Efficient Power-Saving 10-Gb/s ONU Using Uplink Usage-Dependent Sleep Mode Control Algorithm in WDM-PON

Han Hyub Lee, Kwangok Kim, Jonghyun Lee, and Sangsoo Lee

We propose and demonstrate an efficient power-saving optical network unit (ONU) based on upstream traffic monitoring for 10-Gb/s wavelength division multiplexed passive optical networks (WDM-PONs). The power-saving mode controller uses a μ-processor and traffic monitoring modules followed by the proposed power-saving processes to operate the sleep mode ONU. The power consumption of the ONU is effectively reduced from 19.3 W to 6.4 W when no traffic from the users is detected. In addition, we design a power-saving mechanism based on a cyclic sleep mode operation to allow a connectivity check between the optical line terminal and ONU. Our calculation results show that the WDM-PON ONU reduces the power consumption by around 60% using the proposed mechanism.

Keywords: WDM-PON, ONU, power saving.

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I. Introduction

Passive optical networks (PONs) have been widely deployed, and such 10-Gb/s PONs as the 10G E-PON and 10G G-PON are beginning to be deployed to support multiple Internet services requiring a higher user bandwidth [1], [2]. Zhang and others reported that access networks consume around 70% of the overall Internet energy consumption since the amount of access network equipment is quite large [3].

Considering that the power consumption of 10-Gb/s electronics and 10-Gb/s optoelectronics is much higher than that of gigabit devices, many researchers have attempted to reduce the power consumption of 10-Gb/s optical network units (ONUs). Among the many technologies that reduce the power consumption in an ONU, the sleep mode operation is a very attractive option. Many papers have proposed power saving methods for time division multiplexed (TDM) PON ONUs [4]-[6]. Zhang and Ansari [6] proposed sleep mode control and sleep-aware traffic scheduling schemes for energy-efficient 1G E-PON and 10G E-PON.

Since wavelength division multiplexed (WDM) PONs can support high capacity and a long-reach transmission of over 80 km with a bidirectional point-to-point (p-t-p) transmission, 10-Gb/s WDM-PONs have been researched [7]. Currently, a 10-Gb/s WDM-PON is considered a good candidate for a wireless backhaul, which employs a common public radio interface between the baseband unit at a central office (CO) and a remote radio unit at an eNodeB. This network is very suitable for the mobile backhaul because the configuration makes it possible to simplify eNodeBs.

On the issue of power efficiency, recent research results show that the power per user per Gb/s (W/Gb/s) of a p-t-p gigabit Ethernet (GE) network is lower than that of G-PON and E-PON when the available capacity of the CO uplink is limited to 320 Gb/s and the number of users per CO number is in the hundreds [8]. Based on these research results, we expect that a 10-Gb/s WDM-PON as a p-t-p GE network can be more suitable to a green access network if the WDM-PON operates in power-saving mode. Recently, a power-saving method using a pilot tone for monitoring in a WDM-PON based on a reflective semiconductor optical amplifier was proposed. However, the configuration of the optical line terminal (OLT) and ONUs may be complex owing to an analog signal processing of the pilot tones [9].

In this work, we propose and demonstrate an efficient power-saving 10-Gb/s WDM-PON ONU using an embedded power-saving mode controller (PSMC). The PSMC uses a µ-processor and upstream traffic monitoring modules followed by the proposed power-saving processes. Because the 10-Gb/s switch (S/W) is the most power-consuming part in a 10-Gb/s ONU, we optimize the power-saving algorithm to significantly reduce the power consumption of the 10-Gb/s S/W. The ONU shows a 67% reduction in power usage when all GE ports to the users are linked down.

In addition, we design a power-saving mechanism for OLT and ONU based on a cyclic sleep mode operation to allow a conectivity check between the OLT and ONU. We expect that the proposed mechanism will be simple in implementation since a WDM-PON does not require adapting multiple access techniques, owing to a symmetric, dedicated p-t-p communication.

II. Design of Power-Saving ONU

In 10-Gb/s WDM-PONs, an ONU with multiple GE LAN ports is desirable for communicating with customer premises equipment (CPE). In this scenario, as shown in Fig. 1, the traffic status between the ONU and the CPE may vary owing to different network usage behaviors among users, as shown in Fig. 2, in which access traffic experiences a fall and rise based on the time of day. Therefore, the power-saving mode of the ONU should be adapted to the uplink usage between the ONU and CPE to effectively reduce the power consumption.

