Novel Sleep Control for EPON Optical Line Terminal employing Layer-2 Switch Functions

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Abstract—This paper proposes a sleep control function for power saving in the optical line terminal (OLT) of an Ethernet passive optical network (EPON) employing duplicated layer-2 switches (L2SWs). The basic idea is to make one of the duplicated L2SW sleep according to the amount of traffic. Furthermore, this paper proposes a novel sleep control function that uses dynamic bandwidth allocation (DBA) information. The proposed sleep control function calculates the traffic in advance from the DBA information, and switches one of the duplicated L2SW between active and sleep mode based on the accurate traffic predictions. The proposed control function provides exact predictions of the upstream traffic, thus eliminating excess latency due to prediction error. Numerical simulations show the validity of the control proposal.

I. INTRODUCTION

Fiber to the home (FTTH) has been widely deployed for providing broadband access services in recent years. The passive optical network (PON) system, the most popular optical access network system, realizes FTTH cost effectively. PON systems with bit-rates of around 1 Gbit/s were standardized around 2004 and have supported the spread of FTTH. The bandwidth of FTTH is now increasing toward the next generation access network such as 10 Gigabit-class PON systems.

The access network generally consists of PON systems and layer-2 switches (L2SWs). The PON system consists of one optical line terminal (OLT) installed in a central office and multiple optical network units (ONUs) installed in user premises. The L2SW is installed in the central office for further aggregating the traffic from multiple PON systems. The L2SW is often built into the OLT of the PON system. In this case, highly-reliable OLTS can be realized by setting duplicated L2SWs. However, an OLT employing duplicated L2SWs suffers higher power consumption than the original OLT. In particular, the access network systems have much higher power consumption than metro and core network systems because the large amount of network equipment involves [1]. Reducing the power consumption of individual network equipment is important in order to reducing power consumption in the access network system. Therefore, we require lower power consumption of the OLT.

Many studies have targeted power saving approaches for L2SWs based on traffic characteristics. Regarding the physical layer, Energy Efficient Ethernet (EEE) [2], which is targeted at saving energy in Ethernet interfaces, is planned to be standardized by the end of 2010. The EEE is based on low power idle (LPI): it reduces the power consumption of the Ethernet interface when the traffic is idle [3]. Gunarathne et al. [4] proposed another method to reduce the power consumption of the Ethernet interfaces: the adaptive link rate (ALR) control function. The ALR control function reduces power consumption by switching the link rate to match link utilization. Regarding advanced power saving approaches beyond the physical layer, a dynamic link control function which extends the ALR control function to link aggregation [5] has been studied [6], [7]. The dynamic link control function reduces power consumption by switching the numbers of links according to the traffic amount. Accurate estimation of the required transmission capacity is a key issue in the dynamic link control function. Imaizumi et al. [6] proposed a dynamic link control function based on the average traffic and queue size. The dynamic link control function measures the average traffic in each measurement/control interval and estimates the transmission capacity in the next interval by predefined threshold of the average traffic and the queue size on the basis of a simple moving average. Fukuda et al. [7] proposed another dynamic link control function based on the peak traffic. Dynamic link control measures and records the peak traffic value in each monitoring cycle. At the end of each control interval, which includes several monitoring cycles, an empirical distribution is made from the peak traffic values. The transmission capacity in the next control interval is estimated from a predefined percentile in the empirical distribution. However, these sleep control and dynamic link control functions suffer from excess latency due to prediction error. In particular, upstream signals in PON system have much more latency than downstream signals. Therefore, we focus on reducing the latency of upstream signals.

In this paper, we propose a sleep control function for power saving in the OLT that employs duplicated L2SWs. The basic idea is to make one of the duplicated L2SW sleep according to the traffic amount. Furthermore, we propose a novel sleep control function that uses dynamic bandwidth allocation (DBA) information. The proposed sleep control function accurately predicts the traffic by using DBA information, and switches the mode of one of the L2SWs based on the prediction. The proposed sleep control function reduces latency since prediction error is low. We show the validity of sleep control proposal by some numerical simulations.

