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Standards-compliant EPON Sleep Control for Energy Efficiency: Design and Analysis

Jingjing Zhang, *Member, IEEE*, Mina Taheri Hosseinabadi , and Nirwan Ansari, *Fellow, IEEE*

***Abstract*—Owing to the environmental concern, reducing energy consumption of optical access networks has become an important problem for network designers.This paper focuses on reducing energy consumption of optical network units (ONUs) in Ethernet passive optical network (EPON). In EPON, the optical line terminal (OLT) located at the central office broadcasts the downstream traffic to all ONUs, each of which checks all arrival downstream packets so as to obtain the downstream packets destined to itself. Thus, receivers at ONUs have to always stay in the awake status and consume a large amount of energy.**

To address the downstream challenge, we propose a novel sleep control scheme which can efficiently put ONU receivers into sleep without modifying the standardized EPON MAC protocol. The proposed scheme contains two main parts: downstream traffic scheduling rules at the OLT and sleep control schemes at ONUs. By letting ONUs be aware of the downstream traffic scheduling rules, ONUs can infer their own downstream queue status and switch into the sleep status properly; by letting OLT know the sleep control scheme implemented at ONUs, the OLT can accurately infer the sleep status of ONUs and buffer traffic of asleep ONUs accordingly. We also theoretically analyze the impacts of different parameters in the sleep control scheme on the delay and energy saving performances by using semi-Markov chains. It is shown that, with proper settings of sleep control parameters, the proposed scheme can save as high as 50% of the ONU receiver energy.

***Index Terms*—Energy efficiency; Markov chain; Optical networks; Sleep control.**

I. INTRODUCTION

The ever increase of broadband users has drawn global attention to reduce energy consumption in data communication networks [1]–[3]. Owing to the proximity of optical fibers to end users and the passive nature of remote nodes, passive optical networks (PONs) consume the smallest energy per transmission bit among various access technologies including WiMAX, FTTN, and point to point optical access networks [4]–[7]. Nevertheless, it is still desirable to further reduce energy consumption of PONs since every single watt saving will end up with overall terawatt and even larger power saving as PON is deployed worldwide. Reducing energy consumption of PONs becomes even more imperative for the 10G EPON system which provides ten times of the data rate of the 1G EPON system because large data rate provisioning requires high power consumption of both the optical and electrical components of various devices.

Previously, in order to decrease the energy consumption, defining the sleep mode was proposed for idle ONUs [8]. Since traffic of optical network units (ONUs) is rather bursty and changes dynamically [9], putting ONUs into the sleep mode when the ONU does not have downstream or upstream traffic can save a significant amount of ONU energy [8], [10]. According to [11], a multi power level ONU is defined based on the energy consumption of the working part. In the mentioned scheme, the transmitter and receiver can go to the sleep mode separately. However, the transition between the states with all active/awake parts and the receiver being totally asleep actually do not exist since an ONU needs to receive some downstream control packets to perform upstream transitions. Regarding EPON ONUs, the sleep control of transmitters inside ONUs is relatively easier than that of receivers since the arrival of the upstream traffic can trigger the wakeup of asleep transmitters. Ideally, an ONU is desired to stay in the sleep mode with low power consumption when the ONU does not have traffic, and switch back into the active mode when traffic of an ONU arrives. However, the broadcast nature of the EPON downstream transmission disallows an ONU entering the sleep mode. As shown in Fig. 1, the downstream data traffic of EPON ONUs are TDM multiplexed onto a single wavelength, and broadcasted to all ONUs [12]. An ONU has to receive and check all downstream packets, and then decides whether the packets are destined to itself. Since all incoming downstream packets have to be checked, an ONU needs to stay awake all the time to avoid missing its downstream traffic. Formerly, sleep mode was proposed to be enabled in optical network units (ONUs) to reduce their power consumption. To avoid service disruption, asleep ONUs should wake up upon the arrival of downstream or upstream traffic. However, it is challenging to wake up asleep ONUs when downstream ONU traffic arrives in Ethernet PON (EPON). Without proper sleep-aware MAC control, receivers at ONUs need to be awake all the time to avoid missing their downstream packets.

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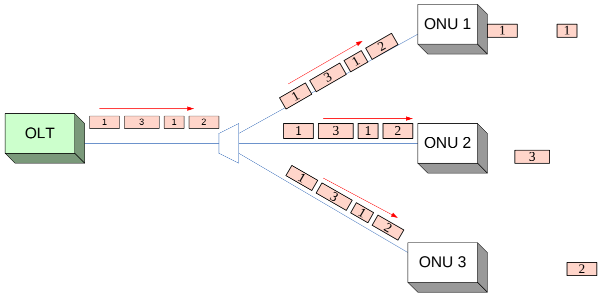

