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ORIGINAL PAPER

Optimization of sleep period in watchful sleep mode for power-efficient passive optical networks

Xiaobo Zeng[1] **· Min Zhu**[2] **· Lu Wang**[2] **· Xiaohan Sun**[2]

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Abstract

The energy consumption in data communication networks has drawn global attention due to the ever-increasing of broadband users. In this paper, we formulated the system performances of the watchful sleep mode in terms of the power consumption and the state transition delay by using the state probability based on arrival traffic profile. And we compared the performances of the watchful sleep mode with the cyclic sleep mode under the same conditions. For above two conflicting performance indexes, the *Sleep* period is a key factor. Thus we designed the *Cost* function to determine the balanced *Sleep* periods for the certain requirements of power saving and state transition delay. And the simulation results verified the balanced *Sleep* period can greatly improves the system performances.

Keywords Watchful sleep mode · Sleep period optimization · Passive optical network (PON) · Energy-saving efficiency (ESE) · State transition delay (TD)

1 Introduction

The energy consumption of data communication networks has drawn global attention due to the ever-increasing of bandwidth and the number of broadband users [1]. And various access technologies which aim at reducing the power consumption were proposed, like Worldwide Interoperability for Microwave Access (WiMAX), Fiber To The Home (FTTH), point-to-point optical access networks and so on [1,2]. But the passive optical network (PON) is considered as the most promising technology with the passive fiber optic splitters which are used to enable a single optical fiber to serve multiple end-points. And it does not have to provision individual fibers between the hub and customers [3–5]. Nevertheless, it is still desirable to further reduce the energy consumption of PON with the worldwide deployment of it. Generally, the optical network units (ONUs) located at the end premises contribute the majority of energy wastage to the PON [6]. Because the PON implements a point to multipoint architecture, and ONUs have to continually listen and inspect the traffics from the Optical Line Terminal (OLT). Hence, the ONUs always remain active, even there is no or light traffics. Therefore, reducing energy consumption of ONUs is essential to achieve the more power-efficient PONs [7].

Recently, the doze mode and the cyclic sleep mode were standardized by ITU-T.987.3 through the supporting of transmission convergence (TC) layer for the ONU [1,8]. They are operated by turning off or on all or part of transceivers (i.e., transmitter and receiver) of the ONUs to realize the state switching between the full power states and low power states [9,10]. The full power states include the *Active held* and *Active free* states. Specifically, the low power state means the *Listen* state for the doze mode and the *Sleep* state for the cyclic sleep mode, respectively. In above two modes, there still exists a transition state (i.e., *Sleep aware* for the cyclic sleep mode or *Doze aware* for the doze mode) between the full power states and the corresponding low power state,

✉ Xiaobo Zeng
zengxiaobo@seu.edu.cn

Min Zhu
minzhu@seu.edu.cn

Lu Wang
luwang@seu.edu.cn

Xiaohan Sun
xhsun@seu.edu.cn

[1] School of Microelectronics, Southeast University, Nanjing 210096, China

[2] National Research Center for Optical Sensing/Communications Integrated Networking, School of Electronic Science and Engineering, Southeast University, Nanjing 210096, China

which can realize the synchronization between the OLT and the ONUs through exchanging the signaling information.

In addition, some related research schemes about energy saving of ONU have been proposed. Zhang et al. [3] have explored the energy efficiency of the ONU by controlling the sleep period. They analyzed the effects of the traffic arrival rate on the energy saving efficiency and the data packet delay via the numerical simulations based on the Markov chain. Bang et al. [2] designed the power management scheme of the ONU for the 10G-PON (i.e., XG-PON) based on the cyclic sleep mode. The power consumption and state transition delay of ONU were analyzed and balanced by using the state probability based on the traffic arrivals to determine the optimal sleep period. Then, the watchful sleep mode was proposed by Khotimsky [11–13], which unified the standardized doze mode and the cyclic sleep mode into an entity. The new mode simplifies the operation of ONU, emulating any one of the standardized modes as a special case by adjusting related parameters. In [13], the watchful sleep mode was demonstrated that it outperforms the former standardized mode using an OMNET++ based simulation in terms of energy efficiency and reduced network signaling. In our previous work [14], we modeled the watchful sleep mode based on the Markov chain and analyzed the effect of every key parameter on the ONU in terms of energy-saving efficiency and data packet delay.