We design a 10-Gb/s ONU that has eight GE LAN ports to the CPE. Figure 3 is a schematic diagram of the proposed 10-Gb/s ONU. A 10-Gb/s S/W aggregates eight GE upstream signals and transmits a 10-Gb/s Ethernet upstream signal to a 10-Gb/s Ethernet physical layer (PHY). A 10-Gb/s XFP optical transceiver (OTRx) is used to transmit an upstream signal to the OLT.

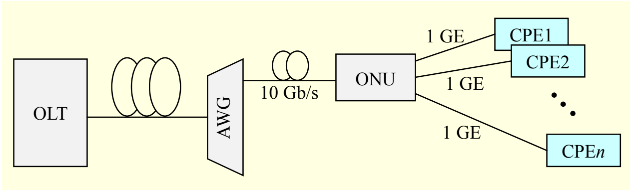

Fig. 1. 10-Gb/s WDM-PON ONU and CPE.

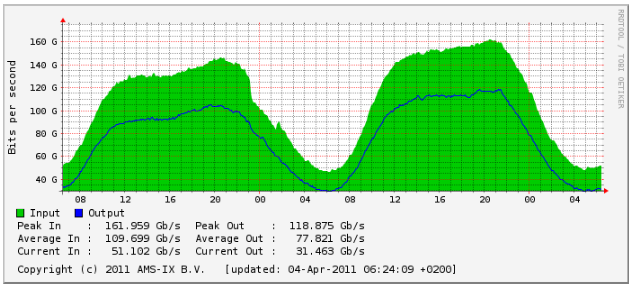

Fig. 2. Amsterdam Internet Exchange daily traffic statistics [10].

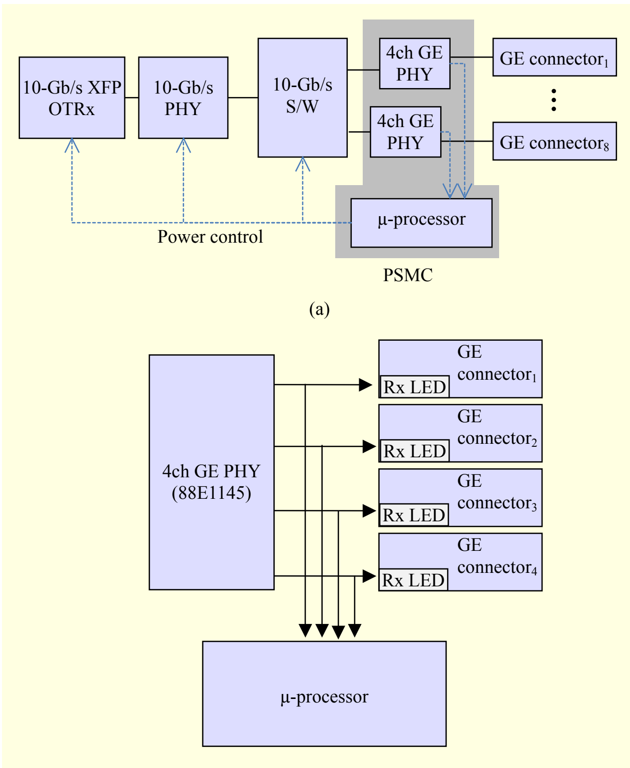

Fig. 3. Schematic diagram of (a) 10-Gb/s WDM-PON ONU and (b) power-saving mode controller.

The PSMC is indicated in gray in Fig. 3. The PSMC consists of a µ-processor and commercial four-channel GE PHYs, in which each four-channel GE PHY has a traffic-indicating function inside. The power consumption of the µ-processor is about 0.1 W, which is negligible compared to the total power consumption of the ONU.

In detail, if the GE PHY does not receive traffic from each GE connector within 1 ms, the GE PHY then periodically sends a link-down alarm signal (LDAS) per connector to the μ-processor.

