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Cross Layer Analysis on ONU Energy Consumption in Smart FiWi Networks

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***Abstract*—Smart Fiber Wireless (SFiWi) networks have attracted great attention due to their ability to become the next generation broadband access networks. FiWi networks integrate optical networks and wireless networks. Access networks consume much energy due to the increase of network participants and the volume of content. To conserve energy consumption in Passive Optical Network (PON), Optical Network Unit (ONU) sleep mode was proposed. The basic idea of ONU sleep mode is to enter sleep state, for an ONU sleep state period while the ONU is in idle situation. Traditional research on ONU sleep showed that long ONU sleep state period results only in increased latency. In this research we prove that excessively long ONU sleep state periods not only cause long latency but also result in more energy consumption. Furthermore, we derive the optimal sleep state period to minimize energy consumption. Also, we show that our derived sleep state period achieves better latency compared to large ONU sleep state period.**

***Index Terms*—Smart FiWi, fiber wireless network, power saving, sleep control, energy efficiency, ONU sleep.**

I. Introduction

RECENTLY, the traffic flowing through networks has been significantly growing due to the spread of numerous network services such as Voice over Internet Protocol (VoIP) and video streaming that are characterized by large volumes of content and massive amounts of data traffic. As a next generation network infrastructure to support such huge traffic, Smart Fiber-Wireless (SFiWi) networks have attracted much attention [1]. SFiWi networks integrate optical and wireless networks. Thus, SFiWi networks have large bandwidth of optical networks and the ubiquity and mobility of wireless networks. According to [2], since Passive Optical Networks (PONs), one of the most popular optical networks, consume much energy in the wired communications network, cutting down the wasteful energy consumption is essential. To reduce the energy consumption of PONs, Optical Network Unit (ONU) sleep mode was proposed.

The ONU sleep mode aims to decrease ONU energy consumption by letting the ONU enter the sleep mode when the ONU is idle. During the sleep mode, the energy consumption of the ONU is low, but it cannot receive data. To avoid missing data traffic, the ONU changes its state between the active and the sleep states periodically. If the sleep state period is short, the ONU energy consumption is high and the latency for connections is short. Thus, sleep state period highly impacts the energy efficiency and the delay. Also, it is essential to determine the sleep state period optimally in order to minimize the ONU energy consumption without sacrificing delay. Moreover, in a SFiWi network, there is a wireless network part, namely, Wireless Local Area Network (WLAN), Ad-Hoc [3], and Wireless Mesh Network (WMN) [4], Satellite Network [5]. In order to minimize the energy consumption in the WLAN part, Power Saving Mode (PSM) was proposed [6]. However, PSM causes additional delay for connections and lengthens the Round Trip Time (RTT). Since the ONU idle period is directly related to RTT, we should carefully take into account the RTT when determining the ONU sleep state period in SFiWi networks.

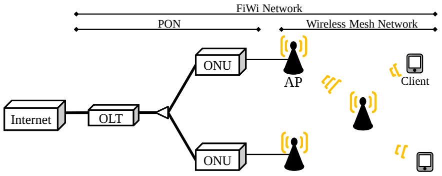

Fig. 1. An example of SFiWi networks.

In our research, within a single RTT, we study the ONU state behavior and analyze ONU energy consumption. We prove that an excessively long ONU sleep state period not only causes long latency but also results in wasteful energy consumption. Moreover, an optimal sleep state period to minimize energy consumption is derived. Also, we show that the derived sleep state period achieves shorter latency compared to large ONU sleep state period. The remaining of this paper is organized as follows. Firstly, we explain the ONU sleep mode mechanism and the data flow process in PON. Secondly, we analyze the ONU energy consumption in SFiWi networks during a data round trip. Finally, we evaluate the ONU energy consumption and discuss the optimal ONU sleep state period.

II. ONU Sleep Mechanism

To reduce wasteful ONU energy consumption, the ONU sleep mode is an attractive proposal. The basic scheme of the ONU sleep mode is to turn off transmitter components when an ONU is idle to reduce wasteful energy consumption. There are several types of ONU sleep mechanism [7], i.e., Dozing, Deep sleep, and Cyclic sleep. The ONU in Cyclic sleep mode periodically turns off and on transmitter components regardless

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of whether there is data traffic in the network or not. Therefore, the ONU can avoid losing data traffic directed to the ONU in the sleep mode.

