A Cooperative ONU Sleep Method for Reducing Latency and Energy Consumption of STA in Smart-FiWi Networks

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***Abstract*—Fiber-Wireless (FiWi) network is a classification of network that combines the massive bandwidth of the optical network and the reach of the wireless network. FiWi networks are usually composed of an optical and a wireless component. Since both components are designed to work independently, some mechanisms, such as the different power saving methods in both components, may not cooperate with each other and this may result in an undesirable performance. In this paper, we identify that the conflicting power saving mechanisms cause unnecessary energy consumption and introduce additional delay to the overall FiWi network. To cope with this problem, we propose a novel ONU sleep method, which dynamically control the ONU sleep period based on the STAs energy control mechanism. Finally, we demonstrate that our proposed method has shorter latency and is more efficient in term of energy consumption than the existing method.**

***Index Terms*—Passive Optical Network (PON), Wireless Local Area Network (WLAN), Fiber Wireless (FiWi) network, Optical Network Unit (ONU) sleep, Power Saving Mode (PSM), Adaptive PSM (APSM), and energy efficiency.**

I. Introduction

THE number of network users and the traffic load offered by those users are steadily increasing. To handle this amount of traffic on a ubiquitous society, Fiber Wireless (FiWi) networks are gaining much attention. FiWi networks are composed of optical and wireless networks [1]. While the optical networks are able to provide a massive amount of bandwidth, it cannot be deploy everywhere due to the deployment cost and the heavy reliance on physical infrastructure. On the other hand, wireless networks are much more flexible and are able to provide services in much larger areas than optical networks. By combining these two different networks, as illustrated in Fig. 1, it is possible to enable high speed connectivity anywhere and anytime by taking advantage of both the high capacity of optical networks and the flexibility of wireless networks [2]. In this work, we focus on the FiWi network that uses Passive Optical Network (PON) and Wireless Local Area Network (WLAN) as its optical network and wireless network component, respectively.

PON is one of the most popular Fiber-To-The-Home (FTTH) networks used to provide broadband communication service. PON is widely deployed because it is a point-to-multipoint architecture, thus having a cheaper deployment cost than other FTTH networks, which are composed of point-to-point architecture [3]. PONs consist of an Optical Line Terminal (OLT), Optical Network Units (ONUs), a passive splitter, and optical fiber cables. The data frames transmitted by an OLT can be received at all ONUs, which are connected to the passive splitter. In addition to a PON, another component of the FiWi network that made up the wireless part is a WLAN. WLAN is also a well-known wireless networking architecture owing to the progress of widely adapted technologies like the IEEE 802.11. Stations (STAs), such as smart phones and laptops, which can communicate wirelessly as long as they are in the communication range. These networks, i.e., PON and WLAN, are developed separately [4], [5]. Therefore, power saving mechanisms in these networks work independently, and, according to [1] and [6], the difference in the communication method between PON and WLAN causes an inefficient use of network resources, reducing Quality of Service (QoS) and energy efficiency. In FiWi networks, it is desirable to establish a cooperative mechanism integrating PON and WLAN seamlessly.

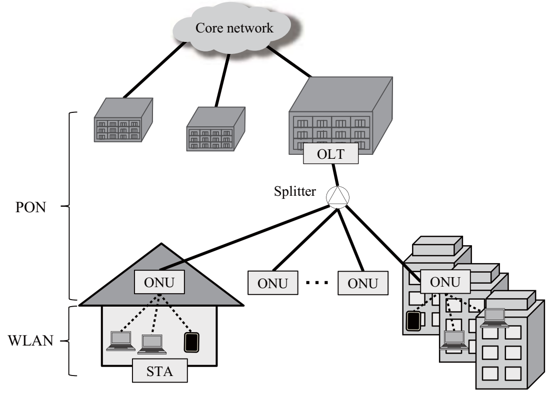


Fig. 1. An example of FiWi network.

Thus, in this paper, we redesign the ONU sleep method for the power saving mechanisms in WLAN to improve the performance in terms of energy efficiency and latency. The proposed method controls the ONU behavior based on the power saving mechanism used by STA in WLAN. The remainder of this paper is organized as follows. In Section II, we briefly summarize power saving mechanisms in FiWi networks and analyze the effects of the mechanisms in terms of latency and energy efficiency. In Section III, we analyze the latency and the energy consumption when both the power saving mechanisms in PON and WLAN are at work. In Section IV, we propose a novel ONU sleep mechanism, which controls ONU sleep period and behavior based on STA energy control mechanisms. Additionally, the analysis of the ONU energy consumption and latency is also presented. In Section V, we show the improvements in network performances introduced by our method. Finally, we conclude the paper in Section VI.

II. Analysis of Conventional Energy Control Mechanisms

As network traffic rapidly increases, energy efficiency is becoming a major problem [7]–[9]. To address this energy efficiency problem in FiWi networks, ONU sleep mechanisms for ONU and Power Saving Mode (PSM) and Adaptive PSM for STA have been proposed. ONU sleep mechanisms periodically turn ONU transmitter components off to reduce unnecessary energy consumption. Although ONU sleep mechanisms can greatly improve the situation in that aspect, they introduce additional delay and enlarge the latency on the connection. PSM, standardized by IEEE 802.11 [10], and Adaptive PSM are designed to reduce energy consumption of the STAs [11], [12]. Both PSM and Adaptive PSM aim to use power efficiently by periodically turning off the STA's transmitter. These power saving mechanisms cause additional delay for transmitting data in a way similar to that of ONU sleep methods. However, power saving mechanisms in WLAN, i.e., PSM and Adaptive PSM, are developed without considering other power saving mechanisms in the network.