In this paper, we modeled the watchful sleep mode of ONU by using state probability based on the traffic arrival profile. Then, we compared the performances of the watchful sleep mode with the cyclic sleep mode which was demonstrated in [2] under the same condition. And we find that the watchful sleep mode is more effective than the cyclic sleep mode. Specifically, within the low power phase, the ONU shuts down the transmitter, while turns off the receiver periodically for a short time to detect the wake-up indication. Simultaneously, the ONU performs the necessary synchronization with the OLT. It is reasonable to assume that the duration of the *Sleep* state would greatly affect the PON system performances: energy-saving efficiency and state transition delay. Because more power can be saved when the duration of *Sleep* state increases. Specifically, the larger sleep period is, the more time the ONU spends in the sleep state. Hence, the energy-saving efficiency of PON tends to be better [7], while the state transition delay would become worse, and vice versa. Thus there exists a trade-off for the two conflicting indexes on the sleep period. It is desirable to obtain the balanced trade-off value of the optimal sleep period for the two conflicting goals, which were demonstrated in the section of simulation results.

The rest of this paper is organized as follows. In Sect. 2, we formulated the power consumption and state transition delay by using the method of state probability based on the traffic arrival profile. And the balanced value of the sleep period was determined for the integrated performance in terms of the *Cost* value. In Sect. 3, we conducted the comparison between the cyclic sleep mode as provided in [2] and the watchful sleep mode under the same condition. Then, we derived the extensive simulation results about the energy-saving efficiency, state transition delay and the cost value. Section 4 concludes this paper.

2 Mathematical model of the watchful sleep mode

The watchful sleep mode of ONU is operated based on the four states: *ActiveHeld, ActiveFree*, *Aware* and *Watch*, as shown in Fig. 1. The first two states constitute the active phase at which the transmitter (TX) and receiver (RX) are both ON. And the ONU stays in the full power level to forward the up-/downstream (US/DS) data traffics. In *Aware* state, the transmitter and receiver of ONU both still remain ON with the full power operation to deal with the necessary synchronization with the OLT. However, the ONU, in the *Watch* state, keeps the transmitter OFF and turns the receiver ON periodically. Thus, the ONU alternates between two different states, which are denoted as the *Sleep* state and *Listen* state, respectively. In the former state, the TX and RX are OFF, while the TX is OFF and the RX is ON for the *Listen* state of ONU. In addition, the *Sleep* and *Listen* states implicitly compose the state pair [i.e., (*Sleep*, *Listen*)], which was marked as *SL*, as shown in Fig. 2. Thus, the *Aware* state and *Watch* state constitute the power saving phase.

For the watchful sleep mode, the ONU cannot directly enter the power saving phase from the *ActiveHeld* state without through the *ActiveFree* state, as shown in Fig. 1.

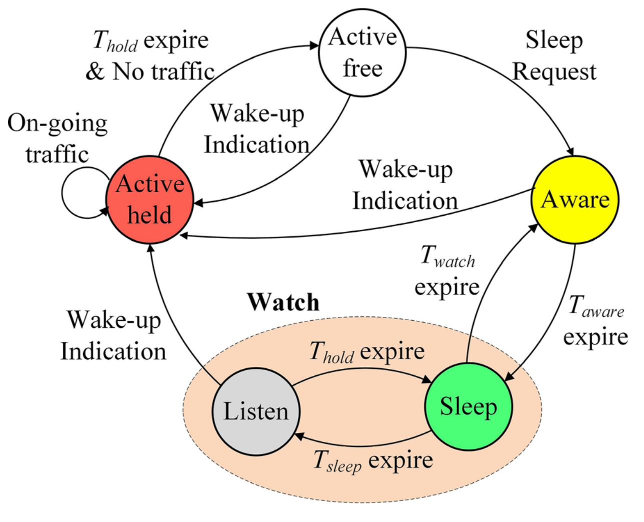
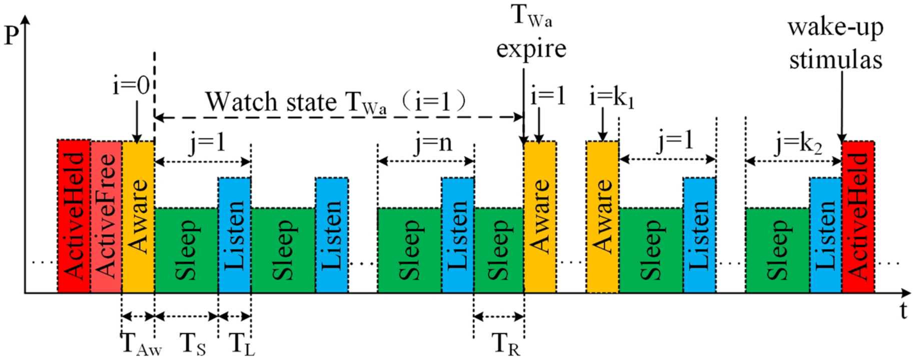