Fig. 1. Downstream transmission in EPON

A number of schemes have been proposed to address the downstream challenge so as to reduce the energy consumption of ONUs. These proposed energy saving schemes can be divided into two major classes. The first class tries to design a proper MAC control scheme to convey the downstream queue status to ONUs, while the second class focuses on investigating energy-efficient traffic scheduling schemes. The two-way or three-way handshake processes performed between the OLT and ONUs are examples of schemes of the first class [13]. Yan *et al.* [14] proposed two downstream scheduling algorithms in order to save the energy in EPON. In the first algorithm, downstream centric scheme (DCS), the OLT buffers the downstream traffic for a specific ONU and will send to it during the prescheduled time slot for upstream traffic. In the second algorithm, upstream centric scheme (UCS), the proper time slot is not only scheduled for upstream traffic but also determined for downstream traffic. More specifically, both upstream and downstream traffic in UCS could trigger the ONU to switch the status from sleep to active, and hence higher delay would be imposed to the system. Typically, in the first class schemes, the OLT sends a control message notifying an ONU that its downstream queue is empty; the ONU optionally enters the sleep mode and then sends a sleep acknowledgement or negative acknowledgement message back to the OLT. While the OLT is aware of the sleep status of ONUs, it can buffer the downstream arrival traffic until the sleeping ONU wakes up. However, to implement the handshake process, the EPON MAC protocol, multipoint control protocol (MPCP) defined in IEEE 802.3ah or IEEE 802.3av, has to be modified to include new MPCP protocol data units (PDUs). In addition, the negotiation process takes at least several round trip times, implying that an ONU has to wait for several round trip times before entering the sleep status after it infers that its downstream queue is empty. This may significantly impair the energy saving efficiency.

Energy saving schemes of the second class tackle the downstream challenge by designing suitable downstream bandwidth allocation schemes. Formerly, Lee *et al.* [15] proposed to implement fixed bandwidth allocation (FBA) in the downstream when the network is lightly loaded. By using FBA, the time slots allocated to each ONU in each cycle are fixed and known to the ONU. Thus, ONUs can go to sleep during the time slots allocated to other ONUs. However, since traffic of an ONU dynamically changes from cycle to cycle, FBA may result in bandwidth under- or over-allocation, and consequently degrade services of ONUs in some degree. Yan *et al.* [16] proposed to schedule the downstream traffic and the upstream traffic simultaneously. Since the downstream traffic of an ONU is sent over the time slots that its upstream traffic is sent, the ONU stays in the awake status during that time period and will not miss its downstream packets. This scheme works well when traffic in the upstream and downstream are symmetric, but it may cause inefficient bandwidth utilization when the downstream traffic outweighs upstream traffic.

This paper proposes a simple and efficient sleep control scheme to tackle the downstream challenge. As compared to existing schemes, the proposed scheme possesses two main advantages. First, it belongs to the second class, and hence can efficiently put ONUs into sleep without modifying the EPON MAC protocol. Also, since it does not require handshaking between OLT and ONUs, the proposed scheme can achieve high energy saving efficiency. Second, the proposed scheme allows dynamic bandwidth allocation among ONUs. Consequently, it achieves high bandwidth utilization. Another major contribution of this paper is that we theoretically analyze the delay and energy saving performances of the proposed sleep control scheme by using semi-Markov chains.

The rest of the paper is organized as follows. Section II details the proposed sleep control scheme. Section III describes the semi-Markov chain model and theoretically analyzes delay and energy saving performances of the proposed scheme. Section IV presents numerical results. Simulation results are given in Section V. Section VI concludes our paper.

II. DESIGN OF A SLEEP CONTROL SCHEME

Rather than focusing on enabling the sleep mode of transmitters and receivers at the same time [14], this paper targets at addressing the downstream challenge only. The proposed scheme can be applied when transmitters and receivers can be independently put into sleep [11]. Another application scenario is when the ONU has downstream traffic only, e.g., file downloading and broadcast TV applications. The proposed scheme is also potentially able to be combined with the upstream traffic scheduling scheme such that both receivers and transmitters can be put into the sleep mode simultaneously. Upstream traffic scheduling is, however, beyond the scope of this paper.

Our main idea[1] can be generalized as follows. First, we set certain downstream traffic scheduling rules at OLT and let the rules be known to ONUs. Since an

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[1] The preliminary idea was first presented at ICC2012 [17].

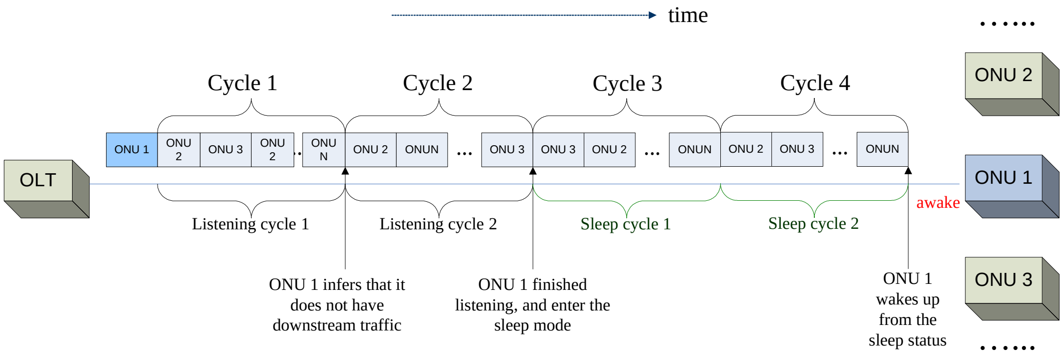

Fig. 2. The sleep control at ONU 1

ONU owns the information of the downstream traffic scheduling rules, it can infer its current downstream queue status based on historical arrival downstream traffic. Second, according to the inferred queue status, ONUs make their own sleep decisions based on some sleep control rules. These sleep control rules implemented at the ONU side is also known to the OLT. Third, based on the sleep control rules, the OLT infers the status of ONUs, and buffers the incoming downstream traffic of asleep ONUs accordingly. Essentially, the *downstream traffic scheduling rules*, the *downstream queue inference at ONUs*, the *sleep control rules*, and the *ONU sleep status inference at the OLT* constitute four key components of the proposed sleep control scheme.

