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Adaptive Power Saving Mechanism for 10 Gigabit Class PON Systems

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SUMMARY This paper proposes a power saving mechanism with variable sleep period to reduce the power consumed by optical network units (ONUs) in passive optical network (PON) systems. In the PON systems based on time division multiplexing (TDM), sleep and periodic wake-up (SPW) control is an effective ONU power saving technique. However, the effectiveness of SPW control is fully realized only if the sleep period changes in accordance with the traffic conditions. This paper proposes an SPW control mechanism with variable sleep period. The proposed mechanism sets the sleep period according to traffic conditions, which greatly improves the power saving effect. In addition, the protocols needed between an optical line terminal (OLT) and ONUs are described on the assumption that the proposed mechanism is applied to 10 Gigabit (10G) class PON systems, i.e. IEEE 802.3av 10G-EPON and FSAN/ITU-T 10G-PON systems. The validity of the proposed mechanism is confirmed by numerical simulations.
key words: *passive optical network, 10G-EPON, 10G-PON, power saving, sleep control*

1. Introduction

Fiber-to-the-home (FTTH) broadband access networks have been widely deployed in recent years [1], [2]. In particular, passive optical networks (PONs) can provide optical access services at low cost, and are widely deployed [3]. A PON is comprised of one optical line terminal (OLT) located at the central office (CO) and multiple optical network units (ONUs) located at user premises as shown in Fig. 1. In addition, the ONUs share optical fibers and optical splitters in connecting to the OLT. In Fig. 1, SNI and UNI denote the service-node interface and the user-network interface, respectively.

High-speed PONs are being actively researched. Standardization of the 10 Gigabit (10G) class PON, which are the next generation access technology, is currently being discussed in IEEE 802.3av [4] and FSAN/ITU-T [5] as shown in Fig. 2. In IEEE 802.3av, standardization of the 10 Gigabit Ethernet PON (10G-EPON) is being discussed based on the framework of the Ethernet PON (EPON) [6]. On the other hand, FSAN/ITU-T is discussing standardization of the 10 Gigabit-capable PON (10G-PON) based on the framework of the Gigabit-capable PON (G-PON) [7].

While past research focused on raising the capacities of network systems, reducing their power consumption has become a major issue from the viewpoints of preventing global warming and reducing operational expenditure (OPEX) [8], [9]. Access networks consume much more power than metro and core networks because of the high number of communication devices involved [10]. It is well-known that putting network devices to sleep when possible is one of the most effective power saving techniques [11], [12]. A network device with the ideal sleep function uses very little power in the sleep mode in the absence of traffic, and wake up immediately when traffic is received.

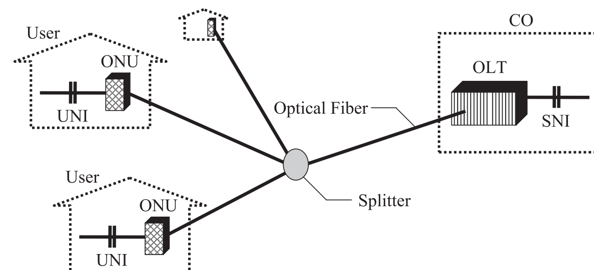

Fig. 1 Configuration of PON.

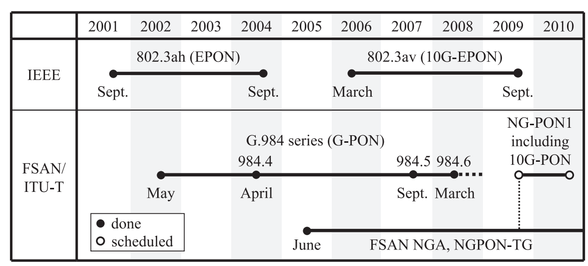

Fig. 2 Standardization schedule.

In order to reduce the power consumed by Ethernet switches, the fundamental mechanism of Energy Efficient Ethernet (EEE) is being discussed in IEEE 802.3az [13] based on the sleep technique which is called Low Power Idle (LPI). However, there remain concerns about the power consumption of emerging high-speed PONs, since the EEE mechanism cannot be directly applied to PON systems since their topology is point-to-multipoint. In the course of discussions on the PON standardization, as shown in Fig. 2, power saving of PON systems has been also treated as a hot topic. Though power saving function will not be included in the standard specification, it is expected that the imple-

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mentation of the power saving function will become a key element after the completion of the standardization. This research is conducted to make a timely contribution to power saving of the next generation 10G class PON systems.