Fig. 2(a) shows an example of the Cyclic sleep operation for downstream traffic. If the OLT has no downstream traffic destined to the ONU, the Optical Line Terminal (OLT) sends a sleep request message that includes the sleep state period, $T_{\rm sl}$. After receiving the sleep request message, the ONU sends an ACK message to the OLT and enters the sleep mode. The ONU turns off its transmitter while it is in the indicated sleep state period, $T_{\rm sl}$. After the sleep state period passes, the ONU enters the active state and sends a confirmation message to the OLT. If the OLT has received any downstream traffic directed to the ONU, the OLT sends a wake up request, $T_{\rm sl}=0$, and transmits the downstream traffic. The ONU that receives the wake up request enters the active mode. On the other hand, if the OLT receives no downstream traffic destined to the ONU, the OLT sends the sleep request message again. In short, while the ONU is in the sleep mode, it periodically changes its state between the active and sleep states to prevent missing downstream traffic and wasting energy.

Fig. 2(b) shows an example of the Cyclic sleep operation of upstream traffic. The ONU in sleep mode cannot receive downstream traffic but can receive upstream traffic from the User Network Interface (UNI). Therefore, the ONU can immediately transfer the upstream traffic by changing its mode forcibly without waiting for the end of the requested sleep state period, $T_{\rm sl}$. If the ONU has upstream traffic to the OLT, the ONU refuses to enter the sleep mode by sending NACK message in response to the sleep request message from the OLT.

III. ANALYTICAL MODEL OF END-TO-END COMMUNICATION UNDER THE CYCLIC SLEEP.

The length of the sleep state period impacts both energy efficiency and the delay. Hence, it is required to estimate the energy consumption and set sleep state periods optimally. In this section, we analyze the ONU's energy consumption in SFiWi networks. We assume that the communication between a client and the Internet is conducted as shown in Fig. 2(c), and analyze ONU energy consumption for a single RTT.

A. Modeling energy consumed in active mode

From Fig. 2(c), there are two parts where the ONU is in active mode. The *1st active mode* is from sending upstream data traffic until receiving the sleep request message, which includes the next sleep state period, $T_{\rm sl}$, sent by the OLT. The *2nd active mode* starts when ACK is sent as a response to the sleep request message indicating $T_{\rm sl}=0$ and ends when the sleep request message is received. The time spent in active mode, $T_{\rm ACM}$, can be obtained as follows:

$$T_{\rm ACM} = 4\tau + \frac{D_{\rm up} + D_{\rm down}}{R}, \tag{1}$$

where τ is the propagation delay between the ONU and the OLT. $D_{\rm up}$ and $D_{\rm down}$ are the amounts of data traffic the ONU send and receive, respectively. R is the link rate of PON. Denote the ONU energy consumption in the active mode as $P_{\rm ac}$ [J/s], we can approximately calculate total amount of energy consumption in the active mode, W_{ac}, as follows:

$$W_{\rm ac} = P_{\rm ac} \cdot T_{\rm ACM}. \tag{2}$$

Note that ONU energy consumption in the active mode is equal to the energy consumption in the active state of the sleep mode. Basically, a certain period of time is required to turn on the ONU transmission components. In this paper, we consider that the transition time from the sleep state to the active state is included in the active state period, $T_{\rm ac}$. Also, the transition period's energy consumption is included in $P_{\rm ac}$.

B. Modeling energy consumed in sleep mode

From Fig. 2(c), during the sleep mode, there are two states of the ONU, i.e., the active and the sleep states. The total amount of the energy consumed in the sleep mode depends on how many times an ONU changes its state. Therefore, we can derive the energy consumption, $W_{\rm sl}$, by using the number of wake up times, N, and the duration of the sleep mode, $T_{\rm sl}$, as follows:

$$W_{\rm sl} = N(P_{\rm ac} \cdot T_{\rm ac} + P_{\rm sl} \cdot T_{\rm sl}) + W_{\sigma}, \tag{3}$$

where $P_{\rm sl}$ [J/s] denotes the ONU energy consumption in the sleep state. $T_{\rm ac}$ and $T_{\rm sl}$ are the active state and the sleep state periods, respectively. W_{σ} indicates the energy consumption in *2nd sleep mode*.