A. *Downstream traffic schedule rule*

Traffic scheduling in both downstream and upstream are not specified in the EPON standards IEEE 802.3ah and IEEE 802.3av. Upstream bandwidth allocation has received extensive research attention in the past years. For upstream scheduling, efficient upstream bandwidth utilization requires the OLT to allocate the bandwidth based on queue reports from ONUs. The time gap between the traffic report and the bandwidth grant process may incur inefficient utilization of upstream bandwidth.

Utilizing the time gap for high network resource utilization has been a key objective in designing bandwidth allocation algorithms for the upstream. Different from the upstream transmission, the downstream transmission does not have the queue report and bandwidth grant process since downstream traffic are queued at the OLT which also makes the downstream traffic scheduling decisions. As IEEE 802.3ah and IEEE 802.3av standards do not specify a dynamic bandwidth allocation scheme for downstream scheduling or upstream scheduling, having a fixed downstream traffic scheduling cycle does not violate the EPON standard. Thus, in designing the downstream traffic scheduling rules, our main objective is to facilitate ONUs infer their own downstream traffic status, rather than maximizing the bandwidth utilization. Below are the designed downstream traffic scheduling rules.

- *Rule 1*: Define the time duration of 2 ms as the downstream traffic scheduling cycle.
- *Rule 2*: In a scheduling cycle, each ONU is allocated with some time durations if it has downstream traffic. Note that ONUs do not have to be allocated with continuous time durations within a scheduling cycle.
- *Rule 3*: If the OLT infers that an ONU is sleeping, it queues the arrival downstream traffic of the ONU until the ONU wakes up.

The reason for setting the scheduling cycle as 2 ms is to guarantee delay and jitter performances of delay-sensitive applications such as voice and video. The purpose of Rule 2 is to help an ONU infer its downstream queue status. Besides, this rule also helps prevent ONUs from being starved. Rule 3 is to avoid asleep ONUs from missing their downstream packets.

B. *Downstream traffic inference at ONU*

According to the downstream traffic scheduling rules, if an ONU fails to receive any downstream data traffic within an EPON traffic scheduling cycle, the ONU can infer that its downstream queue is empty. Thus, rather than being explicitly notified by the OLT about its downstream queue status, an ONU can infer its downstream queue status simply by monitoring the downstream bandwidth allocated among ONUs.

C. *Sleep control rules*

After being aware that its downstream queue is empty, an ONU can choose to enter the sleep mode. We design the following sleep control rules.

"If an ONU does not receive downstream data traffic for x traffic scheduling cycles, it switches into the sleep state, and sleeps for y traffic scheduling cycles."

x traffic scheduling cycles are referred to as listening cycles, and y traffic scheduling cycles are referred to as sleeping cycles. Both x and y are known to the OLT such that the OLT can infer the sleep status of ONUs.

Fig. 2 shows an example of the sleep control rules with $x = 2$ and $y = 2$. At the end of cycle 1, ONU 1

observes that it is not allocated with any time slots during the entire cycle of cycle 1. At that moment, ONU 1 infers that its downstream queue is empty. Since the number of listening cycles equals to 2, ONU 1 continues listening to the channel for one more cycle. At the end of cycle 2, ONU 1 still does not receive any downstream traffic. Then, it switches into the sleep status and sleeps for two cycles since the number of sleeping cycles equals to 2. After cycle 4, ONU 1 wakes up from the sleep status.

D. ONU status inference and traffic scheduling at OLT

To avoid missing the downstream traffic when an ONU is sleeping, the OLT should be aware of the sleep status of the ONU, and then buffer its incoming downstream traffic until the ONU wakes up. To enable the ONU status be accurately inferred by the OLT, we let the OLT own the information of the sleep control algorithm implemented at each ONU. Owing to the fact that an ONU makes its sleep decision based on the downstream bandwidth allocation profile which is also known to the OLT, the OLT can accurately infer the status of each ONU at any time. We can describe the ONU status inference as follows.

"If the OLT does not allocate any time slots to an ONU for x traffic scheduling cycles, the ONU will enter the sleep status in the next y traffic scheduling cycles."

After the OLT infers that an ONU is sleeping, the OLT buffers the arrival downstream traffic of this ONU until the ONU wakes up from sleep.

Fig. 3 illustrates a flow chart of the proposed sleep control scheme. Indicator $''I''$ counts the number of cycles in which no downstream packets are scheduled for the specific ONU. By the time I reaches x, the ONU makes the sleep decision. The OLT is aware of the sleep control algorithm implemented at each ONU. Therefore, the OLT infers the sleep status of each ONU based on the traffic scheduled to each ONU. The OLT buffers the arrival downstream traffic of the ONU during the sleep cycles. Once the OLT finds that an ONU changes its status, the OLT adjusts its traffic scheduling scheme accordingly.