The μ-processor receives alarm signals from the GE PHY periodically and determines the sleep mode level of the ONU. After that, the μ-processor sends control signals to the 10-Gb/s Ethernet S/W, 10-Gb/s PHY, and 10-Gb/s XFP OTRx simultaneously. The proposed configuration is simple and has no effect on the data signal paths between the 10-Gb/s S/W and GE PHYs. Counting input signal bits at the I/O port in the 10-Gb/s S/W may be an alternative traffic-indicating function. However, using higher performance electronics against a 10-Gb/s signal speed may be required, which is also more complex compared to our proposed configuration.

We categorize two levels of sleep mode to harmonize with uplink usage in the ONU. The first mode is partial sleep mode. If no traffic is detected at one GE port of the GE PHY, then the PSMC makes a relevant I/O port of the 10-Gb/s S/W power down. Figure 4 is a flowchart reflecting when the ONU operates in partial sleep mode.

The second mode is full sleep mode. The ONU goes into full sleep mode as soon as the PSMC no longer detects any traffic from the CPE during the sleep mode waiting time. In full sleep mode, the 10-Gb/s S/W, 10-Gb/s PHY, and transmitter (Tx) part of a 10-Gb/s XFP OTRx must be powered down.

The PSMC monitors traffic from the CPE continuously while the ONU is operating in full sleep mode. If traffic is detected by the GE PHY, the ONU immediately wakes up and activates all sleeping parts. Figure 5 shows a flowchart of the ONU operating in full sleep mode.

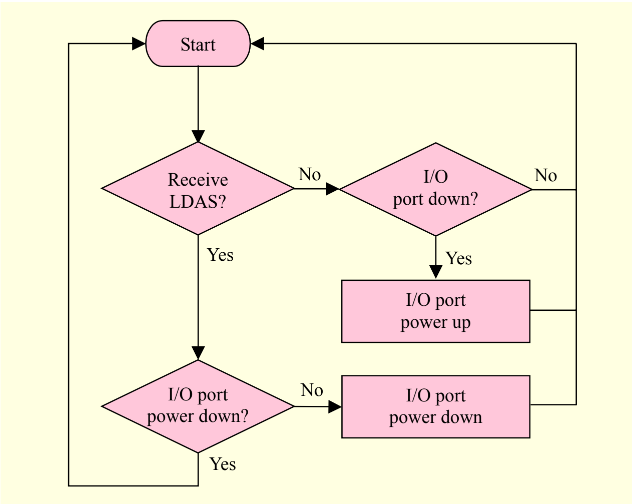

Fig. 4. Flowchart for partial sleep mode of ONU.

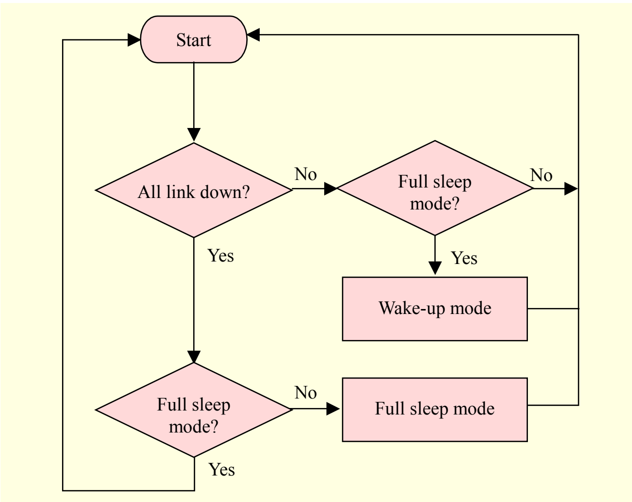

Fig. 5. Flowchart for full sleep mode of ONU.

III. Experiment Results

To verify the power-saving performance of the ONU, we manufacture a prototype ONU and measure the power consumption of the 10-Gb/s S/W, GE PHY, 10-Gb/s Ethernet PHY, and 10-Gb/s XFP OTRx. We use a multiport-managed GE S/W system to generate upstream traffic instead of using the CPE, owing to limited resources in the lab.