In PON systems based on time division multiplexing (TDM), physical detection of downstream signals at a sleeping ONU cannot be used to trigger the active mode, since the downstream signals are physically broadcast to all ONUs. Therefore, the ONUs need to enter the active mode, i.e. wake up, periodically to confirm the presence or absence of downstream traffic. This is termed the sleep and periodic wake-up (SPW) control mechanism in this paper. Wireless communication systems use a similar approach in order to reduce the power consumed by the wireless devices [14]. In the field of wireless communications, SPW control schemes with variable sleep periods as well as constant sleep periods have been researched, and the effectiveness of the former has already shown [15], [16].

This paper proposes an SPW control mechanism with variable sleep period for PON systems. The proposal sets the sleep period according to traffic conditions such as average frame interval, queue length, and class of service (CoS). Therefore, the power saving effect is greatly improved compared to using a constant sleep period. In addition, the protocols needed between an OLT and ONUs are described on the assumption that the proposed mechanism is applied to the 10G class PON systems. The power saving performance of the mechanism and its impact on the quality of service (QoS) are confirmed for 10G class PON systems by numerical simulations.

This paper is organized as follows. The following section presents the SPW technique, the devices responsible for power saving, and the proposed SPW control mechanism. Section 3 introduces a scheme to determine the variable sleep period. An implementation of the proposed mechanism is described in detail in Sect. 4. Section 5 uses numerical simulations to demonstrate its validity. Finally, our conclusion is described in Sect. 6.

2. Power Saving Mechanism

This section presents the power saving functions installed in the OLT and ONU. In addition, the relationships among the power saving functions are clarified by using a block diagram.

2.1 SPW Operation

Figure 3 illustrates the SPW operation of the ONU. The ONU repeatedly switches between active and sleep modes. In Fig. 3, P_a and P_s denote the power consumption of the ONU in the active mode and the power consumption of the ONU in the sleep mode, respectively. In addition, T_a and T_s denote the period during which the ONU is in the active mode and the period during which the ONU is in the sleep mode, respectively. In the sleep mode, the ONU deactivates unused functions to cut its power consumption. This paper focuses on enhancing the effectiveness of the SPW control mechanism, and does not tackle the problem of which functions should be deactivated. In the active mode, the ONU waits for OLT instructions as to the state switching and also monitors upstream traffic.

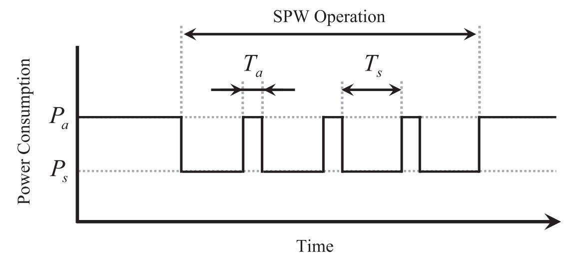

Fig. 3 SPW operation of ONU.

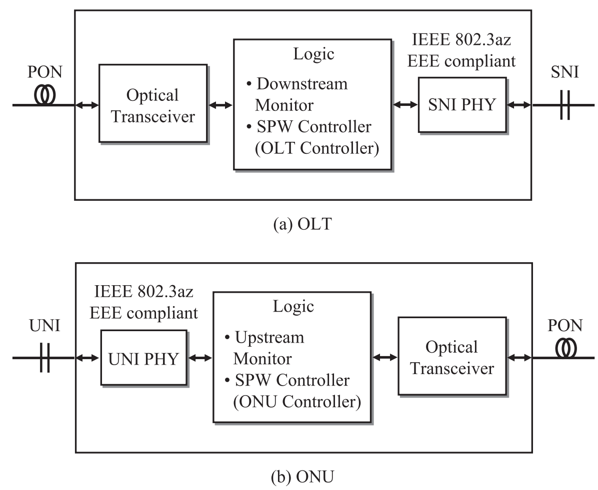

Fig. 4 PON components with power saving functions.