According to the proposed scheme, it is not necessary for the OLT and ONUs to have identical view of the scheduling cycles. Each of them can view the timestamp of receiving the first bit of its traffic as the beginning of its cycle. Based on the above described schemes, ONUs can switch into the sleep mode without modifying the EPON control protocol. The listening time duration of x cycles and the sleep time duration of y cycles determine the energy saving efficiency and quality of service (QoS) performances. Proper setting of x and y needs to consider energy efficiency and QoS of user sessions. In our previous work [11], we described an example in which $x = 1$ and y exponentially increases with the time duration that an ONU's downstream queue remains empty. In this paper, we focus on investigating the impact of x and y on network performances and energy efficiency under different traffic loads. Analytical results below will provide insights on proper settings of x and y for different traffic loads.

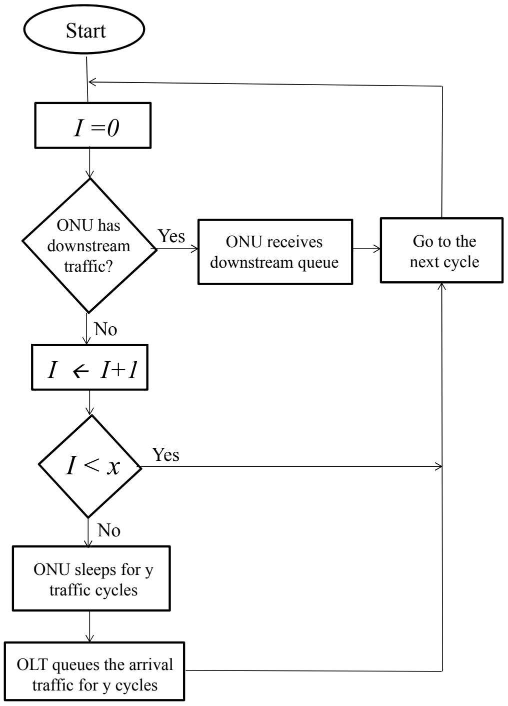

Fig. 3. Flow chart of the sleep control scheme implemented at both OLT and ONUs

III. SYSTEM MODEL AND PERFORMANCE ANALYSIS

In this section, we employ semi-Markov chains to theoretically analyze the delay and energy saving performances of the sleep control scheme. For ease of analysis, we consider Poisson traffic arrival. We assume the downlink packet arrival is a Poisson process with the average rate λ packets/s, and the packet arrival process is independent from the distribution of the packet size. Let N be the number of ONUs and R bits/s be the rate of the downlink channel. Then, each ONU is serviced with the rate of R/N bits/s. The service time of each packet, i.e., packet size$/(R/N)$, is assumed to be exponentially distributed with average value of $1/\mu$. Regarding the transit time between the sleep status and awake status, Wong *et al.* [18] proposed two ONU architectures to reduce the recovery overhead into tens of nanoseconds, which are negligible as compared to the duration of a traffic scheduling cycle. In this paper, we do not consider the transit time.

A. ONU state and state transitions

In the Markov chain model, each ONU has three possible sets of states: active states $\{\mathbb{A}(i)\}_{i=0}^{+\infty}$, listening states $\{\mathbb{L}(j)\}_{j=1}^{x}$, and sleeping state $\mathbb{S}$.

- $\mathbb{A}(i)$ refers to the state that an ONU has i queued downstream packets by the end of a traffic

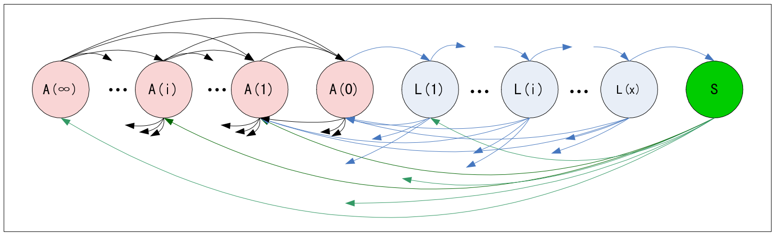

Fig. 4. State transitions in the Markov Chain

scheduling cycle. There is no upper bound of i as the buffer size is assumed to be infinite.

- $\mathbb{L}(j)$ refers to the state that an ONU does not have any downstream packets, and has not received any downstream data traffic for j traffic scheduling cycles. The listening time duration can be as large as x traffic scheduling cycles, where x is the number of listening cycles.
- $\mathbb{S}$ refers to the status that the ONU stays asleep. The sleep time duration equals to y traffic scheduling cycles, where y is the number of sleeping cycles.

Fig. 4 illustrates the state transitions. For a given ONU, assume the number of queued packets equals to α. If $\alpha > 0$, the ONU stays in state $\mathbb{A}(\alpha)$. If $\alpha = 0$, the ONU could possibly stay in the active state $\mathbb{A}(0)$, listening states $\{\mathbb{L}(j)\}_{j=1}^{x}$, or the sleeping state $\mathbb{S}$. During any traffic scheduling cycle, i packets may arrive and j packets may depart for any ONU. There are three main cases of i and j.

