

Dual cyclic power saving technique for XG-PON

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Abstract: In a passive optical network (PON), energy conservation is an important system design goal to satisfy the global demands for an energy efficient green network. In this paper, we show that a separate period control for the transmitter and receiver of an optical transceiver can result in better power saving performances in PON systems. Then, we propose a power saving mode called the Dual Cyclic Sleep (DCS) mode. We have implemented the DCS mode in an ETRI XG-PON system and conducted experiments to show the power saving efficiency of the proposed DCS mode. The results indicate that the DCS mode provides higher power saving efficiency than the doze and cyclic sleep modes.

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1. Introduction

A passive optical network (PON) is a point-to-multipoint network architecture which consists of an optical line terminal (OLT) at a central office and a number of optical network units (ONUs) located at the customer's premises. Since a PON has no active equipment in the path of the signal from the source to the destination, it is inherently more energy efficient than a metallic access network system in providing broadband services [1]. However, there have been continuously increasing demands for further reducing the energy consumption of PONs. It has been reported that the OLT and ONU consume a lot of energy. More specifically, the ONU consumes 60 % of the total power in a PON [2].

Over the last few decades, various power saving methods for mobile communication systems have been studied to prolong the battery life of hand-held devices. Recently, power saving techniques for wired communication devices received considerable attention because of the global energy crisis. A power saving scheme for an Ethernet physical layer has been standardized in IEEE (Institute of Electrical and Electronics Engineers) 802.3az [3]. ITU-T (Telecommunication Standardization Sector of the International Telecommunication Union) has proposed a power saving scheme for an optical access system, which is included in G.987.3 of XG-PON (10-Gigabit-capable Passive Optical Networks) standard [4]. The ONU power saving scheme for an EPON (Ethernet Passive Optical Network) is still under discussion in IEEE P1904.1 SIEPON (Service Interoperability in Ethernet Passive Optical Networks) [3, 5].

In 2013, the European Commission published the "Code of Conduct on Energy Consumption of Broadband Equipment v4.1" to promote the development and deployment of energy-efficient equipment [6]. This document sets the target power consumption of XG-PON ONUs to 5.1 W in the idle-state and 7.3 W in the on-state for 2011-2012, and 4.8 W in the idle-state and 6.2 W in the on-state for 2013-2014. These values are the target on-state power consumption of ONUs with a single gigabit Ethernet interface. The document also specifies the target power consumption of 10/1G-EPON and 10/10G-EPON ONUs.

ITU-T G.987.3 specifies many reasons why ONU power management is required to be implemented. They include a) given functionalities can be realized with higher energy efficiency; b) when a subscriber interface is idle, it is desirable for the ONU to power down the circuitry associated with that interface; c) all the power is saved when a subscriber intentionally switches off an ONU; and d) it is desirable for the ONU to power down during AC power failures to prolong the backup battery lifetime.

Recently, significant research has been conducted for the power conservation of ONUs. Skubic and Hood presented that the cyclic sleep mode can save more power than the doze mode. However, this causes a reduced quality of service (QoS) performance for longer sleep intervals in the XG-PON. Hence, the periods for power saving mode should be carefully determined on

the basis of traffic load and service requirements [7]. Bang *et al.* reported that a sleep period should be determined for balancing the performance between the power saving and short state transition delays [8]. Dixit *et al.* proposed a power consumption model for an ONU and evaluated the ONU power consumption in various next generation optical access architectures [9]. Dinh and Walid proposed a power saving protocol and derived an analytical power consumption model for 10G EPON [10]. Wong *et al.* experimentally demonstrated an ONU architecture in the power saving mode that enabled ONUs to change from the power saving mode to the normal operation mode quickly using a fast clock and data recovery circuit [11]. Shi *et al.* proposed a scheduling scheme based on a service-level-agreement for PON that allows the OLT to change the sleep time. Furthermore, the ONU can quit the power saving mode to send high-priority packets to guarantee a small delay [12]. Zhang and Ansari proposed a power saving mode control and sleep aware traffic scheduling schemes that determined the transitions under two scenarios for 10G EPON: sleep for more than one DBA (dynamic bandwidth allocation) cycle, and sleep within one DBA cycle, where the transmitter and receiver can go to the sleep mode separately [13]. Praet *et al.* demonstrated a new PON technology called Bit-Interleaved PON (Bi-PON) [14]. This technology reduces the energy consumption by using a modified XGTC frame to allow the early selection of relevant bits at the customer's data rate and clock speed. Kani summarized and discussed existing power consumption techniques and power saving issues for PONs in [15].

Previous algorithms mainly focused on how to determine the sleep period for an optical transceiver. In this paper, we propose that a separate period control for the transmitter and receiver of an optical transceiver can result in better power saving performance. Then, we propose a new power saving mode: the dual cyclic sleep (DCS) mode. We have implemented the DCS mode in an ETRI XG-PON system and conducted experiments to show the power saving efficiency of the DCS mode. The results indicate that the DCS mode provides a higher power saving efficiency than the doze and cyclic sleep modes. The main contributions of this paper are as follows:

- We propose the DCS mode that enables the transmitter and receiver to switch between wake-up and sleeping modes with different periods.
- We present the ETRI XG-PON system we developed, the optical transceiver of which supports 10 Gbps downstream and 2.5 Gbps upstream. Then, we show a detailed system model and an analytical model for ONU power consumption.
- We implement the proposed DCS mode as well as the doze and cyclic sleep modes in an ETRI XG-PON system. We empirically evaluate the power saving efficiency and wake-up delay for the proposed DCS mode in the system.

The rest of the paper is organized as follows. In Section 2, we review the power saving mechanisms of XG-PONs in detail and investigate the system parameters related to power saving efficiency. In Section 3, the DCS mode and its analytical model are presented. We introduce the ETRI XG-PON system with power saving techniques in Section 4. Section 5 shows the experimental results, while the conclusions are discussed in Section 6.

2. Motivation: power saving mechanism in XG-PON

The basic mechanism of the power saving modes in an XG-PON is to periodically turn on and off the optical transceiver. In this section, we review the power saving mechanisms for XG-PON and examine the parameters contributing to power consumption of the ONU.