2.2 Power Saving Functions

Figure 4 illustrates the power saving functions installed in the OLT and ONU. First, the OLT functions shown in Fig. 4(a) are described. An OLT is generally comprised of an optical transceiver, a logic part, and an SNI physical layer (PHY) part. In the proposed system, the logic part includes the downstream monitor and the SPW controller. The downstream monitor reads the information of downstream traffic arriving from SNI. The SPW controller, which is called an OLT controller in this paper, instructs the ONU on SPW operation according to the downstream traffic conditions. If the OLT receives downstream traffic intended for a sleeping ONU, the OLT must buffer the frames until the ONU wakes up. Note that the IEEE 802.3az EEE technique is applicable to the SNI PHY part.

Next, the ONU functions shown in Fig. 4(b) are described. An ONU is generally comprised of an optical transceiver, a logic part, and a UNI PHY part. In the proposed system, the logic part includes the upstream monitor and the SPW controller. The upstream monitor reads the information of upstream traffic arriving from UNI. The SPW

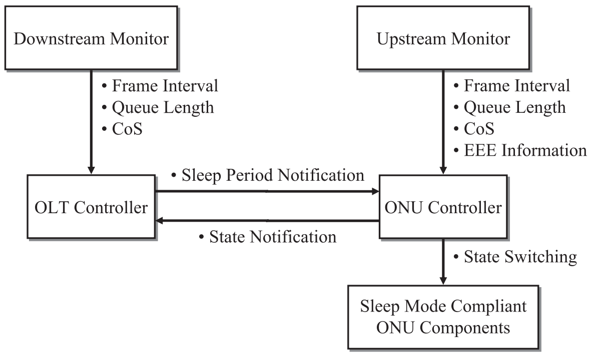

Fig. 5 Block diagram of power saving functions.

controller, ONU controller in this paper, activates or deactivates the ONU in accordance with the OLT instructions. If the ONU receives upstream traffic from UNI, the ONU enters the active mode regardless of the OLT instructions. Note that the IEEE 802.3az EEE technique is applicable to the UNI PHY part.

2.3 SPW Control Mechanism

Figure 5 shows the block diagram of the power saving functions. The function blocks correspond to the functions shown in Fig. 4. The OLT monitors downstream traffic and obtains traffic information such as frame interval, queue length, and CoS. The OLT controller determines whether it forces the ONU to perform the SPW operation on the basis of the downstream traffic information. In SPW control with constant sleep period, the sleep period is prepared in advance. On the other hand, in SPW control with variable sleep period, the sleep period is determined based on the traffic information. The algorithms used to calculate the sleep period are described in the following section.

The OLT controller notifies the ONU whether the ONU should perform the SPW operation. At the same time, the sleep period information can be notified to the ONU if the sleep period is variable. The ONU monitors upstream traffic and obtains traffic information such as frame interval, queue length and CoS. Then, the ONU controller determines whether it enters the sleep mode on the basis of the OLT instructions and the upstream traffic information. If the ONU detects upstream traffic, the ONU enters the active mode regardless of the OLT instructions. The ONU controller notifies the OLT of the ONU state, i.e. the active mode or the sleep mode. In addition, the ONU needs close coordination with the IEEE 802.3az EEE technique if it is applied to the UNI PHY part. The EEE Information described in Fig. 5 means the state notification received from EEE-compliant UNI PHY, i.e. active state or LPI mode. Based on this notification, the ONU detects upstream traffic from UNI.

3. Variable Sleep Period

This section proposes two algorithms to calculate the sleep period for SPW control with variable sleep period. One is an interval-based algorithm and the other is a service-based algorithm.

3.1 Interval-Based Algorithm

In the interval-based algorithm, the OLT determines the presence or absence of downstream traffic by monitoring the average frame interval i_a. The average frame interval i_a at time k, i.e. $i_{a,k}$, is obtained by using the following exponential smoothing calculation

$$i_{a,k} = \alpha i_{k-1} + (1-\alpha)\, i_{a,k-1}, \tag{1}$$

where i_{k-1}, $i_{a,k-1}$ and α denote the instantaneous frame interval at time $k-1$, the average frame interval at time $k-1$ and the smoothing factor which lies between zero and one, respectively.