- If j is smaller than i, the number of queued packets is increased by $j-i$ at the end of the cycle.
- If j is greater than i, the number of queued packets is decreased to either $\alpha-(j-i)$ if $\alpha > j-i$, or 0 otherwise.
- If no packet arrives during a traffic scheduling cycle, i.e., $i = 0$, the ONU state transits from $\mathbb{A}(0)$ to $\mathbb{L}(0)$ if the ONU stayed in state $\mathbb{A}(0)$ in the former cycle, from $\mathbb{L}(k)$ to $\mathbb{L}(k+1)$ if the ONU stayed in state $\mathbb{L}(k)$ in the former cycle, and from $\mathbb{L}(x)$ to $\mathbb{S}$ if the ONU stayed in state $\mathbb{L}(x)$ in the former cycle.

Denote $p^a(\beta,\gamma)$ and $p^d(\beta,\gamma)$ as the probability that β downstream packets arrive at the OLT and depart from the OLT during γ traffic scheduling cycles, respectively. The probability that i packets arrive and j packets depart from the downstream queue equals to $p^a(i,\gamma)\cdot p^b(j,\gamma)$. Then,

- State transitions from $\mathbb{A}(0)$ to $\mathbb{L}(1)$, from $\mathbb{L}(k)$ to $\mathbb{L}(k+1)$, or from $\mathbb{L}(x)$ to $\mathbb{S}$ happen when no packets arrive during the traffic scheduling cycle. The probability of each case equals to $p^a(0,1)$.
- State transition from $\mathbb{L}(j)$ to $\mathbb{A}(k)$ occurs when the number of arrival packets is greater than the number of departure packets by k during the traffic scheduling cycle. The probability equals to $\sum_{i=0}^{+\infty} p^a(k+i,1)\cdot p^d(i,1)$.
- State transition from $\mathbb{A}(i)$ to $\mathbb{A}(i-k)$ happens when the number of arrival packets is smaller than the number of departure packets by k. The probability equals to $\sum_{j=0}^{+\infty} p^d(k+j,1)\cdot p^a(j,1)$.
- State transition from $\mathbb{S}$ to $\mathbb{A}(i)$ happens when i packets arrive during y sleeping cycles. The probability equals to $p^a(i,y)$.
- State transition from $\mathbb{S}$ to $\mathbb{L}(1)$ occurs when no packets arrive during y sleeping cycles. The probability equals to $p^a(0,y)$.

Based on the assumptions of Poisson arrival traffic, $p^a(\beta,\gamma)$ and $p^d(\beta,\gamma)$ can be obtained as follows.

$$p^a(\beta,\gamma) = e^{-\lambda\gamma T}\cdot(\lambda\cdot\gamma T)^{\beta}/\beta! \tag{1}$$

$$p^d(\beta,\gamma) = e^{-\mu\gamma T}\cdot(\mu\cdot\gamma T)^{\beta}/\beta! \tag{2}$$

where T is the duration of a traffic scheduling cycle. After having derived the state transition probabilities, we can obtain the steady state probability of each state, and thus analyze the energy saving and delay performances of our proposed sleep control scheme.

B. Steady state probability

Consider $P(\mathbb{S})$, $\{P(\mathbb{A}(i))\}_{i=0}^{\infty}$, $P(\mathbb{L}(j))\}_{j=1}^{x}$ as the probability of each ONU state when the network is at its steady state. Then, these steady state probabilities satisfy the following constraints.

$$\begin{aligned} P(\mathbb{S})[\sum_{i=1}^{\infty} pr\{\mathbb{S}\to\mathbb{A}(i)\} + pr\{\mathbb{S}\to\mathbb{L}(1)\}] \\ = P(\mathbb{L}(x))pr\{\mathbb{L}(x)\to\mathbb{S}\} \end{aligned} \tag{3}$$

Equation 3 shows the steady state probability of the sleep state. State $\mathbb{S}$ can be reached only via state $\mathbb{L}(x)$. State transition from $\mathbb{S}$ to the other states depends on the number of arrival packets during the traffic scheduling cycle. No arrival packet causes a transition to the state $\mathbb{L}(1)$.

$$\begin{aligned} P(\mathbb{L}(x))[\sum_{i=0}^{\infty} pr\{\mathbb{L}(x)\to\mathbb{A}(i)\} + pr\{\mathbb{L}(x)\to\mathbb{S}\}] \\ = P(\mathbb{L}(x-1))pr\{\mathbb{L}(x-1)\to\mathbb{L}(x)\} \end{aligned} \tag{4}$$

Steady state probability for all the listening states except $\mathbb{L}(1)$ and $\mathbb{L}(x)$ are the same as follows:

$$\begin{aligned} P(\mathbb{L}(j))[\sum_{i=0}^{\infty} pr\{\mathbb{L}(j)\to\mathbb{A}(i)\} + pr\{\mathbb{L}(j)\to\mathbb{L}(j+1)\}] \\ = P(\mathbb{L}(j-1))pr\{\mathbb{L}(j-1)\to\mathbb{L}(j)\}(1<j<x) \end{aligned} \tag{5}$$

$$P(\mathbb{L}(1))[\sum_{i=0}^{\infty} pr\{\mathbb{L}(1) \rightarrow \mathbb{A}(i)\} + pr\{\mathbb{L}(1) \rightarrow \mathbb{L}(2)\}]$$
$$= P(\mathbb{A}(0))pr\{\mathbb{A}(0) \rightarrow \mathbb{L}(1)\} + P(\mathbb{S})pr\{\mathbb{S} \rightarrow \mathbb{L}(1)\} \quad (6)$$

