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PAPER

A Predictive Logistic Regression Based Doze Mode Energy-Efficiency Mechanism in EPON

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SUMMARY Ethernet passive optical network (EPON) is one of the energy-efficient access networks. Many studies have been done to reach maximum energy saving in the EPON. However, it is a trade-off between achieving maximum energy saving and guaranteeing QoS. In this paper, a predictive doze mode mechanism in an enhanced EPON architecture is proposed to achieve energy saving by using a logistic regression (LR) model. The optical line terminal (OLT) in the EPON employs an enhanced Doze Manager practicing the LR model to predict the doze periods of the optical network units (ONUs). The doze periods are estimated more accurately based on the historical high-priority traffic information, and logistic regression DBA (LR-DBA) performs dynamic bandwidth allocation accordingly. The proposed LR-DBA mechanism is compared with a scheme without energy saving (IPACT) and another scheme with energy saving (GDBA). Simulation results show that LR-DBA effectively improves the power consumption of ONUs in most cases, and the improvement can be up to 45% while it guarantees the QoS metrics, such as the high-priority traffic delay and jitter.

key words: *EPON, energy saving, logistic regression, LR-DBA*

1. Introduction

In recent years, green communication for access networks has obtained much attention in the research domain for the emerging economic and environmental concerns [1], [2]. As the access network technology is rapidly evolving, the passive optical network (PON) becomes a popular access network technology to be deployed because it has the least power consumption and the higher data rate among deployed access network technologies [3]. With the advantage of connecting to a variety of legacy Ethernet equipment, Ethernet passive optical networks (EPONs) [4] have been proposed to transmit data in Ethernet frames based on the time-division-multiplexing (TDM) technology on PONs. As pointed in [5], EPONs have been widely deployed in many countries, such as Japan and China. Therefore, reducing the power consumption of EPONs becomes an important issue to achieve the advanced energy-efficient access networks in the green communication infrastructure development [6]–[11].

An EPON consists of multiple optical network units (ONUs) at the customer sites and an optical line terminal (OLT) in the central office. ONUs are connected to the OLT in a tree structure via optical fiber links. Because network medium is shared in the upstream direction, ONUs transmit data in the dedicated time slots to avoid any collision. The OLT executes dynamic bandwidth allocation (DBA) to dynamically assign the upstream bandwidth using two MAC control messages: REPORT and GATE. Studies have shown that the ONUs consume a large portion of energy in this infrastructure [1], [11]–[13]. Therefore, many schemes have been proposed to reduce energy consumption of ONUs, such as [6]–[11].

The *sleep* mode and the *doze* mode are two popular energy-saving solutions for ONUs. In the sleep mode, both the transmitter and the receiver are turned off, while in the doze mode, the receiver is still kept operational. Although the sleep mode is more efficient in terms of energy saving, the ONU needs a long recovery time after it wakes up, which causes a significant degradation of quality of services (QoS) [14]. Therefore, the doze mode is considered the most promising way to achieve energy saving while it can satisfy the QoS metrics.

Determining the doze duration of each ONU is a major challenge in designing energy-efficient EPONs. An improper doze duration causes either an early wake-up or a late wake-up. Recently, many mechanisms have been proposed for adjusting the ONU doze duration to improve the energy saving effect [7]–[11]. As indicated in [8], some previous energy-saving schemes, e.g., [15], [16], focus on achieving maximum energy saving by putting an ONU in the sleep/doze mode for overlong time. However, these approaches may cause an unacceptable delay and violate the delay boundaries for the QoS requirements in the access networks. In [7], a sleep-time sizing mechanism called Sort-And-Shift (SAS) is proposed for time-division-multiplexing-access passive optical networks (TDMA-PONs) to achieve energy saving by shifting the sleep times of ONUs. Although SAS can effectively achieve energy saving by maximizing the ONU sleep time, it does not consider the optimization of the doze period. In [8], a QoS-aware energy-efficient mechanism is proposed to achieve energy saving and simultaneously guarantee QoS. However, this QoS-aware mechanism also focuses on the optimization of the sleep periods. In [9], the sleep duration is calculated based on the current status of the ONU's queue, QoS requirement boundaries, and the estimated upcoming traffic. OLT uses the latest 10 grant messages to