As shown in Fig. 6, the GE PHY and 10-Gb/s S/W are the most power-consuming parts among the subdevices in the ONU. When there is no traffic from the CPE, the power consumption is reduced in the ONU from 27.8 W to 19.3 W, as the commercial GE PHY has an automatic power-saving function, although the PSMC is not operating. Here, it is noted that the power consumption of the 10-Gb/s S/W occupies 64% of the total power consumption. However, the power consumption of the 10-Gb/s S/W is reduced from 12.8 W to 0.2 W when the PSMC is operating. In addition, we can reduce the power consumption of the 10-Gb/s PHY and XFP OTRx from 2.4 W and 3.0 W to 2.1 W and 2.5 W, respectively.

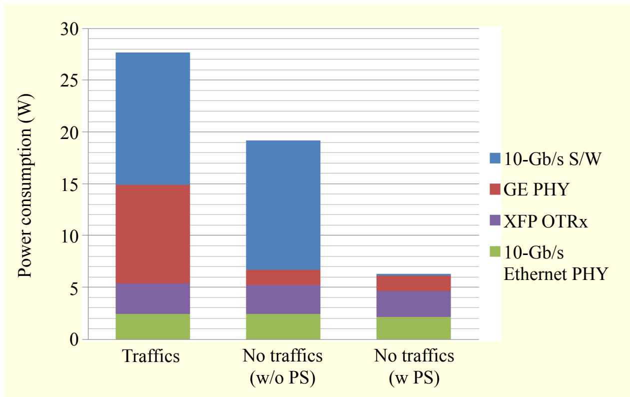

Fig. 6. ONU power consumption.

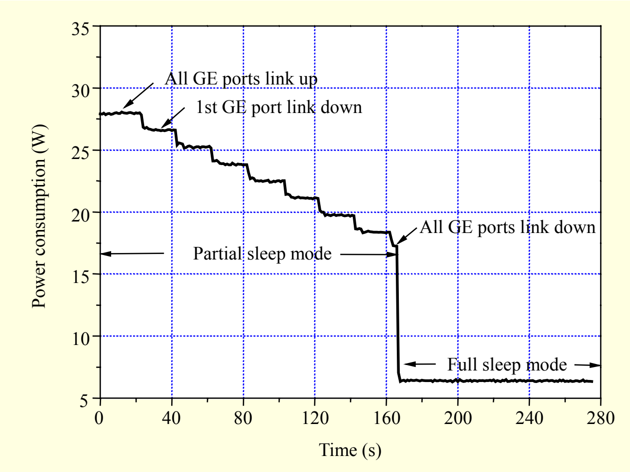

Fig. 7. ONU power consumption during partial sleep mode.

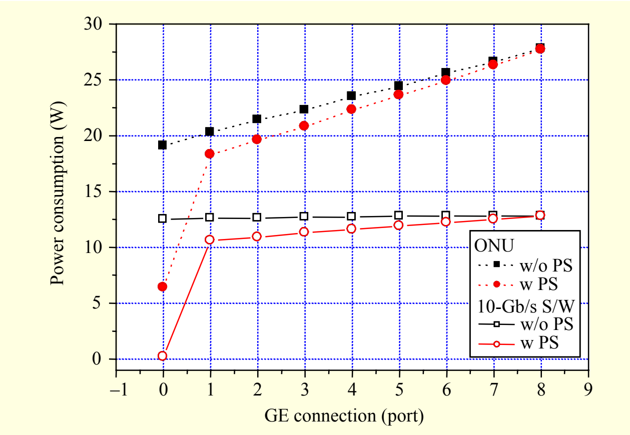

Fig. 8. Power consumption of ONU and 10-Gb/s S/W.

Consequently, the total power consumption decreases from 19.3 W to 6.4 W.

To verify the performance of sleep mode over time, we connect all GE ports and then disconnect the GE ports one by one. Figure 7 shows the variation of measured power consumption of the ONU. The power consumption gradually decreases, depending on the GE port link status, when the ONU operates in partial sleep mode. Finally, after the sleep mode waiting period, the PSMC switches the ONU operation mode to full sleep mode so that the total power consumption is dramatically reduced from 17 W to 6.4 W.

