Photon Netw Commun (2017) 33:26–38
DOI 10.1007/s11107-016-0616-5

The QoS provisioning tri-mode energy saving mechanism for EPON networks

Chien-Ping Liu[1] · **Ho-Ting Wu**[1] · **Kai-Wei Ke**[1]

Received: 4 June 2015 / Accepted: 10 February 2016 / Published online: 1 March 2016

Abstract The Ethernet passive optical network provides broadband Internet access but also consumes a lot of energy. Energy saving mechanisms using the dual-mode—Active and Sleep modes—design for optical network unit (ONU) in EPON still suffer unnecessary energy consumption, especially in asymmetric data flow such as video streaming downloading service. The Doze mode is particularly suitable for handling the asymmetric data flow since it allows the ONU's transmitter to turn off while turning on its receiver to receive data from optical line termination (OLT). However, adding Doze mode into original dual-mode design incur a greater challenge for OLT to identify the current status of the ONU since the ONU cannot transmit any upstream message to OLT at either Doze or Sleep mode. In this paper, we propose a new QoS provisioning tri-mode energy saving scheme, by integrating the Doze mode into original dual-mode design, to allow the ONU to switch to one of the energy saving modes whenever no upstream traffic exists. A high-priority upstream packet, arriving at ONU of energy saving modes, is able to trigger the ONU back to Active mode for QoS provisioning purpose. Performance evaluation via simulation has demonstrated the effectiveness of such mechanism in various asymmetric data flow. Furthermore, we propose two additional enhanced approaches to increase the energy saving effects by deferring the triggering action of the high-priority upstream packet as well as coalescing new arrival packets during waiting time into the same scheduling cycle.

✉ Chien-Ping Liu
clare8628@gmail.com

[1] Department of Computer Science and Information Engineering, National Taipei University of Technology, No. 1, Sec. 3, Chung-Hsiao E. Rd., Taipei 106, Taiwan

Keywords EPON · Tri-mode · Energy saving · QoS · Doze mode · Asymmetric data flow

1 Introduction

At present, lots of Internet access networks are constructed by passive optical networks (PONs) since the PON provides cost-effective solutions for offering broad access service. Besides, the most popular technology among PON technologies is Ethernet PON (EPON). The ONU, a main component of EPON, consumes the major share of energy in such network. To save energy, many schemes [1–3] have been studied to reduce energy consumption by controlling ONU's energy mode. The main energy modes can be categorized into Active, Doze, and Sleep modes, respectively. With the Active mode, both ONU's transmitter and receiver are powered on. In the energy saving Doze mode, the ONU's receiver interface keeps on while its transmitter turns off. For another energy saving Sleep mode, both of the transmitter and receiver interfaces are powered off.

Some previous designs [4,5] adopt the dual-mode design that allows the ONU to switch between Active and Sleep modes periodically in ONU. Such dual-mode design may suffer unnecessary power consumption in certain circumstance. For example, considering an energy saving design without Doze mode in the case of video streaming downloading service, ONU has to stay in Active mode such that the ONU's receiver is able to receive downstream packets from OLT. However, its transmitter also turns on in Active mode even if there is no upstream traffic. It is noted that among Sleep, Doze, and Active modes, only Doze mode allows ONU to use its power-on receiver to receive downstream packets while keeping its transmitter power-off in upstream channel. In addition, a significant part of Internet access is operated in an asymmetric way that a user sends a small amount of request messages in upstream and generally receives much data from downstream. In such circumstance, the receiver power-on ratio is much higher than the transmitter one for ONU. Without the Doze mode, both receiver and transmitter interfaces need to be powered on, i.e., in the Active mode, to handle the asymmetric traffic. It obviously incurs unnecessary power consumption. Thus, the Doze mode is suitable to service that asymmetric traffic while saving power. Therefore, adding Doze mode into operations of ONU will help save considerable energy while keeping the service of downstream traffic.

A well-designed EPON network has to address the trade-off issues between energy saving and quality of service (QoS) performance. That is, ONU's energy mode, i.e., Active, Doze, and Sleep, should accommodate various traffics and switch to corresponding energy mode. Integrating Doze mode for ONU to allow the ONU's receiver to remain open while keeping its transmitter close in the case where only downstream data exist is applicable well for the asymmetric data flow. However, such integration will incur a great challenge for the OLT to identify the current status of ONU since the ONU cannot transmit any upstream message to OLT at either Doze or Sleep mode.

The purpose of this paper was to design an energy saving scheme that extends the period of energy saving while providing the satisfied QoS performance for high-priority messages in EPON. This study utilizes the downstream traffic as implicit information to judge the current energy state of ONU even without exchanging message that allows the ONU to stay in Doze mode longer while only downstream traffic exists for asymmetric traffic. It also enables the dozed ONU to enter Sleep mode directly if both upstream and downstream are idle. Besides, it supports early wake-up mechanism in both energy saving modes to satisfy the QoS requirements of high-priority real-time traffic and to achieve a balance between energy saving and QoS performance.

The design of EPON needs to satisfy QoS while providing the network access. When the energy saving scheme is included into a QoS planned EPON, what is the relationship between saving factors and perceived QoS performance?

The rest of this paper is organized as follows. In Sect. 2, related works on EPONs are discussed. Section 3, the proposed QoS provisioning tri-mode energy saving scheme, is presented. In Sect. 4, the performance of the proposed scheme is evaluated through simulations. Finally, the paper is concluded in Sect. 5.

2 Related works

2.1 The energy saving designs in PONs

Over the past few years, a few energy saving schemes for PONs had been proposed to reduce energy consumption. Kubo et al. [1] designed a power saving mechanism with variable sleep period to reduce power consumed by ONUs. This mechanism allowed ONU to switch between Active and Sleep mode periodically in accordance with the traffic conditions to save energy. Guo et al. [2] further added a Doze mode for an ONU to save more power. Yet, the study focusing on energy saving did not support the early wakeup triggered by high-priority packets when the ONU resides in either Doze or Sleep mode. Yan et al. [3] proposed an energy management mechanism to maximize the energy saving by switching ONUs to Sleep modes and scheduling a suitable wake-up time. However, the packet priority was not considered in this study.

2.2 The QoS designs in PONs

Several studies had been made on improving bandwidth utilization and QoS for EPON networks. The interleaved polling with adaptive cycle time (IPACT) scheme in [6] explored unused bandwidth, leading to an increase in the amount of best-effort bandwidth. The bandwidth guaranteed polling (BGP) algorithm proposed in [7] allowed the upstream bandwidth to be shared based on a service-level agreement between subscriber and service provider. The research of dual deterministic effective bandwidth generalized processor sharing (Dual DEB-GPS) in [8] provided a delay constraint and lossless QoS for maximizing available bandwidth. The approach of the dynamic bandwidth allocation algorithm for multimedia services in [9] prioritized among packet classes into three categories and delivered time-sensitive packets first to increase the bandwidth effectiveness. Moreover, the study of dynamic bandwidth allocation for QoS in [10] investigated on combining gated transmission mechanisms such as multi-point control protocol (MPCP) and DBA schemes with priority scheduling and queue management for differentiated service support. These previous designs improved bandwidth utilization or QoS, but little attention had been given to energy saving.