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calculate the average grant length for each ONU as an estimation of the next grant message. Although the proposed architecture improves the energy consumption, the burstiness characteristic of the traffic is not considered in the traffic estimation which leads to performance degradation. In [10], a two-stage mechanism is introduced to extend the doze duration with acceptable QoS metrics when the ONU is idle in the current cycle to improve energy saving in the doze mode. The doze duration extension is dynamically adjusted according to the amount of the requested bandwidth load. However, the two-stage mechanism considers only two traffic situations: the light load traffic and the heavy load traffic. Moreover, it does not discuss how to dynamically discriminate light load traffic from heavy load traffic. In [11], a QoS provisioning tri-mode energy-saving scheme is proposed to let an ONU enter the doze mode in the absence of upstream traffic and return to the active mode if the high-priority packet arrives. Deferring and coalescing processes are also proposed to extend the energy-saving effects. The average delay for the high-priority traffic of the proposed mechanism reaches up to 20 ms while the upstream traffic load is just 10%.

Based on the aforementioned review of recent energy-saving work for EPONs, a dynamic scheme that can more accurately adjust the doze duration for various traffic loads is a prospective approach for energy-saving improvements with QoS satisfaction. Recently, the emerging development of machine learning technologies provides abundant predictive techniques to obtain accurate prediction results. Therefore, the objective of this work is to devise a predictive scheme for dynamic bandwidth allocation (DBA) by using the machine learning techniques to predict the probability with which ONUs enter the doze mode.

In this paper, we propose a new predictive energy-saving mechanism by using the logistic regression (LR) model [17] to estimate the probability of presence of high-priority traffic given the values of historic REPORT messages and waiting time information. The LR-based dynamic bandwidth allocation (LR-DBA) allocates the bandwidth more accurately based on the LR estimation of the Doze Manager for the upstream traffic of an ONU while the ONU is in the doze mode. Therefore, the energy consumption of ONUs is highly reduced based on the estimated doze duration. The rest of this paper is organized as follows. Section 2 describes the proposed mechanism in details by introducing the new ONU and OLT architectures and the working principle of the LR-DBA computation. Then the system performance has been evaluated with simulations and the experimental results are presented in Sect. 3. Section 4 concludes this paper.

2. Proposed Mechanism

For the simplicity of discussion, we assume that each ONU transits between two states to support energy saving: the active state and the doze state. In the active state, the ONU is fully operational. In the doze state, ONU's transmitter (Tx) is turned off such that the upstream transmission function is disabled while it still receives the downstream traffic from the OLT.

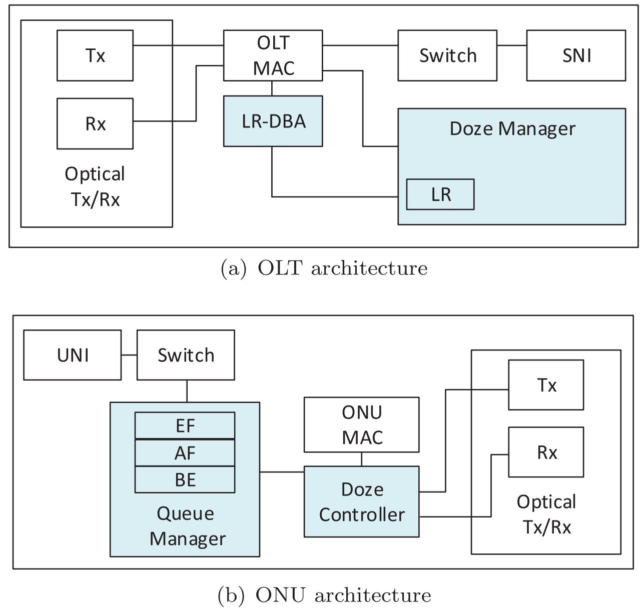


Fig. 1 Proposed OLT and ONU architectures.

2.1 Enhanced OLT and ONU Architectures

Figure 1 (a) shows the enhanced OLT architecture having a Doze Manager for LR-based prediction and an LR-DBA for dynamic bandwidth allocation. The Doze Manager estimates the doze duration based on the past traffic information using the logistic regression model. LR-DBA is responsible for assigning the network bandwidth to the ONUs based on the following parameters: the current ONU states, the estimated doze periods, and the available bandwidth. Moreover, a Queue Manager and a Doze Controller are added in the ONU architecture to support the proposed mechanism as shown in Fig. 1 (b). The Queue Manager classifies and sends the incoming traffic from the user network interface (UNI) to three different queues according to the priority of traffic, expedited forwarding (EF), assured forwarding (AF), and best effort (BE). The Doze Controller is responsible for controlling the ONU's transmitter and synchronizing with the OLT control messages.