In the case of SPW control with constant sleep period, the OLT controller sets a threshold for the average frame interval i_a^{th}. If the average frame interval i_a is greater than or equal to the threshold i_a^{th}, the OLT controller determines that there is no downstream traffic, and the constant sleep period T_c is notified to the ONU. On the other hand, If the average frame interval i_a is less than threshold i_a^{th}, the OLT determines that there is downstream traffic. Therefore, the sleep period T_s is set as

$$\begin{cases} T_s = T_c & \text{if } i_a \geq i_a^{th}, \\ T_s = 0 & \text{if } i_a < i_a^{th}. \end{cases} \tag{2}$$

Instead of the constant sleep period T_c, only one-bit information, i.e. the presence or absence of downstream traffic, can be also utilized as

$$\begin{cases} T_s = 1 & \text{if } i_a \geq i_a^{th}, \\ T_s = 0 & \text{if } i_a < i_a^{th}. \end{cases} \tag{3}$$

In this case, the constant sleep period T_c needs to be notified to the ONU in advance.

In the case of SPW control with variable sleep period, the sleep period T_s changes according to the traffic conditions. For instance, the sleep period T_s is determined as

$$T_s = f(i_a) \tag{4}$$

where $f(i_a)$ denotes a function of the average frame interval i_a. In this research, as an example, it is assumed that the sleep period T_s is determined by the function shown in Fig. 6. In Fig. 6, T_s^{min}, T_s^{max}, i_a^{th1}, and i_a^{th2} denote the minimum sleep period, maximum sleep period, the lower threshold of the average frame interval, and the upper threshold of the average frame interval, respectively.

As described in Sect. 2, if the OLT receives downstream traffic while the ONU is sleeping, the OLT needs to buffer the downstream frames until the ONU wakes up. Upon detecting ONU wake-up, the OLT has to calculate the next sleep period. At this time, the OLT controller takes not only the frame interval but also the queue length into account in determining when the ONU should enter the sleep mode. This is because the OLT has to send the

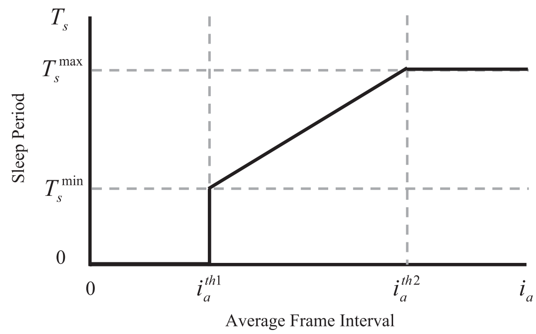

Fig. 6 An example of interval-based variable sleep period.

Table 1 An example of service-based variable sleep period.

CoS value	Priority	Sleep period
0	Low	$T_s = f_1(i_a)$
⋮	⋮	⋮
4	Medium	$T_s = f_2(i_a)$
⋮	⋮	⋮
7	High	$T_s = 0$

frames buffered in the queue during the sleep period T_s to the ONU as a matter of first priority. This means that the ONU does not perform SPW operation again until the downstream queue length in the OLT becomes zero.

3.2 Service-Based Algorithm

In the service-based algorithm, the OLT determines whether the OLT should force the ONU to enter the sleep mode according to the CoS values of the downstream frames. CoS, which indicates service priority, is defined as a three-bit field within the Ethernet frame header. A sleep period is determined for each CoS value. The purpose of the service-based algorithm is to prevent the ONU from entering the sleep mode in the presence of high-priority traffic such as telephony services. With this algorithm, transparent services that are not affected by additional delay can be provided selectively.

Table 1 shows an example of service-based variable sleep period. When the traffic is low-priority, i.e. CoS = 0, SPW operation is activated in the absence of traffic in accordance with the sleep function $f_1(i_a)$. For example, low-priority traffic corresponds to best effort services. On the other hand, when high-priority traffic exists, i.e. CoS = 7, SPW operation is not activated for a certain period even in the absence of traffic. For example, high-priority traffic corresponds to telephony services. When several frames with different class of CoS are simultaneously passed through the PON system, the sleep period function of the higher-priority traffic is selected preferentially. For example, when the highest-priority service (CoS = 7) is being utilized, the SPW operation is not activated even if the other classes of traffic ($\text{CoS} = 0, 1, \cdots, 6$) exist simultaneously. As a result, service degradation is avoided by using the service-based algorithm in the presence of particular traffic.

4. Implementation

In this section, the protocols needed between an OLT and ONUs are described on the assumption that the proposed power saving mechanism is applied to 10G class PON systems, i.e. IEEE 802.3av 10G-EPON and FSAN/ITU-T 10G-PON.

4.1 Message Definition and Utilized Protocols

In order to realize SPW operation, at least three control messages are required. They are the Request message, the ACK/NACK message, and the Confirmation message as shown in Table 2.