2.3 The QoS and energy saving designs in PONs

A few attempts considered both power saving and QoS performance to a certain extent. Mandin [4] introduced a flexible power saving method, which enabled ONU to wake up early from the Sleep mode when a high-priority packet arrived. However, the early wake-up mechanism was only used for Sleep mode. Shi et al. [5] proposed a service-level agreement-based energy-efficient scheme, which adjusted the period of Sleep time for idle ONUs. The scheme divided packets into high- and low-priority types and served high-priority packets first to alleviate high-priority packet delay. However, the Doze mode had not been integrated into ONU's energy level. Hosseinabadi et al. [11] proposed a sleep control scheme to avoid frequent changes in energy modes of ONU by putting ONU in listening mode for a period before going into Sleep mode or changing to Active mode. The scheme uses Active mode to deliver packets and save energy in Sleep mode. The listening mode, which is different from Doze mode, is used to monitor the traffic state to reduce the frequency of mode change. This mode cannot be used for delivering packets. The work in [12] proposed a simple architecture which integrated the Doze mode for switching energy saving modes and supported QoS performance design. However, the mechanism implemented to follow a fixed energy saving modes switching order, i.e., Active, Sleep, and then Doze mode. Therefore, the Doze mode cannot return back Sleep mode directly even if channel is idle. Instead, the dozed ONU had to change to Active mode first and then to Sleep mode, which incurs unnecessary energy consumption.

Therefore, a scheme that considers the network performance by allowing early wake-up mechanism on the energy saving modes as well as the energy saving on three energy levels including Active, Doze, and Sleep modes has not been studied extensively so far.

3 Proposed scheme

3.1 The QoS provisioning tri-mode energy saving scheme

The proposed scheme aims at improving the energy saving effect in EPON especially when both upstream and downstream channels are idle as well as the asymmetric traffic flows arise in ONU while remaining satisfied QoS performance. There are seven ONU energy transition paths designed in the work as shown in Fig. 1. The uppercase letters A, D, and S are represented ONU's Active, Doze, and Sleep modes, respectively. Detailed switching rules are explained as follows.

For the path (1), the Active ONU transits to the Doze mode, if all upstream packets are delivered, but downstream packets still exist. For the path (2), the Active ONU switches into the Sleep mode, when both upstream and downstream packets including high- and low-priority packets are delivered. For the path (3), the dozed ONU switches to Active mode, if a high-priority upstream packet arrived at the ONU or the maximum energy saving time was reached for avoiding deregistration by OLT in MPCP protocol. For the path (4), the slept ONU changes to Active mode, if a high-priority upstream packet arrived at the ONU.

In the path (5), the slept ONU transits to Doze mode after counting down a Y milliseconds. Note that ONU stayed at Sleep mode can neither send nor receive messages. Thus, both the ONU and the time-synced OLT synchronize the period of this state by counting down the same Y milliseconds. After the time expired, the slept ONU enters Doze mode and OLT simultaneously records that the ONU has entered Doze mode in polling table.

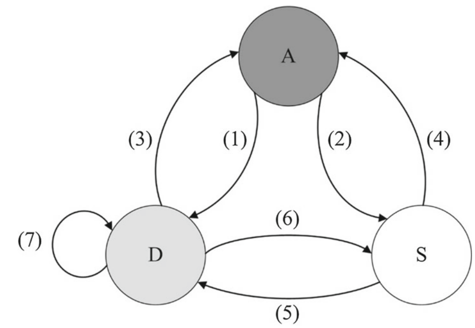

Fig. 1 Tri-mode state transition diagram

It is also worthwhile to note that a dozed ONU cannot send report messages to OLT. Thus, OLT cannot receive those request messages to schedule the ONUs. Fortunately, ONU can receive messages from OLT in this mode. This scheme uses the fact that the dozed ONU is able to receive downstream traffic from OLT. Furthermore, the state of receiving downstream traffic can be used as implicit information to break the limitation that the dozed ONU cannot send messages.

The following facts are noted for an ONU operated in the Doze mode: First, the ONU still can receive downstream traffic from OLT, and second, the OLT continues sending downstream traffic to ONU. In our proposed scheme, we assume that OLT will notify the ONU at the end of downstream transmission period by piggybacking queue size information within the downstream data. The information of downstream traffic can be used to identify ONU in which energy mode follows two steps: First, OLT uses the Gate message in downstream traffic to tell ONU the information of downstream queue size for ONU calculating the remaining transmission time. Therefore, OLT knows when the ONU should go to Sleep mode and ONU can estimate the time to sleep. Once the ONU enters the Sleep mode, a sleep timer is activated, where the sleep time is a predefined period and is activated on both OLT and ONU simultaneously. The OLT can thus realize when the ONU will wake up. The status of this sleep timer can also be used to identify an ONU in Sleep mode or not. If this timer is activated, the OLT identifies ONU in Sleep mode. Otherwise, OLT infers that ONU stays in Doze or Active mode. Second, the case of receiving or no-receiving Report message is the possible response after OLT sends Gate message, like a probing signal, in downstream traffic. The OLT can judge ONU is in Active mode by checking whether it can receive Report message after OLT sends the Gate message in a period of time. Otherwise, the ONU staying in Doze mode is identified.

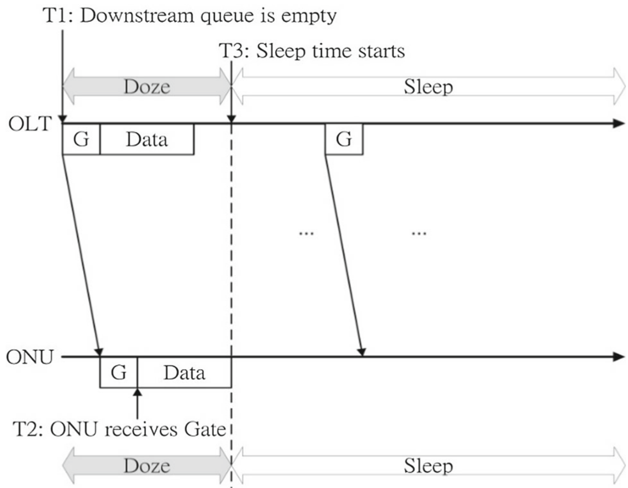

Fig. 2 OLT side drives ONU to change mode from Doze to Sleep

As illustrated in Fig. 2, the ONU receives downstream traffic right after the propagation delay T_p. Since the delay is a constant value in fixed network architecture, it means that the OLT can infer the time, T_3, when this ONU completes receiving data for the current traffic as shown in Fig. 2.

Using the implicit information and the inferring method, both OLT and ONU are able to know the ending time of downstream transmission, which triggers the path (6). Thus, OLT directly records that the ONU is going to Sleep and ONU transits to Sleep mode naturally without exchanging any message with the OLT. Otherwise, a dozed ONU loops in Doze mode, i.e., the path (7), if OLT perceives itself sending packets continuously. Note that the dozed ONU keeps staying in the Doze mode until the conditions in path (3) hold and then switch to Active mode,

3.2 The enhancement of energy saving

Adding the path (6) described in the above section benefits energy saving because ONU can return to Sleep mode in one energy transition step instead of two steps: Doze to Active mode and then Active to Sleep mode. Besides, the path (7) enables ONU staying in Doze mode longer. Through the proposed scheme, the number of Active mode being entered during overall operation cycles can be reduced because it enables that a dozed ONU transits to Sleep mode directly without passing Active mode and stays in Doze mode to maximum energy saving time as long as possible. However, when the high-priority packet arrives or maximum energy saving timer expires, the proposed scheme will transit an energy saving ONU into Active mode. Once the ONU changes to Active mode, the new arrived packets including high- and low-priority packets and/or the low-priority packets accumulated in the previous power saving mode need to be digested. The ONU may need to stay in Active mode for extended time to delivery those packets. The energy saving can be enhanced if frequency of Active mode for ONU can be decreased further. There are two strategies introduced in the following that reduce the ratio of ONU in Active mode: first the deferring process and second the coalescing process.