2.2 LR-DBA Design

Figure 2 shows the operation flowchart of the proposed LR-DBA mechanism. After the OLT receives the REPORT messages from ONUs, it extracts the reported queues' status and calculates the doze period T_{Doze} based on the queue status and the QoS requirements. It is worth noting that the LR-DBA proposed in this paper is an offline DBA in which it first receives REPORT messages from all active ONUs and then calculates and assigns bandwidth allocation. LR-DBA does not assign bandwidth to the ONU if T_{Doze} is more than

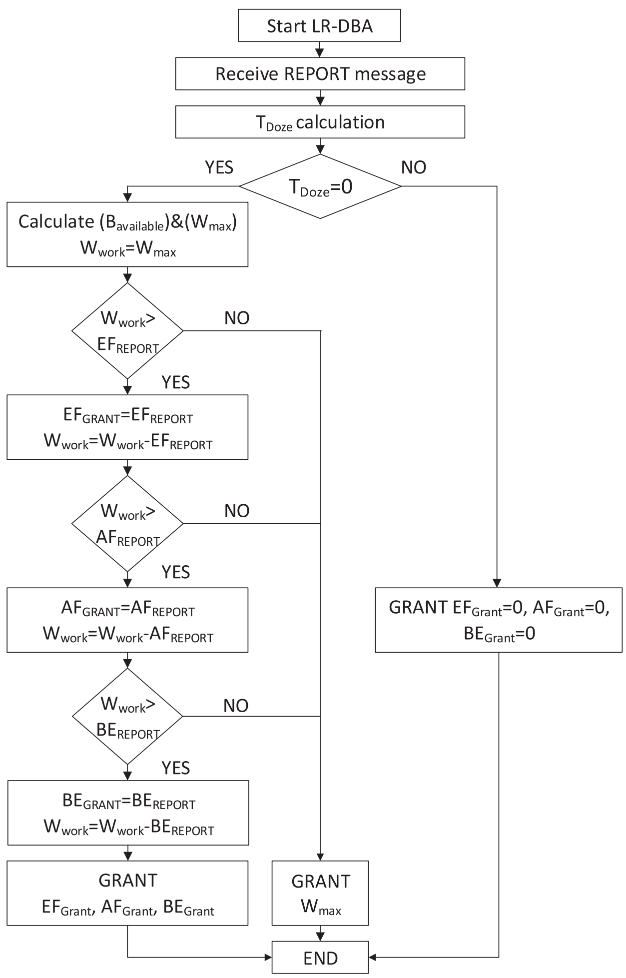


Fig. 2 Proposed LR-DBA bandwidth allocation flowchart.

zero. In this case, the bandwidths to be granted for the EF (EF_{grant}), AF (AF_{grant}), and BE traffic (BE_{grant}) are set to zero. If T_{Doze} is equal to zero, it calculates the maximum transmission window based on the number of active ONUs and grants the bandwidth based on the available bandwidth and the requested bandwidth. In Fig. 2, $B_{available}$ is the initial available bandwidth for each ONU, W_{max} denotes the maximum transmission window, and W_{work} is the working variable of W_{max}. The bandwidth requests for the EF, AF, and BE traffic are denoted as EF_{report}, AF_{report}, and BE_{report}.

The ONU either enters the doze mode after receiving a GATE message with zero bandwidth assignment, or enters the active mode after receiving a GATE message with non-zero bandwidth assignment. This mechanism has two following advantages. First, it keeps the ONU architecture simple because it does not need to keep track of the doze duration in ONUs. Second, it can use the original MPCP scheme without modification because the ONU Doze Controller operates based on the granted bandwidth. It is worth mentioning that the ONU receiver is still operational during the doze mode so it can receive the GATE message.