First, we present the control protocols defined in 10G class PON systems. In 10G-EPON systems, enhanced MAC control messages will be defined for flexible use of Multi-Point Control Protocol (MPCP) messages. In 10G-PON systems, it is assumed that the Physical Layer Operations, Administration and Maintenance (PLOAM) messages are utilized for ONU management as in the G-PON system. The enhanced MAC control messages of 10G-EPON systems and the PLOAM messages of 10G-PON systems can be utilized for implementing the SPW control mechanism.

4.2 Sequence of SPW Operation

SPW operation for downstream traffic is described. The sequence of SPW operation is shown in Fig. 7. If there is no downstream traffic for the ONU, the OLT sends a Request message including sleep period T_s to the ONU. The sleep period T_s is set by the algorithms described in Sect. 3. Including T_s in the Request message makes it possible to use variable sleep periods and so further optimize the power saving efficiency. Upon receiving its Request message, the ONU sends an ACK message back to the OLT and enters the sleep mode.

After expiration of the sleep period T_s, the sleeping ONU enters the active mode. The ONU then sends a Confirmation message to the OLT to check for the existence of downstream traffic for the ONU. Upon receiving the Confirmation message, the OLT forwards the frames buffered during the sleep period T_s to the ONU. After frame transfer is completed, in the absence of additional downstream traffic for the ONU, the OLT sends a Request message including sleep period T_s to the ONU. On the other hand, in the presence of downstream traffic for the ONU, the OLT sends another Request message whose sleep period T_s is set to zero in order to keep the ONU active and forwards the downstream traffic. The Request message is also used to acknowledge the Confirmation message. Note that the upstream bandwidth needed to send the control messages is consistently assigned by the dynamic bandwidth allocation (DBA) [3] function of the OLT. When the ONU wakes up

Table 2 Definition of required messages.

Message name	Up/Down	Function	Trigger	Times sent (example)	Effect of receipt
Request	Down	To put the ONU to sleep or to keep the ONU active. To inform the sleep period.	When there is no downstream traffic at the OLT or when the OLT receives the Confirmation message.	3	The ONU acknowledges the request and switches its mode.
ACK/NACK	Up	To indicate reception of the Request message. To inform the state of the ONU.	When the ONU receives the Request message.	1	This message ensures reliable transfer of the Request message.
Confirmation	Up	To check for the presence or absence of downstream traffic.	When the ONU enters the active mode from the sleep mode.	3	The OLT instructs the ONU to switch mode depending on the traffic conditions.

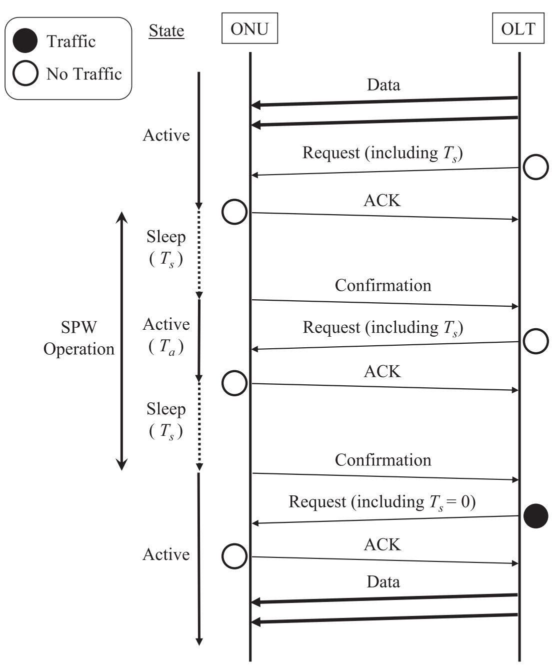

Fig. 7 SPW operation for downstream traffic.

