

Synchronized Power Saving Mechanisms for Battery-Powered Mobile Terminals in Smart FiWi Networks

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Synchronized Power Saving Mechanisms for Battery-Powered Mobile Terminals in Smart FiWi Networks

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Abstract—By combining optical networks and wireless networks, Fiber Wireless (FiWi) networks are able to provide broadband and flexible communication. In order to reduce energy consumption of STations (STAs) and Optical Network Units (ONUs), there are several power saving mechanisms in optical networks and wireless networks. Generally, power saving mechanisms lead to delay. The delay problem becomes more critical in FiWi networks where multiple power saving mechanisms are used at the same time to reduce energy consumption. In this paper, we analyze the delay by considering the relationship between the power saving mechanisms, which independently control the STAs and the ONUs in FiWi networks, and point out the problem that two delays can occur at the same time. In order to address the problem, we propose a novel power saving mechanism of STAs, which controls the STAs by synchronizing two power saving mechanisms for ONUs and STAs. Through mathematical analysis and numerical evaluation, we confirm that the proposed method can significantly reduce energy consumption without any increase in latency.

I. INTRODUCTION

Smart Fiber Wireless (SF_iWi) networks are the access networks integrating optical networks and wireless networks [1]. In wireless networks, many mobile users can have ubiquitous and flexible communication when they are in the communication range of the networks. However, wireless networks have a problem that the capacity is relatively small. In contrast, optical networks cannot provide flexible and ubiquitous communication, but they have high capacity and can provide long distance communication. SF_iWi networks are expected to be widely deployed in the future because they are able to achieve large coverage and high capacity by combining the advantages of optical networks and wireless networks [2].

In this paper, we focus on a SF_iWi network composed of a Wireless Local Area Network (WLAN) [3] and a Passive Optical Network (PON) [4]. The structure of the considered network is shown in Fig. 1. In order to widely deploy SF_iWi networks in the future, energy efficiency problem in both WLAN and PON systems, which is already important [5], becomes much more critical. It is also because network energy consumption is increasing drastically due to the increase of the number of users and transmitted data volume recently [6]. That

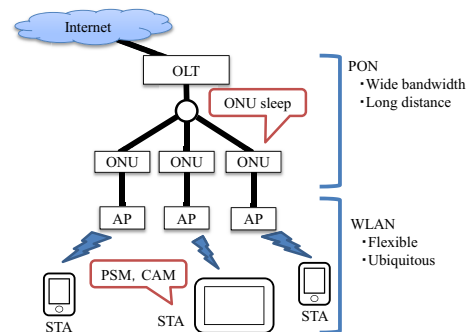


Fig. 1. Structure of a SF_iWi network.

renders energy efficiency in the Information and Communication Technology (ICT) industry as one of the most important research directions [7].

PON is one of the most well known optical access networks [8], which consists of an Optical Line Terminal (OLT), multiple Optical Network Units (ONUs), a splitter, and many optical fiber cables. The data is divided by a passive splitter and delivered from one OLT to multiple ONUs through optical fiber cables. To conserve ONU energy consumption, ONU sleep has been developed. ONU sleep is the mechanism that an ONU suspends and reduces energy consumption [9].

In a WLAN, even though the mobile terminals, which are referred to as STations (STAs), have mobility and ubiquitousness as two main advantages, they have limited-capacity batteries. In order to improve energy efficiency in WLAN, Power Saving Mode (PSM) has been considered. PSM is a power saving mechanism standardized by IEEE 802.11 standard association to conserve battery energy [10].

PSM and ONU sleep have been studied separately in literature [11], [12], [13]. However, using PSM or ONU sleep individually cannot fully utilize the advantages of the two parts, WLAN and PON. Recently, the combination of ONU sleep and PSM has been considered to reduce energy consumption not only in ONU but also in STA in literature [1]. However, this approach faces a big challenge that the latency

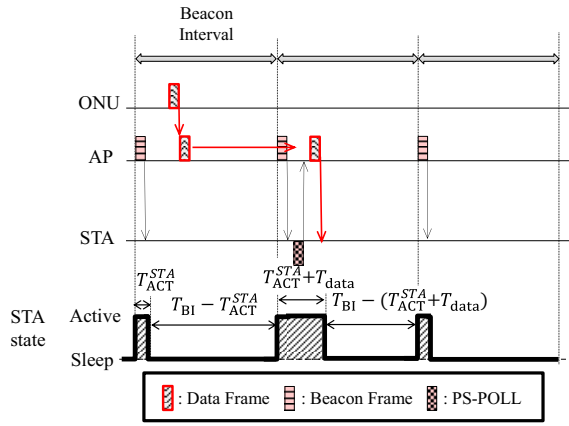


Fig. 2. PSM process.