$$P(\mathbb{A}(i))\sum_{j\neq i} pr\{\mathbb{A}(i)\rightarrow\mathbb{A}(j)\}=\sum_{j\neq i} P(\mathbb{A}(j))pr\{\mathbb{A}(j)\rightarrow\mathbb{A}(i)\}$$
$$+\sum_{j\neq i} P(\mathbb{L}(j))pr\{\mathbb{L}(j)\rightarrow\mathbb{A}(i)\}+ P(\mathbb{S})pr\{\mathbb{S}\rightarrow\mathbb{A}(i)\} \quad (7)$$

$$P(\mathbb{A}(0))[\sum_{i\neq 0} pr\{\mathbb{A}(0) \rightarrow\mathbb{A}(i)\} + pr\{\mathbb{A}(0) \rightarrow \mathbb{L}(1)\}] =$$
$$\sum_{i\neq 0}P(\mathbb{A}(i))pr\{\mathbb{A}(i)\rightarrow\mathbb{A}(0)\}+\sum_{j\neq i} P(\mathbb{L}(j))pr\{\mathbb{L}(j)\rightarrow\mathbb{A}(0)\} \quad (8)$$

Additionally, the sum of the probabilities of all states should equal to 1, i.e.,

$$P(\mathbb{S}) + \sum_{i=0}^{+\infty} P(\mathbb{A}(i)) + \sum_{j=1}^{x} P(\mathbb{L}(j)) = 1 \quad (9)$$

The steady state probabilities can thus be obtained by solving the above equations (3)-(9).

C. Performance analysis

1) Power saving: Denote $P(\mathbb{S})$, $\{P(\mathbb{A}(i))\}_{i=0}^{\infty}$,and $P(\mathbb{L}(j))\}_{j=1}^{x}$ as the probability of each ONU state when the network reaches its steady state. Denote $W(\mathbb{A})$, $W(\mathbb{L})$, and $W(\mathbb{S})$ as the power consumption when an ONU is in the active, listening, and sleep state, respectively. Then, since the time duration of these states are 1 cycle, 1 cycle, and y cycles, respectively, the energy consumption in these three states are $W(\mathbb{A})$, $W(\mathbb{L})$, and $y \cdot W(\mathbb{S})$, respectively. The average energy consumption equals to

$$W(\mathbb{A})\cdot\sum_{i=0}^{\infty} P(\mathbb{A}(i))+W(\mathbb{L})\cdot\sum_{j=1}^{x} P(\mathbb{L}(j))+y\cdot W(\mathbb{S})\cdot P(\mathbb{S}) \quad (10)$$

2) Extra delay: Denote $E[\delta|\mathbb{S}]$, $E[\delta|\mathbb{L}]$, and $E[\delta|\mathbb{A}]$ as the conditional expectation of the delay for the packets which arrive when an ONU is sleeping, listening, and active, respectively. Then, the average delay equals to

$$E[\delta|\mathbb{S}]\cdot P(\mathbb{S})+E[\delta|\mathbb{L}]\cdot\sum_{j=1}^{\infty}P(\mathbb{L}(j))+E[\delta|\mathbb{A}]\cdot\sum_{i=0}^{\infty}P(\mathbb{A}(i)) \quad (11)$$

For packets which arrive when an ONU is sleeping, they have to wait until an ONU wakes up from the sleep status before being transmitted. The average waiting time equals to $y/2$ cycles since the sleep time duration equals to y cycles. We refer to this delay as "wait-to-wakeup" delay. In addition, a packet has to wait until the completion of the transmission of all other packets arrived prior to its arrival. For the jth packet arrival when an ONU is sleeping, it has to wait for the transmission of all the first $j - 1$ packets. Since on average each packet takes $1/\mu$ time to be transmitted, the average waiting time for the jth packet equals to $(j - 1) \cdot 1/\mu + y/2 \cdot T$. For the case that there are k arrival packets when an ONU is asleep, the average delay of these k packets equals to $\frac{\sum_{j=1}^{k}(j-1)\cdot 1/\mu+y/2\cdot T}{k} = \frac{(k-1)}{2}\cdot 1/\mu + \frac{y}{2}\cdot T$. We refer to this delay as "queuing delay". We can further derive the conditional expectation of the delay for packets which arrive when an ONU is sleeping.

$$E[\delta|\mathbb{S}] = y/2 \cdot T + \sum_{i=1}^{\infty}[p^a(i, y)(i - 1) \cdot 1/\mu] \quad (12)$$

For packets which arrive when an ONU is in the active status or listening status, they do not need to wait until an ONU wakes up, and thus do not experience "wait-to-wakeup" delay. Considering the queuing delay, we can derive that the average waiting time for these packets is

$$E[\delta|\mathbb{L}] = \sum_{i=1}^{\infty}[p^a(i, x)(i - 1) \cdot 1/\mu] \quad (13)$$

$$E[\delta|\mathbb{A}] = \sum_{i=1}^{\infty}[p^a(i, z)(i - 1) \cdot 1/\mu] \quad (14)$$

x in Equation (13) and z in Equation (14) represent a traffic scheduling cycle in the listening and active state, respectively.