Fig. 1 Watchful sleep mode state machine of ONU

Fig. 2 The power management of the watchful sleep mode



But the ONU that stays in the *ActiveFree* state can freely enter the power saving phase if there is no arrival traffic for the duration of this state. Alternatively, the ONU can back to the *ActiveHeld* state from the *ActiveFree* state if it got the wake-up indication signals. During the power saving phase, the ONU operates in an circulation of the full power *Aware* and the low power *Watch* state. Further, for the *Watch* state, the ONU operates in an inner circulation which consists of the *Listen* state and *Sleep* state (i.e., (*Sleep*, *Listen*), *SL*). When there exists the arrival traffics in the ONU during *Aware* state or the duration of *SL* state pair, a wake-up indication would occurs immediately. Then, the ONU can directly get rid of the power saving phase and enters into the *ActiveHeld* state. If the data traffic arrived during the *Sleep* period, these data would be cache into the buffer queues of the ONU which was assumed to be unlimited until T_{sleep} expired, as shown in Fig. 1. Because the ONU only can transfer to the *ActiveHeld* state at the end of the *Sleep* period or during the *Listen* state. Then, the ONU would process the data traffics immediately.

The duration time of the *Sleep* and *Listen* state, in this paper, is denoted as T_S and T_L, respectively. Thus the duration of *Watch* state equals to $T_{Wa} = n\times(T_S+T_L)+T_R$, where the T_R is the remaining time of T_{Wa} and the $T_R(T_S+T_L)$, as shown in Fig. 2. In other words, the period of *Watch* state is not necessarily the integral multiple of the duration of the state pair (*Sleep, Listen*). It is noted that the labels of *Aware* state start from $i = 0$ and the *Watch* state start from $i = 1$ for the convenience of mathematical notation, as shown in Fig. 2, where i is an integer. Let $T_{Aw}(i)$ and $T_{Wa}(i)$ depicting the sojourn time of the i-th periods for the *Aware* and *Watch* state, respectively, according to the multiples of a 125 µs XG-PON transmission convergence frame [1]. Thus the *Watch* state can be considered as dividing into several *SL* state pairs, as shown in Fig. 2. In this case, for the j-th *SL* state pair, the $T_S(j)$ and $T_L(j)$ were marked as the sojourn time of the $Sleep(j)$ and $Listen(j)$ state, respectively. Here, we assumed that the indication events for arrival traffic in the system were informed to the next state at the end of each state for the ONU.

Since the counting process of arrival data packets is independent with each other and exponentially distributed with the inter-arrival time gap, thus the Poisson process can be assumed for the traffic arrivals process. Specifically, the traffic arrival rates for the upstream and downstream are denoted to be $\lambda_u > 0$ and $\lambda_d > 0$, respectively. The inter-arrival time of the upstream and downstream can be expressed by the exponential function with the mean of $1/\lambda_u$ and $1/\lambda_d$, respectively. According to the stationary increments property of Poisson arrival process, the number of arrival packets in a time increment of length depends only on length of the increment and not when it starts. Therefore, the occurrence probability of wake-up indication $P\,(Aw = k_1, SL = k_2)$ can be derived as follows.

In Eq. (1), let the *Aw* and *SL* depicting the ordinal marks of the *Aware* state and the (*Sleep*, *Listen*) state pair, respectively. Both the $k_1(k_1 = 0, 1, 2, 3, \ldots)$ and $k_2(k_2 = 1, 2, 3, \ldots, n)$ are integer. According to the situation of the ONU receiving a wake-up indication and entering the full power mode (i.e., *ActiveHeld* state), the probability of $P\,(Aw = k_1, SL = k_2)$ can be calculated under the following three cases. (i) $k_1 = k_2 = 0$ represents that the ONU gets the wake-up indications at the first *Aware*(0) state. (ii) For the $k_2 = 0, k_1 \neq 0$, it means that the ONU obtains the wake-up indication during the period of the k_1-th $Aware(k_1)$ state ($T_{Aw}(k_1)$) which was indicated by the first expression, or the remaining *Sleep* state (i.e., $T_R(k_1)$) which was expressed by the second expression. (iii) For $k_1 \neq 0, k_2 \neq 0$, it indicates that the ONU receives the wake-up indication at the k_2-th (*Sleep*, *Listen*) state pair of the k_1-th*Watch* state, as shown in Fig. 2. It should be noted that $\prod_{i=x}^{y} e^{-f(i)} = 1$, if the x was larger than the y.

$$P\begin{pmatrix} Aw = k_1 \\ SL = k_2 \end{pmatrix} = \begin{cases} 1 - e^{-(\lambda_u+\lambda_d)T_{Aw}(0)} & k_1 = k_2 = 0 \\ \left\{1 - e^{-(\lambda_u+\lambda_d)T_{Aw}(k_1)}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} & \\ \quad + \left\{1 - e^{-(\lambda_u+\lambda_d)T_R(k_1)}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} & \\ \quad \times \prod_{i=1}^{n} e^{-(\lambda_u+\lambda_d)[T_S(i)+T_L(i)]} & k_1 \neq 0, k_2 = 0 \\ \left\{1 - e^{-(\lambda_u+\lambda_d)[T_S(k_2)+T_L(k_2)]}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} & \\ \quad \times \prod_{i=1}^{k_2-1} e^{-(\lambda_u+\lambda_d)[T_S(i)+T_L(i)]} & k_1 \neq 0, k_2 \neq 0 \end{cases} \tag{1}$$