To verify the power-saving effect of partial sleep mode, we measure the power consumption of the ONU and the 10-Gb/s S/W by disconnecting the GE ports gradually. As we mentioned above, the commercial PHY chipset has a power management function, so the power consumption of the ONU is reduced although the ONU operates without a power-saving function, as shown in Fig. 8. However, the 10-Gb/s S/W consumes power constantly during our experiment. On the other hand, the power consumption of the 10-Gb/s S/W could be reduced by applying the power-saving function to the ONU since the relevant I/O ports of the 10-Gb/s S/W are turned off during partial sleep mode. Consequently, the 10-Gb/s S/W consumes 2.3 W less when eight GE ports are disconnected during partial sleep mode.

IV. Power Saving Allows OLT-ONU Connectivity Check

The WDM-PON ONU should have a cyclic synchronized wake-up function to support a connectivity check between the OLT and ONU. Thus, the WDM-PON requires a specified wake-up mode time during its sleep mode operation. Figure 9 describes an ONU-driven power-saving mechanism to allow OLT-ONU communication in the WDM-PON. According to IEEE 802.3az (Energy Efficient Ethernet), the Tx is put in low power idle (LPI) mode to reduce power consumption when there is no data to send [11]. We extend the LPI mode concept from IEEE 802.3az to WDM-PON OLT-ONU communication. If the ONU does not receive a user data frame from the CPE, the ONU goes into full sleep mode after sending a sleep message to the OLT accordingly. When the ONU operates in full sleep mode, all of the active components also operate in sleep mode, although the downstream receiver (Rx) part remains on continuously; this feature functions the same way the proposed full sleep mode functions, which was described in the previous section. We call this “dozing mode” [12].

If the OLT receives the ONU’s sleep message, the OLT goes into sleep mode, but the Rx remains on continuously. The ONU automatically activates once it receives upstream traffic from the CPE. After sending both a wake-up alarm and loopback message to the OLT, the ONU waits until receiving the OLT response message. On the OLT side, if the OLT Rx obtains the message from the ONU, the OLT wakes up immediately and sends a response to the ONU in due order. Finally, the ONU begins to send upstream traffic to the OLT. In addition, we consider a synchronized wake-up of the ONU because the connectivity check between the OLT and ONU should be required in the network.

Figure 10 shows a schematic diagram of the timeline for a cyclic synchronized wake-up mode and sleep mode. When the WDM-PON ONU operates without a power-saving function (free running), the total power of the ONU used can be calculated from the total operating time and full power consumption. However, when the WDM-PON ONU operates in sleep mode, we should carefully consider the sleep cycle and synchronized wake-up time when calculating the total power used.

Based on the concept described in Fig. 10, we define the

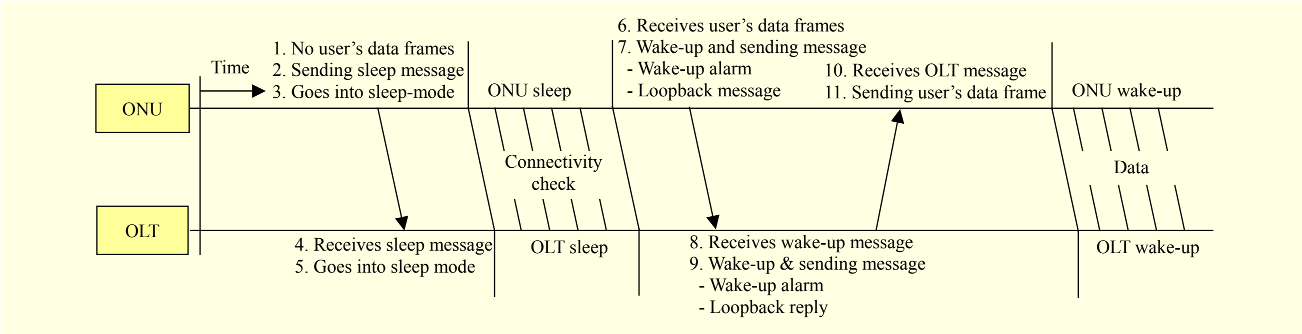

Fig. 9. Procedure of ONU driven power saving mechanism in WDM-PON.