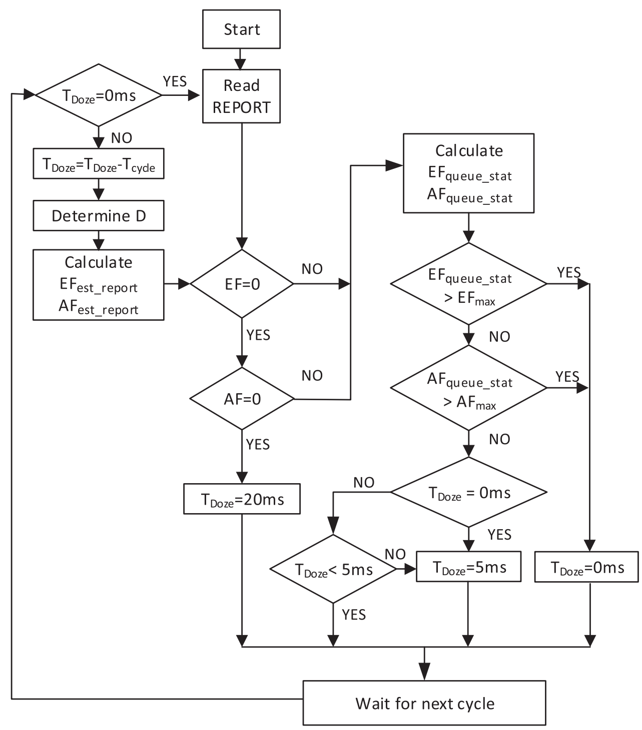


Fig. 3 Doze period calculation.

2.3 Doze Period Calculation

The doze period (T_{Doze}) is calculated in the Doze Manager of the OLT based on prediction results of the LR model according to the historical REPORT messages of the EF traffic and the AF traffic in each cycle. Figure 3 shows the calculation of the ONU doze period. In the calculation process, the boundary delay requirements are maintained for the QoS consideration. As described in [18] for the real-time service level agreements (SLA) specification, a typical SLA would commit to achieve an EF backbone delay of less than 5 ms. Therefore, the maximum boundary delays for EF and AF traffic are set to 5 ms, and the maximum boundary delay for BE traffic is set to 20 ms as discussed in [8].

The Doze Manager decides T_{Doze} according to the queue sizes of EF and AF, which are obtained for the REPORT message (EF_{report} and AF_{report}) or are estimated from the historical REPORT messages (EF_{est_report} and AF_{est_report}). If both EF and AF are equal to zero, T_{Doze} is set to 20 ms, i.e., the ONU can enter the doze mode for a maximum allowed period. Otherwise, T_{Doze} is decided according to the reported or estimated queue status of EF and AF. If EF or AF are not zero, the EF and AF queue status in each cycle are estimated as EF_{queue_stat} and AF_{queue_stat} to decide the doze duration T_{Doze}. If $EF_{queue\_stat} > EF_{max}$ or $AF_{queue\_stat} > AF_{max}$, T_{Doze} is set to zero because either the required EF queue size is more than the EF_{max} threshold or the required AF queue size is more than AF_{max}. If $EF_{queue\_stat} \leq EF_{max}$ and $AF_{queue\_stat} \leq AF_{max}$, T_{Doze} is set to at most 5 ms for the aforementioned QoS consideration.

To estimate the required queue sizes of EF and AF in the next cycle, the Doze Manager utilizes a multivariate logistic regression model for prediction decision. In this work, we assume these historical REPORT messages of the EF/AF queue status are independent. Therefore, the multivariate logistic regression model is used to calculate the probability $Pr(Y = 1|X)$ that the ONU will receive high-priority traffic (e.g., EF), where $X = \{X_1, X_2, \ldots, X_n\}$ is the vector of the predictor variables, e.g., REPORT messages and waiting time information, and Y means the presence of high-priority traffic. $Pr(Y = 1|X)$ is calculated as follows:

$$Pr(Y = 1|X) = \frac{e^{\beta_0+\beta_1 X_1+\cdots+\beta_n X_n}}{1 + e^{\beta_0+\beta_1 X_1+\cdots+\beta_n X_n}}. \quad (1)$$

The logit transformation of $Pr(Y = 1|X)$ is calculated as follows:

$$\begin{aligned} g(Pr(Y = 1|X)) &= \log\left(\frac{Pr(Y = 1|X)}{1 - Pr(Y = 1|X)}\right) \\ &= \beta_0 + \beta X, \end{aligned} \quad (2)$$

where $\beta = \{\beta_1, \beta_2, \ldots, \beta_n\}$ is the vector of the model parameters which are estimated by constructing a likelihood function and numerically searching for a best approximation to maximize the probability accuracy based on the historical X.