3.2.1 The deferring process

The early wake-up mechanism in [12] triggers the ONU to change to Active mode whenever the high-priority packet arrives. The mechanism leads to extremely low packet delay for high-priority packets but decreases the effects of energy saving. In fact, the longer the ONU stays in Sleep and Doze mode, the power saving effect is better enhanced. Thus, the energy saving effects can be improved if high-priority packets in power saving mode of ONU are deferred to certain allowable latency. That is, the switch back to Active mode from either power saving mode due to early wake-up mechanism is postponed to an acceptable amount of time whenever ONU operates in Sleep and Doze modes.

Moreover, to effectively control the deferring process, the maximum delay for high-priority packets should be less than the maximum energy saving time in the proposed scheme, since the ONU will be already switched to Active mode by the maximum energy timer. In addition, the Sleep mode timer prevents the transmission and reception of both upstream and downstream low-priority packets for such amount of time. Similarly, the maximum delay in deferring process should not excess this timer to preclude the above issues.

3.2.2 The coalescing process

The definition of the related parameters described in coalescing process is listed in Table 1. First, the procedure of the MPCP protocol is shown in Fig. 3. ONU sends Report message to OLT to request the bandwidth size of R_i for delivering packets. OLT receives those messages from all ONUs then to grant each request with grant bandwidth size of G_i. There are packets with size A_i arriving during the waiting time period WT_i after sending Report message till receiving

Table 1 Coalescing process parameters

G_i	Grant size in cycle *i*
D_i	Data size in cycle *i*
R_i	Report size in cycle *i*
A_i	Total packet length of all arrived packets in cycle *i*
AR_i	Packet arrival rate in cycle *i*
CT_i	The time duration of cycle *i*
TT_i	Total packet transmission time in cycle *i*
WT_i	Waiting time in cycle *i*
α	Credit ratio

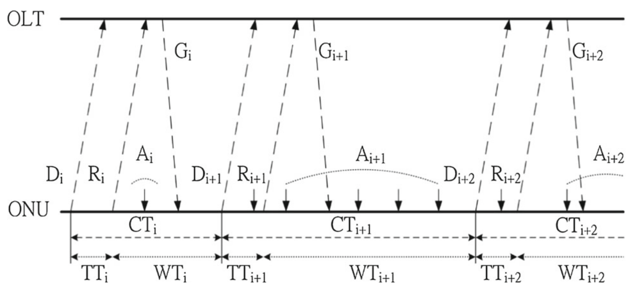

Fig. 3 Packets arrive after request sent

Grant message from OLT in the cycle i. If those new arrived packets are not to be granted, then they have to be scheduled on next cycle $i+1$ as the request R_{i+1}. ONU has to wait to deliver those uncovered packets in next cycle and keeps in the Active mode without entering energy saving mode to save energy. In other words, if OLT can provide extra credit for those packets in each cycle, it is more likely to allow ONU to transmit all of its queued message and report the request size of $R_{i+1}=0$. In such case, the ONU will be able to switch to the power saving mode to save more energy.

The object of the coalescing process was to meet the ONU's total request demands including R_i and A_i within cycle i. That is if OLT grants a perfect size, which is lower than the size of MTW limited by MPCP, to the ONU, the report size in next cycle R_{i+1} for this ONU can be zero if:

$$G_i = R_i + A_i \tag{1}$$

However, packets arrive at ONU randomly, an exact grant size G_i for that ONU has to be predicted. More precisely, the grant size includes two parts: current request size R_i and new arrived size A_i. Because current request size R_i is a nonrandom value sent by ONU, therefore only the size of new arrived packets A_i needs to be predicted.

The coalescing process estimates the new arrived size A_i in the current cycle from those arrived sizes in previous cycles. It is noted that the next request size R_{i+1} in cycle $i+1$ is the sum of current request size R_i plus new arrived request size A_i to subtract grant size G_i in cycle i as illustrated in Fig. 3. It can be expressed in the recursive form:

$$R_{i+1} = R_i + A_i - G_i \tag{2}$$

Since the period of cycle time CT_i of an ONU being served changes dynamically according to the request quantity in each cycle, the arrival rate AR_i has to be measured in each cycle. By observing Eq. (2), the OLT in cycle $i+1$ can calculate the previous cycle arrived length A_i and arrival rate AR_i for each ONU during the previous waiting time WT_i as:

$$A_i = R_{i+1} + G_i - R_i, \quad \mathrm{AR}_i = \frac{A_i}{\mathrm{WT}_i} \tag{3}$$

Besides, OLT calculates the mean arrival rates $\overline{\mathrm{AR}}_i$ of latest m cycles as the estimated arrival rate $\hat{A}_{i+1}$ for real arrival rate A_{i+1} by:

$$\hat{A}_{i+1} = WT_{i+1} \cdot \overline{\mathrm{AR}}_i, \quad \overline{\mathrm{AR}}_i = \frac{1}{i}\sum_{k=i-(m-1)}^{i} \mathrm{AR}_k \tag{4}$$

To take into consideration the burst traffic appeared in network, another parameter, credit ratio α, is included to allow the real arrived size A_{i+1} larger than the estimated value $\hat{A}_{i+1}$. Combining the request length R_{i+1} and estimated $\hat{A}_{i+1}$ with adjusted credit ratio, in cycle $i+1$ the final grant size G_{i+1} given by OLT for an ONU becomes:

$$G_{i+1} = R_{i+1} + \hat{A}_{i+1} \times (1+\alpha) \tag{5}$$

Comparing $G_{i+1} = R_{i+1} + A_{i+1}$ from Eq. (1) for cycle $i+1$, if the estimated size $\hat{A}_{i+1} \times (1+\alpha)$ in Eq. (5) is equal to actual size A_{i+1}, the request size, R_{i+2}, in cycle $i+2$ for ONU becomes zero. This means ONU can deliver all packets in current cycle $i+1$ and then switch to energy saving mode instantly, without continuously staying at the Active mode for next cycle, to save more energy.

Note that if the estimated size is smaller than actual required size, it indicates that the grant size is too small such that the ONU cannot go to energy saving mode and has to wait for transmitting the remaining packets in next cycle. On the contrary, if the estimated size is larger than the actual size, the excessive bandwidth given by OLT represents the channel idle time. The period cannot be utilized by other ONUs since the service time has been scheduled solely for this ONU. All other ONUs will waste energy if they have been staying at Active mode.