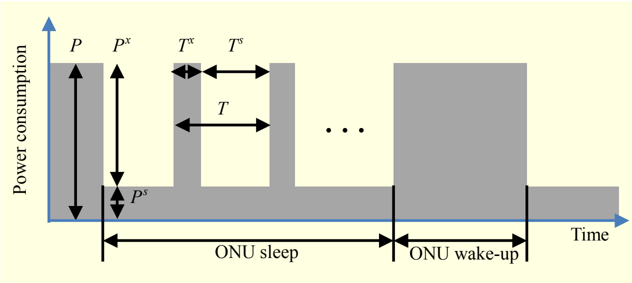

Fig. 10. Schematic diagram of timeline for cyclic synchronized wake-up mode and sleep mode (P: power consumption in wake-up mode, P^s: power consumption in full sleep mode, P^x: power consumption difference between wake-up mode and sleep mode, T^s: sleep mode time, T^x: wake-up mode time, and $T^x + T^s = T$: sleep cycle).

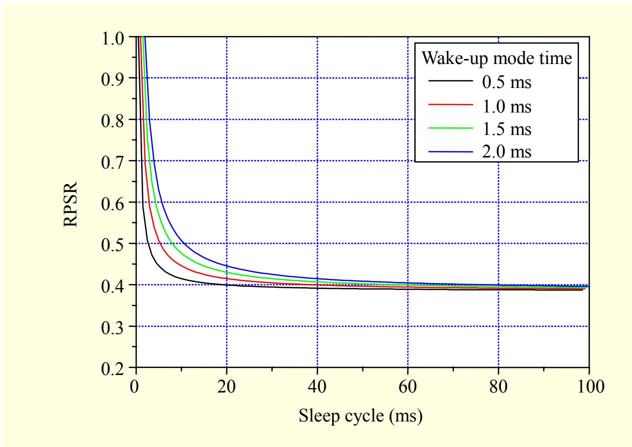

Fig. 11. RPSR of ONU as function of sleep cycle.

relative power-saving ratio (RPSR), which is a function of the power consumption and operating time. The RPSR is the ratio between the total power consumption during the sleep mode operation involving a cyclic synchronized wake-up and the total power consumption without the sleep mode operation. The following shows the equation used to calcuate the RPSR.

$$
\begin{aligned}
RPSR &= \frac{P^{\text{sleep mode}}}{P} = \frac{(P^x + P^s)\times T^x + (P^s \times T^s)}{P\times T} \\
&= \frac{P^s}{P} + \frac{(P^x + T^x)}{P\times T} = 1 - \frac{(P^x \times (T - T^x))}{P\times T} \\
&= 1 - \frac{P^x}{P}\times\left(1 - \frac{T^x}{T}\right).
\end{aligned} \tag{1}
$$

When TDMA-PON ONU transitions from sleep mode to wake-up mode, a longer wake-up mode time (approximately 2 ms) is required for the ONU to recover the OLT clock from the downstream, owing to multiple access techniques. However, the WDM-PON requires a shorter wake-up mode time for activating the ONU because of its logical p-t-p connection. We assume that the wake-up mode time (T^x) will be shorter than 1 ms, considering that a connectivity check procedure is very simple. Figure 11 shows the calculated RPSR as a function of the sleep cycle (T) and wake-up mode time (T^x) based on (1). The RPSR decreases dramatically when increasing the sleep mode time. A 58% improvement in power consumption can be achieved in the ONU when the sleep cycle and wake-up mode time are set to 20 ms and 1 ms, respectively. From these results, we recognize that the power saving achieved using the sleep mode operation is very suitable for a WDM-PON.

V. Conclusion

Using the proposed power-saving mode controller (PSMC), the power consumption is reduced effectively in a 10-Gb/s WDM-PON ONU when no uplink traffic from the CPE is detected. The PSMC is simply constructed with the μ-processor and GE PHYs. The PSMC controls the operating mode of the major subdevices, such as 10-Gb/s S/W in the ONU. We successfully demonstrated the power saving of a 10-Gb/s WDM-PON ONU. In addition, we designed a power-saving mechanism based on a cyclic sleep mode operation to allow a connectivity check between the OLT and ONU. Our calculation results show that the WDM-PON ONU can reduce around 60% of the power consumption using the power-saving mechanism with a cyclic sleep mode operation. We believe that the proposed mechanism will enable us to realize an efficient power-saving WDM-PON ONU.

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