Using Eq. (1), the average power consumption $E[P_{PS}]$ and average state transition delay $E[D]$ can be formulated based on the Poisson traffic arrival profile. The average power consumption $E[P_{PS}]$ can be derived based on above three cases of Eq. (1), respectively, as expressed in Eq. (2).

$$\begin{aligned} E[P_{PS}] &= (1 - e^{-(\lambda_u+\lambda_d)T_{Aw}(0)}) \times P_{Aw} \\ &+ \left(\left\{1 - e^{-(\lambda_u+\lambda_d)T_{Aw}(k_1)}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)}\right) \\ &\times \left(\frac{P_{Aw}T_{Aw}(0) + \sum_{i=1}^{k_1}[T_{Aw}(i)P_{Aw} + n(T_S P_S + T_L P_L) + T_R(i)P_S]}{T_{\mathrm{Aw}}(0) + \sum_{i=1}^{k_1}[T_{\mathrm{Aw}}(i) + T_{\mathrm{Wa}}(i)]}\right) \\ &+ \left(\left\{1 - e^{-(\lambda_u+\lambda_d)T_R(k_1)}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} \times \prod_{i=1}^{n} e^{-(\lambda_u+\lambda_d)[T_S(i)+T_L(i)]}\right) \\ &\times \left(\frac{P_{Aw}T_{Aw}(0) + \sum_{i=1}^{k_1-1}[T_{Aw}(i)P_{Aw} + n(T_S P_S + T_L P_L) + T_R(i)P_S] + n(T_S P_S + T_L P_L) + T_R(i)P_S}{T_{Aw}(0) + \sum_{i=1}^{k_1-1}[T_{Aw}(i) + T_{Wa}(i)] + T_{Wa}}\right) \\ &+ \left(\left\{1 - e^{-(\lambda_u+\lambda_d)[T_S(k_2)+T_L(k_2)]}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} \times \prod_{i=1}^{k_2-1} e^{-(\lambda_u+\lambda_d)[T_S(i)+T_L(i)]}\right) \\ &\times \left(\frac{P_{Aw}T_{Aw}(0) + \sum_{i=1}^{k_1-1}[T_{Aw}(i)P_{Aw} + n(T_S P_S + T_L P_L) + T_R(i)P_S] + \sum_{i=1}^{k_2}(T_S(i)P_S + T_L(i)P_L)}{T_{Aw}(0) + \sum_{i=1}^{k_1-1}[T_{Aw}(i) + T_{Wa}(i)] + \sum_{i=1}^{k_2}[T_S(i) + T_L(i)]}\right) \end{aligned} \tag{2}$$

where the P_{Aw}, P_L, P_S are the amount of consumed energy per unit time of the *Aware*, *Listen* and *Sleep* state of the ONU, respectively. The P_A is the power of ONU that stays in the full power states.

Because the ONU can switch into the *ActiveHeld* state immediately from the *Aware* state and the transition time between them is too short (i.e., tens of nanoseconds) and negligible. Thus we can assume that there is no state transition delay for the first case (i.e., $k_1 = k_2 = 0$). For the second case (i.e., $k_2 = 0$, but $k_1 \neq 0$), as expressed in Eq. (1), the state transition delay can be occurred only when the ONU obtains the wake-up indication during the period of $T_R(k_1)$ in the k_1-th remaining *Sleep* state. And the probability of obtaining the wake-up indications during $T_R(k_1)$ can be calculated as the following expression Eq. (3).

Table 1 Connotation of the parameters

Parameter	Semantics	Alternative values
P_A	Power of the *Active* state	10 W
P_L	Power of the *Listen* state	4 W
P_S	Power of the *Sleep* state	0.5 W
T_{Wa}	Duration of the *Watch* state	10 s
T_S	Duration of the *Sleep* state	10 ms
T_{Aw}	Duration of the *Aware* state	5 ms
T_L	Duration of the *Listen* state	0.125 ms
T_R	Remaining period of the *Watch* state	–
λ_u	Arrival rate of upstream traffic	1E−3 ∼ 1
λ_d	Arrival rate of downstream traffic	1E−3 ∼ 1

$$
\begin{aligned}
P\left(T_R = k_1\right) = {} & \left\{1 - e^{-(\lambda_u+\lambda_d)[T_{\mathrm{R}}(k_1)]}\right\} \\
& \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{\mathrm{Aw}}(i)} \\
& \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{\mathrm{Wa}}(i)} \\
& \times \prod_{i=1}^{n} e^{-(\lambda_u+\lambda_d)[T_{\mathrm{S}}(i)+T_{\mathrm{L}}(i)]}
\end{aligned}
\tag{3}
$$