3.2.3 The integration of the deferring and coalescing processes

The deferring process helps ONU stay in energy saving mode because this process puts off the timing to activate early wake-up mechanism when high-priority packet arrives at ONU of Sleep or Doze mode. Hence, the ONU can remain in energy saving mode for a longer time. Besides, the coalescing process provides ONU an extra credit to satisfy both requirements of current request and the new arrived request during waiting time. This may result in a higher chance that all packets of both requests can be delivered together in the same cycle. Therefore, ONU can change to the energy saving mode as early as possible. It can be observed that the coalescing process terminates the period of ONU in Active mode as early as possible and the deferring process extends the ratio of ONU staying in Sleep or Doze mode as long as possible. Consequently, the combined effects of energy saving by the integration of the deferring and coalescing processes are expected to be significant.

4 Performance evaluation

The performance evaluation of the proposed mechanism is conducted through simulation results. The simulation includes four aspects: (1) the performance of the proposed QoS provisioning tri-mode energy saving scheme; (2) the comparison between dual-mode and tri-modes; (3) the impact of deferring process; and (4) the impact of integration on deferring and coalescing processes. The metrics evaluated in simulation comprise energy state ratio, average cycle time, downstream packet delay, and upstream packet delay. The parameter settings for simulation are listed in Table 2. Note that both upstream and downstream loadings are normalized such that the normalized value of 1 represents a total of 1.6 Gbps requested bandwidth if all 16 ONUs requested 100 Mbps in EPON network. This value corresponds to the result that each ONU transmits or receives 100 Mbps in the upstream or downstream channel, respectively. The normalized value of 0.625 represents an overloading channel for either upstream or downstream channel.

4.1 The performance of the proposed QoS provisioning tri-mode energy saving scheme

Different traffic sources affect performance significantly. To test the response by different traffic sources, we input Poisson and self-similar traffic to the EPON network with proposed

Table 2 Simulation parameter settings

Parameter	Value
ONU count	16
Downstream channel capacity	1 Gbps
Upstream channel capacity	1 Gbps
OLT–ONU distances	20 km
Traffic pattern I	Poisson
Traffic pattern II	Self-similar
Guard interval	5 µs
Frame size	64–1518 bytes
ONU queue size	8 Mbytes
Maximum transmission window (MTW)	15,000 bytes
Simulation time	10 s
Upstream scheduling method	IPACT limited service
Y (timer for Sleep to Doze mode)	20 ms
Maximum energy saving time	997 ms (<1 s)
Deferring time	1.5 ms
Credit ratio	0.1, 1

scheme, where the self-similar traffic can be constructed by multiplexing a large number of ON/OFF sources that have ON and OFF period lengths. In this simulation, the self-similar traffic generator refers from [13] with setting the parameters: alpha on, alpha off, and beta on to 1.4, 1.2, and 1, respectively.

For Poisson traffic, the number of incoming packets follows the Poisson distribution and the length of each packet is typically modeled as an exponential distribution. One difference between two traffic sources for our power saving scheme is that the self-similar traffic has the obvious and long-tailed OFF period, in contrast to Poisson traffic. Thus, we can expect that ONU has higher chance to stay at power saving mode, i.e., Doze or Sleep mode, longer in self-similar traffic. Comparing Figs. 4 and 5 for the same upstream loading at 0.1, the Active mode ratio in self-similar is lower than that in Poisson traffic. It is because ONU in period of OFF period for self-similar traffic is prone to staying in power saving mode longer without having to switch between Active and power saving modes frequently. Since the self-similar traffic is a more realistic model and can reflect the bursty nature of packet data. Thus, for the following sections, we only show the simulation results with self-similar traffic model.

Besides in both Figs. 4 and 5, there is a similar variation between normalized downstream loading of 0.55 and 0.70 for different traffics source. We take Fig. 5 as an example to explain this variation phenomenon. There are two key points to watch: the point 1, i.e., the ratio of Sleep mode becomes zero at traffic loading 0.6, and the point 2, i.e., the downstream loading by the OLT to each ONU is more than MTW when loading beyond 0.65, as shown in the Figure. Along with the increase in downstream loading to 0.6, which is close to the full capacity for downstream channel, the ratio of Sleep mode start going to zero since the downstream queue at ONU is not empty at any time. According to the designed rule, ONU can only stay in either Active or Doze mode. The ONU staying in Sleep mode will keep its upstream low-priority packets in the buffering queue. However, the state of Sleep mode disappeared at downstream loading 0.65. The upstream low-priority packets originally accumulated at ONU of Sleep mode, according to our rule, will drive the ONU to switch to Active mode. In addition, we use a downstream centric scheduling algorithm; the upstream packets are scheduled to deliver whenever OLT needs to deliver downstream packets. Hence, the increasing downstream loading also increases the delivery of upstream packets, as shown in the going up Active mode curve between loading 0.6 and 0.65 in the figure, until the downstream loading reaches full loading. The increasing ratio of Active mode leads to the ratio reduction in Doze mode since ONU in Active mode must digest those accumulated low-priority upstream packets, which has been buffered for a period of time completely before the ONU can go back to Doze mode.

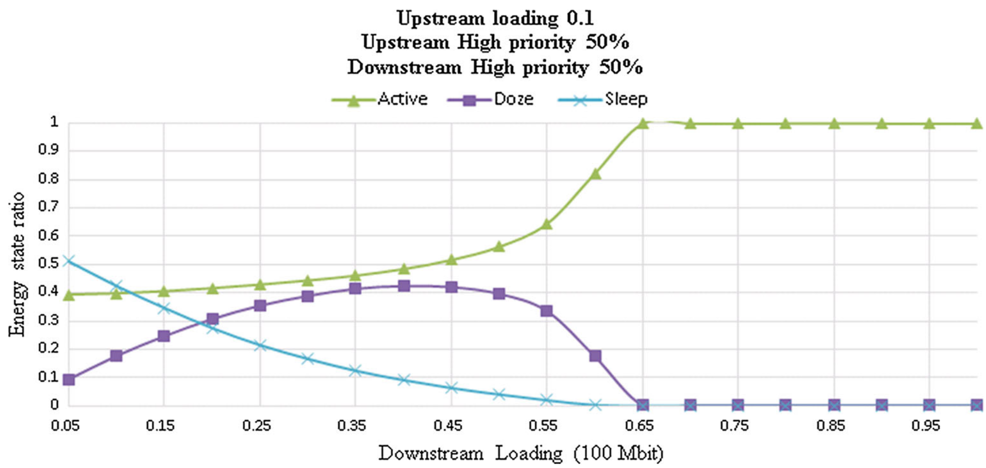

Fig. 4 Energy state ratio of the proposed scheme in upstream loading 0.1 for Poisson traffic

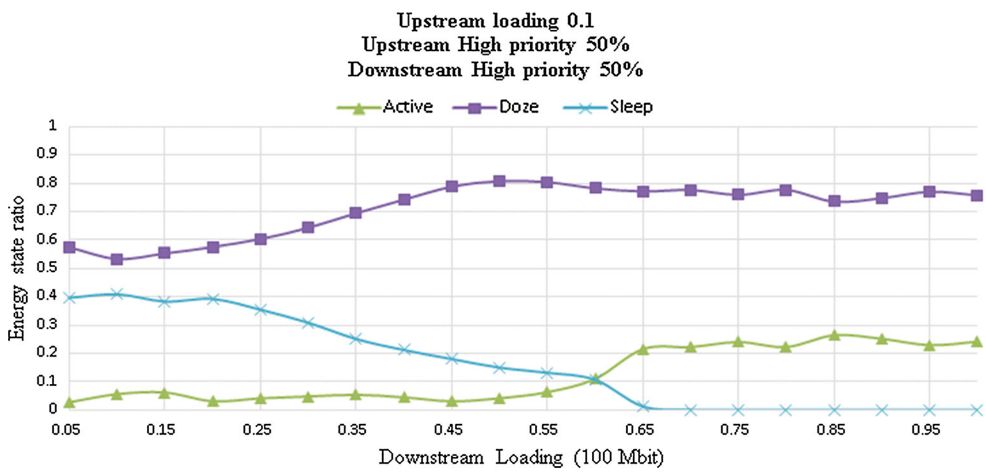

Fig. 5 Energy state ratio of the proposed scheme in upstream loading 0.1 for self-similar traffic

