Sleep and Adaptive Link Rate Control for Power Saving in 10G-EPON Systems

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Abstract—This paper proposes a novel power-saving mechanism for the 10 Gbit/s Ethernet passive optical network (10G-EPON) systems that are currently being discussed in IEEE 802.3av. The proposed power-saving mechanism includes a sleep control function and an adaptive link rate (ALR) control function. The sleep control function switches the modes of optical network units (ONUs), i.e. active and sleep modes, depending on the presence or absence of traffic. The ALR control function switches the link rate between the optical line terminal (OLT) and an ONU, i.e. 1 Gbit/s or 10 Gbit/s, depending on the quantity of traffic. The proposed hybrid mechanism offers effective power management of ONUs on the basis of the traffic conditions. The proposed hybrid mechanism is validated by some numerical simulations.

I. INTRODUCTION

Internet bandwidth has been growing rapidly in recent years, and the existing network systems currently consume large amounts of power [1]. There are concerns about the further increase in power consumption given the expected growth in telecommunication networks. From the viewpoint of not only preventing global warming but also reducing the operational expenditure (OPEX), power efficient telecommunication networks are becoming a serious issue [2]. In particular, broadband access network systems have much higher power consumption than metro and core network systems because of the high number of communication devices involved [3]. Many studies have targeted power-saving devices connected via point-to-point links such as switches and routers. For instance, Energy Efficient Ethernet (EEE) is scheduled to be standardized in IEEE 802.3az by 2010 [4]. There are two main approaches to addressing the power-saving issue. They are the functions of sleep and adaptive link rate (ALR) control.

Gupta et al. [5] proposed a power management mechanism for LAN switches that is based on the sleep control function. The performance of the sleep control function was also evaluated quantitatively under realistic conditions [6]. The sleep control function can reduce idle power consumption of the device in the absence of traffic on the link. A low-power idle (LPI) mode which is a kind of sleep modes will be adopted as a power-saving mechanism for the EEE. Tamura et al. [7] proposed an extra active period in order to eliminate the high-frequency mode transition between active and sleep modes which increases the power consumption.

Gunaratne et al. [8] proposed an ALR control function for Ethernet links. In general, a low-rate link consumes less power than a high-rate link. The ALR control function reduces overall power consumption by varying the link rate to match the quantity of traffic. Blanquicet et al. [9] proposed the Rapid PHY Selection (RPS) mechanism to switch among multiple link rates without affecting the transmission performance. Zhang et al. [10] developed a hardware prototype of the ALR system and analyzed its performance.

Nedevschi et al. [11] compared the performance of the sleep and ALR control functions. They showed that the sleep control function is effective against bursty traffic since it can reduce power consumption during idle periods. However, the sleep control function does not work at all in the presence of traffic on the link. On the other hand, the ALR control function works even in the presence of low-rate traffic. However, the ALR control function yields less power savings than the sleep control function in the absence of traffic on the link, since the ALR control function keeps the low-rate link active.

In this paper, we focus on reducing the power consumption of optical access networks, especially passive optical networks (PONs), which are expected to see a drastic increase in power consumption [12]. The standardization of the 10 Gbit/s Ethernet PON (10G-EPON) system, which is one of the next generation access network systems, is currently being discussed in IEEE 802.3av [13]. This paper proposes a novel power-saving mechanism for the 10G-EPON system. The proposed mechanism applies both the sleep and ALR control functions to achieve effective power management on the basis of the traffic conditions.

This paper is organized as follows. The following section presents the basic configuration of the 10G-EPON system. Section III proposes the hybrid mechanism which includes both the sleep and ALR control functions. The power-saving functions are described in detail in Section IV. Section V demonstrates the validity of the proposed mechanism by numerical simulations. Finally, our conclusion is described in Section VI.