For the third case (i.e., $k_1 \neq 0$ and $k_2 \neq 0$), strictly, the state transition delay can be occurred only when the ONU obtains the wake-up indication during the period of *Sleep*(k_2) state of the k_2-th (*Sleep*, *Listen*) state pair in the k_1-th *Watch* state, and not during the period of $Listen(k_2)$ state. In addition, due to the fact that the period T_S of *Sleep* state is much larger than T_L of the *Listen* state, as expressed in Table 1, thus the average state transition delay can be obtained by multiplying $P\left(Aw = k_1, SL = k_2\right)\left(k_1 \neq 0, k_2 \neq 0\right)$ with a half period of T_S. Therefore, the average state transition delay $E[D]$ of all situations can be expressed as Eq. (4).

$$
\begin{aligned}
E\left[D\right] = {} & \left(\left\{1 - e^{-(\lambda_u+\lambda_d)T_R(k_1)}\right\} \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)}\right. \\
& \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} \\
& \left.\times \prod_{i=1}^{n} e^{-(\lambda_u+\lambda_d)[T_S(i)+T_L(i)]}\right) \times \frac{T_{\mathrm{R}}}{2} \\
& + \left(\left\{1 - e^{-(\lambda_u+\lambda_d)[T_S(k_2)+T_L(k_2)]}\right\}\right. \\
& \times \prod_{i=0}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Aw}(i)} \times \prod_{i=1}^{k_1-1} e^{-(\lambda_u+\lambda_d)T_{Wa}(i)} \\
& \left.\times \prod_{i=1}^{k_2-1} e^{-(\lambda_u+\lambda_d)[T_S(i)+T_L(i)]}\right) \times \frac{T_{\mathrm{S}}}{2}
\end{aligned}
\tag{4}
$$

As mentioned before, there is a trade-off between above two indexes: the average power consumption and average state transition delay. Specifically, pursuing the lower power consumption would results in the larger state transition delay, and vice versa. And the duration of the *Sleep* state is the key parameter for ONU system performances. Because more power can be saved when the duration of *Sleep* state increases. Thus, it is desirable to obtain the optimal and balance value of the sleep period which satisfies the requirement of power consumption and the shorter state transition delay simultaneously. Let P_g and D_g depicting the ideal goals of the desired energy consumption and the state transition delay, respectively. Hence, we designed the *Cost* function for integrating above two conflict indexes, as expressed in Eq. (5), under the specific situation with US/DS data arrival rates (i.e., λ_u, λ_d) with the similar concept as [12]. In this paper, the *Cost* function means the expenditure which should be paid to achieve the goal of P_g and D_g. In other words, that is the gaps between the estimated $E[P_{sw}]$ and $E[D]$ and these target goal.

$$
\begin{aligned}
Cost_{\lambda_u,\lambda_d} = {} & \alpha \frac{\max[(E[P_{sw}] - P_g), 0]}{P_{\max} - P_g} \\
& + \beta \frac{\max[(E[D] - D_g), 0]}{D_{\max} - D_g}
\end{aligned}
\tag{5}
$$

where the $P_{\max} = P_A$ is the power of ONU that stays in the full power states. The $D_{\max}$ is the maximum of the state transition delay. $P_{\max} - P_g$ and $D_{\max} - D_g$ are used to normalize their measured values of the performance indexes, respectively. The α and β are the weight factors of two conflicting indexes, respectively, which follows the constraint of $\alpha + \beta = 1 (0 \leq \alpha \leq 1$ and $0 \leq \beta \leq 1)$. By calculating the minimum cost, the optimized and balanced sleep period can be obtained which satisfies the requirement of power consumption and the shorter state transition delay, simultaneously . In our simulations, the above two conflicting indexes should be treated equally, i.e., let $\alpha = \beta = 0.5$.

3 Performance evaluation

In this section, we evaluated the performances of the watchful sleep mode based on above mathematical model from the perspective of numerical simulation which was conducted in the Mathematica platform [15]. According to [1], the power consumptions of ONU that stays in the *Active* (including *ActiveHeld*, *ActiveFree*, and *Aware* state), *Listen* and *Sleep* states were set to be 10w, 4w and 0.5w, respectively. In *Aware* state, the ONU just configures the time-delay regulations and deals with the necessary synchronizations with the OLT. The *Watch* state can be considered as the aggregation which consists of a number of (*Sleep*, *Listen*) *SL* state pairs and the short