After calculating the probability $Pr(Y = 1|X)$ with Eq. (1), the doze manager uses a threshold P_T to make the final prediction decision D. If $D = 1$, the doze duration will be adjusted. The decision D is made according to the predicted $Pr(Y = 1|X)$ as follows:

$$D = \begin{cases} 1 & Pr(Y = 1|X) > P_T, \\ 0 & Pr(Y = 1|X) \leq P_T. \end{cases} \quad (3)$$

Different values can be used for the threshold P_T for the various traffic loads to obtain the more accurate predictions. In this work, we assume $P_T = 0.5$ in our experiments to demonstrate the effectiveness of the proposed LR-DBA scheme in a general case.

Moreover, the EF and AF queue status in each cycle are estimated during the doze mode to avoid queue overflowing and packet dropping. If the estimated EF and AF queue status are more than the threshold (EF_{max} and AF_{max}) during the doze mode, the OLT assigns the bandwidth to the ONU for the next cycle. The EF queue estimation (EF_{queue_stat}) is done as follows:

$$EF_{queue\_stat} = \begin{cases} EF_{queue\_stat} + EF_{est\_report} & \text{Doze mode}, \\ EF_{report} & \text{Active mode}, \end{cases} \quad (4)$$

where EF_{report} is the reported EF queue status when the ONU is active, and EF_{est_report} is the estimated EF_{report} when the ONU is in the doze mode. If the ONU is in the active mode, EF_{queue_stat} is the currently reported EF_{report}. If the ONU is in the doze mode, both the previous EF_{queue_stat} and EF_{est_report} will be considered in the current EF_{queue_stat}. EF_{est_report} is defined as an arithmetic average of the latest m EF traffic loads as follows:

$$EF_{est\_report} = \begin{cases} \sum_{i=1}^{m} \frac{EF_i}{m} & D = 1, \\ 0 & D = 0, \end{cases} \quad (5)$$

where EF_i is the EF_{report} of the previous i-th REPORT message in which $EF_{report} > 0$. In this work, we use $m = 10$ to calculate the average as used in [9]. Although the estimated EF_{est_report} may not be accurate, the QoS requirement is still maintained because the doze duration T_{Doze} is in the range of 0–5 ms. However, the inaccurate EF_{est_report} may hurt the effectiveness of energy saving when the traffic load is light but the estimated EF_{est_report} is large than zero. In this situation, the doze duration of the ONU will be short and the ONU will consume more power. Our experiments demonstrate this inaccuracy problem which will be investigated as a future work.

The AF queue status is estimated as follows:

$$AF_{queue\_stat} = \begin{cases} AF_{queue\_stat} + AF_{est\_report} & \text{Doze mode}, \\ AF_{report} & \text{Active mode}, \end{cases} \quad (6)$$

where AF_{report} is the reported AF queue status when the ONU is active, and AF_{est_report} is the estimated AF_{report} when the ONU is in the doze mode. As EF_{est_report}, AF_{est_report} is defined as an arithmetic average of the latest m AF traffic loads as follows:

$$AF_{est\_report} = \begin{cases} \sum_{i=1}^{m} \frac{AF_i}{m} & D = 1, \\ 0 & D = 0, \end{cases} \quad (7)$$

where AF_i is the AF_{report} of the previous i-th REPORT message in which $AF_{report} > 0$ and $m = 10$ in the experiments. In Fig. 3, $T_{Doze} = 0$ ms means that the ONU is in the active mode or it will enter the active mode for the next cycle.