II. CONFIGURATION OF BASE SYSTEM

This section describes the configuration of the basic system to which we apply the proposed control mechanism. The Ethernet PON (EPON) and a configuration of the asymmetric 10G-EPON are presented. In addition, a system consisting of the existing 1G-EPON [14] and the asymmetric 10G-EPON is also described.
A. EPON

A PON is comprised of one optical line terminal (OLT) located at a central office (CO) and multiple optical network units (ONUs) located at user premises. The OLT and ONUs are connected by optical fibers and optical splitters which are passive devices. The PON can provide optical access services at low cost because the multiple ONUs can share the transmission equipment such as the OLT, the optical fibers and the optical splitters.

In the EPON system, the transmission of the downstream signals to the ONUs is based on time division multiplexing (TDM), and the transmission of the upstream signals from the ONUs is based on time division multiple access (TDMA). The Multi-Point Control Protocol (MPCP) is utilized to emulate point-to-point operation in this point-to-multipoint environment. The downstream signals are physically broadcast to all ONUs, and each ONU discards the frames intended for the other ONUs. Frame destination is specified by the logical link identifier (LLID). The upstream bandwidth allocation for each ONU is performed by the dynamic bandwidth allocation (DBA) algorithm in the OLT. Moreover, the upstream and downstream signals are multiplexed by wavelength division multiplexing (WDM) technology.

B. Asymmetric 10G-EPON

The asymmetric 10G-EPON system, which is one of the 10 Gbit/s class EPON systems being discussed in IEEE 802.3av, has a 1 Gbit/s (1G) uplink and a 10 Gbit/s (10G) downlink as shown in Fig. 1. The OLT has a 10 Gbit/s transmitter (10G Tx) and a 1 Gbit/s receiver (1G Rx), and each ONU has a 1 Gbit/s transmitter (1G Tx) and a 10 Gbit/s receiver (10G Rx). The 1G upstream signals and the 10G downstream signals are multiplexed by WDM technology. In Fig. 1, the interfaces SNI and UNI denote the service-node interface and the user-network interface, respectively.

In this research, 10/1GBASE-PRX30 is adopted as the physical layer specification of the asymmetric 10G-EPON. The draft baseline of the 10/1GBASE-PRX30 is shown in Table I. The nominal 1G upstream wavelength is 1310 nm and the nominal 10G downstream wavelength is 1577 nm. The channel insertion loss is 29 dB.

C. Coexistence of 1G-EPON and Asymmetric 10G-EPON

The 10G-EPON specification will support the coexistence of the existing 1G-EPON and the asymmetric 10G-EPON as shown in Fig. 2 and Table I. The coexistence system has a 1G uplink and 1G and 10G downlinks. The OLT has a 1 Gbit/s and 10 Gbit/s transmitter (1G/10G Tx) and a 1G Rx. On the other hand, each 1G ONU has a 1G Tx and a 1G Rx, and each 10G ONU has a 1G Tx and a 10G Rx. The 1G upstream signals, the 1G downstream signals and the 10G downstream signals are multiplexed by WDM technology. The nominal 1G downstream wavelength is 1490 nm.

The coexistence system makes it possible to realize smooth migration from the existing 1G-EPON to the asymmetric 10G-EPON. For existing 1G-EPON users, we do not need to replace the 1G-EPON ONUs which have been deployed with newly-developed ONUs. For 10G-EPON users, we only replace the 1G-EPON OLT with a 10G-compatible OLT at the CO and deploy 10G-EPON ONUs at the user premises. Therefore, the existing 1G-EPON users remain nearly unaffected by the system upgrade.

III. PROPOSED HYBRID MECHANISM

This section proposes the power-saving mechanism, which is easily applied to the coexistence system shown in Fig. 2. In addition, the power-saving 10G ONU with the hybrid mechanism, which includes both sleep and ALR control functions, is described.

A. Concept of Hybrid Mechanism

The concept of the proposed hybrid mechanism in the coexistence system is shown in Fig. 3. The hybrid mechanism includes the sleep and ALR control functions. The sleep control function switches ONU mode, i.e. active or sleep mode, depending on the presence or absence of traffic. On the other hand, the ALR control function switches between two downlink rates, i.e. 1G and 10G, depending on the quantity of traffic.