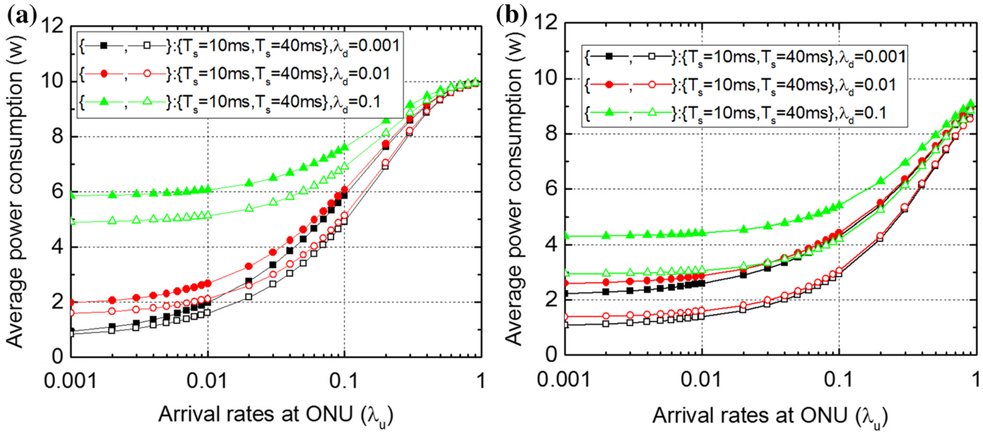
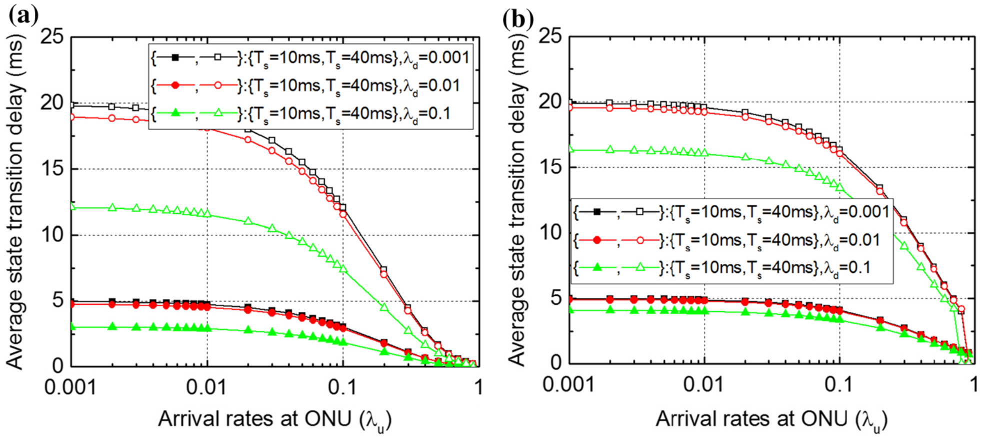


Fig. 3 Average power consumption of **a** watchful sleep mode, **b** cyclic sleep mode under different US traffic arrival rates

Fig. 4 Average state transition delay of **a** watchful sleep mode, **b** cyclic sleep mode under different US traffic arrival rates



remaining time of T_R. And T_R is shorter than the period of a *SL* state pair [i.e., $T_R(T_S + T_L)$]. All involved parameters in our simulations are listed in Table 1. In addition, in order to validate the effectiveness of the watchful sleep mode, we calculated the average power consumption and state transition delay of the ONU for the cyclic sleep mode under the same condition and compared the results of two modes of ONU. From the comparison, we can find that the watchful sleep mode is more effective than the cyclic sleep mode for the ONU.

In Fig. 3, the parameters of T_S and λ_d take the corresponding values from the set of 10, 40 ms and $\{0.001, 0.1, 1\}$, respectively. The US traffic arrival rate λ_u independently increases from 0.001 to 1. The average power consumptions of the watchful sleep mode and the cyclic sleep mode are shown in Fig. 3a, b, respectively. From Fig. 3, we can find that when the US/DS traffic arrival rates of λ_u and λ_d is larger, the ONU tends to consume more energy, which will results in the lower energy efficiency. Because the ONU will more likely to stay in the *ActiveHeld* state, thus the sojourn time at the *Sleep* state will decreases. From the comparison of the results revealed from Fig. 3a, b, respectively, we can find that the watchful sleep mode is more effective than the cyclic sleep mode. Specifically, the power consumption of watchful sleep mode trends to saturation of 10w when the $\lambda_u = 0.7$, while the energy curve of the cyclic sleep mode is not reach the saturation even when the $\lambda_u = 1$. Although the cyclic sleep mode trends to better energy efficiency for the heavy traffic situation, the watchful sleep mode would be better as the saturation characteristics when the λ_u larger. In addition, the watchful sleep mode is better than the cyclic sleep mode when the traffic load is light.

In Fig. 4, we can find that the average state transition delays are gradually decrease with the increase in the λ_u for both sleep modes of ONU. Specifically, the average state transition delay of the watchful sleep mode can quickly converge to 0 and maintain stable, while the curves of the cyclic sleep mode with $T_s = 40$ ms drops down to 0. And the delays of the cyclic sleep mode with $T_s = 10$ ms cannot converge to 0 even when $\lambda_u = 1$. From the comparison of the results revealed from Fig. 4a, b, we can find that the watchful sleep mode is better and more effective than the cyclic sleep mode. The watchful sleep mode with smaller average transition delay can achieve higher efficiency for the ONU.