will be longer than the latency of the traditional method, where Continuously Active Mode (CAM) is used together with ONU sleep. It is because the total latency is the sum of the latency of PSM and the latency of ONU sleep. Therefore, in this paper, we propose a novel power saving mechanism, which can reduce energy consumption similarly to the conventional approach of combining PSM and ONU sleep while reducing the latency as much as the best approach, where CAM is combined with ONU sleep, in terms of latency.

In our proposed method, the start time of ONU sleep and PSM is synchronized. In this way, our method has only ONU sleep delay. It is different from the conventional approach in SFiWi where two delays of ONU sleep and PSM occur. In our proposed method, although the latency is only ONU sleep delay, the power saving mechanism works in two places, ONU and STA. As a result, while our proposed method consumes the same energy with the conventional approach, the latency becomes much shorter. The effectiveness of our proposal is verified by using mathematical analysis and numerical evaluation.

The remainder of this paper is organized as follows. Section II describes the existing power saving mechanisms, PSM in WLAN, and ONU sleep in PON. Section III demonstrates the effect of PSM and ONU sleep on the latency. Additionally, the energy consumption of a STA is analyzed in this section. Section IV shows our proposed synchronization method for the sleep time of ONU and STA. The results of numerical analysis are presented in Section V. Finally, concluding remarks are provided in Section VI.

II. POWER SAVING MECHANISMS IN WLAN AND PON

A. PSM in WLAN

A STA with CAM is always in active state so that can receive data anytime. However, such a STA will waste energy when it does not receive data. A mechanism to save energy is the PSM. A STA with PSM in WLAN has two states, the active state and the sleep state. When a STA is in active state, it can send and receive data. On the other hand, when a STA is in sleep state, it can not receive data, and thus, the data sent from ONU is buffered at AP, as shown in Fig. 2. In that case, a delay between AP and STA occurs. When we take into account energy consumption, active state consumes high energy while sleep state consumes low energy.

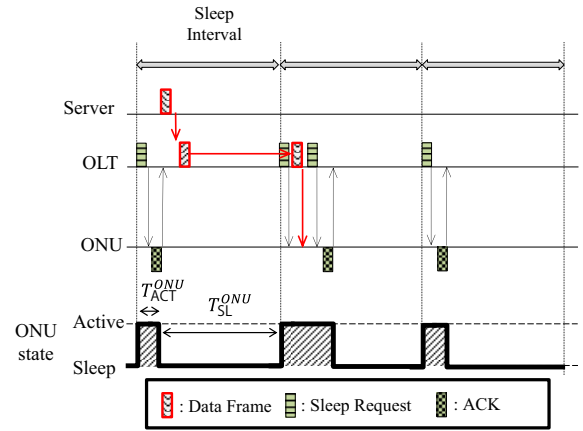


Fig. 3. ONU sleep process.

In SFiWi networks, a STA in the coverage area of an AP can inform the AP its own mode, PSM or CAM. After that, the AP can decide the method to send data to the STA.

In PSM mode, each AP periodically sends a beacon frame to STAs to inform its own existence with a fixed interval called beacon interval. The beacon interval is usually set to 100ms [12]. Each STA switches from sleep state to active state every beacon interval to receive the beacon frame from the AP. In order to let the STA know about the buffer status at the AP, the Traffic Indication Map (TIM) is included in the beacon frame when there is data sent to the STA. When the TIM is found in the beacon frame, it is understood that the AP is storing data frames for the STA. Then, the STA replies to the AP by a specific frame called Power Save Poll (PS-Poll). After the STA receives all stored data, it enters sleep state until the current beacon interval finishes. If the TIM is not included in the beacon frame, the STA enters sleep state immediately.

B. ONU sleep in PON

In the ONU sleep mode, there are also two states, active state and sleep state. When an ONU is in active state, it can send and receive data immediately. In contrast, an ONU in sleep state cannot send and receive data, and thus, delay occurs. Regarding the energy consumption, the ONU in active state consumes high energy. While, the energy consumption of the ONU in sleep state is low since the ONU is idle.