In other words, since FiWi networks are separated into optical domain and wireless domain, many power saving mechanisms exist in these domains, such as ONU sleep, PSM and Adaptive PSM. Additionally, these mechanisms operate independently and are designed for different purposes. Therefore, the amount of energy that can be reduced and the protocol for transmitting data are different among different mechanisms. In this section, we analyze the impacts of the additional delay caused by each power saving mechanism. In addition, to simplify the analysis, we consider the propagation delays between ONU and OLT and between Access Point (AP) and STA as zero. Moreover, it is assumed that the downstream data arrives to OLT or AP randomly for simplicity.

A. Delay introduced by ONU sleep

An ONU that is implemented with the ONU sleep method has two energy consumption modes, active and sleep mode, with the ONU taking on different modes depending on the situation [13]. When the ONU has traffic to send or receive, it is in active mode. Otherwise, it is in sleep mode. While the ONU is in active mode, it can send or receive data traffic, but consumes more energy. On the other hand, while the ONU is in sleep mode, it consumes much less energy but cannot receive any downstream traffic transmitted by the OLT. Therefore, ONUs will periodically alternate between sleep and active mode to receive traffic from the OLT, as shown in Fig. 2. The sleep period interval is determined by the OLT. When the sleep period ends, the ONU will briefly become active to check for incoming data at the OLT, then, the ONU sends a wake up massage (Confirmation in Fig. 2) to the OLT. If

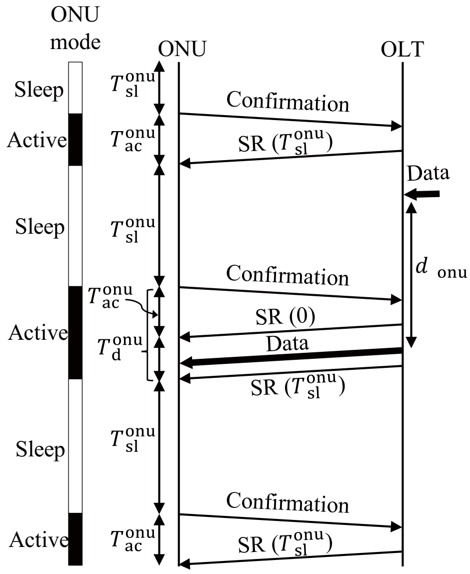


Fig. 2. An example of the communication with ONU sleep in PON.

there are no incoming data at the OLT, the OLT will send a Sleep Request (SR) with the predetermined sleep period to the ONU. However, if a confirmation message is received by the OLT when there is incoming data, the OLT will send a SR with sleep period of zero to request the ONU to not go back to sleep and transmit the data to the ONU. After the data transmission is completed, the OLT will send another SR message with the predetermined sleep interval to request the ONU to go back to sleep.

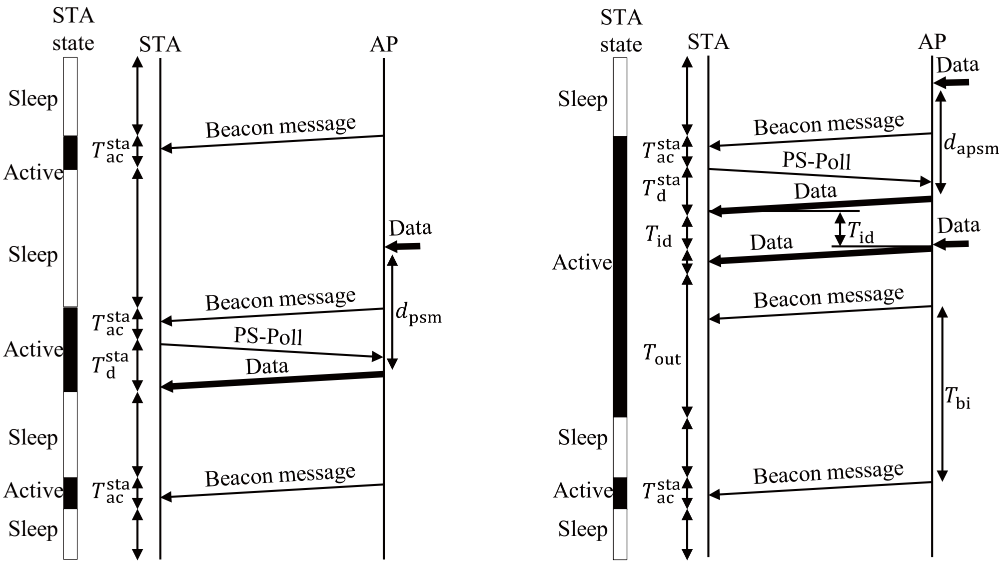
Since the OLT only takes action when it receives a confirmation message from the ONU, when the downstream data arrives at the OLT right after the ONU switched to the sleep mode, the data will have to be buffered at the OLT until the sleep interval expires. Therefore, the expected value of $d_{\rm onu}$, which is the delay caused by the ONU sleep, is derived as the following expression, with $T_{\rm ac}^{\rm onu}$ and $T_{sl}^{\rm onu}$ representing active and sleep mode period of ONU sleep, respectively.

$$\begin{aligned} d_{\rm onu} &= 0 \cdot \frac{T_{\rm ac}^{\rm onu}}{T_{\rm sl}^{\rm onu} + T_{\rm ac}^{\rm onu}} + \int_0^{T_{\rm sl}^{\rm onu}} t \cdot \frac{1}{T_{\rm sl}^{\rm onu} + T_{\rm ac}^{\rm onu}} dt \\ &= \frac{1}{T_{\rm sl}^{\rm onu} + T_{\rm ac}^{\rm onu}} \cdot \frac{(T_{\rm sl}^{\rm onu})^2}{2}. \end{aligned} \tag{1}$$

The first and second term in the first row of Eq. 1 are the expected delay when the data arrives during the active and sleep mode, respectively. Note that we assume that the data is transmitted immediately when it arrives during the active mode and hence does not have any delay and that the incoming data arriving at the OLT can arrive at any given time.