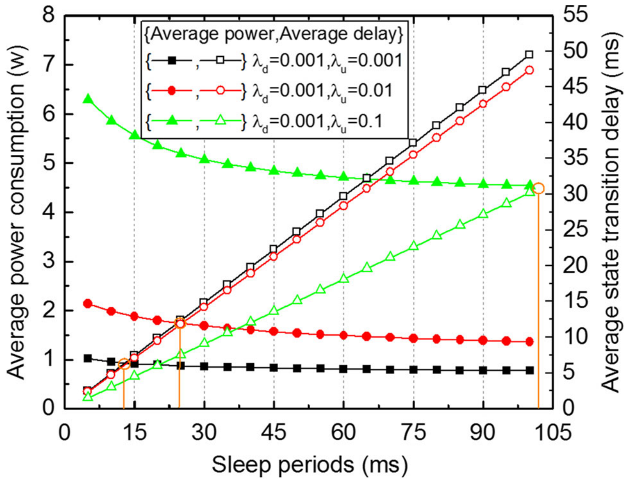


Fig. 5 The average power consumption and the average transition delay versus the sleep periods

Based on above analysis, for the watchful sleep mode, we can find that the smaller T_S would leads to the greater average power consumption, but the average transition delay trends to smaller, and vice versa. Thus, there exists a trade-off for the duration of *Sleep* state T_S between two conflicting performances. Therefore, we would determine an appropriate sleep period for the ONU, which is the optimal and balanced sleep periods between the trade-off for power saving and short delay of the watch sleep mode.

As shown in Fig. 5, the λ_d was fixed to be 0.001, while the λ_u was set to be 0.001, 0.01 or 0.1 for three different situations, respectively. The *Sleep* periods T_S independently increases from 5 to 100 ms. With the increasing of T_S, the average power consumption reveals a gentle descent tendency, while the average state transition delay rapidly increases in a linear way. In addition, with the increasing of the US traffic arrival rate λ_u, the average power consumption trended to larger, while the average state transition showed an opposite trends and became smaller. Because the ONU would more likely to stay in full power phase to deal with the traffic data. Here, when the T_S increases, the gain of the power saving efficiency would become saturated, while the negative effect of the state transition delay increases almost linearly. Intuitively, the cross points, as shown in Fig. 5, were the potential optimized values of the *Sleep* period for the certain cases. There are about 12, 25 and 102 ms for the cases of $\lambda_u = 0.001, 0.01$ and 0.1, respectively. On the other side, we can find that the average power consumption rapidly decrease within the range of less than 60 ms of the sleep periods. However, there is no prominent power saving when the sleep