The hybrid mechanism activates the sleep control function in the absence of traffic on the link, and the ALR control function in the presence of traffic on the link. This means that the hybrid mechanism overcomes the disadvantages of the individual sleep and ALR control functions. Therefore, the hybrid mechanism can provide more effective power-saving performance than either the sleep control function or the ALR control function.
TABLE I
STANDARD SPECIFICATION

<table>
<thead>
<tr>
<th>Name</th>
<th>Wavelength</th>
<th>Physical bitrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G-EPON (1000BASE-PX20)</td>
<td>Upstream 1260–1360 nm</td>
<td>1.25 Gbit/s</td>
</tr>
<tr>
<td></td>
<td>Downstream 1480–1500 nm</td>
<td>1.25 Gbit/s</td>
</tr>
<tr>
<td>Asymmetric 10G-EPON (10/1GBASE-PRX30)</td>
<td>Upstream 1260–1360 nm</td>
<td>1.25 Gbit/s</td>
</tr>
<tr>
<td></td>
<td>Downstream 1575–1580 nm</td>
<td>10.3125 Gbit/s</td>
</tr>
</tbody>
</table>

B. Power-Saving 10G ONU with Hybrid Mechanism

We describe the proposed hybrid mechanism as applied to the ONUs in the coexistence system shown in Fig. 2. This assumption is readily achievable on the basis of the IEEE 802.3av specification, and is also supported by the evolution scenario from the existing 1G-EPON system to the next generation 10G-EPON system. The detailed functions of the proposed power-saving 10G ONU are shown in Fig. 4. The power-saving 10G ONU has a 1G Tx and a 1 Gbit/s and 10 Gbit/s receiver (1G/10G Rx). The PON LSI includes the power-saving function provided by the proposed hybrid mechanism.

The hybrid mechanism in the power-saving 10G ONU is described as follows. The ONU transits to the sleep mode in the absence of traffic on the link. At the end of each sleep period, the ONU wakes up to confirm if frames are being forwarded to it. On the other hand, the ONU maintains the active mode in the presence of traffic on the link, and switches between the 1G Rx and the 10G Rx depending on the quantity of traffic on the downlink. The ONU can save a lot of power by deactivating the unused functions including the transceivers and LSIs.

IV. POWER-SAVING FUNCTIONS

This section details the power-saving functions in the proposed hybrid mechanism, i.e. the sleep and ALR control functions.

A. Sleep Control Function

The sleep control function makes it possible to use much less power by deactivating the unused functions in the absence of traffic on the link. However, the downstream signals in the TDM-based PON are physically broadcast to all ONUs. This means that the physical detection of downstream signals at a sleeping ONU cannot be used as a wake-up trigger. To address this issue, a sleep and periodic wake-up (SPW) operation is adopted as the sleep control function. In SPW operation, the sleeping ONU wakes up periodically to confirm if frames are being forwarded to it.

The message exchange for sleep control is shown in Fig. 5. The OLT monitors the downstream traffic for each ONU, and sends a Request message to the ONU that does not have any downstream traffic. We assume here that the OLT determines the presence or absence of downstream traffic on the basis of the downstream frame interval $i$. The Request message includes sleep parameters, i.e. the sleep time $T_s$ calculated as (1)

$$
\begin{align*}
T_s &= T_{s} & \text{if } i \geq i_{th}, \\
T_s &= 0 & \text{if } i < i_{th},
\end{align*}
$$

where $T_s$ and $i_{th}$ denote the desired sleep time and the threshold of the downstream frame interval, respectively. The desired sleep time $T_s$, the active time $T_a$ including the transition time from the sleep mode to the active mode $T_t$, and the threshold of the downstream frame interval $i_{th}$ are key parameters for sleep control.
Upon receiving its Request message, the ONU sends an ACK message back to the OLT and enters the sleep mode. In the presence of upstream traffic from the UNI, however, the ONU refuses to enter the sleep mode and sends a NACK message to the OLT. After the desired sleep time $T_s$, the sleeping ONU enters the sleep mode. In the presence of upstream traffic from the UNI, however, the OLT keeps the ONU in active mode by setting $T_s$ to zero. When the ONU detects upstream traffic from the UNI, it wakes instantly from the sleep mode.