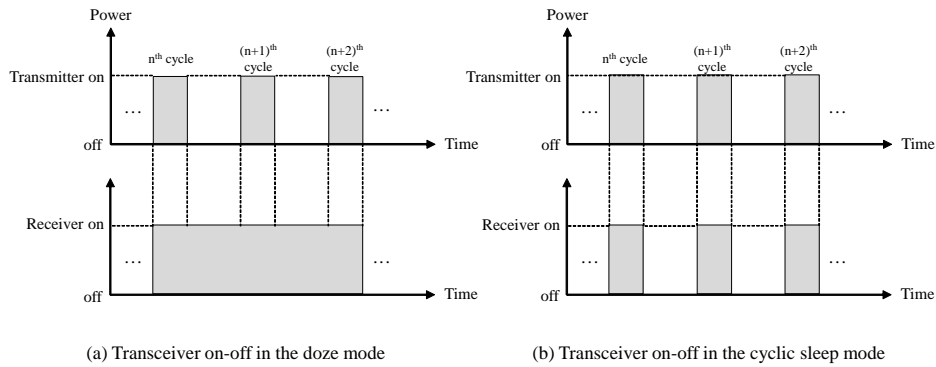


Fig. 1. Diagram showing the transceiver on-off operation in the doze and cyclic sleep modes

2.1. Overview of power saving mechanism in XG-PON

In 2009, ITU-T published the G.sup 45 GPON (gigabit-capable passive optical networks) power conservation standard [16]. It describes four basic ONU power saving methods, which are power shedding, doze, cyclic sleep, and deep sleep. Power shedding is the ability of an ONU to reduce power consumption during AC power outages in which nonessential functions and services are powered off. In the doze mode, the ONU's sending function is set to sleep while its receiving function is kept awake. A typical implementation of the doze mode sets the transmitter laser drivers and associated electrical functions to sleep. In the cyclic sleep mode, the sending and receiving functions of the ONU are periodically deactivated. Thus, the cyclic sleep mode can save more power than the doze mode. In the deep sleep mode, ONU's sending and receiving functions are deactivated. Because an ONU in the deep sleep mode does not negotiate with an OLT, some downstream data losses may occur when the ONU wakes up. Figure 1 shows the operations of a transmitter and receiver in the doze and cyclic sleep modes. In Fig. 1, the gray regions correspond to an active duration that consumes electric power. The cyclic sleep and doze modes are included in G.987.3 as a power saving method in the XG-PON. However, the deep sleep mode is not included since some downstream data losses may occur [15].

Sleep_Request and Sleep_Allow PLOAM (physical layer operation administration and maintenance) messages and FWI (forced wakeup indication) bit indication are defined for the signaling between the OLT and sleeping ONU. PLOAM messages and FWI bit are multiplexed into a header field in the XGTC (XG-PON transmission convergence) frame. G.987.3 recommends that the support of the doze mode is mandatory. The support of the cyclic sleep mode is optional for both the OLT and ONU.

2.2. Parameters for ONU power management

The OLT uses OMCI (ONU management and control interface) to discover the ONU's power management capabilities and configure its power management attributes and modes [17]. To control the power management behavior of an ONU, the OLT and ONU maintain a pair of power management state machines, which operate in partial state alignment. The signaling mechanism used to coordinate the OLT and ONU state machines is based on the PLOAM messages. The PLOAM messages are exchanged between the OLT and ONU at the time of state transitions. In the power management operations, the parameters that are related to the power saving efficiency are as follows:

- T_{aware} is the local ONU timer that controls the dwell time in the doze aware or sleep

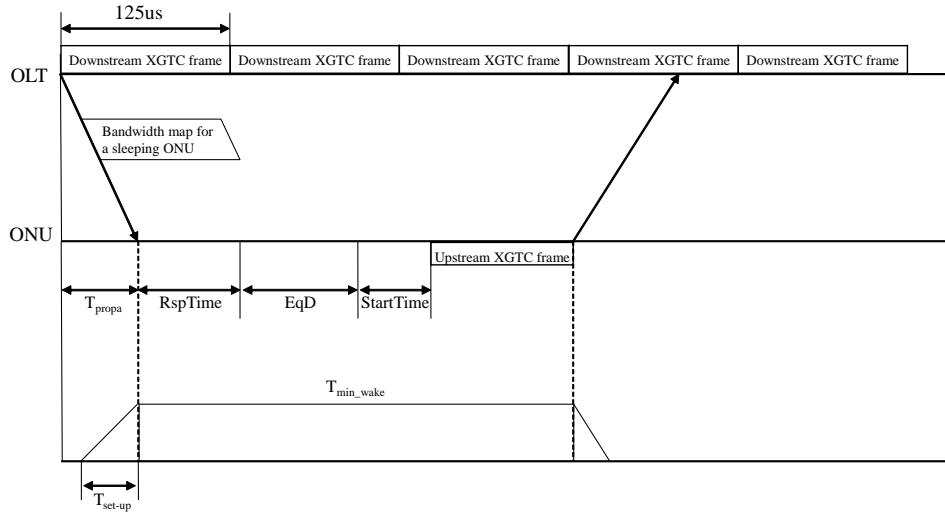


Fig. 2. Timing chart of OLT and ONU

aware states. It is prearranged for the ONU to receive control messages such as a Sleep_Allow(OFF) PLOAM message or to acknowledge an FWI bit. This parameter is kept as short as possible for power reduction.

- T_{sleep} is the local ONU timer at ONU that controls the dwell time in the asleep or listen states. The ONU may save the power consumption until this timer expires. The ONU in the power saving mode can send an upstream XGTC frame only after the ONU receives upstream bandwidth maps. Bandwidth map is a bandwidth allocation information field multiplexed in the XGTC frame header. It includes the start and stop time for upstream frame and is used to notify ONUs of when they can send upstream frames to the OLT in TDM-based XG-PON. The ONU may send user traffic and control messages such as PLOAM and OMCI only after receiving bandwidth maps from the OLT. Therefore, the wake-up delay highly depends on the service interval of upstream bandwidth map (SI_{BWmap}) rather than T_{sleep} , which is discussed in Section 3. SI_{BWmap} is defined as a period for which the OLT sends an upstream bandwidth map to a specific ONU.
- T_{set-up} includes the initialization times of the optical transceiver, clock recovering time in a CDR (clock and data recovery) chip, Psync (physical synchronization sequence) synchronization time in the ONU's MAC (medium access control), and time for turning on the ONU MAC's full function. They depend on the hardware performance. Meanwhile, the ONU should wake up earlier than the expiration of T_{sleep} to meet the provisioned T_{aware} duration. The control time of a transceiver is also considered since the transmitter and receiver of the optical transceiver are normally controlled via serial interfaces. For example, IIC (inter-integrated circuit) interface by the controller or ONU MAC is used.

Figure 2 shows the timing chart of an OLT and sleeping ONU in the cyclic sleep mode when they exchange XGTC frames while the ONU is in the T_{aware} state. T_{min_wake} denotes the minimum time for which the optical transceiver of the ONU is kept on. The OLT sends a downstream XGTC frame every 125 μs. The ONU transmits XGTC frames when the downstream frame has a corresponding bandwidth map for the ONU. If the bandwidth map has PLOAM and OMCI

messages during the power saving mode, it takes $500 \mu\text{s}$ ($125 \mu\text{s} \times 4$ frames) to send upstream traffic as shown in Fig. 2. Note that the delays such as T_{propa} (propagation delay), $RspTime$ (response time), EqD (equalization delay), and $StartTime$ (start time delay) contribute to the processing time to make an upstream XGTC frame ready. It needs extra time for the ONU to turn on the receiver and transmitter of the optical transceiver before the T_{sleep} timer expires.