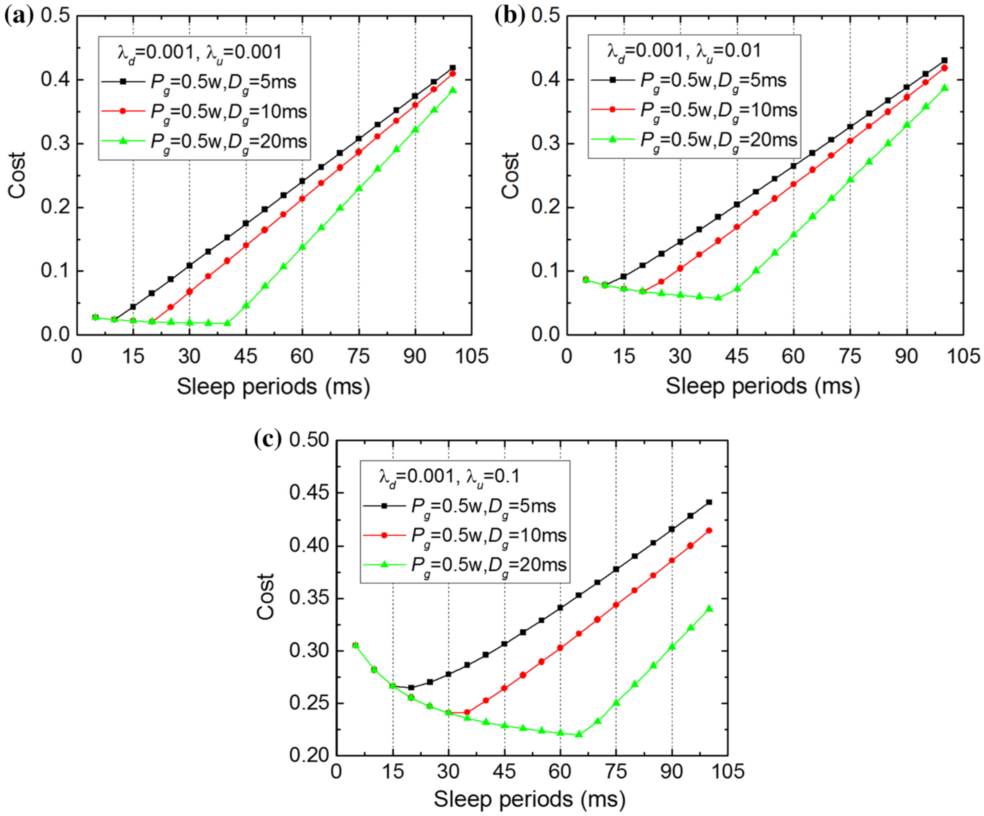


Fig. 6 The paid cost to reach the P_g and D_g verses the sleep periods for the certain cases of **a** $\lambda_u = 0.001$, **b** $\lambda_u = 0.01$ and **c** $\lambda_u = 0.1$ with the $\lambda_{d,fix} = 0.001$

period is greater than 60 ms, while the average state transition delay increases almost linearly. Thus, power saving is more dominant. And it can be used to obtain the optimized sleep period with the saturation characteristic. Thus, we set the maximum sleep period to be 60 ms for the next step of the simulations.

Based on above analysis of the numerical results revealed in Fig. 5, the investigation of the *Cost* as expressed in Eq. (5) was conducted at the different US/DS traffic arrival rates of λ_u and λ_d as shown in Fig. 6. In order to equally consider the average power consumption and the average state transition delay, we set the $\alpha = \beta = 0.5$ for Eq. (5). And the P_g was set as 0.5 W, which is same as the minimum power of P_S. Because more power can be saved when the duration of *Sleep* state increases, thus it is reasonable to set P_g as 0.5W. In addition, we adopt the different values of the goal delay D_g according to the results of Fig. 4a, and set the value as 5, 10, or 20 ms for the certain cases, respectively, as shown in Fig. 6. Thus, the optimal and balanced sleep periods between the trade-off for power saving and short delay can be determined. As indicated in Fig. 6, for fixed value of $\lambda_{d,fix} = 0.001$, the minimum paid cost would be higher when the λ_u increases from 0.001 to 0.01, and to 0.1. Specifically, in Fig. 6a, the optimal sleep period can be chosen with 10, 20, and 40 ms for the goals of $D_g = 5, 10$, and 20 ms, respectively, to maximize the power saving for the certain goals of average state transition delay. In Fig. 6b, the paid cost is much more than the case of $\lambda_{d,fix} = 0.001$, $\lambda_{u,fix} = 0.001$ expressed in Fig. 6a, while the optimal sleep periods are not drift for $\lambda_{d,fix} = 0.001$, $\lambda_{u,fix} = 0.01$. However, the optimal sleep periods of the case of $\lambda_{d,fix} = 0.001$, $\lambda_{u,fix} = 0.1$ are drift to be 15, 35, and 65 ms for the goals of $D_g = 5, 10$, and 20 ms, respectively, as shown in Fig. 6c.

Thus, through Eq. (5), the optimal and balanced sleep periods can be determined for the certain cases of $\lambda_{d,}$ and λ_u, which satisfy the requirement of power saving and optimal state transition delay.

4 Conclusion

In this paper, we modeled the watchful sleep mode of ONU by using the state probability based on the Poisson traffic arrival profile. Then we compared the performances of the watchful sleep mode with the cyclic sleep mode under the same condition. And we found that the watchful sleep mode is more effective than the cyclic sleep mode. Hence, we determined the balanced and optimal values of the *Sleep* periods for the *Cost* under the certain requirements of power saving and state transition delay. It is expected that the optimized system parameters are help to improve the performances of the ONU with the watchful sleep mode.

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Xiaobo Zeng received the B.S. degree in electronic information science and technology from Hunan University of Science and Technology, Hunan, China, in 2015. He is currently pursuing the M.Eng. degree in IC Engineering at the Southeast University, Jiangsu, China. His current research interests include optical communications, cloud radio access networks and optical transport network for 5G.

Min Zhu received a double Ph.D. degree from the Ecole normale superieure de Cachan, France, and Shanghai Jiao Tong University, China, in 2012. From 2011 to 2013, he worked as a research fellow at Nanyang Technological University, Singapore. In 2013, he joined the Department of Electronic Engineering, Southeast University, where he is currently an associate professor. His research interests include optical access networks and systems, optical grid, network resource scheduling, and optimization algorithms.

Lu Wang received the B.S. degree in electronic engineering from Southeast University, Nanjing, China, in 2016, where she is currently pursuing the master's degree.

Xiaohan Sun was a Visiting Professor with the Research Laboratory of Electronics at MIT, Cambridge, MA, USA, from 2002 to 2004. She is a currently a Professor with the School of Electronics Science and Engineering, Southeast University, Nanjing, China.