B. Delay introduced by PSM

STAs in PSM [14] support two energy consumption states: the active state, where the STAs are in operation, and the sleep state, where the STAs are inactive. Basically, a STA operating under PSM remains in the sleep state except for scenarios where the STA is receiving beacon messages from the AP or



(a) An example of the communication with PSM in WLAN.

(b) An example of the communication with Adaptive PSM in PON.

Fig. 3. An example of the communication with power saving mechanisms in WLAN.

the STA is sending or receiving data traffic. In Fig. 3(a), the AP broadcasts a beacon message at the beginning of the beacon interval, $T_{\rm bi}$, (a typical beacon interval is set to 100ms) and the STA is scheduled to wake up before every beacon interval. The AP uses the Traffic Indication Map (TIM) included in the beacon message to inform STAs of the data currently buffered at the AP. If the TIM shows that the data addressed to that STA is stored in the AP, the STA remains in active state. Each STA checks the TIM to see if there are any data to be received from the AP. If there are some data to be received, the STA will remain active and send a PS-Poll frame to request the AP to transfer the data. On the other hand, the STA goes back to sleep if there are no available data. In this way, the STAs operating under PSM remain in the sleep state unless the beacon message is received. Thus, PSM can drastically reduce energy consumption.

One drawback of PSM is that since the AP can only transmit data to STA at the start of the beacon interval, the incoming data that arrive at the AP before the end of the current beacon interval have to wait until the next beacon interval. This drawback is referred to as the *RTT round up effect* [11], [15], [16]. It is necessary to take the beacon interval into account when calculating the delay due to STA sleep in PSM, $d_{\rm psm}$, because STAs can only receive data at the beginning of the beacon interval. In other words, when some data arrive at the AP while the intended STA is sleeping, the data will be buffered until the beginning of the next beacon interval. However, if the data arrive when the intended STA is active, the data can be sent to the STA without any additional delay. Thus, we can derive the expected delay caused by PSM operation to be as the following expression, with $T_{\rm ac}^{\rm sta}$ which denoting the active state period of the STA.

$$\begin{aligned} d_{\rm psm} &= 0 \cdot \frac{T_{\rm ac}^{\rm sta}}{T_{\rm bi}} + \int_{0}^{T_{\rm bi}-T_{\rm ac}^{\rm sta}} t \cdot \frac{1}{T_{\rm bi}} dt \\ &= \frac{1}{T_{\rm bi}} \cdot \frac{(T_{\rm bi} - T_{\rm ac}^{\rm sta})^2}{2}. \end{aligned} \tag{2}$$

C. Delay introduced by Adaptive PSM

Adaptive PSM is used by mobile devices in WLANs to achieve energy efficiency and high performance [17], [18]. Basically, Adaptive PSM operation is similar to PSM operation. An example of a STA operating under Adaptive PSM is shown in Fig. 3(b). In contrast to PSM, where the STAs immediately transition to the sleep state right after receiving the TIM (if there are no available data), the STAs operating in Adaptive PSM remain in the active state until the *PSM timeout*, $T_{\rm out}$, is over. *PSM timeout* is set to be between 100ms and 200ms according to [12]. Therefore, it means that if the idle period is shorter than the *PSM timeout*, the data transmission can be completed without any delay, because the STA is still active until the end of the *PSM timeout*. The idle period, T_{id}, is the time period from the last action committed by the STA, such as sending or receiving data traffic, to when the downstream data arrive at the AP. Therefore, delay in Adaptive PSM is summarized as follows:

$$d_{\rm apsm} = \begin{cases} 0 & (T_{\rm id} < T_{\rm out}) \\ d_{\rm psm} & (otherwise). \end{cases} \tag{3}$$

From the above expression, it is shown that the delay in Adaptive PSM is affected by the value of $T_{\rm id}$. Additionally, the value of $T_{\rm id}$ depends on the pattern of traffic arriving at AP.

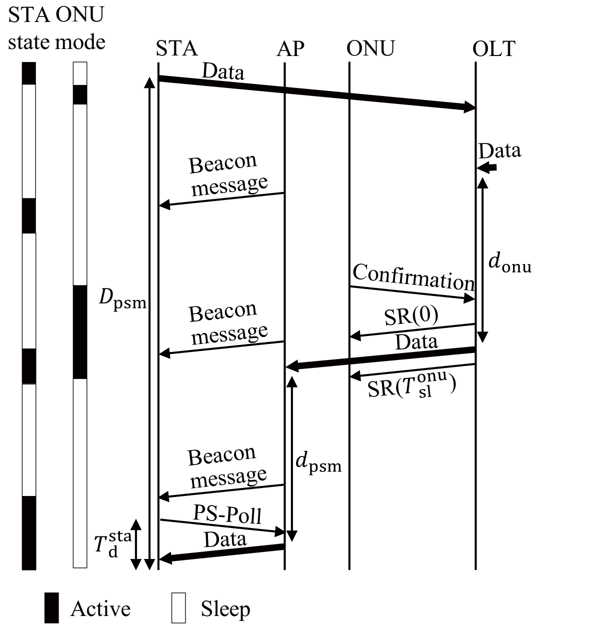


Fig. 4. An example of communication over a network with PSM and ONU sleep mechanisms.