An example of ONU sleep process is shown in Fig. 3. When the ONU is in sleep state and the data from the server is sent to the OLT, the data is buffered at the OLT. Therefore, the data is stored until the next time the ONU wakes up. This causes the delay between OLT and ONU. The OLT informs all ONUs the sleep interval. Then, each ONU sends an ACK to the OLT and enters sleep state to obey OLT's message. If there is data coming to the ONU when it is in sleep state, the OLT stores the data. After the sleep interval, the ONU becomes active and the OLT sends the stored data with message telling that next sleep time is 0ms. In this way, the ONU sleep can reduce the energy consumption but causes unnecessary delay because the data has to be stored at the OLT for a certain period of time.

III. NETWORK PERFORMANCE IN SFiWi NETWORKS

A. The effect of PSM and ONU sleep on the latency

In SFiWi network, the latency occurs for buffering data following ONU sleep and PSM in OLT and AP, respectively. Therefore, in order to analyze the effect of ONU sleep and PSM on the latency, we consider the time of buffering data.

The STA with CAM is constantly in active state and the STA can always receive the data. Therefore, there is considerably no time for buffering data at APs. Let B_{AP}^{CAM} denote the buffering time at AP when the STA is with CAM in SFiWi network. Thus,

$$B_{AP}^{CAM} = 0. \quad (1)$$

On the other hand, in PSM, when data arrives at the AP, the AP cannot send the data if the STA is in sleep state. As a result, the time for buffering data at the AP, B_{AP}^{PSM} , occurs because the data is stored at the AP until the STA wakes up. This buffering time is determined by the time when the data arrives at the OLT. We can approximately calculate B_{AP}^{PSM} as follows:

$$\begin{aligned} B_{AP}^{PSM} &= \int_0^{T_{ACT}^{STA}} 0 \cdot \frac{1}{T_{BI}} dt + \int_{T_{ACT}^{STA}}^{T_{BI}} (t - T_{ACT}^{STA}) \cdot \frac{1}{T_{BI}} dt \\ &= \frac{1}{2} \cdot \frac{(T_{BI} - T_{ACT}^{STA})^2}{T_{BI}}, \end{aligned} \quad (2)$$

where T_{ACT}^{STA} is the time of the STA in active state, and T_{BI} is the beacon interval time.

In ONU sleep mode, the ONU has two states, active state and sleep state. Let time of the ONU in active state be T_{ACT}^{ONU} , and that in sleep state be T_{SL}^{ONU} . The ONU delay is affected by ONU sleep. This latency is determined by the time when the data arrives at the OLT and the time for buffering data. Thus, the buffering time of data in OLT, B_{OLT} , is calculated as follows:

$$\begin{aligned} B_{OLT} &= \int_0^{T_{ACT}^{ONU}} 0 \cdot \frac{1}{T_{ACT}^{ONU} + T_{SL}^{ONU}} dt \\ &+ \int_{T_{ACT}^{ONU}}^{T_{ACT}^{ONU} + T_{SL}^{ONU}} (t - T_{ACT}^{ONU}) \cdot \frac{1}{T_{ACT}^{ONU} + T_{SL}^{ONU}} dt \\ &= \frac{1}{2} \cdot \frac{(T_{SL}^{ONU})^2}{T_{ACT}^{ONU} + T_{SL}^{ONU}}. \end{aligned} \quad (3)$$

However, in actual SFiWi networks, ONU sleep is combined with either CAM or PSM. Firstly, we consider the combination of CAM and ONU sleep. Although the AP can send data immediately to the STA with CAM, the OLT cannot send data to the ONU when the ONU is in sleep state. Therefore, by using Eqs. 1 and 3, we can calculate the sum of buffering time when CAM and ONU sleep are combined, B_{CAM} , as follows:

$$\begin{aligned} B_{CAM} &= B_{AP}^{CAM} + B_{OLT} \\ &= \frac{1}{2} \cdot \frac{(T_{SL}^{ONU})^2}{T_{ACT}^{ONU} + T_{SL}^{ONU}}. \end{aligned} \quad (4)$$

Secondly, we consider the combination of PSM and ONU sleep. An example of the communication with ONU sleep and