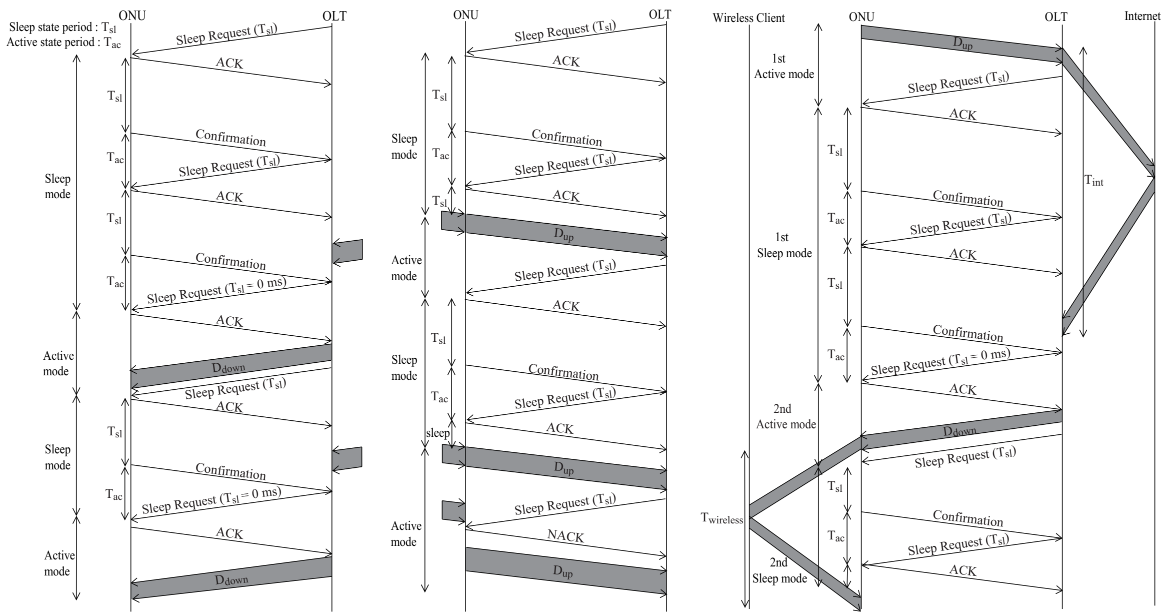
Assuming that the sleep and active state periods are constant, the number of active states and sleep states in the sleep mode are determined by the ONU sleep mode period. We first derive the sleep mode period. Within an RTT, there are two times where an ONU can enter the sleep mode as shown in Fig. 2(c). In the *1st sleep mode*, the ONU enters the sleep mode after sending ACK as a response to the sleep request message and ends when the sleep request message is received which indicates $T_{\rm sl}=0$. Accordingly, the *1st sleep mode* period is derived from the RTT between the OLT and the Internet, $T_{\rm int}$. Then, the number of active-sleep cycles in the *1st sleep mode*, $N_{\rm int}$, is calculated as follows:

$$N_{\rm int} = \left\lceil \frac{T_{\rm int}}{T_{\rm ac} + T_{\rm sl}} \right\rceil. \tag{4}$$

The *2nd sleep mode* starts when ACK is sent as a response to the sleep request, and ends when upstream data traffic sent by the client is received. Because the ONU in the sleep state does not turn off its interface to the user, the ONU can receive upstream traffic even in sleep mode. Moreover, because an ONU can be woken up forcibly, the ONU can immediately transmit the upstream data traffic after receiving the upstream data traffic. Hence, the *2nd sleep mode* period is the same as the RTT between the ONU and the client, $T_{\rm wireless}$. The number of the active-sleep cycles in the *2nd sleep mode*, $N_{\rm wireless}$, is calculated as follows:

$$N_{\rm wireless} = \left\lfloor \frac{T_{\rm wireless}}{T_{\rm ac} + T_{\rm sl}} \right\rfloor. \tag{5}$$

In the *2nd sleep mode*, the ONU wakes up not only at the end of a sleep-active cycle due to incoming unforeseen upstream



(a) An example of the sleep mode process of downstream traffic.
(b) An example of the sleep mode process of upstream traffic.
(c) An example of the communication with the sleep mode.