In Fig. 2, T_{set-up} includes the time for initializing the optical transceiver and clock recovery, and for turning on the ONU MAC's full function; these are required for the ONU to go to the normal operation state. Although the timer value is in a unit of $125 \mu\text{s}$, as described in the XG-PON standard, if the power saving mode protocol is based on a software implementation, it incurs a longer delay due to the process scheduling time because the T_{sleep} and T_{aware} cannot be smaller than the scheduling timer. In order to maximize the power saving efficiency, T_{aware} should be minimized.

2.3. Wake-up delay

G.987.3 does not provide the specific wake-up and sleep conditions; however, they are required for implementing the power saving mechanisms of the system. There may exist several types of sleep and wake-up conditions according to the service scenarios. This paper considers the following scenarios for deciding the wake-up and sleep conditions.

- **Doze mode:** When the OLT detects downstream traffic that is destined to a sleeping ONU, the OLT sends a downstream XGTC frame with FWI bit or Sleep_Allow(OFF) PLOAM messages in order to wake up the sleeping ONU. The ONU can parse the downstream XGTC frame at any time because the receiver of the optical transceiver is always on in the doze mode. Then, the ONU immediately wakes up and transits to the normal operation mode. When the sleeping ONU detects upstream traffic or link-up from UNIs, LWI (local wake-up indication) occurs. The ONU immediately wakes up and gets ready to send Sleep_Request(Awake) PLOAM messages to the OLT. At this time, however, the ONU waits for the bandwidth map from the OLT to send a Sleep_Request(Awake) PLOAM message. Thus, the period of T_{sleep} and T_{aware} as well as SI_{BWmap} should be determined to minimize the wake-up time while maximizing the effect of power saving. Longer T_{sleep} periods save more power; however, a smaller SI_{BWmap} value is required.
- **Cyclic sleep mode:** The OLT may send a downstream XGTC frame containing FWI bit or Sleep_Allow(OFF) PLOAM messages to wake up the sleeping ONU. At this moment, however, the OLT should send them during the T_{aware} duration. Otherwise, the OLT has to send redundant downstream XGTC frames until it receives the Sleep_Request(Awake) PLOAM messages from the sleeping ONU, because both the receiver and transmitter of the optical transceiver turn on and off periodically in the cyclic sleep mode. The OLT should know the T_{aware} and T_{sleep} of each sleeping ONU and send downstream XGTC frames during T_{aware} to wake up the sleeping ONU. For the upstream case, the situation is nearly identical to the doze mode. When a sleeping ONU detects upstream traffic from the UNIs, it immediately wakes up and sends the OLT a Sleep_Request(Awake) PLOAM message. T_{sleep} , T_{aware} , and SI_{BWmap} contribute to the wake-up delay of the sleeping ONU.

2.4. Approach for increasing power savings

In order to further reduce the power consumption, the sleeping ONU should shut down the optical transceiver for as long as possible. This requires a high T_{sleep} . However, a high T_{sleep} causes a slow wake-up for the sleeping ONU, which results in a large packet transfer delay of buffered upstream and downstream traffic. Regarding the cyclic sleep mode, it has been reported

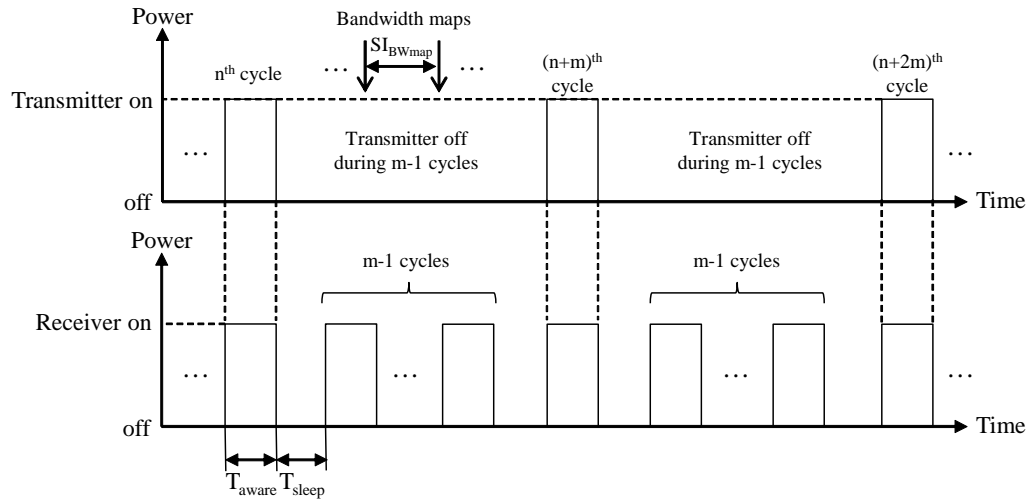


Fig. 3. Transceiver on-off operation in the DCS mode

that a T_{sleep} of 20 to 50 ms is a good power saving duration for the cyclic sleep mode [18, 19]. In this paper, we propose the DCS mode that separately controls the sleeping periods for the transmitter and receiver of an optical transceiver to further reduce the power consumption while maintaining a small wake-up delay. In addition, a short service interval of upstream bandwidth map for the sleeping ONU can provide a short upstream transfer delay. We discuss these issues in detail and describe the DCS mode in the following sections.

3. Proposed power saving technique

Based on the investigation of the doze and cyclic sleep mode operations, we propose a new power saving scheme called DCS mode that separately controls the sleeping periods for the transmitter and receiver of an optical transceiver to further reduce the power consumption while maintaining a small wake-up delay.

3.1. Dual cyclic sleep mode

In the cyclic sleep mode, the receiving function of the sleeping ONU is periodically turned on to catch a downstream signal because the sleeping ONU must recover the clock and receive bandwidth maps during the sleep mode. While a longer sleep period conserves more power, it causes the OLT to wait longer to wake up the sleeping ONU. During the sleep aware period, the ONU can receive FWI or Sleep_Allow(OFF) PLOAM messages from the OLT and then wake up. This implies that a longer sleep period increases packet delays and requires a larger buffering memory size. Hence, the sleep period should be carefully determined with this tradeoff.