**B. ALR Control Function**

The ALR control function makes it possible to use much less power by deactivating the unused functions in the presence of low-rate traffic. The coexistence system assumed here has two downlink rates: 1G and 10G. The ALR control function switches between the 1G downlink and the 10G downlink depending on the quantity of traffic.

The message exchange for ALR control is shown in Fig. 6. The OLT monitors the downstream traffic for each ONU, and sends a Request message to the ONU to switch its downlink rate. We assume here that the OLT determines downlink rate switching based on the downstream bandwidth $B$. The Request message includes link rate parameters, i.e. the desired downlink rate $D$, calculated by (2)

\[
\begin{align*}
D &= 10G \quad \text{if } B \geq B^{th}, \\
D &= 1G \quad \text{if } B < B^{th},
\end{align*}
\]

where $B^{th}$ denotes the threshold of the downstream bandwidth. The threshold of the downstream bandwidth $B^{th}$ and the transition time of downlink rate switching $T_s$, which is the same value as the transition time in sleep control, are key parameters for ALR control. Upon receiving a Request message, the ONU sends an ACK message back to the OLT. The ONU then activates/deactivates the modules as needed to implement the new link rate.

**C. Hybrid Mechanism**

The hybrid mechanism includes the sleep and ALR control functions as described in Section III. The parameter settings of the hybrid mechanism are shown in Table II. These parameters were set to provisional values, since the 10G-EPON system is still under standardization and development.

The simulation parameters are shown in Table III. The parameters were set to provisional values, since the 10G-EPON system is still under standardization and development. In other words, there is a possibility that the parameters may change in the future. For example, the increase of the transition time $T_{t}$ will result in large power consumption. In addition, the desired sleep time $T_s$ should be determined on the basis of the maximum acceptable delay which remains to be investigated. However, the superiority of the proposed mechanism remains, even if the parameters change.

In the simulations, we assumed that there was only downstream traffic whose arrival rate followed the Poisson distribution. The frame size was set to 1250 bytes. In addition, the maximum downstream bandwidth for each ONU running the 1G downlink was set to 100 Mbit/s, and the maximum downstream bandwidth for each ONU running the 10G downlink was set to 1 Gbit/s.

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**Table II**

<table>
<thead>
<tr>
<th>Parameter Settings in Hybrid Mechanism</th>
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</thead>
<tbody>
<tr>
<td>$B &gt; B^{th}$</td>
</tr>
<tr>
<td>$B &lt; B^{th}$</td>
</tr>
<tr>
<td>$T = 0$ and $D = 10G$</td>
</tr>
<tr>
<td>$T = 0$ and $D = 1G$</td>
</tr>
<tr>
<td>NA</td>
</tr>
<tr>
<td>$T = T_s$ and $D = 1G$</td>
</tr>
</tbody>
</table>

**Table III**

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>$T_s$</th>
<th>10 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired sleep time</td>
<td>$T_s$</td>
<td>2 ms</td>
</tr>
<tr>
<td>Transmission delay between OLT and ONU</td>
<td>$T_p$</td>
<td>0.2 ms</td>
</tr>
<tr>
<td>Power consumption in sleep mode</td>
<td>$P_s$</td>
<td>1 W</td>
</tr>
<tr>
<td>Power consumption in active mode (1G)</td>
<td>$P_{1G}$</td>
<td>5 W</td>
</tr>
<tr>
<td>Power consumption in active mode (10G)</td>
<td>$P_{10G}$</td>
<td>10 W</td>
</tr>
</tbody>
</table>

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This section describes the simulations conducted to confirm the power-saving performance of the sleep control function, the ALR control function and the proposed hybrid mechanism.

**A. Assumptions**

The simulation parameters are shown in Table III. The parameters were set to provisional values, since the 10G-EPON system is still under standardization and development. In other words, there is a possibility that the parameters may change in the future. For example, the increase of the transition time $T_{t}$ will result in large power consumption. In addition, the desired sleep time $T_s$ should be determined on the basis of the maximum acceptable delay which remains to be investigated. However, the superiority of the proposed mechanism remains, even if the parameters change.