Figure 6 exhibits the downstream packet delay for upstream loading 0.1. The average high- and low-priority packet delays of downstream keep in a low value of 9.0 and 9.6 ms. But they arise dramatically around at saturated point, the normalized loading 0.625, because of channel overloading. The variation in the worst-case delay in Fig. 6 is quite large because ONU would go to power saving mode for a long OFF period and return Active mode in a burst ON period. For the upstream packet delay in Fig. 7, the average high-priority packet delay of upstream keeps in a small value of 3.9 ms. The average low-priority packet delay is around 13.8 ms, which is higher than high-priority packet. The variation in maximum upstream delays is also large as the bursty nature of the traffic.

4.2 The comparison between dual-mode and tri-mode

Figure 8 shows the energy state ratio in upstream loading 0.1 for dual-mode. For an easier way to compare dual-mode in Fig. 8 with tri-mode in Fig. 5, a metric of the total normalized power consumption is defined as summation of the power consumption multiplying energy state ratio for each mode, where the power consumption is the normalized power ratio for Doze and Sleep to Active mode referred, and averaged from [14–18], the ratios for Doze and Sleep to Active are 0.3 and 0.1, respectively.

After converting energy state ratio to normalized power consumption value as shown in Fig. 9, the ONU with tri-mode consumes the power value around 0.25 while below downstream loading 0.6. Beyond the loading 0.6, the tri-mode ONU increases the power consumption to normalized power value 0.5. In contrast, dual-mode ONU consumes a huge amount of power to value 1, i.e., no energy saving effect. Since without Doze mode, ONU needs to use Active mode with higher power consumption to serve asymmetric traffic.

However, we also found the power consumption of the tri-mode ONU is higher than that of using dual-mode while below downstream loading 0.55. The reason is that ONU tends to stay in Sleep mode in certain lower downstream loading. According to our design, the slept ONU switches

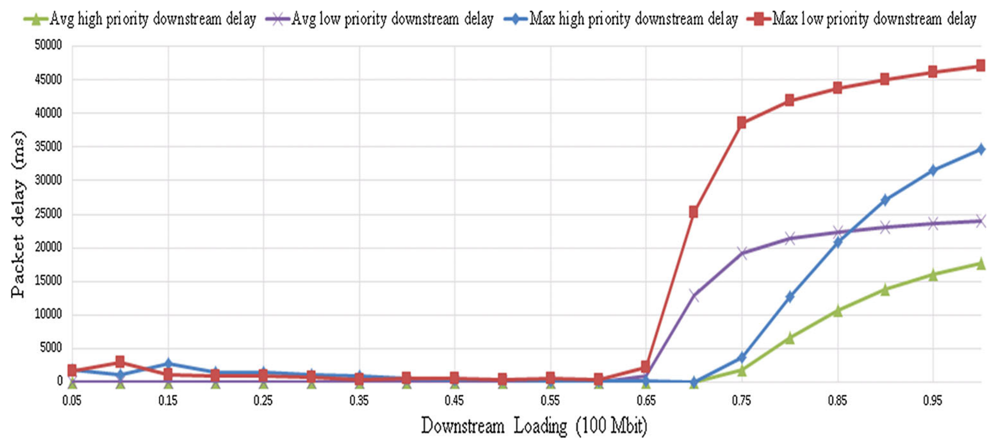

Fig. 6 Downstream packet delay of the proposed scheme in upstream loading 0.1

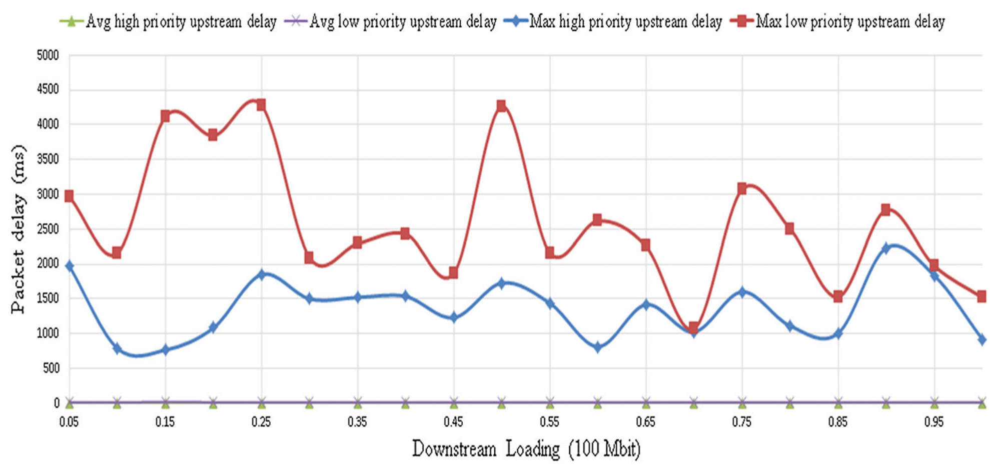

Fig. 7 Upstream packet delay of the proposed scheme in upstream loading 0.1

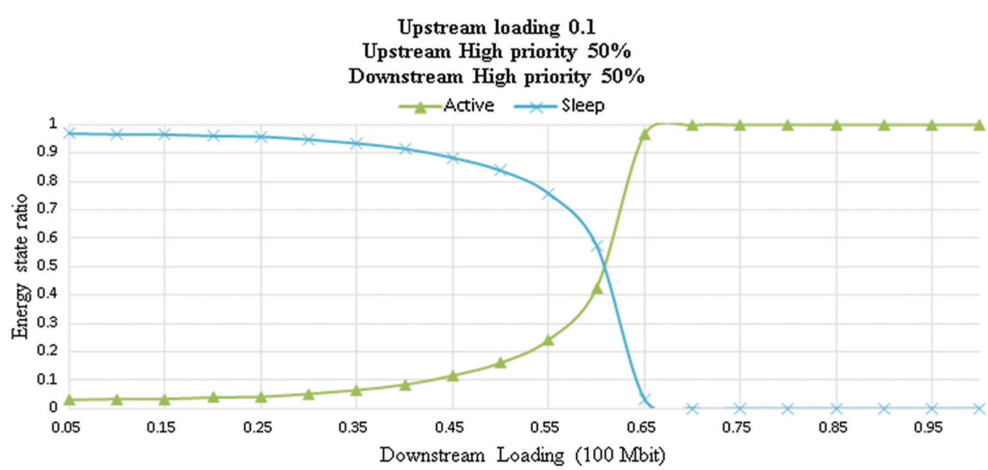

Fig. 8 Energy state ratio in upstream loading 0.1 for dual-mode

to Doze mode after its sleep timer expired. This succeeding Doze mode starts serving the downstream traffic that consumes higher power, which is also benefit to Qos performance. In contrast to higher downstream loading in the design, ONU tends to stay in Active mode. ONU changes Active mode to Doze mode once the downstream-only traf-