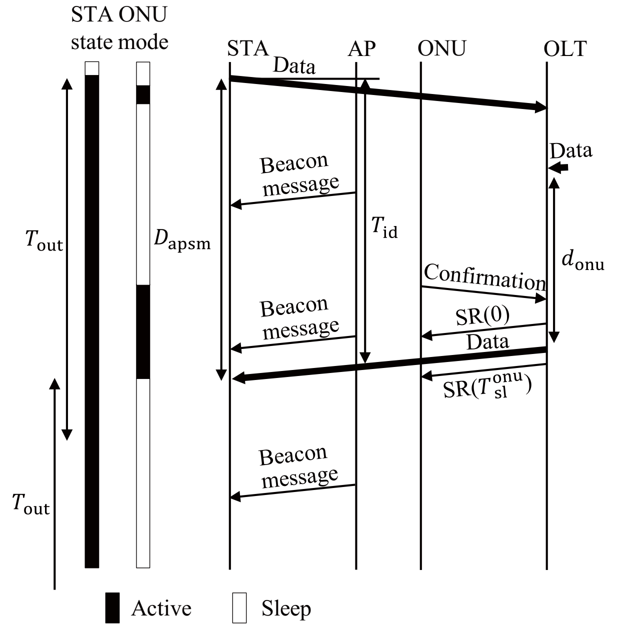


Fig. 5. An example of communication over a network with Adaptive PSM and ONU sleep mechanisms.

III. Performance Analysis of FiWi Network with independently operating power saving mechanisms

In FiWi network, because it is composed of WLAN and PON, the several power control mechanisms described in Sec. II work independently and simultaneously, resulting into a negative impact in the network performance. We analyze the latency and energy consumption for a round-trip transmission from the STA when both power saving mechanisms in PON and WLAN are in operation, and point out inefficiencies due to the ONU sleep mechanism working without considering the STA power saving mechanisms.

A. Impact on communication with PSM by ONU sleep

Fig. 4 shows an example of communication where ONU sleep and PSM mechanisms are in work. According to our previous work [6], we analyzed and clarified inefficiencies by focusing on a network where ONU sleep and PSM are both used. However, that work assumes that the sleep period is shorter than the beacon interval, ($T_{\mathrm{sl}}^{\mathrm{onu}} < T_{\mathrm{bi}}$). In this paper, we consider that the sleep period may be longer than the beacon interval. By using Eq. 1 and Eq. 2, which express the delay caused by PSM and ONU sleep operations, respectively, the latency in ONU sleep and PSM mechanisms, D_{psm}, is derived as follows:

$$\begin{aligned} D_{\mathrm{psm}} &= d_{\mathrm{base}} + d_{\mathrm{onu}} + d_{\mathrm{psm}} \\ &= d_{\mathrm{base}} + \frac{1}{2} \cdot \left\{ \frac{(T_{\mathrm{sl}}^{\mathrm{onu}})^2}{T_{\mathrm{sl}}^{\mathrm{onu}} + T_{\mathrm{ac}}^{\mathrm{onu}}} + \frac{(T_{\mathrm{bi}} - T_{\mathrm{ac}}^{\mathrm{sta}})^2}{T_{\mathrm{bi}}} \right\}, \end{aligned} \quad (4)$$

where d_{base} shows the latency including the delay between OLT and an outside data source. Note that d_{base} does not include the delay caused by the power saving mechanisms. When comparing Eq. 1, Eq. 2, and Eq. 4, we can see that delay occurs at both the OLT and the AP, which drastically have impacts latency. Moreover, even with a much shorter sleep period of PSM and STA is ready to receive data traffic from the ONU with only a small delay, ONU does not send the data immediately since the data can be sent from the OLT only after the expiration of the sleep period. Therefore, the STA wakes up and cannot receive any data, resulting in a waste of energy. Note that, in the case where the ONU sleep period is shorter than the one of the STA, the ONU will waste energy by contrast.

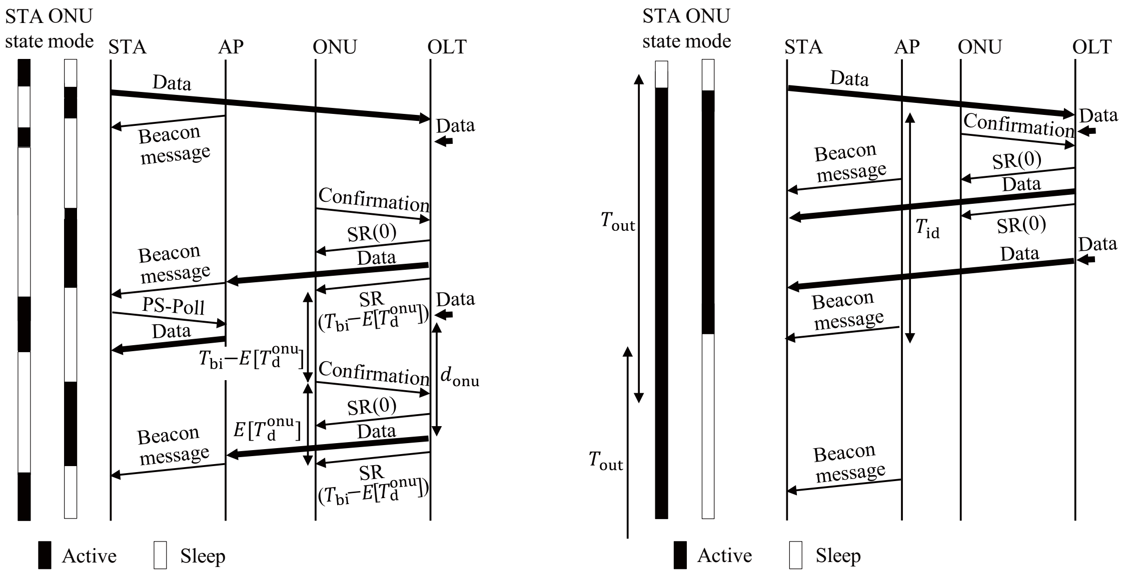
Energy consumed during D_{psm} increases when the delay becomes longer. During D_{psm}, excluding the data transmission period, $T_{\mathrm{d}}^{\mathrm{sta}}$, the STA repeats the state transition every beacon interval, as shown in Fig. 4. Thus, the energy consumed by the STA, J_{psm}, is derived from $W_{\mathrm{ac}}^{\mathrm{sta}}$ and $W_{\mathrm{sl}}^{\mathrm{sta}}$, which represent STA energy consumption in the active and sleep state, respectively, as follows:

$$\begin{aligned} J_{\mathrm{psm}} &= \left\{ T_{\mathrm{d}}^{\mathrm{sta}} + \frac{D_{\mathrm{psm}} - T_{\mathrm{d}}^{\mathrm{sta}}}{T_{\mathrm{bi}}} \cdot T_{\mathrm{ac}}^{\mathrm{sta}} \right\} \cdot W_{\mathrm{ac}}^{\mathrm{sta}} \\ &+ \left\{ \frac{D_{\mathrm{psm}} - T_{\mathrm{d}}^{\mathrm{sta}}}{T_{\mathrm{bi}}} \cdot (T_{\mathrm{bi}} - T_{\mathrm{ac}}^{\mathrm{sta}}) \right\} \cdot W_{\mathrm{sl}}^{\mathrm{sta}}. \end{aligned} \quad (5)$$

From above, we can confirm that longer latency increases energy consumption.

B. Impact on communication with Adaptive PSM by ONU sleep

In this section, we clarify the influence of ONU sleep on the performance of the STA with Adaptive PSM. We consider the idle period to be a time interval from when the data leave the STA to when acknowledgment is returned to the AP, since we are considering the round-trip transmission from



(a) Case where all STAs in the WLAN are communicating with PSM.

(b) Case where all STAs in the WLAN are communicating with Adaptive PSM.

Fig. 6. An example of communication with cooperative ONU sleep.

the STA. Under this condition, in the network, the STA with Adaptive PSM remains in active state during the *PSM timeout*. Nevertheless, the ONU remains in sleep mode and postpones its downstream data traffic transmission to AP. In this case, although the delay does not occur at the AP, the delay does occur at the OLT. Finally, the idle period, $T_{\rm id}$, becomes longer due to ONU sleep, as shown in Fig. 5. Therefore, the latency is derived as follows:

$$D_{\rm apsm} = \begin{cases} d_{\rm base} + d_{\rm onu} & (T_{\rm id} < T_{\rm out}) \\ d_{\rm base} + d_{\rm onu} + d_{\rm psm} & (otherwise). \end{cases} \tag{6}$$

The energy consumption significantly increases when Adaptive PSM is in operation because the STA has to be active throughout the *PSM timeout* period. The total amount of energy consumed depends on whether or not the idle period is longer than the *PSM timeout* period. When the idle period is shorter than the *PSM timeout* period, the STA remains in active state all the time. On the other hand, when the idle period is longer than the *PSM timeout*, the STA state is controlled by the PSM operation after the expiration of the *PSM timeout*. Then, the energy consumed by the STA, $J_{\rm apsm}$, is expressed as follows:

$$J_{\rm apsm} = \begin{cases} D_{\rm apsm} \cdot W_{\rm ac}^{\rm sta} & (T_{\rm id} < T_{\rm out}) \\ \left\{ T_{\rm out} + T_{\rm d}^{\rm sta} + \dfrac{D_{\rm apsm} - (T_{\rm out} + T_{\rm d}^{\rm sta})}{T_{\rm bi}} \cdot T_{\rm ac}^{\rm sta} \right\} \cdot W_{\rm ac}^{\rm sta} & \\ + \dfrac{D_{\rm apsm} - (T_{\rm out} + T_{\rm d}^{\rm sta})}{T_{\rm bi}} \cdot (T_{\rm bi} - T_{\rm ac}^{\rm sta}) \cdot W_{\rm sl}^{\rm sta} & \\ & (otherwise). \end{cases} \tag{7}$$

Herein, it is confirmed that the energy consumption increases when the latency increases. Hence, shorter latency does not only improve the communication speed but also improves energy efficiency.

IV. Cooperative ONU sleep

The existing ONU sleep method has long latency and inefficient energy consumption by the STA when the STA communicate through PSM or Adaptive PSM. In order to shorten the latency and minimize energy consumption, we propose the novel ONU sleep method which controls the ONU behavior based on the power saving mechanisms used by the STA. Generally, STAs using PSM and Adaptive PSM exist in the same WLAN simultaneously. If the ONU cooperates with one of the two power saving mechanisms, the performance with the other one will decrease. Hence, to cooperate, it is desirable that the ONU sleep method changes its control method dynamically following the condition in the WLAN. Our proposed method, shown in Fig. 6, dynamically changes the sleep method based on the condition of the WLAN at every beacon interval.

1) Case where all STAs in the WLAN are communicating with PSM: At the beginning of the beacon interval of the WLAN, if the STAs with PSM are communicating over the network, the ONU estimates the total amount of incoming data traffic during the next beacon interval and calculates the amount of time required to transmit the data traffic, $E[T_{\rm d}^{\rm onu}]$. In order to send the data during the next beacon interval, the ONU must be in active mode at that time. During the remainder of the beacon interval, the ONU will be idle, so that the next sleep period of the ONU is set to $T_{\rm bi} - E[T_{\rm d}^{\rm onu}]$.

TABLE I
PARAMETER SETTINGS.