When a sleeping ONU wakes up from an LWI event, it is not ready for transmitting until it receives the bandwidth map from the OLT. Meanwhile, the ONU can immediately turn on the transmitter if the transmitter is in the sleeping period. When a wake-up is triggered by either the OLT or ONU, it takes a period of T_{set-up} to turn on the transmitter if it is in the sleeping period. However, it does not significantly affect the total wake-up delay because T_{set-up} is relatively small. This implies that SI_{BWmap} is more critical in determining the wake-up delay than the sleeping period of the transmitter. In the ETRI XG-PON system, the SI_{BWmap} value can be

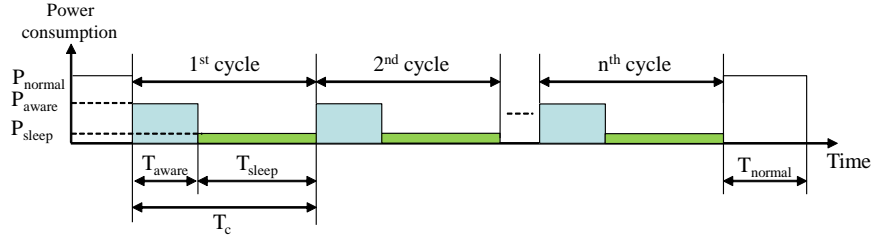


Fig. 4. Sleep cycles for the cyclic and DCS modes

configured from 125 μ s to 32 ms.

However, the transmitter cannot be turned off in the power saving mode for too long time because of the following reasons:

- If the sleeping ONU does not send any upstream signal during the sleep period, the OLT does not know whether this ONU is working correctly. The upstream signal works as a keep-alive signal.
- In order to report the OLT ONU's status during the sleep period, the transmitter should be turned on. The ONU may send a dying gasp indication [4] or PLOAM/OMCI messages even though the ONU is in the power saving mode.

From these observations, we propose a new power saving mode, the DCS mode. The main idea of the DCS mode is not to turn on the transmitter of the optical transceiver at every sleep cycle, but to turn it on at every m sleep cycles ($m \geq 1$). Note that the OLT can check the ONU's upstream signal at every m sleep cycles as a keep-alive signal. Figure 3 shows the sleep cycles of the DCS mode. The transmitter of the optical transceiver is turned on after every m sleep cycles while the receiver is turned at every sleep cycle. Because the transmitter is turned on less frequently, the DCS mode can provide a higher power saving efficiency than the doze and cyclic sleep mode. If the operator permits the sleeping ONU to send some upstream traffic (e.g., the control packets such as BPDU (bridge protocol data unit)) during the sleep period, a smaller m can be set. However, in this case the reduction of power consumption will be less.

3.2. Power and delay analysis

We derive an analytical model for the power consumption and wake-up delay for a sleeping ONU. We assume that the arrival rate of the upstream or downstream packets to a particular ONU follows the Poisson distribution [8, 10, 12]. The parameters used in Fig. 4 and Figs. 6–7 are described in Table 1.

3.2.1. Power consumption

Figure 4 depicts the sleep cycles of a sleeping ONU for both cyclic and DCS modes. Note that P_{aware} for the DCS mode is much lower than that for the cyclic mode because the transmitter for the DCS mode is turned on only every m sleep cycles. Let $p_k(\tau)$ denote the probability that there are exactly k packets during a time interval τ . Then, $p_k(\tau)$ is given by

$$p_k(\tau) = \frac{(\lambda \tau)^k}{k!} e^{-\lambda \tau}, \quad (1)$$

Table 1. Parameter description for the cyclic and DCS modes

Parameter	Description
T_{aware}	Time spent by ONU in the sleep aware state
T_{sleep}	Time spent by ONU in the asleep state
T_c	Time for one sleep cycle, which is equal to $(T_{aware} + T_{sleep})$
T_d	Delay from the power saving mode to the instant when the ONU is ready for transmitting
P_{normal}	Power consumption of the normal state
P_{aware}	Power consumption during T_{aware}
P_{sleep}	Power consumption during T_{sleep}
N_s	Average number of sleep cycles until the ONU wakes up
D_{OTRX_init}	Delay for turning on and initializing the optical transceiver
D_{func}	Delay for turning on ONU MAC's full functions
D_{clk}	Delay for the clock recovery
SI_{BWmap}	Service interval of upstream bandwidth map for a sleeping ONU
BWmap	Bandwidth map
LWI	Local wake-up indication

where λ is the number of packets per unit time. The probability that there is at least one packet arriving during one cycle T_c is can be determined using

$$\sum_{k=1}^{\infty} p_k(T_c) = 1 - p_0(T_c) = 1 - e^{-\lambda T_c}. \quad (2)$$

Let $p(n)$ be the probability that the ONU wakes up after n cycles when no upstream and downstream packets come during the first $(n-1)$ cycles and at least one packet comes during the n -th cycle. Then, $p(n)$ is calculated in [10, 22] as follows

$$p(n) = \begin{cases} 1 - e^{-\lambda T_c} & \text{for } n = 1 \\ e^{-\lambda(n-1)T_c} (1 - e^{-\lambda T_c}) & \text{otherwise.} \end{cases} \quad (3)$$

By Eq. (3), the average number of sleep cycles until the wake-up can be obtained by

$$N_s = \sum_{n=1}^{\infty} n \cdot p(n). \quad (4)$$

The total energy consumed by an ONU during N_s cycles for the cyclic mode becomes

$$E_{cyclic} = N_s \cdot (T_{aware} (P_{tx} + P_{rx}) + T_{sleep} P_{sleep}), \quad (5)$$

where P_{tx} and P_{rx} are the power consumption by the transmitter and receiver during T_{aware} , respectively. Note that P_{aware} for the cyclic mode is equal to $(P_{tx} + P_{rx})$. Then, the average power consumption for the cyclic sleep operation is obtained by

$$P_{cyclic} = \frac{E_{cyclic} + T_{normal} P_{normal}}{N_s T_c + T_{normal}}. \quad (6)$$

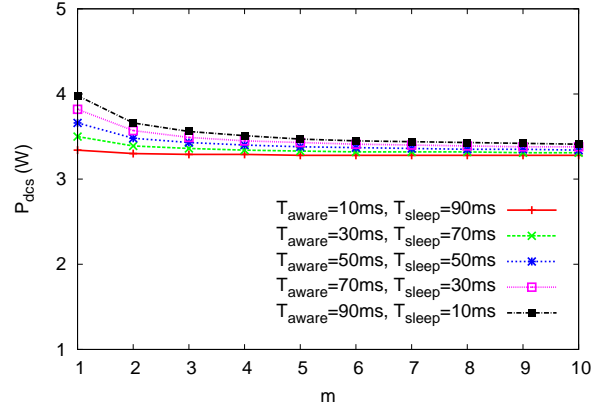


Fig. 5. Plots of P_{dcs} with respect to m for $T_c = 100$ ms

The normalized power consumption of the cyclic sleep operation is given by the ratio of P_{cyclic} to P_{normal} :

$$P'_{cyclic} = \frac{T_{aware} N_s (\eta_{tx} + \eta_{rx}) + T_{sleep} N_s \eta_{sleep} + T_{normal}}{N_s T_c + T_{normal}}, \quad (7)$$

where $\eta_{tx} = P_{tx}/P_{normal}$, $\eta_{rx} = P_{rx}/P_{normal}$, and $\eta_{sleep} = P_{sleep}/P_{normal}$. Note that $P'_{cyclic} = 1$ when $\eta_{sleep} = \eta_{aware} = 1$.