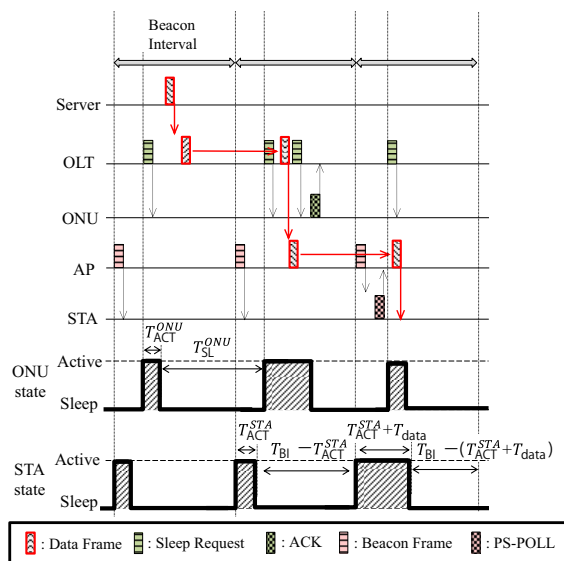


Fig. 4. The process of ONU sleep with PSM.

PSM is shown in Fig. 4. In SFiWi network, the downlink data is buffered at the OLT because of the ONU sleep. Moreover, when the STA is in sleep state, the downlink data transmitted from OLT is also buffered at the AP. In other words, when the STA is with PSM, in addition to the delay of ONU sleep, more latency may occur because the arriving data may be stored at the AP. Then, both of the delays at the OLT and the AP may occur. Using Eqs. 2 and 3, we calculate the sum of buffering time of data when PSM and ONU sleep are combined, B_{PSM} , as follows:

$$\begin{aligned} B_{PSM} &= B_{AP}^{PSM} + B_{OLT} \\ &= \frac{1}{2} \cdot \frac{(T_{BI} - T_{ACT}^{STA})^2}{T_{BI}} + \frac{1}{2} \cdot \frac{(T_{SL}^{ONU})^2}{T_{ACT}^{ONU} + T_{SL}^{ONU}} \end{aligned} \quad (5)$$

We can see two buffering times of data in SFiWi network from Eq. 5. These affect the delay, and thus, it is necessary to use the power saving mechanisms effectively.

B. Energy consumption in a STA

The STA with CAM is always in active state. In SFiWi networks, energy consumption of STA with CAM in one second, W_{CAM} , is obtained as follows:

$$W_{CAM} = W_{ACT}, \quad (6)$$

where W_{ACT} is the consumption rate of the STA in active state. On the other hand, since the STA with PSM has two states, active state and sleep state, the energy consumption of STA with PSM in one second, W_{PSM} is obtained as follows:

$$W_{PSM} = J_{ACT}^{PSM} + J_{SL}^{PSM}, \quad (7)$$

where J_{ACT}^{PSM} and J_{SL}^{PSM} are energy consumption of STA in active state and in sleep state, respectively. In the case of PSM, the STA in active state has the time to wake up and to handle the data. Both energy consumptions can be expressed as follows:

$$J_{ACT}^{PSM} = W_{ACT} \cdot (T_{data} + T_{ACT}^{STA} \cdot \frac{1}{T_{BI}}), \quad (8)$$

$$J_{SL}^{PSM} = W_{SL} \cdot (1 - (T_{\text{data}} + T_{\text{ACT}}^{STA} \cdot \frac{1}{T_{\text{BI}}})) , \quad (9)$$

where W_{SL} is the consumption rate of the STA in sleep state and T_{data} is the total period of time to handle the data in one second.

IV. PROPOSED SLEEP TIME SYNCHRONIZATION METHOD

We propose a novel power saving mechanism for STAs to help decrease the latency in SFiWi network. In addition to reducing the delay, the proposed method can improve the energy efficiency. In this section, we first describe our proposed method, and then analyze the latency and the energy consumption.

A. Proposed sleep time synchronization method

The main idea of this method is to synchronize the sleep time of ONU and STA. When the ONU wakes up, the STA also wakes up at the same time. The ONU wakes up to receive the data, and send it to the AP. At the same time, the STA wakes up, and the AP can send the data to the STA immediately. In this way, the data is sent from the ONU to the STA without delay caused by buffering data.