$d_{\rm base}$: Latency without delay caused by the power saving mechanisms	50ms
$T_{\rm ac}^{\rm onu}$: Active mode period of ONU sleep	1ms
$T_{\rm sl}^{\rm onu}$: Sleep mode period of ONU sleep	50ms, 100ms, or 200ms
$T_{\rm ac}^{\rm sta}$: Active state period of STA using PSM or Adaptive PSM	1ms
$T_{\rm out}$: The period that the STA using Adaptive PSM remains in active state (*PSM timeout*)	95ms
$T_{\rm bi}$: The interval of every beacon message from AP	100ms
$T_{\rm d}^{\rm sta}$: Time spent for transmitting data traffic	1ms
$W_{\rm ac}^{\rm sta}$: STA energy consumption in the active state	1.3W
$W_{\rm sl}^{\rm sta}$: STA energy consumption in the sleep state	0.5W

The sleep period of the ONU sleep is determined without taking into account the sleep period of the PSM, which leads to a long latency even if the sleep period of the STA is short. By contrast, our proposed method can ensure that the traffic is transmitted by the AP immediately. In other words, in our proposed method, the traffic intended for the STA operating under PSM is temporarily buffered at the OLT. The proposed method allows the traffic to arrive at the AP just before the end of the beacon interval. Therefore, the data can be transferred from the OLT to the STA as if only the ONU sleep mechanism is in action, i.e. there is no effect from PSM sleep. Since the ONU sleep period is set to be $T_{\rm bi} - E[T_{\rm d}^{\rm onu}]$, the latency is calculated by using Eq. 1. Additionally, since $T_{\rm bi}$ is expressed as the sum of $T_{\rm ac}^{\rm onu}$ and $T_{\rm sl}^{\rm onu}$, and $T_{\rm ac}^{\rm onu}$ equals to $E[T_{\rm d}^{\rm onu}]$, $T_{\rm sl}^{\rm onu}$ equals to $T_{\rm bi} - E[T_{\rm d}^{\rm onu}]$. Thus, the latency is expressed as follows:

$$D_{\rm psm}^{\rm pro} = d_{\rm base} + \frac{1}{T_{\rm bi}} \cdot \frac{(T_{\rm bi} - E[T_{\rm d}^{\rm onu}])^2}{2}. \quad (8)$$

Moreover, the energy consumption of the STA relays on the latency as shown by Eq. 5. Thus, the energy consumption of the STA in our proposal is calculated by substituting $D_{\rm psm}^{\rm pro}$ into Eq. 5. Since $D_{\rm psm}^{\rm pro}$ is smaller than $D_{\rm psm}$, the energy consumption of the STA in our proposal is lower than that of the conventional ONU sleep. Therefore, it is expected that our proposed method improves energy efficiency.

2) Case where any STA with Adaptive PSM is communicating in the WLAN: STAs with Adaptive PSM waste their power when there is additional delay introduced by the ONU sleep. Hence, in order to improve the performance of the STA, the ONU should transfer the data immediately. In our proposed method, the next sleep period is set to zero, thus allowing the ONU to stay in active mode until end of the beacon interval.

While the conventional ONU sleep mode causes *Round Up Effect* even though the STA with Adaptive PSM expects low delay communication, in our proposed method, the sleep mode period is set to 0, and the downstream traffic is quickly transmitted. The latency on the connection is equivalent to when there is no ONU sleep mode, and latency is given based on Eq. 2 as follows:

$$D_{\rm apsm}^{\rm pro} = \begin{cases} d_{\rm base} & (T_{\rm id} < T_{\rm out}) \\ d_{\rm base} + d_{\rm psm} & (otherwise). \end{cases} \quad (9)$$

In the same way of the case where all STAs in the WLAN are communicating with PSM, the energy consumption of the STA changes with the latency as shown in Eq. 7. Therefore, since our proposed method decreases the latency, the energy consumption is also decreased with the proposal.

V. EVALUATION

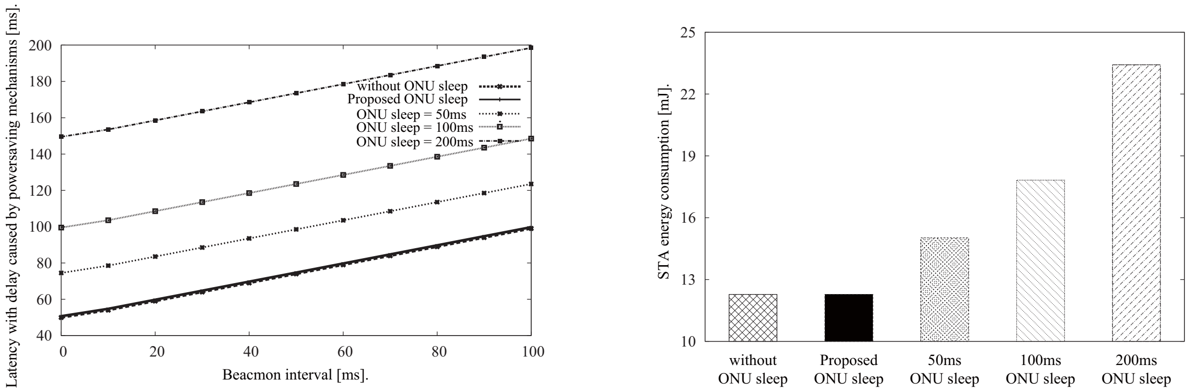
In this section, we evaluate the STA energy consumption and the impact of the power saving mechanisms on the latency. We then compare the proposed ONU sleep method with the existing method. Through numerical evaluation, we prove that the effectiveness of our proposed method for ONU sleep method.