Under the proposed DCS, the total energy consumed by an ONU is given by

$$E_{dcs} = T_{aware} \left(\left\lfloor \frac{N_s}{m} \right\rfloor P_{tx} + N_s P_{rx} \right) + N_s T_{sleep} P_{sleep}. \quad (8)$$

The average power consumption for the DCS is obtained by

$$P_{dcs} = \frac{E_{dcs} + T_{normal} P_{normal}}{N_s T_c + T_{normal}}. \quad (9)$$

The normalized power consumption for the DCS is given by

$$P'_{dcs} = \frac{T_{aware} \left(\left\lfloor \frac{N_s}{m} \right\rfloor \eta_{tx} + N_s \eta_{rx} \right) + T_{sleep} N_s \eta_{sleep} + T_{normal}}{N_s T_c + T_{normal}}. \quad (10)$$

This implies that the power for turning on the transmitter is reduced by a factor of approximately $1/m$ in comparison with the cyclic sleep operation, which periodically turns on and off both the transmitter and receiver.

Figure 5 plots P_{dcs} for five different sets of T_{aware} and T_{sleep} with respect to m . Note that the T_c values are the same for all five cases. We used $\lambda = 0.01$, $P_{tx} = 0.7$, $P_{rx} = 0.7$, $T_{normal} = 15$, $P_{normal} = 4.7$, and $P_{sleep} = 0.6$ in this experiment. We observe that the power consumption is significantly reduced and levels off as m increases when T_{aware} is much larger than T_{sleep} .

3.2.2. Delay for OLT driven wake-up

The wake-up delay (WUD) is defined by the transition time elapse from the power saving mode to the instant when the ONU is ready for transmitting. WUD may significantly affect the upstream or downstream QoS because the traffic should be buffered until the sleeping ONU wakes up and becomes the normal operation state. This transition incurs a delay due to the following

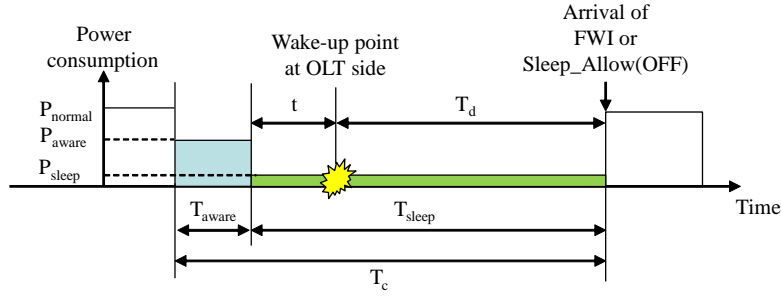


Fig. 6. Delay for an OLT driven wake-up

operations: 1) turning on and initializing the optical transceiver (D_{OTRX_init}), 2) turning on its full functions (D_{func}), and 3) the clock recovery from downstream signal (D_{clk}).

Figure 6 shows the delay for an OLT driven wake-up. Under the assumption that the XGTC frame with FWI or Sleep_Allow(OFF) PLOAM message includes the bandwidth map, we consider two possible cases. The first one is that the sleeping ONU receives the FWI or Sleep_Allow(OFF) PLOAM message when the ONU is in T_{aware} duration. In this case, since the transmitter is already turned on and the clock is synchronized, the delay for an OLT driven wake-up is calculated using

$$T_{d1} = D_{func}. \quad (11)$$

The second case involves an ONU in the T_{sleep} duration as shown in Fig. 6. The ONU's wake-up probability is assumed to be the same during the entire T_{sleep} duration. It implies that the delays until the ONU receives FWI indication or a Sleep_Allow(OFF) message follow the uniform distribution. Hence, the average delay can be expressed as half of the duration (i.e., $T_{sleep}/2$), and the total wake-up delay is calculated using

$$T_{d2} = \frac{T_{sleep}}{2} + T_{set-up}, \quad (12)$$

where $T_{set-up} = D_{OTRX_init} + D_{func} + D_{clk}$. By Eqs. (11) and (12), the average delay of OLT driven wake-up in the cyclic sleep mode is obtained using

$$T_{cyclic-olt} = \frac{T_{aware}}{T_c} T_{d1} + \frac{T_{sleep}}{T_c} T_{d2}. \quad (13)$$

In the DCS, the average wake-up delay for an OLT driven wake-up is calculated using

$$T_{dcs-olt} = \frac{T_{aware}}{mT_c} T_{d1} + \frac{mT_{sleep} + (m-1)T_{aware}}{mT_c} T_{d2}, \quad (14)$$

because the transmitter is turned on for one T_{aware} time and turned off for $(mT_{sleep} + (m-1)T_{aware})$ time for m sleep cycles in the DCS mode.

3.2.3. Delay for ONU driven wake-up

Figure 7 shows the ONU driven wake-up delay, which is given by the delay from the detection of the wake-up condition by the sleeping ONU to sending a Sleep_Request(Awake) PLOAM message to notify the OLT of its wake-up. We consider two cases for the ONU driven wake-up delay. First, when an LWI occurs during the T_{aware} state, the delay for an ONU driven wake-up is calculated using

$$T_{d3} = \frac{SI_{BWmap}}{2} + D_{func}. \quad (15)$$

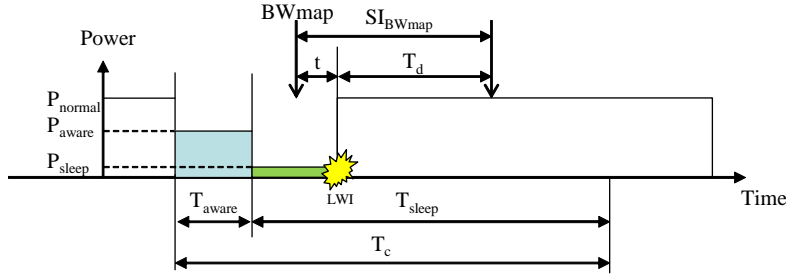


Fig. 7. Delay for an ONU driven wake-up

When an LWI occurs in the T_{sleep} duration, the delay differs with respect to the $T_{\text{set-up}}$. In Fig. 7, t refers to the moment when the LWI occurs after receiving BWmap. If $t < (SI_{\text{BWmap}} - T_{\text{set-up}})$, $T_d = (SI_{\text{BWmap}} - t)$. Otherwise, $T_d = 2 SI_{\text{BWmap}} - t$, because the ONU misses the bandwidth map right after the LWI event, and has to wait for the next bandwidth map. Note that the ONU can transmit only after it receives the bandwidth map. In this case, the delay T_{d4} is obtained using

$$T_{d4} = \frac{SI_{\text{BWmap}}}{2} + T_{\text{set-up}}. \quad (16)$$

This result implies that the delay of the ONU driven wake-up depends on SI_{BWmap} while that of the OLT driven wake-up depends on T_{sleep} .