The remainder of this paper is organized as follows. Sec-
tion II presents the basic configuration of the OLT with duplicated L2SWs and describes the basic idea of making one of the duplicated L2SWs sleep. Section III proposes the novel sleep control function utilizing DBA information and demonstrates the validity of the function by numerical simulations. Finally, our conclusion is described in Section IV.

II. SYSTEM CONFIGURATION

This section describes the basic configuration of the OLT in the access network system. In addition, we describe the application of the sleep control function to the OLT for power saving.

A. Base System

A typical access network system for FTTH consists of a PON system and an L2SW as shown in Fig. 1. The PON system is a point-to-multipoint optical communication system in which an OLT communicates with multiple ONUs via one or more passive optical splitters. The L2SW is an aggregator, it uses multiple line cards (LCs) to aggregate traffic from multiple OLTs to the metro and core network. In Fig. 1, SNI denotes the service-node interface.

The OLT consists of multiple PON-interfaces (PON-IFs) configured for EPON, and two switches (SWs) that provide the multiplexing function and the redundant function. The multiplexing function combines upstream signals from each PON-IF to the L2SW, and de-multiplexes downstream signals from the L2SW to each PON-IF. In the OLT, for instance, SW1 multiplexes the upstream signals of PON-IFi (i = 1, 2, ..., n), and SW2 multiplexes the upstream signals of PON-IFj (j = n + 1, n + 2, ..., 2n). The downstream signals are distributed according to the virtual identifier given by the virtual local area network tag of the frame. The redundant function can continue communication via the remaining normal SW to assure redundancy against failure of the active SW or a link, i.e. one normal SW multiplexes the upstream signals and de-multiplexes downstream signals of all PON-IFs.

B. Power Saving Mechanism

A sleep control function is added to the OLT to realize OLT power saving. The sleep control function switches SW2 in the OLT between active and sleep modes according to the traffic amount. SW1 communicates between all PON-IFs and L2SW, when SW2 is the sleep mode. A state diagram of an OLT with this sleep control function is shown in Fig. 2. Each state indicates a pair of SW1 state and SW2 state, where the SW1 has two states: active (ACT) and fail (FAIL). SW2 has three states: active (ACT), fail (FAIL), and sleep (SLP). The initial state is (ACT, ACT), and sleep mode is (ACT, SLP). SW1 transition is vertical, while SW2 transition is horizontal. The transition into the sleep mode can only proceed from (ACT, ACT). Note that the sleep mode prevents the detection of a link failure at SW2, hence the OLT transits from (ACT, SLP) to (ACT, ACT) once, and thence to (ACT, FAIL).

The configuration of the OLT employing this sleep control function is shown in Fig. 3. The PON-IF has a selector (SEL) which selects one of the two SWs. SEL control in the SWs switches SEL modes in the PON-IF via a control bus (backplane). Sleep control monitors traffic characteristics such as the average traffic and queue size of the multiplexer and de-multiplexer (MUX/DEMUX) in SW1 and SW2. The traffic characteristics of SW2 are monitored via the control bus. The sleep control in SW1 determines OLT state based on the traffic characteristics, and it switches the SEL in PON-IFj (j = n + 1, n + 2, ..., 2n) to SW1 when the OLT enters the sleep mode.

An example of the procedure used to switch the sleep mode and active mode between the OLT and L2SW is shown in Fig. 4. The sleep control of SW1 monitors the upstream traffic for each PON-IF, and sends a Request message to enter sleep mode if SW1 determines to enter the sleep mode in the next control interval. Upon receiving the Request message, LC1 sends an ACK message back to SW1 and sends a Sleep message to LC2. Upon receiving the ACK message, SW1 also sends another Sleep message to SW2. However, when the
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amount of traffic from the core network is large, LC1 refuses to enter the sleep mode and sends a NACK message to SW1. After forwarding the frames buffered to SW2 (LC2), LC2 (SW2) sends a Complete message to SW2 (LC2) via LC1 and SW1. SW2 and LC2 enter the sleep mode, after exchanging Complete message with each other. On the other hand, SW1 sends another Request message to LC1 and a Wake message to SW2 if SW1 determines to return the active mode in the next control interval. Upon receiving the Request message, LC1 sends an ACK message back to SW1 and sends a Wake message to LC2. When SW2 and LC2 receive the Wake message, they wake up instantly from the sleep mode.