In the simulations, we assumed that there was only downstream traffic whose arrival rate followed the Poisson distribution. The frame size was set to 1250 bytes. In addition, the maximum downstream bandwidth for each ONU running the 1G downlink was set to 100 Mbit/s, and the maximum downstream bandwidth for each ONU running the 10G downlink was set to 1 Gbit/s.
In sleep control, the average downstream frame interval $i^n_k$ was utilized in place of the instantaneous downstream frame interval $i_k$, where subscript $k$ denotes the value at time $k$. The average downstream frame interval $i^n_k$ is calculated by using the exponential smoothing calculation of (3)

$$i^n_k = \alpha i_{k-1} + (1 - \alpha) i^a_{k-1},$$  

(3)

where $\alpha$ ($0 < \alpha < 1$) and subscript $k-1$ denote the smoothing factor and the value at time $k-1$, respectively. The smoothing factor $\alpha$ was set to 0.2 in the simulations. In ALR control, the average downstream bandwidth $B^n_k$ was utilized in place of the instantaneous downstream bandwidth $B_k$. The average downstream bandwidth $B^n_k$ was calculated from the average downstream frame interval $i^n_k$ and the frame size.

B. Sleep Control

The performance of the sleep control function was compared by varying the threshold of the downstream frame interval $i^a_k$. The simulation results are shown in Fig. 7. The average power consumption of an ONU with only the sleep control function is shown in Fig. 7(a). The average queuing delay of the downstream traffic at the OLT is shown in Fig. 7(b).

The sleep control function reduced the power consumption in the low-rate range as shown in Fig. 7(a). In the simulations, the power consumption converged to about 2.80 W at around 10 Mbit/s. The theoretical power consumption in the absence of traffic $P_{ab}$ is given by

$$P_{ab} = (T_a \times P_{10G} + T_s \times P_s) / (T_a + T_s).$$  

(4)

As shown in Table III, the sleep time $T_s$ was set to 10 ms and the active time $T_a$ was set to 2.4 ms. It was assumed that the active time $T_a$ was equal to the sum of the transition time $T_t$ and the round-trip transmission delay between the OLT and ONU $2T_p$. Therefore, the theoretical power consumption in the absence of traffic was 2.74 W, which approximates the simulation results at around 0.01 Mbit/s. The sleep control function increased the queuing delay in the low-rate range as shown in Fig. 7(b). The average queuing delay converged to 5 ms at around 0.01 Mbit/s, since the sleep time was set to 10 ms and the frames arrived randomly.

In addition, it was confirmed that decreasing the threshold improved the power-saving performance while increasing the queuing delay especially in the range between 0.01 Mbit/s and 10 Mbit/s. The sleep time $T_s$ and the threshold of the downstream frame interval $i^a_k$ should be designed based on the desired queuing delay and the average traffic bandwidth.

C. ALR Control

The performance of the ALR control function was compared by varying the threshold of the downstream bandwidth $B^a_k$. The simulation results are shown in Fig. 8. The average power consumption of the ONU with only the ALR control function is shown in Fig. 8(a). The average queuing delay of the downstream traffic at the OLT is shown in Fig. 8(b).

The ALR control function reduced the power consumption in the high-rate range as shown in Fig. 8(a). In the simulations, the power consumption converged to $P_{10G} = 5$ W at around 10 Mbit/s and to $P_{10G} = 10$ W at around 1000 Mbit/s. The ALR control function increased the queuing delay in the high-rate range as shown in Fig. 8(b). However, the queuing delay imposed by ALR control was much smaller than that imposed by sleep control.

In addition, it was confirmed that increasing the threshold improved the power-saving performance while increasing the
functions in isolation at the cost of a slight increase in the queuing delay.

VI. CONCLUSION

This paper proposed a novel power-saving mechanism created by combining the sleep and ALR control functions. The proposed hybrid mechanism was applied to the asymmetric 10G-EPON system. Numerical simulations showed that the hybrid mechanism yielded more effective power management of the ONU on the basis of the traffic conditions compared to its component functions in isolation at the expense of a slight increase in queuing delay.

REFERENCES