By Eqs. (15) and (16), the average wake-up delay is given by

$$T_{\text{cyclic-onu}} = \frac{T_{\text{aware}}}{T_c} T_{d3} + \frac{T_{\text{sleep}}}{T_c} T_{d4}. \quad (17)$$

Under the DCS, the average wake-up delay is calculated using

$$T_{\text{dcs-onu}} = \frac{T_{\text{aware}}}{mT_c} T_{d3} + \frac{mT_{\text{sleep}} + (m-1)T_{\text{aware}}}{mT_c} T_{d4}. \quad (18)$$

4. ETRI XG-PON system with power saving techniques

In this section, we introduce the ETRI XG-PON system platform that we have developed. Afterwards, we address two more techniques for further enhancing the power saving performance of an ONU MAC.

4.1. XG-PON system platform

Figure 8 shows the ETRI XG-PON OLT and ONU systems. The optical transceiver supports 10 Gbps downstream and 2.5 Gbps upstream. We developed ITU-T G.987.3 compliant OLT and ONU MACs using Xilinx Virtex-5 LX155t FPGA (field programmable gate array) chips, G.987.3 software protocol stack, G.988 OMCI, and the DBA algorithm. The main features of our system are as follows:

- 9.9953 Gbps (1577nm) downstream and 2.488 Gbps (1270nm) upstream
- Supports up to 60km logical reach
- Supports 128 ONUs and 1024 T-CONTs (traffic containers) for each PON port
- Hardware-based DBA that supports fast convergence times [20]

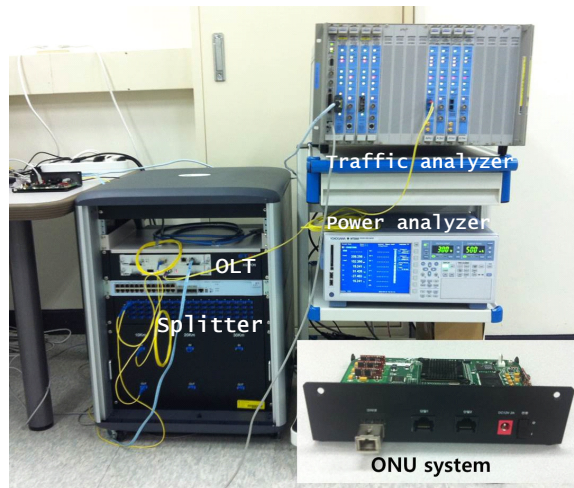


Fig. 8. ETRI XG-PON system platform

- Upstream and downstream FEC (forward error correction)
- Classification based on the IEEE 802.1p, 802.Q, and IPv4 ToS (type of service)

4.2. Clock gating technique for power saving

Clock gating is a technique that can reduce the dynamic power dissipation. In synchronous digital circuits, the clock tree is responsible for a significant amount of power dissipation up to 40 % [21]. Clock gating reduces the number of unwanted switchings of clocks by disabling them. We use the clock gating technique (CGT) to achieve higher power saving efficiency when the ONU is in the power saving mode.

ETRI ONU MAC consists of four major function blocks, which are the PON interface, XGTC framer/deframer, XGEM framer/deframer, and subscriber-related interfaces. Each block can work separately to handle the upstream and downstream packets. The main idea of the CGT is that the essential part of the blocks may work when the ONU is in the power saving mode. The clock gating control register regulates clocks belonging to each block. For example, only downstream related blocks work when the ONU is in the listen state of the doze mode. At this time, the transmitter of the optical transceiver is also turned off. When the ONU is in the doze aware state, all blocks work, and the transceiver is turned on. Both downstream and upstream blocks do not work when the ONU is in the sleep state of the cyclic sleep mode. The receiver and transmitter of the optical transceiver are also turned off such that the ONU consumes less power than when it is in the doze mode.

4.3. Fast wake-up technique

The ONU is capable of sending upstream traffic only when it receives bandwidth maps from the OLT. The OLT assigns bandwidth maps to a sleeping ONU such that the ONU is able to send a Sleep_Request(Awake) to the OLT without waiting for a T_{sleep} period to expire. Thus, the ONU can terminate the power saving mode whenever there is upstream traffic. Below is the procedure that we propose for the fast wake-up when an ONU detects the wake-up condition.

1. A sleeping ONU detects the incoming packets from the UNI, which triggers an LWI event.

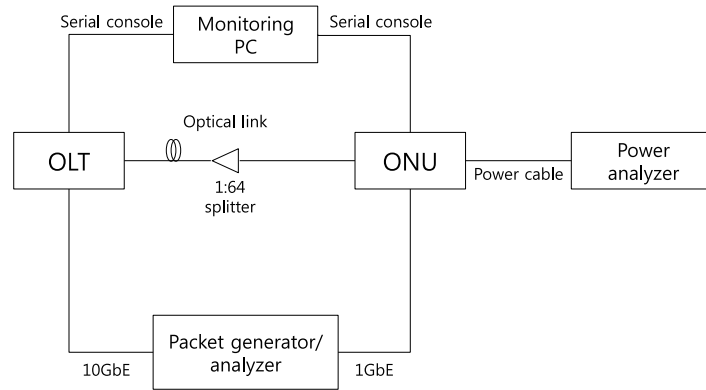


Fig. 9. Experimental setup

2. The ONU immediately turns on the optical transceiver and activates all ONU's MAC function blocks.
3. The ONU sends a Sleep_Request(Awake) PLOAM message to the OLT. The message is buffered until the ONU receives the bandwidth map from the OLT.
4. If the OLT receives a Sleep_Request(Awake) PLOAM message, it immediately sends the bandwidth to receive upstream data. At this time, the grant size of the bandwidth map affects a packet transfer delay of the buffered upstream traffic.
5. The ONU starts working in a normal operation mode.

We can send a bandwidth map quickly to the sleeping ONU for fast wake-up because our DBA engine is based on hardware implementations such that the SI_{BWmap} value can be configured from 0 to 255, which corresponds to 125 μ s to 32 ms [20].

5. Performance evaluation

We have performed experiments to evaluate the power saving efficiency and wake-up delay performance. We implemented the DCS, doze, and cyclic sleep modes in XG-PON OLT and ONU systems.