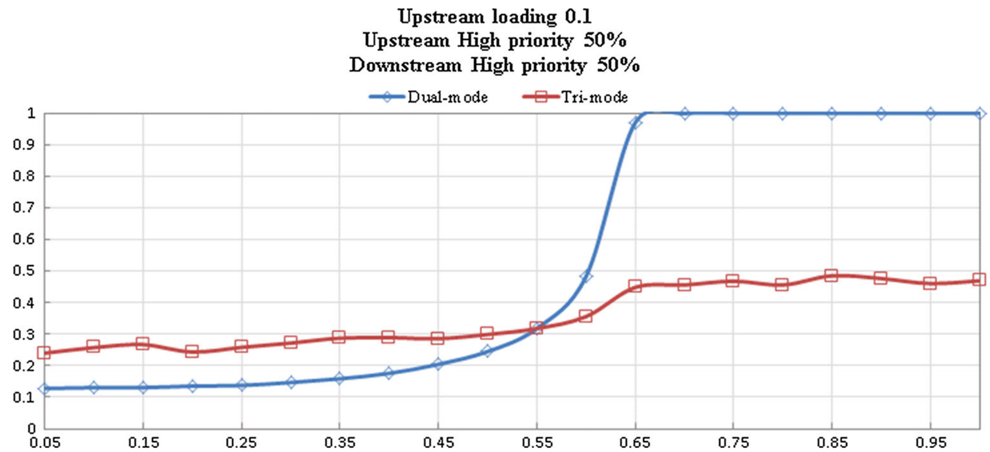

Fig. 9 Normalized power consumption for using dual-mode and tri-mode ONU in upstream loading 0.1

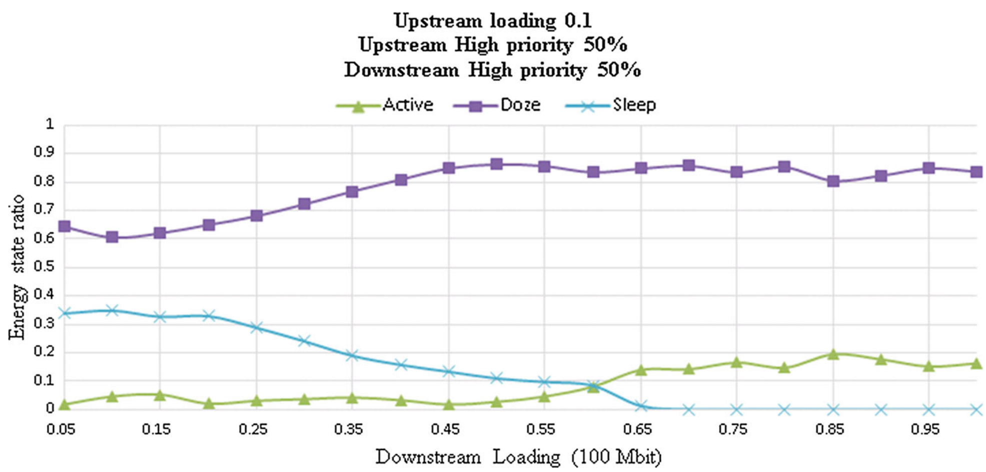

Fig. 10 Energy state ratio in upstream loading 0.1 for proposed scheme using deferring process

fic remains. At this moment, the Doze mode plays a role to help ONU serve downstream-only traffic instead of Active mode in dual-mode that saves energy.

The result shows that the tri-mode ONU maintains pretty low-power consumption for downstream loading beyond downstream loading 0.55 though its power consumption is higher than that of using dual-mode below loading 0.55. More energy can be saved if a new designed scheme keeps using dual-mode in lower downstream loading such as to design a dynamic scheme which can adaptively use dual-mode or tri-mode according to varied traffic loading.

4.3 The impact of deferring process

The deferring process delays the high-priority packets, which otherwise will be delivered by early wake-up mechanism without delay, to extend the ratio of energy saving mode for ONU. Figure 10 shows the energy state ratio of the proposed scheme with deferring process of maximum upstream high-priority delay of 1.5 ms in the case of upstream loading 0.1. The ratio of ONU Active state is lower than the scheme without using deferring process as shown in Fig. 5. Both ratio of Doze and Sleep modes are increased to compare with Fig. 5. It is because the high-priority packets arriving during energy saving state in either Doze or Sleep will be deferred to the maximum time of 1.5 ms. ONU can stay in energy saving mode longer, and this increased energy saving ratio results in the decrease in Active mode. The upstream packet delay of the scheme with deferring process has similar results in Fig. 7 of the base scheme, i.e., without using deferring process. The average high- and low-priority packet delay is a value of 12.6 and 23.4 ms which is a little bit higher than the base scheme. The deferring process let ONU stay in energy saving mode longer to decrease the energy consumption but increase the delay. The delay is higher than our deferring setting 1.5 ms because of the physical constraint. Figure 11 exhibits the normalized power consumption for proposed scheme using deferring process in upstream loading 0.1 compared to base scheme in Fig. 5. The energy is saved in higher downstream loading, namely loading beyond 0.6. However, the energy

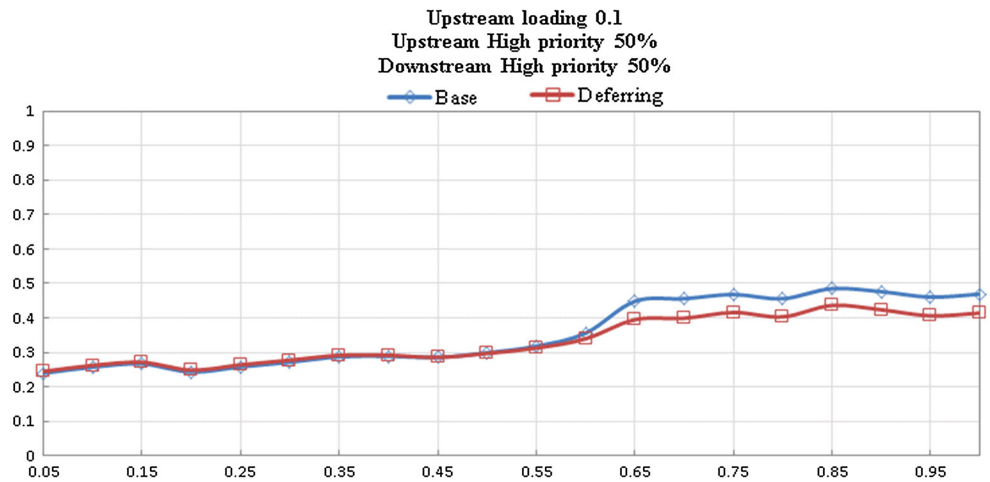

Fig. 11 Normalized power consumption for proposed scheme using deferring process in upstream loading 0.1