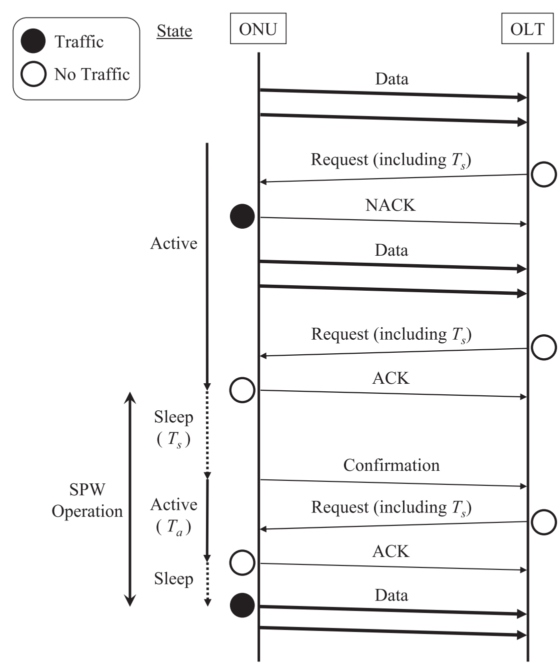

Fig. 8 SPW operation for upstream traffic.

just after the bandwidth assignment is done, the Confirmation message has the possibility to wait for up to two DBA grant cycles.

Next, SPW operation for upstream traffic is described. The sequence of SPW operation is shown in Fig. 8. Upon receiving a Request message, the ONU that is receiving upstream traffic refuses to enter the sleep mode and sends a NACK message to the OLT, since the ONU has upstream traffic from UNI. If a sleeping ONU receives upstream traffic from UNI, it enters the active mode instantly and forwards the upstream traffic. Note that upstream frame transfer is performed after upstream bandwidth allocation by the DBA function of the OLT.

In the sequence of SPW operation, the number of ONUs communicating with the OLT changes in each DBA grant cycle, since a sleeping ONU cannot send any frames to the OLT until they wake up. In the proposed mechanism, a sleeping ONU remains registered for the OLT even if the ONU does not communicate with the OLT, and the OLT consistently assigns at least minimum upstream bandwidth to each registered ONU including a sleeping ONU so that the ONU can send a control message in every DBA grant cycle. Note that the OLT can differentiate a sleeping ONU from a non-registered ONU by setting an appropriate timeout period which is longer than a sleep period. Thus, when the sleeping ONU receives upstream traffic from UNI, the ONU can wake up and report required upstream bandwidth to the OLT without waiting for a sleep period to expire.

The change of the number of ONUs communicating with the OLT does not affect the proposed power saving mechanism, since whether each ONU performs SPW operation or not is determined independently on the basis of traffic conditions for each ONU. However, it is also true that the frame transfer time can be longer, if the number of ONUs communicating with the OLT is larger and the upstream/downstream bandwidth assigned to each ONU is smaller. In this case, low-rate traffic continues to be at the ONU, and there are fewer chances to perform SPW operation. As a result, power saving performance of the proposed mechanism can deteriorate. Further studies on energy efficient bandwidth allocation algorithms are considered as our future works.

5. Performance Evaluation

This section describes the numerical simulations used to confirm the power saving performance of the proposed mechanism in 10G class PON systems and its impact on QoS. First, the performance of the SPW control mechanism with constant sleep period is shown. Next, the performance of the SPW control mechanism with variable sleep period and the interval-based algorithm is verified.

5.1 Assumptions

The simulation parameters are shown in Table 3. Transition time T_t was included in sleep period T_s. The parameters were set to provisional values, since the 10G class PON systems are still under standardization and development. In other words, there is a possibility that the parameters, especially power consumption in sleep mode P_s and power consumption in active mode P_a, may change in the future. The amount of reduced power is greatly affected by power consumption in each mode. At least, however, an ONU with the proposed mechanism consumes less power than a normal ONU if the power increase arising in switching between the active and sleep modes is negligible. Therefore, it is considered that the proposed mechanism works well even if power consumption in each mode changes.

The simulation assumed that there was only downstream traffic whose arrival rate followed a Poisson distribution. The frame length was set to constant value 1250 bytes. In addition, only one ONU was connected to the OLT to confirm the effect of traffic conditions for an ONU on power saving performance. In the simulations, the performance of the SPW control mechanism was assessed by varying the control parameters.

5.2 Constant Sleep Period

Figures 9–11 show the simulation results for constant sleep period. The average ONU power consumption is shown in Fig. 9. The average queuing delay of the downstream traffic at the OLT is shown in Fig. 10. In addition, the relationship between the power consumption and the queuing delay is shown in Fig. 11. It was assumed that there was no frame loss. In the simulation, the performance was assessed by varying the threshold of the average frame interval, i_a^{th}, and the sleep period T_s.