Figure 9 shows the experimental setup for the performance evaluations. We used one ONU and splitter with 64 split ratio. The measurement includes the power consumption of the PON components such as the ONU MAC and optical transceiver rather than the entire system. Note that other system parts may be turned off during the sleep period. The minimum value of both T_{aware} and T_{sleep} is 10 ms since the minimum scheduling time of the ONU software is 10 ms.

5.1. Power saving efficiency

Figure 10 shows the power consumption of doze, cyclic sleep, DCS modes, and the analytical result P_{dcs} for DCS mode in (9) with respect to T_{sleep} when $T_C=100$ ms. Note that $T_{sleep} + T_{aware} = T_C$. For the DCS mode, m is set to 10. The analytical result P_{dcs} is computed with $\lambda = 0.01$, $P_{tx} = 0.7$, $P_{rx} = 0.7$, $T_{normal} = 15$, $P_{normal} = 4.7$, and $P_{sleep} = 0.6$. The ONU MAC and optical transceiver of the ETRI ONU system consume 4.7 W during the normal operation mode, in which the ONU is activated and receives bandwidth maps for the PLOAM, OMCI, and T-CONT1 without any traffic. All three modes consume the same amount of energy when the sleep period is 0. In Fig. 10, as T_{sleep} increases, the power consumption decreases because

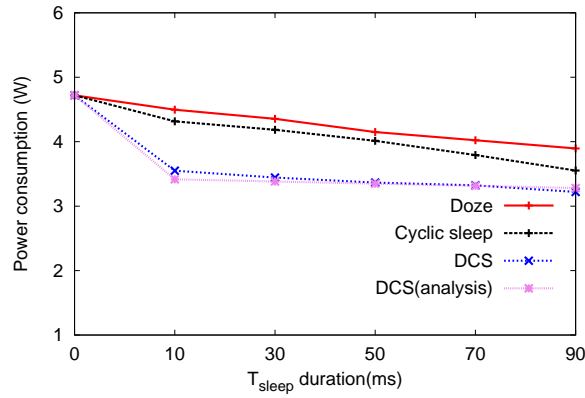


Fig. 10. Power consumption with respect to T_{sleep} when $T_C=100$ ms

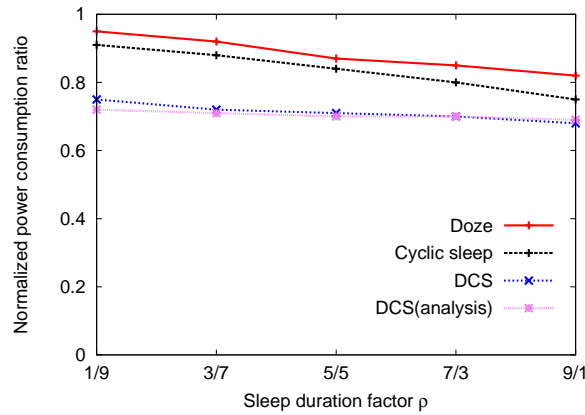


Fig. 11. Power saving efficiency

the ONU sleeps for a longer time when T_C is fixed. For the doze mode, the receiver is always kept on, and as a result, its power consumption is the highest among the three modes, as shown in Fig. 10. The proposed DCS mode consumes the least power among the modes. Meanwhile, as T_{aware} increases, the power consumption increase because the ONU sleeps for a shorter time when T_C is fixed.

We define a sleep duration factor ρ as the ratio of T_{sleep} to T_{aware} as follows:

$$\rho = \frac{T_{sleep}}{T_{aware}}. \quad (19)$$

Figure 11 shows the normalized power consumption, which is the ratio of the power consumption of each mode to that of the normal operation mode. As shown in Fig. 11, larger ρ achieves lower power consumption. This implies that a larger ρ can save more power. In Fig. 11, we observe that the power consumption greatly depends on the value of ρ .

Figures 12(a) and 12(b) show the power consumption measured by an Agilent N6705B DC power analyzer during the sleep cycles when $m = 2$ and 9, respectively, for the DCS mode. In Fig. 12, the X-axis denotes the time, and one grid represents one second. The Y-axis denotes

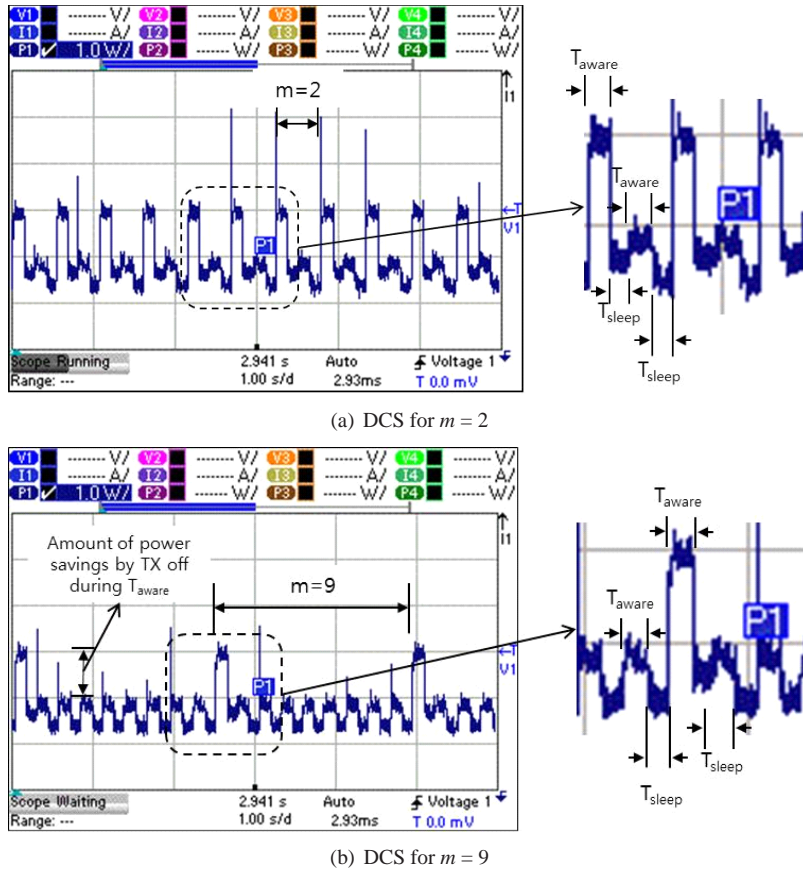


Fig. 12. DCS power consumption during the sleep cycles

the power consumption in Watts, and one grid represents 1 W. Both T_{sleep} and T_{aware} are configured to 100 ms in these experiments. In Fig. 12, the power consumption during the T_{aware} period is dramatically reduced when the transmitter is turned off under the DCS mode. These experiments show that more power savings can be achieved when we use larger m values in the DCS mode.