Fig. 2. Sleep mode operation

data traffic. The value of σ lies between 0ms and the sum of T_{ac} and T_{sl}. The value of σ and the energy consumption for σ are derived as follows:

$$\sigma = T_{\mathrm{wireless}} - \left\lfloor \frac{T_{\mathrm{wireless}}}{T_{\mathrm{ac}} + T_{\mathrm{sl}}} \right\rfloor (T_{\mathrm{sl}} + T_{\mathrm{ac}}), \tag{6}$$

$$W_{\sigma} = \begin{cases} P_{\mathrm{sl}} \cdot \sigma & (\sigma < T_{\mathrm{sl}}) \\ P_{\mathrm{sl}} \cdot T_{\mathrm{sl}} + P_{\mathrm{ac}} \cdot (\sigma - T_{\mathrm{sl}}) & (\sigma \geqq T_{\mathrm{sl}}), \end{cases} \tag{7}$$

Using Eqs. 3-7, we can express the total energy consumption during the sleep mode, W_{sl}, as follows:

$$\begin{aligned} W_{\mathrm{sl}} = & \left(\left\lceil \frac{T_{\mathrm{int}}}{T_{\mathrm{ac}} + T_{\mathrm{sl}}} \right\rceil + \left\lfloor \frac{T_{\mathrm{wireless}}}{T_{\mathrm{ac}} + T_{\mathrm{sl}}} \right\rfloor \right) \\ & \cdot (P_{\mathrm{ac}} \cdot T_{\mathrm{ac}} + P_{\mathrm{sl}} \cdot T_{\mathrm{sl}}) + W_{\sigma}. \end{aligned} \tag{8}$$

Using Eqs. 2 and 8, the total amount of energy consumption during a data round trip, W [J], is expressed as follows:

$$\begin{aligned} W = & P_{\mathrm{ac}} \left(4\tau + \frac{D_{\mathrm{up}} + D_{\mathrm{down}}}{R} \right) \\ & + \left\lceil \frac{T_{\mathrm{int}}}{T_{\mathrm{ac}} + T_{\mathrm{sl}}} \right\rceil (P_{\mathrm{ac}} \cdot T_{\mathrm{ac}} + P_{\mathrm{sl}} \cdot T_{\mathrm{sl}}) \\ & + \left\lfloor \frac{T_{\mathrm{wireless}}}{T_{\mathrm{ac}} + T_{\mathrm{sl}}} \right\rfloor (P_{\mathrm{ac}} \cdot T_{\mathrm{ac}} + P_{\mathrm{sl}} \cdot T_{\mathrm{sl}}) + W_{\sigma}. \end{aligned} \tag{9}$$

and the optimal sleep state period is derived as follows:

$$T_{\mathrm{sl}}^{\mathrm{opt}} = \arg\min_{T_{\mathrm{sl}}} W. \tag{10}$$

Then, we focus our attention on the relationship between W and T_{sl} by ignoring the constant value such as the first term in Eq. 9. Additionally, we assume that the active state period is much smaller ($T_{\mathrm{ac}} \ll T_{\mathrm{sl}}$), thus we can regard σ as being less than T_{sl} and $T_{\mathrm{ac}} + T_{\mathrm{sl}}$ as T_{sl} Therefore, following approximate equation can be derived.

$$\begin{aligned} W = & P_{\mathrm{sl}} \cdot T_{\mathrm{sl}} + (P_{\mathrm{ac}} \cdot T_{\mathrm{ac}} + P_{\mathrm{sl}} \cdot T_{\mathrm{sl}}) \left\lfloor \frac{T_{\mathrm{int}}}{T_{\mathrm{sl}}} \right\rfloor \\ & + (P_{\mathrm{ac}} - P_{\mathrm{sl}}) T_{\mathrm{ac}} \left\lfloor \frac{T_{\mathrm{wireless}}}{T_{\mathrm{sl}}} \right\rfloor + const. \end{aligned} \tag{11}$$

Note that we set a tight boundary condition to arrive at Eq. 11. Here, we assume $T_{\mathrm{int}} \approx T_{\mathrm{wireless}} \equiv T$. When T_{sl} is ∞, the first term become ∞ while the second and third terms become 0. Moreover, as long as T_{sl} is greater than T, ceiling functions keep the value, 0, even if T_{sl} decrease. Therefore, in this situation, the optimal sleep state period is $T + \varepsilon$. ε is used to make the denominator larger than the numerator in Eq. 11.

IV. NUMERICAL ANALYSIS

In this section, we evaluate the ONU energy consumption by using Eq. 9 and confirm that optimal sleep state period exists according to each network condition. Also, we compare the optimal sleep state period derived with the numerical analysis.