In all cases, the power consumption converged to P_a = 10 W at the average frame interval of around 1 ms. Above this value, the power consumption was smaller with T_s = 10 ms than with T_s = 5 ms. In addition, decreasing i_a^{th} resulted in lower power consumption. On the other hand, the queuing delay converged to 0 ms at the frame interval of around 1 ms, and 50% of T_s at the frame interval of around

Table 3 Simulation parameters.

Name	Variable	Value
Smoothing factor	α	0.2
Transition time	T_t	2 ms
Round-trip transmission delay	T_r	0.2 ms
Power consumption in sleep mode	P_s	1 W
Power consumption in active mode	P_a	10 W

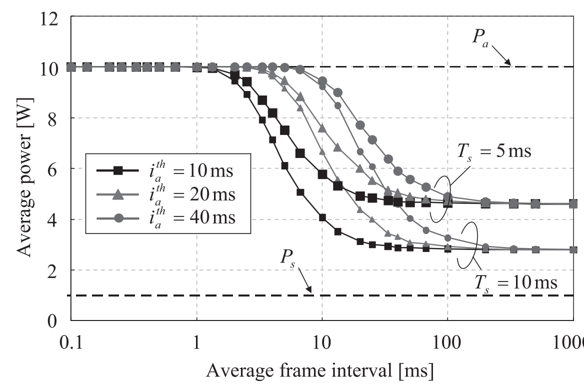

Fig. 9 Power consumption (constant sleep period).

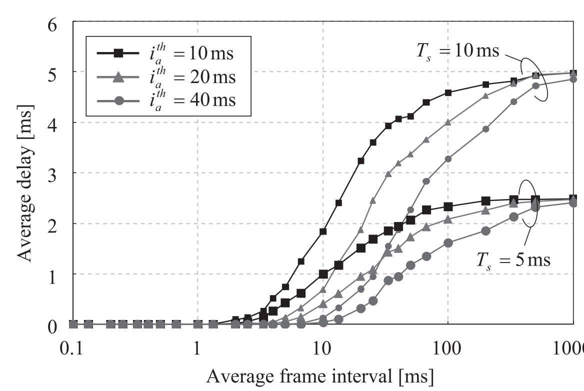

Fig. 10 Queuing delay (constant sleep period).

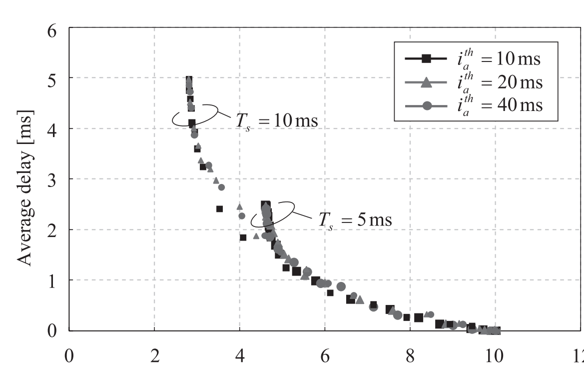

Fig. 11 Relationship between power consumption and queuing delay (constant sleep period).

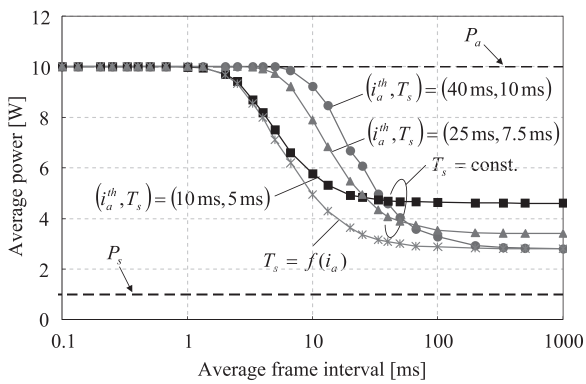

Fig. 12 Power consumption (variable sleep period).

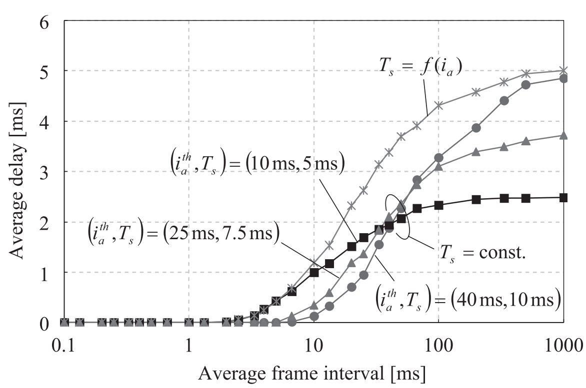

Fig. 13 Queuing delay (variable sleep period).