Figure 13 shows the power consumption of the DCS mode when the transmitter of the optical transceiver is turned on after every m sleep cycles. We used two different sets of T_{aware} and T_{sleep} values. As shown in Fig. 13, the power consumption becomes lower when m increases. From Fig. 13, we observe that the DCS mode effectively reduces the power consumption, when large T_{aware} and small T_{sleep} are used. On the other hand, when $T_{aware} = 10$ ms and $T_{sleep} = 90$ ms, the effect of m on the power consumption tends to be small because power saving is already achieved with large T_{sleep} .

5.2. Wake-up delay

We measured the upstream wake-up delay with 1, 50, 100, 150, 200, and 255 $SI_{BW_{map}}$ values for PLOAM and OMCI, which correspond to the service intervals for upstream bandwidth map of 0.25, 6.375, 12.625, 18.875, 25.125, and 32 ms, respectively. The delay is the waiting time until the first data packet in the ONU arrives at the OLT after waking-up. The OLT sends bandwidth

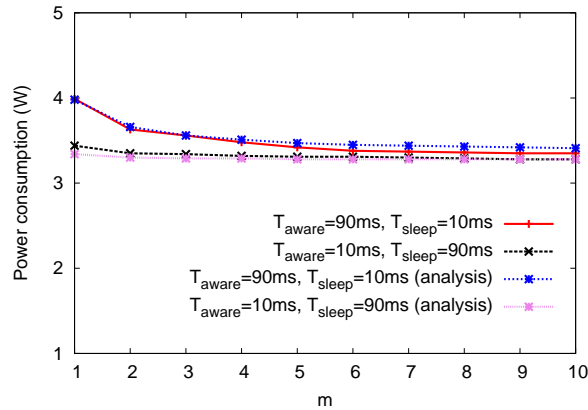


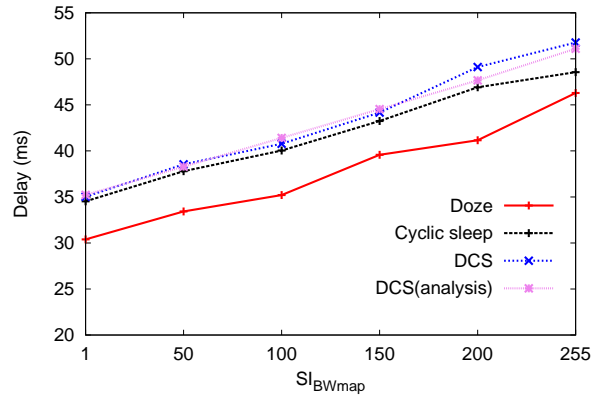
Fig. 13. Power consumption with respect to m in the DCS mode

maps for the PLOAM and OMCI with the configured SI_{BWmap} value when the ONU sleeps. However, the OLT sends the bandwidth map for the upstream data (T-CONT1 grant) as soon as the ONU notifies the OLT of its wake-up via a Sleep_Request(Awake) PLOAM message. The experimental parameters are given below.

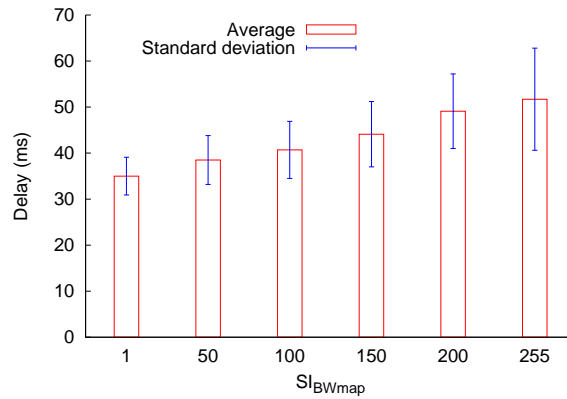
- Traffic load: 1 Mbps
- Packet length: 64 Bytes
- T-CONT1 grant: 100 Mbps
- Power saving mode: DCS
- T_{sleep} , T_{aware} durations: 50 ms

In the experiment, the OLT is configured to continuously send bandwidth maps for traffic, PLOAM and OMCI to the activated ONU. When the ONU sleeps, it sends bandwidth maps only for PLOAM and OMCI messages with a configured interval of SI_{BWmap} . After the ONU wakes up, the OLT sends bandwidth maps for upstream traffic. Because the OLT knows that the ONU goes to sleep when it receives a Sleep_Request(Sleep) PLOAM message from the ONU, it immediately changes the bandwidth maps as soon as it receives a Sleep_Request(Sleep) PLOAM message. The OLT sets SI_{BWmap} to 1 for PLOAM and OMCI in the normal operation state of the ONU, and the OLT changes SI_{BWmap} for the sleeping ONU to the value configured for experimental evaluation.

Figure 14(a) depicts the delay measurements for an ONU driven wake-up under each power saving mode. The doze mode gives the smallest delay because T_{set-up} in the doze mode is smaller than that in the cyclic sleep and DCS modes. The delay of the DCS mode is almost same as that of the cyclic sleep mode, and it becomes slightly longer for large SI_{BWmap} values. In Fig. 14, m is set to 10 for the DCS mode. Note that the delay of DCS modes depends on the value of m , and it can be reduced with a smaller value. There exists a certain discrepancy between DCS(analysis) and the measured DCS for $SI_{BWmap} = 200$ in Fig. 14(a). This is perhaps due to that the reported value included a few delay measurement samples with a large delay. Note that the delay variance increases as SI_{BWmap} increases as shown in Fig. 14(b), which shows the delay measurements for an ONU driven wake-up. It confirms that the delay becomes larger with larger SI_{BWmap} values. The delay variation is smaller for small SI_{BWmap} values. As discussed in Section 3, the delay for an ONU driven wake-up is related to SI_{BWmap} . Therefore, SI_{BWmap} should be carefully configured to satisfy the desired QoS requirements.



(a) Delay



(b) Delay variance for DCS mode with $m = 10$

Fig. 14. Comparison of delay for ONU driven wake-up

6. Conclusion

In this paper, we analyzed the power saving modes in an XG-PON system and proposed an enhanced power saving scheme called the DCS mode, which separately controls the sleeping periods for the transmitter and receiver of an optical transceiver to further reduce the power consumption while maintaining a small wake-up delay. Instead of turning on the transmitter of the optical transceiver at every sleep cycle, DCS turns it on after every m sleep cycles, which effectively reduces the power consumption in the awake state during the sleep mode. We have implemented the DCS, doze, and cyclic sleep modes in an ETRI XG-PON system, which is also equipped with clock gating and fast wake-up techniques for enhancing the power saving performances. We conducted experiments to compare the power saving efficiency of the DCS mode with that of other sleep modes. The results showed that the DCS mode provides a higher power saving efficiency than the doze and cyclic sleep modes.