A. Assumptions

We assume that the RTT between the OLT and the server, T_{int}, is 10ms. The propagation delay between the OLT and the ONU, τ, is 0.5ms. The amount of the data traffic sent from Internet, D_{down}, is 1500 bytes, which is the maximum frame size. We assume D_{up} is 40 bytes by setting it to the size of a TCP ACK message. The energy consumption in the sleep state, P_{sl}, and the energy consumption in the active state, P_{ac}, are 1 W and 10 W, respectively [8]. The active sleep state period, T_{ac}, is 1ms. The link rate between the ONU and the OLT, R, is 1 Gbps following the popular PON standard

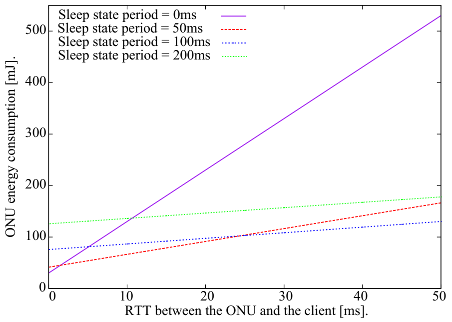


Fig. 3. Relationship between RTT and energy counsumption.

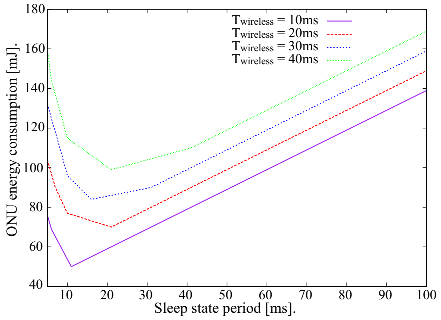


Fig. 4. Relationship between the sleep state period and energy consumption.

such as Ethernet-PON (EPON). The transition time to change ONU state is included in active period T_{ac}, and the energy consumption is the same as in the active state, P_{ac}.

B. *Analysis results*

Fig. 3 shows the relationship between ONU energy consumption and the RTT between the ONU and the client with different sleep state periods. In this figure, we compare the result of various ONU sleep state periods, namely, T_{sl} equal to 0ms, 5ms, 50ms, and 200ms. Each line has a respective curve, and the longer the sleep state period is, the more the curve decreases. Therefore, when the RTT is short, the optimal sleep state period is short, likewise, when the RTT is long, the optimal state period also becomes long. For example, in Fig. 3, when the RTT is 10ms, the optimal sleep state period is 50ms. However, when the RTT is 100ms, the optimal sleep state period is 100ms. Hence, we should take account of that the optimal sleep state periods vary depending on the propagation delay in wireless network.

Sleep mode is used for cutting on ONU energy consumption in return for decreasing throughput. It does not make sense that the ONU operating sleep mode consumes higher than the continuously active ONU with 0ms sleep. However, the ONU energy consumption with 100ms sleep and 200ms sleep are higher than the ONU with 0ms sleep at the short RTT. Hence, we should decide the sleep state period, which consumes at least lower energy than the ONU with 0ms sleep.

Fig. 4 shows the analysis results of relationship between the sleep state period, T_{sl}, and the energy consumption with different RTTs in wireless network, T_{wireless}. From Fig. 4, it can be seen that the energy consumption is high when the sleep state is short. Additionally, the energy consumption is also high when T_{sl} is long. This is because ONU also consumes energy even when it is in the sleep state, and downstream traffic need to wait at the OLT until ONU wakes up this results in unnecessary wasted of energy. We confirmed all curves are negative-convex functions, and thus, there is an optimal sleep state period that minimizes ONU energy consumption. Through the numerical analysis, we derived that $T_{\mathrm{sl}}^{\mathrm{opt}} = T + \varepsilon$ when $T_{\mathrm{int}} \approx T_{\mathrm{wireless}} \equiv T$. Comparing this optimal sleep state period and the curve with $T_{\mathrm{wireless}} = 10ms$ in Fig. 4., we confirmed that both of them indicate same optimal sleep state period.

V. CONCLUSION

In this paper, we analyzed the energy consumption by focusing on the ONU behavior during a data round trip in SFiWi networks. So far, it has been known that the long sleep state period decreases the energy consumption. However, we clarified that excessively long sleep state periods leads to long additional delay and the ONU consumes much energy. Furthermore, we showed that an optimal sleep state period that minimizes the ONU energy consumption exists. Moreover, we proved that the optimal sleep state period depends on RTT. Finally, through numerical analysis, we derived an optimal sleep state period and confirmed that it leads to minimum energy consumption.

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