frame has size of 1250 bytes. In general, the overhead in both schemes is less than 4% in any considered test scenario. From the Fig. 6

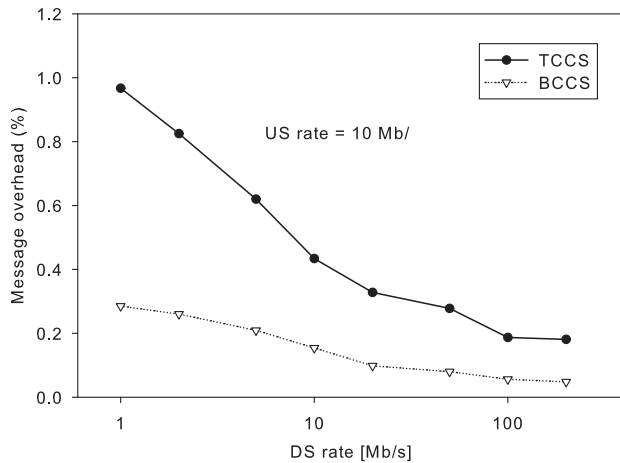


Figure 8. Control message overhead

and 8, the BCCS not only provides greater energy efficiency but also utilizes less bandwidth for control messages compared to the TCCS. This is because in the BCCS, the sleep control schedules better so that when a sleep request is generated, it is accepted at the ONU and the ONU sleep for whole expected sleep time.

VI. CONCLUSION

This paper proposed the *cooperative cyclic sleep* (CCS) scheme for saving energy in 10 Gb/s TDM PONs. In the CCS, the sleep control determines the sleep triggering, the wake-up triggering and the expected sleep time for an ONU based on the end-user QoS constraint and the buffer size limitation, of both DS and US transmission direction.

Two approaches for determining the sleep triggering and wake-up triggering were considered and experimentally evaluated, i.e., the *Traffic-based Cooperative Cyclic Sleep* (TCCS) scheme and *Quality of Service-based Cooperative Cyclic Sleep* (BCCS) scheme. In the former scheme, the triggering decisions are taken based on the observed DS and US traffic load. Meanwhile, in the latter one, the decisions are taken by considering the DS and US data buffer status.

The two proposed sleep schemes were implemented and evaluated in FPGA-based testbed. Experimental results shown that the BCCS outperforms the TCCS in terms of energy efficiency by taking full advantage of allowable QoS to maximize ONU sleep time. In addition, the BCCS is more bandwidth efficient than the TCCS because it utilizes less overhead for sleep-related control messages.

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