III. PROPOSED SLEEP CONTROL FUNCTION

This section proposes the sleep control function, which is easily applied to the OLT shown in Fig. 1.

A. Conventional Sleep Control Function

This section describes the conventional sleep control function based on the simple moving average method [6]. The conventional sleep control function measures average traffic amount and queue size at each measurement/control interval to forecast the traffic amount in the next measurement/control interval. Let $B_0, B_1, \ldots, B_n$ be a time series of average traffic values, where $B_n$ is the current measured value and $B_0 = 0$. Let $Q$ be the current measured queue size. A state transition table of the conventional sleep control function is shown in Table 1. $B_{th}$ and $Q_{th}$ denote the predefined threshold of bandwidth and queue size, respectively. Let $c_1$ and $c_2$ be condition variables. $c_1 \land c_2$ means the conjuction of $c_1$ and $c_2$. $c_1 \lor c_2$ means the disjuction of $c_1$ and $c_2$. $\overline{c_1}$ means the negation of $c_1$. The OLT enters the sleep mode from the active mode if $Q > Q_{th}$ and $B_n \leq B_{th}$, or $Q < Q_{th}$ and $(B_{n-1} + B_n) \leq 2B_{th}$ and $B_{n-1} > B_{th}$. The OLT returns to the active mode from the sleep mode if $Q > Q_{th}$ and $B_n \geq B_{th}$, or $Q < Q_{th}$ and $(B_{n-1} + B_n) \leq 2B_{th}$.

B. DBA in EPON

In the EPON system, upstream transmission from the ONUs is based on time division multiple access. The multi-point control protocol (MPCP) is utilized to emulate point-to-point operation in this point-to-multipoint environment. The upstream bandwidth allocation for each ONU is performed by the dynamic bandwidth allocation (DBA) algorithm in the OLT. We explain the mechanism of the upstream transmission between OLT and ONUs in EPON system using Fig. 5.

1) The OLT sends a Gate message to get the accumulated queue size of the ONUs.

2) Each ONU receives the Gate message and returns a Report message that indicates the amount of upstream data stored in the ONU’s queue, in accordance with the allowed transmission slot.

3) The OLT receives the Report messages and calculates the allowed transmission slot consisting of the transmission start time and transmission duration for each ONU. This calculation is based on the amount of upstream data stored in the ONU’s queue. The OLT sends the Gate message again.

4) Each ONU receives the Gate message and is notified of two allowed transmission slots. One is for sending the next Report message and the other is for sending upstream data.

5) In next DBA cycle, the ONU sends the Report message and the upstream data that had been stored in ONU’s queue in accordance with the allowed transmission slot. Upstream transmission in the EPON system suffers higher latency than the downstream transmission which is based on time division multiplexing. The sleep control function, however, has a major advantage because the OLT can estimate ONU’s transmission requirement in advance. Note that the control interval is synchronized with DBA cycle. Start time of control interval also shifts to just after receiving Report.

![Fig. 4. Sleep control procedure.](image-url)

![Fig. 5. Upstream transmission between OLT and ONUs in EPON system.](image-url)
messages from each ONU.

C. Proposed Sleep Control Function using DBA Information

We propose a sleep control function that is based on DBA information. The DBA information, a transmission requirement for each ONU, is carried by Report messages. The proposed sleep control function calculates the traffic amount in advance by using DBA information, and uses the accurate traffic prediction to switch one of the duplicated L2SW between active and sleep modes.

The proposed sleep control function monitors the Report messages from all ONUs to forecast the next transmission capacity. Let $R_0, R_1, \ldots, R_n$ be a time series of summed transmission requirements for each ONU, such that $R_i \geq B_{i+2}$ for all natural numbers $i$. i.e. $R_{n-1}$ indicates the transmission requirements in the next control interval, and $R_n$ indicates the transmission requirement in next two control intervals. A state transition table of the proposed sleep function is shown in Table II. The OLT enters the sleep mode from the active mode if $Q \leq Q_{th}$ and $R_n \leq B_{th}$ and $R_{n-1} \leq B_{th}$. Otherwise, the OLT returns to the active mode from the sleep mode. Note that $B_{i+2} \geq B_{th}$ if $R_i \geq B_{th}$ for each natural number $i$.