A. Evaluation scenario

We assume that the considered network is made up of a PON and WLANs. The PON is composed of an OLT and multiple ONUs, and each WLAN is composed of an AP and multiple STAs. The STAs are using PSM or Adaptive PSM. We assume that the PON and WLAN follow IEEE 802.3 and IEEE 802.11 standards, respectively. The existing ONU sleep periodically alternates between active and sleep mode where the active interval is 0.1ms and the sleep interval is set to 50ms, 100ms or 200ms. The energy consumed by the STA is 1.3w and 0.5w while the STA is in active and sleep state, respectively [19]. The WLAN sends a beacon message at the beginning of every beacon interval. We assume that the latency without any delay on the connection is 50ms. *PSM timeout period* is set to 95ms. Table I shows the list of parameter settings.

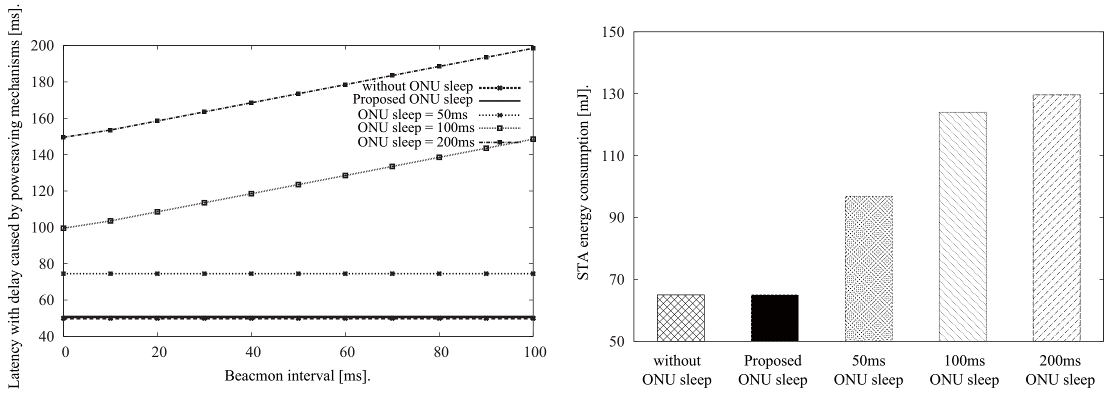
B. Evaluation results in a scenario where STAs are operating under PSM

Fig. 7 shows the latency and energy consumption in the scenario where all STAs are operating under PSM. Firstly, in Fig. 7(a), we compared the latency of the existing and proposed ONU sleep methods. From the figure, it can be seen that the delay when ONU sleep is in operation increases with the amount of time ONU spends sleeping. In contrast, our proposed method achieves the same latency in the case where ONU sleep is not applied. This means that our proposed method does not introduce any additional delay to the PSM. This is because the ONU with the proposed method wakes up before the AP sends the beacon message containing information regarding the buffered data in the AP. Secondly,



(a) Latency. (b) Energy consumption.

Fig. 7. Latency and energy consumption in a scenario where the STAs are operating under PSM.



(a) Latency in the STAs using Adaptive PSM. (b) Energy consumption in the STAs using Adaptive PSM.

Fig. 8. Latency and energy consumption in a scenario where both STAs that are operating under PSM and STAs that are operating under Adaptive PSM coexist.

Fig. 7(b) shows the result of energy consumption of the STA with PSM where all STAs in WLAN are using PSM. From this result, when the ONU is using the existing ONU sleep method, the energy consumption of the STA is more than the energy consumed by the STA without ONU sleep. On the other hand, the energy consumption is conserved when the ONU is controlled by our proposed method.

From the results, it is clearly shown that the proposed method achieves lower latency and energy consumption of STAs than that of conventional ONU sleep when the STAs are operating under PSM. Although the result for latency and energy consumption are the same as the results of the case where ONU sleep is not applied, the proposed method decreases the energy consumption of the ONU by switching the ONU to sleep mode when data do not come. Thus, the proposed method decreases the energy consumption of the STAs and the ONUs while keeping the latency at a minimum value when PSM is utilized in the STAs.

C. Evaluation results in a scenario where STAs are operating under PSM and Adaptive PSM

Fig. 8 shows energy consumption of the STAs when STAs with PSM or Adaptive PSM communicate in the network. Note that the beacon interval used in the WLAN is set to 100ms. Additionally, we assume that the value of T_{id} is smaller than the value of T_{out}. Since the result of latency and energy consumption of STAs when PSM is utilized in the STAs is same as the result in the case where all STAs are operating under PSM, we omitted those results here. Firstly, Fig. 8(a) shows the result of latency of the STAs with Adaptive PSM when both STAs with PSM and Adaptive PSM exist in the WLAN simultaneously. From the figure, it is seen that the latency of the existing ONU sleep mechanism is longer than the one with no ONU sleep. Additionally, the latency of ONU sleep when the sleep period is 100ms and 200ms increases following the increase of beacon interval. This is because the additional delay was generated by the expiration of *PSM timeout* due to the delay caused by the ONU sleep.

On the other hand, since our proposed method ensures that the additional delay never occurs, the latency in our proposed method is comparable to the latency when ONU sleep is not used. Secondly, Fig. 8(b) shows the result of energy consumption of the STA with Adaptive PSM when STAs using PSM and Adaptive PSM coexist. When the STAs are using Adaptive PSM, the STAs remain in active state and consume a lot of energy. Therefore, it is important to shorten latency and reduce wasteful energy consumption. From the result, the STAs communicating under existing the ONU sleep method consume more energy than the STAs communicating without ONU sleep. On the other hand, the energy consumption is reduced when the ONU is controlled by our proposed method. From these results, it is understood that the proposed method achieves lower latency and energy consumption in the STAs also in the case where both PSM and adaptive PSMs are utilized in the network.