Since the conventional PSM method determines the time for the STA to be in the sleep state regardless of the ONU sleep, the AP cannot always send the data to the STA because the STA might be in sleep state when the AP wants to send. Therefore, the latency caused by STA's sleep state can occur. However, when we synchronize the sleep time of ONU and STA, the ONU active-sleep cycle becomes the same as the beacon interval and there is no buffering time in the AP. As a result, our proposed method have the sum of buffering time as short as the buffering time when CAM and ONU sleep are combined. Furthermore, unlike the combination of CAM and ONU sleep, where much energy is consumed due to the continuous active state, the energy consumption in our method is much lower. It is proved that the energy consumption of our method is as low as the energy consumption in the traditional method of combining PSM and ONU sleep.

B. Expected performance enhancement

1) *Latency analysis*: in our method, data is buffered at the OLT. The STA wakes up right after the ONU sleep ends because the sleep time of ONU and STA is synchronized. Then, the data buffered at the OLT during the ONU sleep is transmitted to the AP, and the AP sends data to the STA immediately. Therefore, there is no buffering time in AP caused by PSM. It is affected by only ONU sleep. We can calculate the sum of buffering time, B_{PRO} , which occurs in SFiWi network using our proposed method as follows:

$$B_{\text{PRO}} = \frac{1}{2} \cdot \frac{(T_{\text{SL}}^{\text{ONU}})^2}{T_{\text{ACT}}^{\text{ONU}} + T_{\text{SL}}^{\text{ONU}}} . \quad (10)$$

In comparison with Eqs. 4 and 5, since this sum of buffering time does not include the buffering time at AP, it is shorter than the sum of buffering time with PSM and equals the sum of buffering time with CAM.

TABLE I. NOTATION

Parameter	Definition
$B_{\text{AP}}^{\text{CAM}}$	Buffering time at AP when STA is with CAM
$B_{\text{AP}}^{\text{PSM}}$	Buffering time at AP when STA is with PSM
$T_{\text{ACT}}^{\text{STA}}$	Time when STA is in active state
T_{BI}	Beacon Interval
B_{OLT}	Buffering time at OLT when ONU is with ONU sleep
$T_{\text{ACT}}^{\text{ONU}}$	Time when ONU is in active state
$T_{\text{SL}}^{\text{ONU}}$	Time when ONU is in sleep state
B_{CAM}	Sum of buffering time at OLT and AP when STA is with CAM and ONU is with ONU sleep
B_{PSM}	Sum of buffering time at OLT and AP when STA is with PSM and ONU is with ONU sleep
W_{CAM}	Energy consumption in one second when STA is with CAM
W_{ACT}	Energy consumption in one second when STA is in active state
W_{PSM}	Energy consumption in one second when STA is with PSM
$J_{\text{ACT}}^{\text{PSM}}$	Energy consumption when STA with PSM is in active state
$J_{\text{SL}}^{\text{PSM}}$	Energy consumption when STA with PSM is in sleep state
T_{data}	Total time to handle the data in one second
W_{SL}	Energy consumption in one second when STA is in sleep state
B_{PRO}	Sum of buffering time in OLT and AP in our proposed method
W_{PRO}	Energy consumption in one second in our proposed method
$J_{\text{ACT}}^{\text{PRO}}$	Energy consumption in our proposed method when STA is in active state
$J_{\text{SL}}^{\text{PRO}}$	Energy consumption in our proposed method when STA is in sleep state

2) *STA energy consumption analysis*: in the conventional method, the STA and the ONU wake up several times during the beacon interval in different timings, and consume energy inefficiently. However, the STA and the ONU wake up just one time during the beacon interval in our method. Therefore, in one second, the energy consumption of the STA, W_{PRO} , is calculated as follows:

$$W_{\text{PRO}} = J_{\text{ACT}}^{\text{PRO}} + J_{\text{SL}}^{\text{PRO}} , \quad (11)$$

where $J_{\text{ACT}}^{\text{PRO}}$ and $J_{\text{SL}}^{\text{PRO}}$ are the energy consumption of STA in active state and in sleep state, respectively. $J_{\text{ACT}}^{\text{PRO}}$ and $J_{\text{SL}}^{\text{PRO}}$ can be calculated as follows:

$$J_{\text{ACT}}^{\text{PRO}} = W_{\text{ACT}} \cdot (T_{\text{data}} + T_{\text{ACT}}^{\text{STA}} \cdot \frac{1}{T_{\text{BI}}}) , \quad (12)$$

$$J_{\text{SL}}^{\text{PRO}} = W_{\text{SL}} \cdot (1 - (T_{\text{data}} + T_{\text{ACT}}^{\text{STA}} \cdot \frac{1}{T_{\text{BI}}})) . \quad (13)$$

As a result, Eq. 11 becomes similar to Eq. 7. Thus, the energy consumption in our method equals to that in the combination of PSM and ONU sleep.