As an example of implementation of the proposed sleep control function, the sleep control in the SW$_i$ receives DBA information from the MPCP control via the control bus for each PON-IF. The sleep control also determines the state of the OLT in accordance with the state transition table as shown in Table II.

D. Performance Evaluation

This section describes the simulations conducted to confirm the power saving performance of the conventional and proposed sleep control functions. The simulations used average and maximum latency, and utilization of SW$_2$ as metrics of power saving performance. The simulation parameters are summarized in Table III. In the system configuration, we assumed that the OLT included two PON-IFs and each PON-IF communicates with one ONU. Transmission latency between the ONU and the OLT was ignored for simplicity. The queue sizes in both SW$_1$ and SW$_2$ were set as infinite because we focus on the latency due to prediction errors. In the sleep control function, the wake-up latency corresponds to the latency in switching from the sleep mode to the active mode, and sleep latency corresponds to the latency to switch from the active mode to sleep mode. We assumed that there was only upstream traffic, whose arrival interval and amount in each DBA cycle followed a Poisson distribution. The frame size was set to 1250 bytes. In addition, the maximum upstream traffic amount of each ONU was set to 10 Gbit/s.

We now present the simulation results and first show the fundamental behavior of the sleep control functions. The input traffic amount of each ONU was 5 Gbit/s, and was measured at 1 ms intervals. The traffic amount of each PON-IF and the link rate of SWs in case of the conventional and proposed sleep control functions are shown Figs. 6 and 7, respectively. The conventional sleep control function suffered several prediction errors and switched the link rate more frequently. On the other hand, the proposed sleep control function exactly predicted the traffic amount of each PON-IF and appropriately switched the link rate. The proposed sleep control function switches to the active mode with no wake-up latency because it calculates traffic amount in the second next control interval and transits to the active mode in advance.

The average and maximum latency with the conventional and proposed sleep control functions are shown in Figs. 8 and 9, respectively. The proposed sleep control function reduced the average latency in the range of 5 Gbit/s to 20 Gbit/s. The maximum latency of the proposed sleep control function was relatively constant at 2 ms. Little excess latency was observed with the proposed sleep control function because maximum latency in the PON system was about 2 ms.

Fig. 10 shows the utilization of SW$_2$ versus average traffic amount. Note that we defined the utilization as the ratio of the time SW$_2$ stayed in non-sleep mode. You can see that the utilization is slightly higher with the proposed function. This is because SW$_2$ enters the sleep mode only when the condition to enter the sleep mode is satisfied in two continuous cycles. The proposed sleep control function is effective for reducing excess latency with the same OLT power consumption as the conventional function.
E. Service Impact

In the conventional sleep function for the OLT with duplicated L2SWs, frame loss may occur due to errors in predicting the traffic amount. Such mis-prediction is likely to happen if highly bursty traffic is input when the L2SW is in the sleep mode. The frame loss degrades service quality. It can be reduced by employing a longer queue size (i.e., larger buffer memories) but this increases the system cost. On the other hand, the proposed sleep control function doesn’t drop frames because it provides exact predictions in terms of the upstream traffic. Thus, the proposed sleep control function can reduce OLT power consumption without decreasing service quality. Moreover, further power savings are possible because OLT queue size can be minimized.

IV. CONCLUSION

This paper described a sleep control function for power saving in the OLT that employs duplicated L2SWs. We introduced a state diagram, OLT configuration, and a sleep procedure that makes one of the L2SWs sleep in the OLT. Furthermore, this paper proposed a novel sleep control function using a DBA information. The proposed sleep control function accurately calculates the traffic in advance by using DBA information, and switches the mode of one L2SW. Numerical simulations showed that the sleep control function offers reduced latency due to its low prediction error.

REFERENCES