VI. Conclusion

FiWi network is a network that integrates both optical and wireless networks. Originally, optical and wireless networks are designed to operate independently. Therefore, the power saving mechanisms used by these networks do not consider the existence of one another. In this work, we focused on the multiple power saving mechanisms, which are working at the different components in the FiWi network. We independently analyzed the energy consumption and delay caused by each power saving mechanism. Using the analysis, we investigated and confirmed that there are delay and energy efficiency problems in the FiWi network when different power saving mechanisms are simultaneously at work at both the optical and wireless components. To resolve delay and energy efficiency problems, we proposed a novel ONU sleep method, which dynamically controls the ONU sleep period based on the STAs' energy control mechanism. We demonstrated that our algorithm can simultaneously reduce latency and unnecessary energy consumption.

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References

[1] Z. M. Fadlullah, H. Nishiyama, N. Kato, U. Hirotaka, K. Suzuki, and N. Yoshimoto, "Smart FiWi Networks: Challenges and Solutions for QoS and Green Communications," *IEEE Intelligent Systems,* vol. 28, no. 2, pp. 86-91, Mar. 2013.

[2] S. He, G. Shou, Y. Hu, and Z. Guo, "Performance of Multipath in Fiber-Wireless (FiWi) Access Network with Network Virtualization," *IEEE Military Communications Conference (MILCOM) 2013,* pp. 928-932, 18-20 Nov. 2013.

[3] P. W. Shumate, "Fiber-to-the-Home: 1977—2007," *Journal of Lightwave Technology,* vol. 26, no. 9, pp. 1093-1103, May 2008.

[4] F. Aurzada, M. Scheutzow, M. Reisslein, N. Ghazisaidi, and M. Maier, "Capacity and Delay Analysis of Next-Generation Passive Optical Networks (NG-PONs)," *IEEE Transactions on Communications,* vol. 59, no. 5, pp. 1378-1388, May 2011.

[5] A. P. Jardosh, G. Iannaccone, K. Papagiannaki, and B. Vinnakota, "Towards an Energy-Star WLAN Infrastructure," *IEEE Workshop on Mobile Computing Systems and Applications 2007,* pp. 85-90, 8-9 Mar. 2007.

[6] K. Togashi, H. Nishiyama, N. Kato, H. Ujikawa, K. Suzuki, and N. Yoshimoto, "On the effect of cooperation between power saving mechanisms in WLANs and PONs," *IEEE International Conference on Communications (ICC) 2013,* pp. 6225-6229, Jun. 2013.

[7] R. Tucker, "Green Optical Communications—Part II: Energy Limitations in Networks," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 17, no. 2, pp. 261-274, Mar.-Apr. 2011.

[8] R. Kubo, J. I. Kani, Y. Fujimoto, N. Yoshimoto, and K. Kumozaki, "Sleep and adaptive link rate control for power saving in 10g-epon systems, " *IEEE Global Telecommunications Conference (GLOBECOM) 2009,* pp. 1-6, Dec. 2009.

[9] A. Nag, M. Tornatore, and B. Mukherjee, "Energy-efficient and cost-efficient capacity upgrade in mixed-line-rate optical networks," *IEEE/OSA Journal of Optical Communications and Networking,* vol. 4, no. 12, pp. 1018-1025, Dec. 2012.

[10] IEEE Computer Society, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 2007.

[11] X. Yi, S. Xilong, C. Xijian, and J. Zhengwei, "An adaptive PSM mechanism in WLAN based on traffic awareness," *10th IEEE International Conference on Sensing and Control (ICNSC) 2013,* pp. 568-573, Apr. 2013.

[12] N. Ding, A. Pathak, D. Koutsonikolas, C. Shepard, Y. C. Hu, and L. Zhong, "Realizing the full potential of psm using proxying, " *2012 Proceedings of IEEE INFOCOM,* pp. 2821-2825, 25-30 Mar. 2012.

[13] R. Kubo, J. I. Kani, H. Ujikawa, T. Sakamoto, Y. Fujimoto, N. Yoshimoto, and H. Hadama, "Study and demonstration of sleep and adaptivelink rate control mechanisms for energy efficient 10g-epon, " *IEEE/OSA Journal of Optical Communications and Networking,* vol. 2, no.9, pp.716-729, Sep. 2010.

[14] IEEE Computer Society LAN MAN Standards Committee. IEEE Std 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Aug. 1999.

[15] H. Yong, Y. Ruixi, M. Xiaojun, and L. Jun, "The IEEE 802.11 Power Saving Mechanism: An Experimental Study," *IEEE Wireless Communications and Networking Conference (WCNC) 2008,* pp. 1362-1367, Mar.-Apr. 2008.

[16] J. Manweiler, and R.R. Choudhury, "Avoiding the Rush Hours: WiFi Energy Management via Traffic Isolation," *IEEE Transactions on Mobile Computing,* vol. 11, no. 5, pp. 739-752, May. 2012.

[17] S. Pack, and Y. Choi, "An adaptive power saving mechanism in IEEE 802.11 wireless IP networks," *Journal of Communications and Networks,* vol. 7, no. 2, pp. 126-134, Jun. 2005.

[18] E. Rozner, V. Navda, R. Ramjee, and S. Rayanchu, "NAPman: network-assisted power management for wifi devices," *In Proceedings of the 8th ACM international conference on Mobile systems (MobiSys '10),* NY, USA, 91-106, 2010.

[19] Y. He, R. Yuan, X. Ma, and J. Li, "The IEEE 802.11 Power Saving Mechanism: An Experimental Study," *IEEE Wireless Communications and Networking Conference (WCNC) 2008,* pp. 1362-1367, Mar.-Apr. 2008.

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