IV. NUMERICAL RESULTS FOR THE MARKOV MODEL

In the Markov model, we assume each ONU is allocated with a fixed amount of time durations in each resource allocation cycle, and on average one packet from the ONU is scheduled in each traffic scheduling cycle, i.e., $\mu = 1$. Since ONUs do not share resources among each other in the model, we analyze a single ONU behavior. As the recovery time is neglected in comparison to the duration of the traffic scheduling cycle, the proposed ONU architecture in [8] can be exploited. Thus, the power consumption of the ONU receiver in the active and sleep status are selected as 3.85 W and 1.28 W, respectively. As for the listening status, clearly the power consumption has to be within the range of $[1.28, 3.85]$. Since we cannot retrieve the exact number from publicly available literature, we conducted our simulations using different values for the power consumption of the ONU receiver in the listening status. Owing to the space constraint, we only show the results using 2.5, but the observations and conclusions can be similarly drawn for other values.

Fig. 5 illustrates the energy saving performances under different traffic arrival rates. The results are obtained by considering 1 cycle duration for both listening and sleep periods. The average traffic arrival rate λ increases from 0.01 to 1. As the arrival traffic

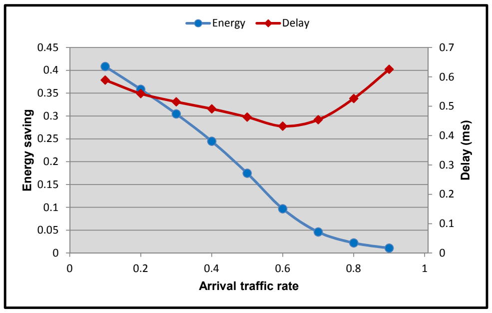

Fig. 5. Energy saving and delay vs. Traffic arrival rate for Poisson traffic

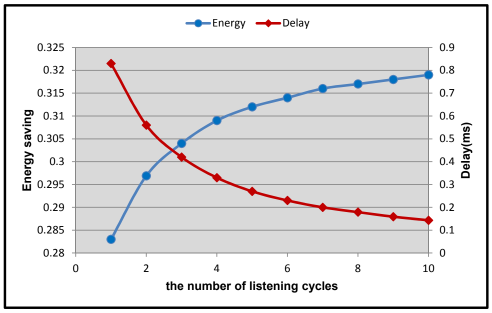

Fig. 6. Energy saving and delay vs. the number of listening cycles for Poisson traffic

rate increases, both the sleep state probability and listening state probability decrease, and thus the energy saving decreases. When the arrival rate equals to 10% of the departure rate, the energy saving is as large as 40%.

We introduce the definition of the "wait-to-wakeup" delay to facilitate the analysis of delay performance. For packets which arrive when an ONU is sleeping, they have to wait until an ONU wakes up from the sleep status before being transmitted. The average waiting time equals to $y/2$ cycles since the sleep time duration equals to y cycles. We refer to this delay as the "wait-to-wakeup" delay.

Regarding delay performances, when the traffic rate is small, the queuing delay is small, and the average delay is dominated by the "wait-to-wakeup" time. When the traffic rate increases beyond some certain value, the probability that an ONU stays in the sleep status is small, and the "wait-to-wakeup" time takes a small portion of the overall average delay. Thus, the average delay is dominated by the queuing delay when the traffic rate is large enough. Fig. 5 shows that the delay first decreases with the increase of the traffic rate. This is because the overall average delay is dominated by the "wait-to-wakeup" time in this case. With the increase of the traffic rate, the sleep state probability decreases, and the "wait-to-wakeup" time decreases, therefore resulting in the decrease of the average delay. Fig. 5 also shows that delay increases when the traffic rate increases beyond some point. In this case, delay is dominated by the queuing delay. With the increase of the traffic rate, the queuing delay increases, and thus the average delay increases.

Fig. 6 illustrates the impact of the listening time duration x on the energy saving and delay by fixing the average traffic arrival rate λ as 0.148 while the number of sleep cycles y equals to 2 cycle. With the increase of the listening cycles x, the probability that an ONU stays in the listening state increases, and the probability that an ONU stays in the sleep state decreases. The reduction of the sleep state probability may result in the decrease of the active state probability since a smaller number of packets are backlogged and the time duration required to transmit these packets is smaller. If the listening state probability increases, the sleep state probability decreases, and the active state probability decreases; the energy consumption may increase and may also decrease. For the particular setting of the power consumption of different states as shown in this example, the energy saving increases with the increase of the number of listening cycles.

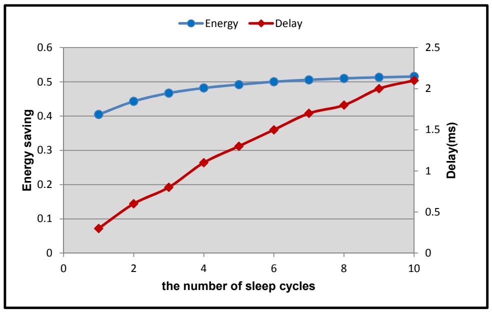

Fig. 7. Energy saving and delay vs. the number of sleep cycles for Poisson traffic

For delay performances, delay decreases with the increase of the listening time owing to the decrease of the sleep state probability. As stated before, because of the "wait-to-wakeup" time, packets experience longer delay if they arrive when an ONU stays in the sleep status as compared to those arrive when an ONU stays in the active and listening status. Thus, the decrease of the sleep state probability results in the decrease of the average packet delay.