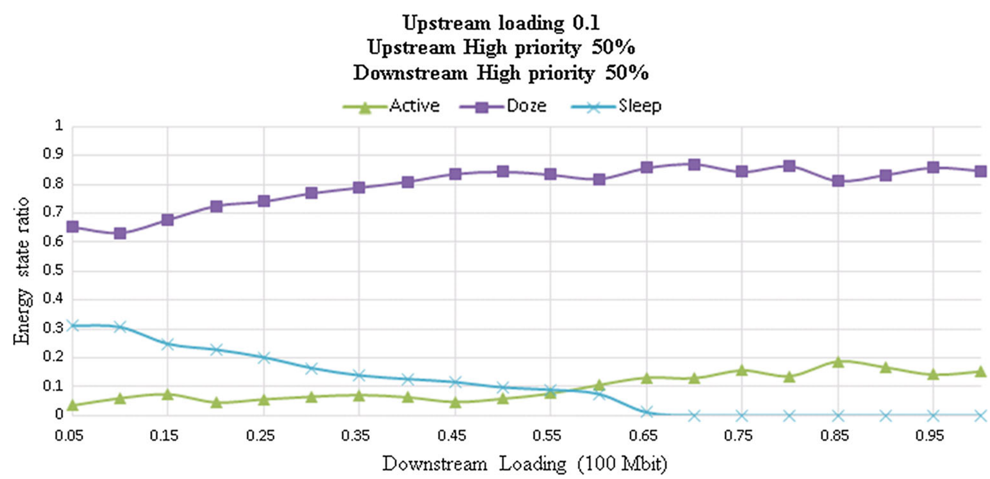

Fig. 12 Energy state ratio in upstream loading 0.1 on integrating both deferring and coalescing process

saving effect is not obvious since the Active ratio below downstream loading 0.6 is already quite low in self-similar traffic as shown in Fig. 10, and thus, the effect of saving energy is limited.

4.4 The impact of integrating on both deferring and coalescing processes

Figure 12 shows the energy state ratio in upstream loading 0.1 on adding coalescing process for the proposed scheme with deferring process. The coalescing process decreases Sleep mode ratio below downstream loading 0.6, and it also slightly decreases the Active ratio beyond downstream loading 0.6 as shown in Fig. 12. For an easier way to observe, we again aggregate three energy state ratios into the normalized power consumption defined in Sect. 4.2 as shown in Fig. 13.

Figure 13 shows that the scheme with deferring process and adding coalescing process consumes a little bit higher power than the base, i.e., Fig. 5, in upstream loading 0.1 below lower downstream loading 0.6. It is because reserving extra bandwidth by coalescing process may also increase the ratio of ONU staying in Active mode when burst traffic arrives at lower downstream loading. While in higher downstream loading, this process saves energy, but the saving effect is not obvious. It is because the ON and OFF periods in self-similar traffic have huge gap that affects the prediction accuracy for granting a suitable size in coalescing process. Thus, the saving effect is limited for self-similar traffic.

Figure 14 shows the average cycle time in upstream loading 0.1 of proposed scheme versus scheme with both deferring and coalescing processes. The scheme with deferring and coalescing process will increase the average cycle time below downstream loading 0.6 in comparison with base scheme. Furthermore, Fig. 15 shows the average high priority packet downstream delay for scheme with deferring and coalescing process between downstream loading 0.05 and 0.6 in most cases is lower than the base of Fig. 5. That is why, the scheme with deferring and coalescing process has

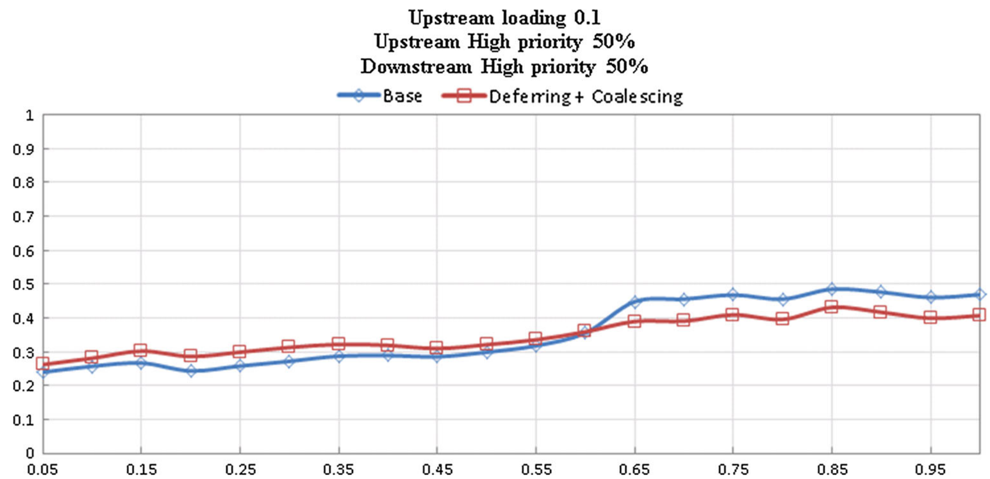

Fig. 13 Normalized power consumption in upstream loading 0.1 on integrating both deferring and coalescing process

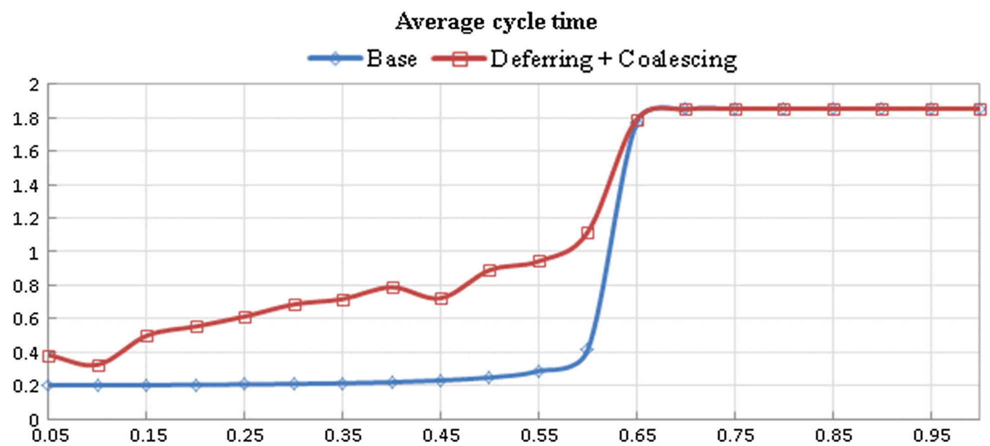

Fig. 14 Average cycle time in upstream loading 0.1 of proposed scheme versus scheme with both deferring and coalescing processes

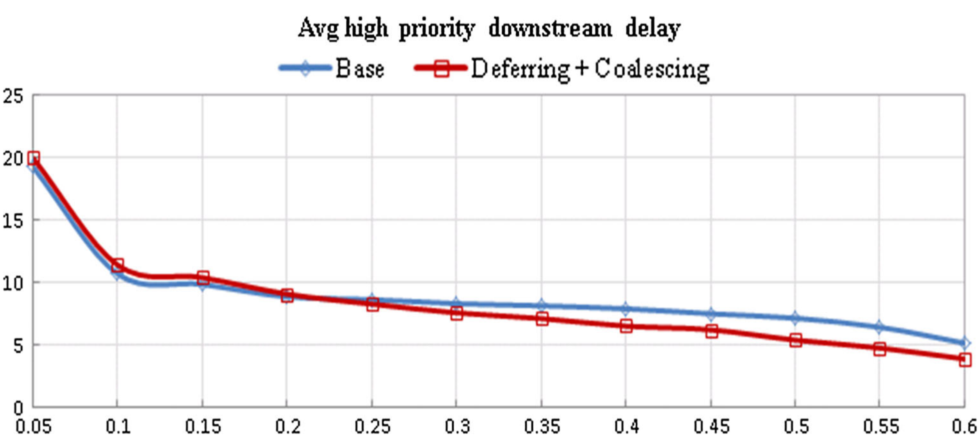

Fig. 15 Average high-priority packet downstream delay in upstream loading 0.1 between downstream loading 0.05 and 0.6

higher power consumption than base scheme of Fig. 5 below downstream loading 0.6 as shown in Fig. 13. It also implies that during this period of loading, ONU has higher QoS performance.