3. Performance Evaluation

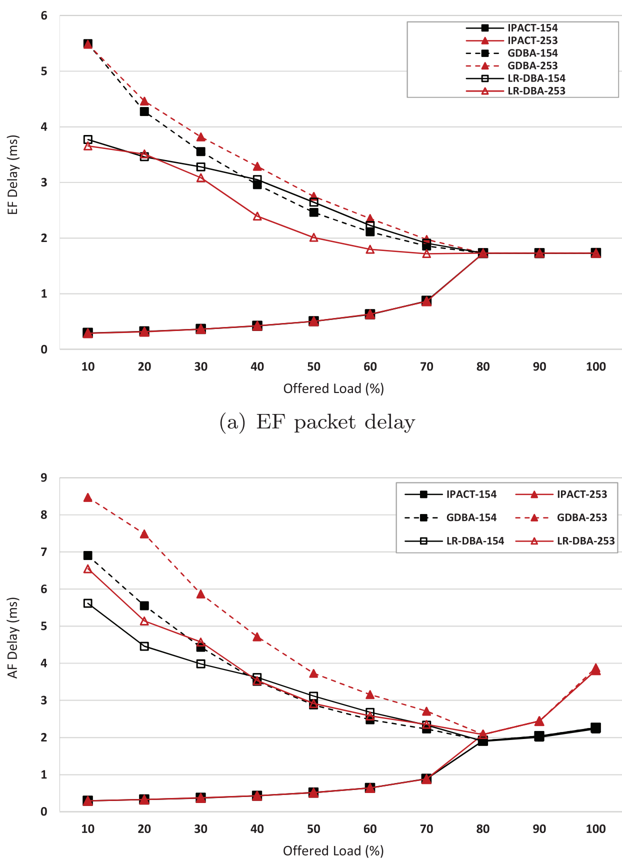
To evaluate the system performance in terms of packet delay, EF jitter, packet loss, and energy-saving, the system model is set up in the OPNET simulator with one OLT and 32 ONUs. The upstream/downstream channel capacity is 1 Gb/s and the distance between the OLT and ONUs is between uniformly 10 to 20 km. When the offered traffic is 100%, the total bandwidth is 1 Gbps for all 32 ONUs. The ONU buffer size is set to 5 Mb. The network traffic model chosen for AF and BE generates high burst traffic with the burst parameter of 0.8 and generates high-priority traffic (e.g., EF) using Poisson distribution with a fixed packet size of 70 bytes. Because most network traffic can be characterized by self-similarity and long-range dependence [19], we utilize this model to generate highly bursty BE and AF traffic classes with a Hurst parameter of 0.7 and the packet sizes that are uniformly distributed between 64 and 1518 bytes. The guard time is used to discriminate the allocated transmission windows of two ONUs. In this work, the guard time is set to 5 μs. The wattage values for an ONU in the active mode and the doze mode are 3.85 W and 1.7 W, respectively.

Table 1 Simulation parameters.

Parameter	Value
Number of ONUs	32
Up/Down link capacity	1 Gbps
OLT-ONU distance	10–20 km
ONU wakeup overhead time	0.125 ms
ONU active-mode power consumption	3.85 W
ONU doze-mode power consumption	1.7 W
ONU buffer size	5 Mb
Maximum transmission cycle time (T_{cycle})	1 ms
Guard time	5 μs
DBA computation time	10 μs

Table 2 Simulation scenarios.

Scenario	EF (%)	AF (%)	BE (%)
154	10	50	40
253	20	50	30



(a) EF packet delay

(b) AF packet delay

Fig. 4 High priority packet delay.

Table 1 summarizes the simulation parameters. In the simulation, we compared the system performance of the proposed LR-DBA architecture with that of Green DBA (GDBA) [9] and normal IPACT [20] in different scenarios shown in Table 2. Each scenario is identified with the percentages of the simulated EF, AF, and BE traffic in the offered load. Based on the scenarios, we measured the packet delay, the EF jitter, and the BE packet loss ratio as shown in Figs. 4, 5, and 6.

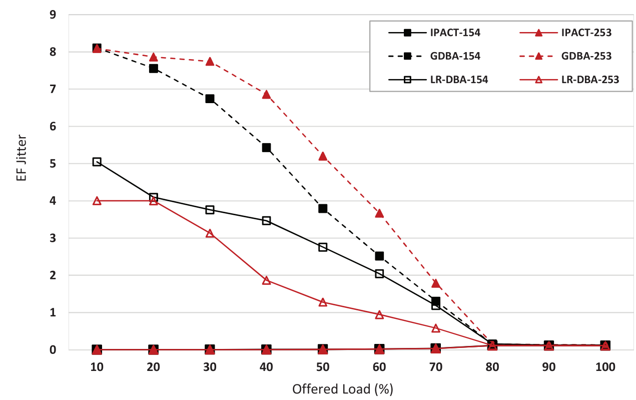


Fig. 5 EF jitters.

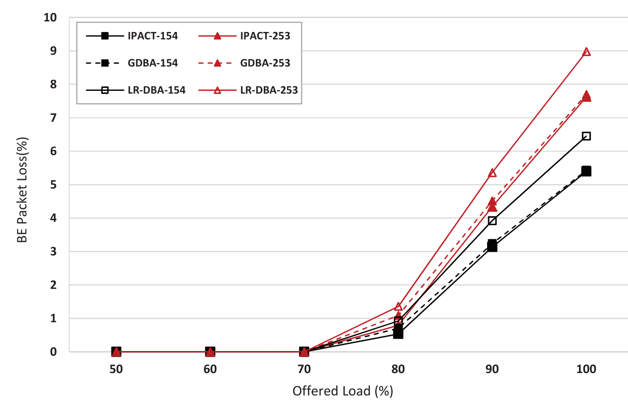


Fig. 6 BE packet loss.