Fig. 7 shows the impact of the number of sleeping cycles y on the performances while the number of listening cycles x equals to 2 and the average traffic arrival rate λ is set to 0.148. With the increase of the number of sleeping cycles y, the energy saving increases since the energy consumption in the sleep status is the smallest among all three sets of states. On the other hand, with the increase of y, the probability that an ONU stays in the sleep status decreases. Thus,

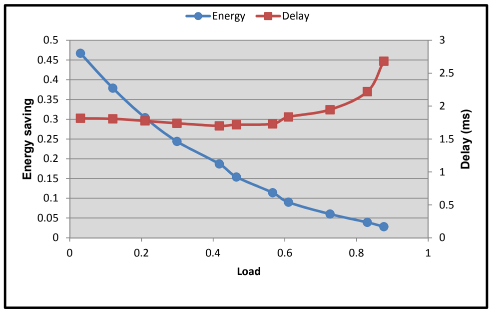

Fig. 8. Energy saving and delay vs. Traffic arrival rate for self-similar traffic

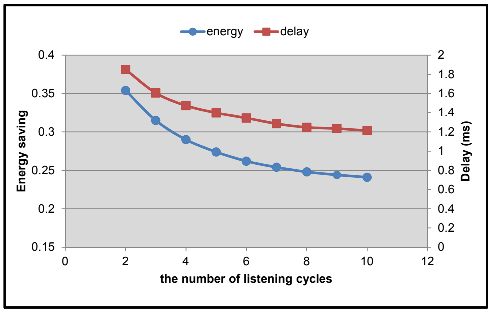

Fig. 9. Energy saving and delay vs. the number of listening cycles for self-similar traffic

the rate of the energy saving is slower than that of the sleep time duration.

Regarding delay performances, delay increases with the increase of the sleep time since longer “wait-to-wakeup” time will be incurred with larger sleeping time. The delay almost increases linearly with the increase of the sleep time because the “wait-to-wakeup” time dominates the overall delay and increases linearly with the number of sleeping cycles y.

V. Simulation model and results

We study the performances of the sleep control scheme for non-Poisson traffic using simulations. Consider a 10G EPON system supporting 32 ONUs. The downstream traffic scheduling cycle duration equals to 2ms. Since self-similarity is exhibited in many applications, we input each ONU with self-similar traffic [19]. The Hurst parameter is set as 0.8. The packet length is uniformly distributed between 64 bytes to 1518 bytes. The downstream traffic scheduling is as follows. If the total queued traffic in a cycle is less than the maximum value which can be accommodated by the cycle, all the packets being queued are scheduled; otherwise, the bandwidth allocated to each ONU is proportional to its requested bandwidth.

Fig. 8 shows the system performances under different traffic load. Here, “load” is defined as the ratio between the total arrival traffic and the network capacity. It can be seen that the trend of both delay and energy saving performances with respect to traffic load is similar to numerical results of the Markov model for the Poisson traffic profile.

Fig. 9 illustrates the impact of the listening cycle number on the system performances. Similar to the theoretical analysis of the Poisson traffic, delay performance decreases with the increase of the listening cycle durations. However, different from the results of Poisson traffic, energy saving decreases with the increase of the listening cycle durations for the self-similar traffic. This illustrates that the burstiness of the traffic profile affects the steady state probabilities of the active, listening, and sleep states. With the increase of the listening cycles, the listening state probability increases, but both the sleeping state and the active state probabilities decrease. For the self-similar traffic case, energy saving decreases with the increase of the number of listening cycles.

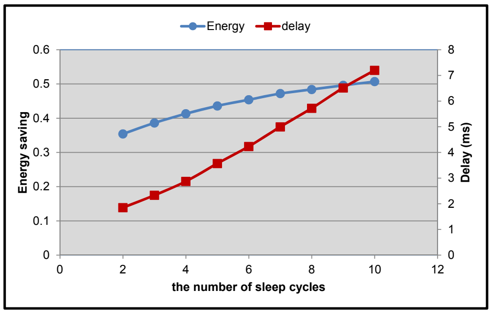

Fig. 10. Energy saving and delay vs. the number of sleep cycles for self-similar traffic

Fig. 10 shows the impact of the number of the sleep cycles on the system performances for the self-similar traffic. Similar to the Poisson traffic case, delay increases almost linearly with the increase of the sleep cycles since the “wait-to-wakeup” time dominates the overall packet delay, and energy saving increases with the increase of the sleep cycles, but is almost constant when the number of sleep cycles is increased to a certain number.

VI. Conclusion

We have proposed a simple sleep control scheme which efficiently puts EPON ONUs into the sleep mode for energy saving. Downstream traffic scheduling rules at the OLT and sleep control rules at ONUs constitute two main parts of the proposed scheme. The sleep control scheme does not require modification of the EPON MAC protocol. It also eliminates the need of the handshake process and allows dynamic downstream bandwidth allocation. Therefore, it achieves high efficiency in both energy saving and bandwidth utilization. We have theoretically analyzed performances of the proposed scheme by employing semi-Markov chains. We have also demonstrated and evaluated the energy saving and delay performances of our proposal scheme by changing the sleep control parameters. It is illustrated that as large as 50% energy saving can be achieved when the network is lightly loaded.

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