1000 ms. In addition, increasing i_a^{th} decreased the queuing delay. SPW operation generates two kinds of queuing delays. One is a delay caused by buffering of frames during the sleep period T_s. The other is a delay caused by message exchange after activation of the ONU. The peak value of the total queuing delay is equal to the sum of T_s and a four-way transmission delay for Request, Confirmation, Request, and ACK messages.

It was confirmed that increasing the sleep period T_s or decreasing the threshold i_a^{th} improved the power saving performance while increasing the queuing delay. T_s and i_a^{th} should be designed to satisfy acceptable queuing delay values.

5.3 Variable Sleep Period

Figures 12–14 show the simulation results with variable sleep period. The function shown in Fig. 6, $f(i_a)$, was used to determine the sleep period. The control parameters T_s^{min}, T_s^{max}, i_a^{th1}, and i_a^{th2} were set to 5 ms, 10 ms, 10 ms, and 40 ms, respectively. The average ONU power consumption is shown in Fig. 12. The average queuing delay of the downstream traffic at the OLT is shown in Fig. 13. In addition, the relationship between the power consumption and the queuing delay is shown in Fig. 14. It was assumed that there was no frame loss. In the simulation, the power saving performance was compared against the case of the SPW control

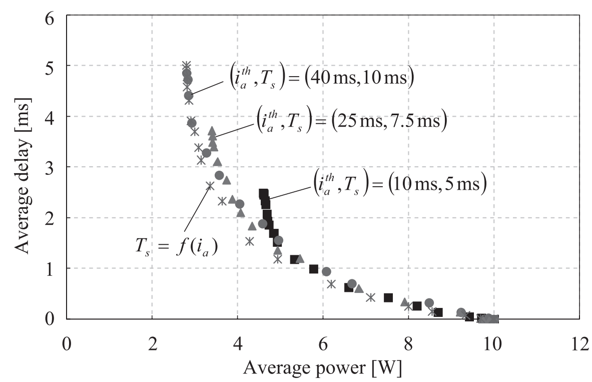

Fig. 14 Relationship between power consumption and queuing delay (variable sleep period).

mechanism with constant sleep period.

With variable sleep period, the power consumption converged to P_a = 10 W at the average frame interval of around 1 ms. At higher values, the variable sleep period approach yielded lower power consumption than constant sleep period. On the other hand, the variable sleep period yielded a queuing delay that converged to 0 ms at the frame interval of around 1 ms, and 50% of the maximum sleep period T_s^{max} at the frame interval of around 1000 ms.

It was confirmed that varying the sleep period improved the power saving performance while increasing the queuing delay. Therefore, the mechanism with variable sleep period is superior to the mechanism with constant sleep period in adaptability to varying traffic. On the other hand, the mechanism with variable sleep period requires more complicated algorithms than the mechanism with constant sleep period. The control parameters of function $f(i_a)$ should be designed to satisfy acceptable queuing delay values. By using the service-based algorithm described in Sect. 3, the proposed mechanism can be also applied to services that cannot accept any queuing delay.

6. Conclusion

This paper proposed a novel SPW control mechanism with variable sleep period as an effective power saving mechanism for 10G class PON systems. Two algorithms to calculate the sleep period, i.e. interval-based and service-based algorithms, were also proposed. In addition, the protocols needed between the OLT and ONUs in 10G-EPON systems and 10G-PON systems were described: we proposed protocols to implement the variable sleep period technique, which further optimizes the power saving efficiency. The performance of the SPW control mechanism was assessed by simulations in which the control parameters varied. The simulations confirmed that increasing the sleep period T_s, decreasing the traffic threshold i_a^{th}, or using the variable sleep period improved the power saving performance while increasing the queuing delay. The control parameters should be designed with a consideration of the QoS desired.

As future works, we intend to consider the selection of sleep mode trigger and an appropriate function that determines the optimum sleep period. In addition, bursty traffic which comes during the sleep period prevents the ONU from performing SPW operation immediately. This indicates there is a possibility that the power saving performance deteriorates. Simulations in the presence of bursty traffic are also considered as our future works.

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