Figure 4 depicts the packet delay for the EF and AF traffic versus the offered load. In the light offered load, EF or AF packets may be generated with large intervals. In this case, both GDBA and LR-DBA experience high delays, because ONUs have more chance to enter the doze mode and the incoming packets are queued in the ONU until it transits to the active mode and sends the packets. However, the AF and EF delays in light load traffic are higher than those in heavy load traffic. The reason is that the ONU goes to the doze mode less frequently in the presence of high-priority traffic. Figure 5 shows the EF jitter versus traffic load. Although the EF jitter for both LR-DBA and GDBA is higher than that for IPACT in light load traffic, LR-DBA has a better performance compared to GDBA. The BE packet loss ratio is zero in all scenarios when the traffic load is below 70% as shown in Fig. 6. Because the priority of BE is lower than the priorities of EF and AF, the BE traffic will have packet loss when the offered traffic load is larger than 70%. Compared with GDBA and IPACT, LR-DBA has a slightly higher BE packet loss ratio in the high traffic load.

Figure 7 depicts the power consumption improvement versus the traffic load. Considering the paper length, this paper illustrates only the results for the scenario 154. LR-DBA improves power consumption up to 45% compared to IPACT and up to 30% compared to GDBA while the traffic load is lower than 80%. If the traffic load is heavy and more

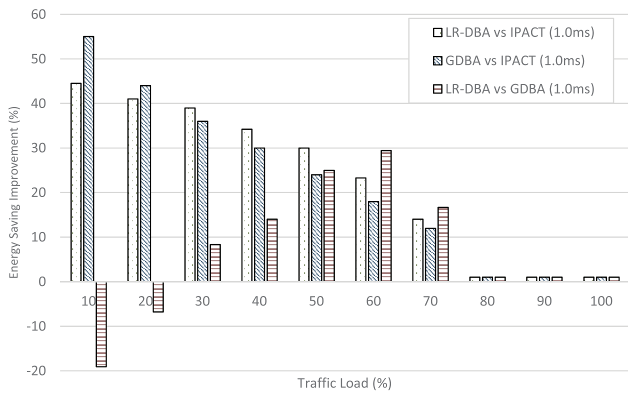


Fig. 7 Power consumption improvement.

than 80%, ONUs always stay in the active mode. However, the effectiveness of energy saving is sacrificed when the traffic load is light. Therefore, GDBA outperforms LR-DBA at the 10% and 20% traffic loads. The main reason is that the estimated average EF_{est_report} is not zero in most of the time, and thus the doze duration is usually short in LR-DBA. One possible approach to mitigate this problem is to get a more accurate EF_{est_report}. This will be investigated in our future work.

4. Conclusion

In this paper, a new predictive doze mode energy-saving mechanism in EPONs is proposed. This mechanism takes advantages of logistic regression to calculate the ONU's doze duration according to the traffic history and the QoS metrics. Moreover, OLT's and ONU's architectures are enhanced to manage the doze mode mechanism. The Doze Manager in OLT is responsible for deciding the doze period and cooperates with LR-DBA to assign a proper bandwidth allocation to each ONU. The simulation results show that the proposed mechanism can significantly enhance the energy saving without sacrificing the QoS metrics.

For the future work, there are several issues to be investigated. First, we will discuss the issue of employing a predictive model for the sleep mode in the time and wavelength division multiplexed PONs (TWDM-PONs). Second, a more accurate estimation approach for estimating the EF and AF traffic loads will be considered to improve the energy-saving performance. Moreover, in Service Interoperability in Ethernet Passive Optical Networks (SIEPONs), the Early Wakeup mechanism is provided for both OLT and ONU such that ONUs can transmit upstream data as soon. The integration of the Early Wakeup mechanism into the traditional DBA scheme will be also discussed in our future research.

Acknowledgments

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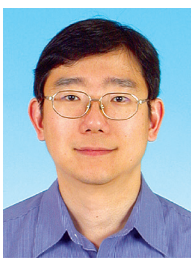

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