5 Conclusion

The EPON network design needs to address the trade-off issues between energy saving and performance. The ONU's system should switch dynamically to corresponding mode for various traffic scenarios. The proposed mechanism jointly considers the saving energy and network performance by extending the period of ONU staying in energy saving modes and returning Active mode while high-priority packet arrives. Besides, the proposed scheme utilizes the existing traffic as implicit information without exchanging message to allow ONU to stay in Doze mode while only downstream traffic exists for asymmetric data flow and return to Sleep mode directly if both upstream and downstream channels are idle. Using this implicit information as perceiving downstream traffic provides the dozed ONU an opportunity to synchronize with OLT and thus breaks the limitation that the message is unable to handshake for the dozed ONU. As for the slept ONU, its transmitter and receiver can neither send nor receive message from OLT. Our work uses the timer design in Sleep mode to synchronize the energy state between ONU and OLT. The proposed scheme uses Doze mode and combines early wake-up mechanism in energy saving mode to provide satisfactory QoS performance. In addition, this scheme further delays the high-priority packet in allowable bound in energy saving mode and delivers the remaining packets in one cycle time to end transmission as early as possible in Active mode to maximize the energy saving effect. Performance evaluations through extensive simulations have demonstrated the effectiveness of our proposed mechanisms to achieve power saving while providing satisfactory QoS performance. For the future works, the simulation with larger scale setting such as NG-PON and a dynamic mode switching scheme for different traffic loadings to further enhance energy saving effect will be performed and studied.

References

[1] Kubo, R., Kani, J., Fujimoto, Y., Yoshimoto, N., Kumozaki, K.: Adaptive power saving mechanism for 10 Gigabit class PON systems. IEICE Trans. Commun. **E93–B**(2), 280–288 (2010)
[2] Guo, X., Shou, G., Xiao, Q., Hu, Y., Guo, Z.: Toward green PON with adaptive sleep mode. In: IC-NIDC, pp. 184–188 (2012)
[3] Yan, Y., Wong, S.-W., Valcarenghi, L., Yen, S.-H., Campelo, D. R., Yamashita, S., Kazovsky, L., Dittmann, L.: Energy management mechanism for Ethernet passive optical networks (EPONs). In: IEEE International Conference on Communications (ICC), 2010, pp. 1–5 (2010)
[4] Mandin, J.: EPON powersaving via sleep mode. In: IEEE 802.3av Meeting (2008)
[5] Shi, L., et al.: Efficient PON with sleep-mode ONU: progress, challenges, and solutions. IEEE Netw. Mag. **26**(2), 36–41 (2012)
[6] Kramer, G., Mukherjee, B., Pesavento, G.: IPACT: a dynamic protocol for an Ethernet PON (EPON). IEEE Commun. Mag. **40**(2), 66–73 (2002)
[7] Ma, M., Zhu, Y., Cheng, T.: A bandwidth guaranteed polling MAC protocol for Ethernet passive optical network. Proc. IEEE INFOCOM **1**, 22–31 (2003)
[8] Zhang, L., et al.: Dual DEB-GPS scheduler for delay-constraint applications in Ethernet passive optical networks. IECE Trans. Commun. **E86–B**(5), 1575–1584 (2003)
[9] Choi, S.-I., Huh, J.-D.: Dynamic bandwidth allocation algorithm for multimedia services over Ethernet PONs. ETRI J. **24**(6), 465–468 (2002)
[10] Assi, C., et al.: Dynamic bandwidth allocation for quality-of-service over Ethernet PONs. IEEE JSAC **21**(9), 1467–1477 (2003)
[11] Hosseinabadi, Mina Taheri, Ansari, Nirwan: Multi-power-level energy saving management for passive optical networks. J. Opt. Commun. Netw. **6**(11), 965–973 (2014)
[12] Liu, C.-P., Wu, H.-T., Chiang, Y.-T., Chien, S.-C., Ke, K.-W.: An energy saving mechanism of EPON networks for real time video transmission. In: 7th International Conference on Digital Image Processing, Los Angeles (2015)
[13] Kramer, G.: On generating self-similar traffic using pseudo-Pareto distribution. University of California, Davis (2001)
[14] Dinh, N., Walid, A.: Power saving protocol for 10G-EPON systems: a proposal and performance evaluations. In: IEEE GLOBECOM, Anaheim, CA (2012)
[15] Shi, L., Mukherjee, B., Lee, S.-S.: Energy-efficient PON with sleep-mode ONU: progress, challenges, and solutions. IEEE Netw. **26**, 36–41 (2012)
[16] Herreria-Alonso, S., Rodriguez-Perez, M., Fernandez-Veiga, M., Lopez-Garcia, C.: On the use of the doze mode to reduce power consumption in EPON systems. J. Lightwave Technol. **32**, 285–292 (2013)
[17] Suzuki, N., Kobiki, K., Igawa, E., Nakagawa, J.: Dynamic sleep-mode ONU with self-sustained fast-lock CDR IC for burst-mode power saving in 10 G-EPON systems. IEEE Photonics Technol. Lett. **23**, 1796–1798 (2011)
[18] Igawa, E., Nogami, M., Nakagawa, J.: Symmetric 10G-EPON ONU burst-mode transceiver employing dynamic power save control circuit. In: IEEE Optical Fiber Communication Conference and Exposition (OFC/NFOEC), Los Angeles, CA (2011)

Chien-Ping Liu received the M.S. degree in Electronic Engineering from Fu Jen Catholic University, Taipei, Taiwan, in 2000. He is currently pursuing his Ph.D. degree in Computer Science and Information Engineering at National Taipei University of Technology. His current research interests include optical and wireless networks.

Ho-Ting Wu received his B.S. degree from National Taiwan University in 1986, and both the M.S. and Ph.D. degrees from the University of California, Los Angeles, in 1989 and 1994, all in Electrical Engineering. Since 1996, he has been on the faculty at National Taipei University of Technology, Taiwan, where he is currently a Professor in the Department of Computer Science and Information Engineering. His current research interests include multimedia communications, optical and wireless networks.

Kai-Wei Ke received the Ph.D. degree in Electrical Engineering from Georgia Institute of Technology, USA, in 1996. Currently, he is a Professor of Computer Science and Information Engineering, National Taipei University of Technology, Taiwan, ROC. His research interests include traffic modeling, Internet protocols, and call admission, resource allocation, routing algorithms, and performance evaluation for wireless multimedia communication networks.