V. NUMERICAL ANALYSIS

In this section, we perform a numerical analysis by using Eqs. 4, 5, 6, 7, 10, and 11 to evaluate the performance of our proposed method. In the SFiWi network such as shown in Fig. 1, we consider the data transmission and evaluate the sum of buffering time of data. Each STA works with PSM to decrease the energy consumption. An energy consumption of a STA in the active state, W_{ACT} , is 1.28W, and that in the sleep state, W_{SL} , is 0.53W [14]. In addition, the beacon interval, T_{BI} , is set to 100ms. The ONU active time, $T_{\text{ACT}}^{\text{ONU}}$, is 0.5ms [15]. Regarding the energy consumption, we calculate the energy consumption per second. The link rate between an AP and a STA is 300Mbps. The battery of STA is 3000mAh and works in 3.7V. Three mechanisms, CAM, PSM, and our proposed method, are evaluated.

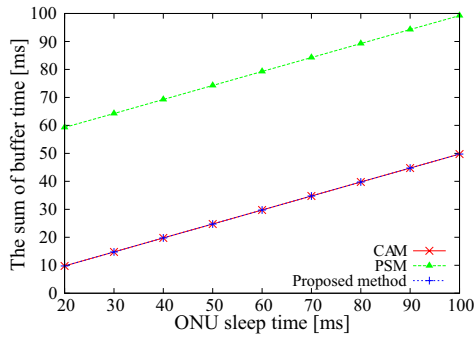


Fig. 5. The latency in SFiWi network.

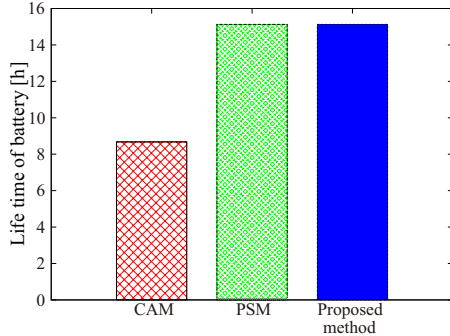


Fig. 6. Life time of battery in STA.

Fig. 5 shows the plot of the sum of buffering time using Eqs. 4, 5 and 10. The X-axis shows the ONU sleep time. The Y-axis shows the sum of buffering time at OLT and AP. From this result, we can see that when the ONU sleep time increases, the sum of buffering time also increases. The result also shows that CAM and our proposed method have similar performance in terms of buffering time. Since the sum of buffering time becomes short, the latency also becomes short and the throughput increases. Therefore our proposed method is expected to improve network throughput.

Fig. 6 shows the life time of battery when the amount of transferred data in a beacon interval is 2MB. The result shows that the energy consumption at the STA using our proposed method is the same as the energy consumption with PSM. In comparison with CAM, our method improve the life time by 42%.

As shown in Figs. 5 and 6, when we try to decrease the latency in conventional methods, the energy consumption increases. Thus, the latency and the energy consumption in the conventional methods have a trade-off relationship. In contrast, the latency in our method is as good as that in CAM while the energy consumption in our method is as good as that in PSM.

VI. CONCLUSION

SFiWi networks need power saving mechanisms since STAs have limited batteries and ONUs consume much energy. The PSM and the ONU sleep are two well-known power saving mechanisms in SFiWi networks. They are expected to be used together in order to reduce energy consumption. In this paper, we analyzed the impact of two power saving mechanisms working simultaneously in SFiWi networks on network latency. Two major problems, latency and energy consumption were revealed. In order to solve the problems,

we proposed a novel power saving mechanism for STAs, which controls STAs by synchronizing two power saving mechanisms, PSM and ONU sleep. The analysis and numerical results demonstrated that the proposed method can reduce the delay as much as the best conventional method in terms of latency. Moreover, the energy consumption in our proposed method is also as much as that in the best conventional method in terms of energy consumption. Regarding our future work, in this paper, we assume only one packet frame within a beacon interval. In the future, we will consider multiple packet frames at a same time. In addition, we are also interested in other traffic patterns.

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