Impact of Sleep Period Variation Pattern on Energy-Delay Performances of Watchful Sleep Mode in PON

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Abstract: We have modeled the watchful sleep mode based on the Markov chain and proposed four different variation patterns of the sleep period to get the optimal tradeoff between the energy-saving efficiency and the transition delay.
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1. Introduction

The public awareness and the industry efforts have been focused to the energy consumption of the passive optical network (PON) which is viewed as the most cost-effective access technology [1]. Since the optical network units (ONUs) located at the end premises contribute the majority of energy to the PON, improving the energy efficiency of ONU is essential for realizing the goal of the lower-cost PON. Hence some energy-saving modes such as the Doze and Cyclic Sleep modes are standardized for the ONUs in recent years. They are operated by turning off all or part of transceivers in the ONUs to enter into energy-saving states when there is no or light traffics arrival [2].

Recently, the watchful sleep mode was proposed by D. A. Khotimsky etc. [3] to unify above two standardized ONU saving modes into a single power management mode, which simplifies the operation of energy-saving mode in ONUs. It is noted that the sleep period in the mode is a significant parameter, and its duration and variation pattern severely affect two performances: energy-saving efficiency and transition delay. There is a trade-off for the sleep period between the conflicting index as the larger sleep period tends to be better energy-efficiency, but increases the transition delay or packet loss due to the limited buffer, and vice versa [4]. In this paper, we will study the impact of several different variation patterns of the sleep period on the system performances for the watchful sleep mode.

2. Mathematic Model Based on Markov Chain

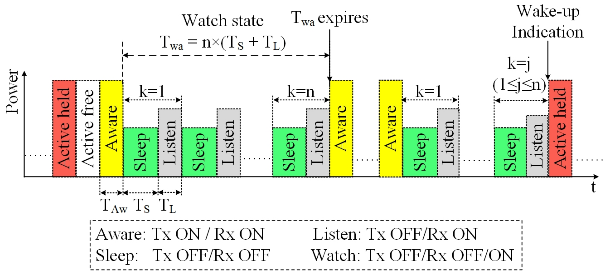

Fig. 1. Power consumption of the ONU

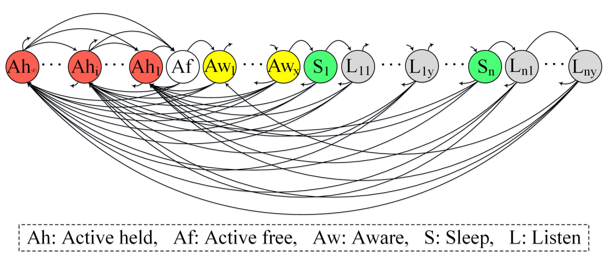

Fig. 2. State transition of ONU in the Markov chain

The watchful sleep mode at the ONU is operated based on five states: *Active held*, *Active free*, *Aware*, *Listen* and *Sleep*, as shown in Fig.1. The first two states constitute the active phase, and the later three states comprise the power saving phase of the ONU. When the ONU stays in the active phase, the ONU operates at full power with both the transmitter (TX) and receiver (RX) switched on and send the UP-/Down-stream (US/DS) traffic. During the power saving phase, the ONU alternates between *Aware* state (full power) and *Watch* state (low power) until the wake-up indication occurs. In the *Watch* state, the ONU swaps between the *Listen* and *Sleep* states, and their duration time are denoted as T_L and T_S, respectively. The two state parameters are critical for improving the system performances. It is assumed that the *Watch* state contains *n* pairs of <*Sleep*, *Listen*> state, and $T_{wa} = n \times (T_S + T_L)$, where T_{wa} is the duration of the *Watch* state as shown in Fig.1. In the *Watch* state, the TX of ONU is always OFF, while the RX is periodically ON for a short time to detect for wake-up indication, creating two possible power levels: i) the TX and RX are OFF (*Sleep* state), ii) the TX is OFF and RX remains ON (*Listen* state). If there exit the packets arrival during the *Sleep* state, a wake-up indication is generated from the OLT and processed by the ONU at the end of the *Sleep* state. When T_{wa} expires, the ONU returns to the *Aware* state. If the burst traffic arrives at the *j*-th <*Sleep*, *Listen*> pair, the state of ONU will transfer from the *Listen* into *Active held* state directly.

The Markov chain was used to theoretically analyze the average transition delay and energy-saving efficiency for the watchful sleep mode as shown in Fig. 2. The Poisson traffic arrival mode was chosen for simplifying the analysis with the average traffic arrival rate (λ packets/s), and the packet arrival process is independent from the distribution of packet size. The service time of each packet follows the exponential distribution with the average value of $1/\mu$. In the Markov chain model, each state is divide into several scheduling cycles. Ah_i (i=1,2,…) refers to the *Active held* state that ONU has i packets queued by the end of a scheduling cycle. Af is a transitional state from *Active held* to *Aware* state which was divided into x cycles (i.e. Aw_j, j=1,2,…x). In the *Watch* state, $\mathrm{L}_{k,l}$ (k=1,2…n, l=1,2,…y) is the k-th *Listen* state that the ONU has not received any packet for l cycles. The time duration of *Sleep* state S_k (k=1,2,…n) equals to z cycles, and cannot be interrupted until the time is expired. Except the *Sleep* state, the other states may be transferred to another one at the end of any one cycle. The probabilities of b DS packets arrival at ONU or b US packets departure from it during g cycles are respectively denoted as $p^a(b, g)$ or $p^d(b, g)$.

$$p^a(b,g) = e^{-\lambda gT}(\lambda gT)^b / b!, \quad p^d(b,g) = e^{-\mu gT}(\mu gT)^b / b! \tag{1}$$

According to the principle of the balance equations in the Markov chains, the arrival frequency to a certain state equals to the departure frequency to the state. Thus, the steady-state probability $P(\theta)$ of any state θ satisfies:

$$P(\theta)\sum_{\pi\neq\theta} pr(\theta\to\pi) = \sum_{\pi\neq\theta} P(\pi)pr(\pi\to\theta), \quad \sum_{any\ \theta\in\Phi} p(\theta) = 1 \tag{2}$$

where the state π is the other states in the state set Φ except the θ, and $pr(\theta\to\pi)$ is the transition probability from the θ to π. The steady probabilities of all states in the state set Φ are unique and follow the normalization constraint.

State transition from Af to Aw_1, from Aw_j to Aw_{j+1}, from Aw_x to S_1, from $\mathrm{L}_{k,l}$ to $\mathrm{L}_{k,l+1}$, from $\mathrm{L}_{k,y}$ to S_{k+1} happen when no packet arrive during a scheduling cycle, and the probability of each case is $p^a(0,1)$. If the case occurs in z cycles of *Sleep* sate, the transition probability from S_k to $\mathrm{L}_{k,1}$ is $p^a(0,z)$. When the number of arrival packets is greater than the number of departures by k during a cycle, the state transition from $\mathrm{L}_{k,l}$, Af, Aw_j to Ah_k, from Ah_i to Ah_{i+k}, the probability is $\Sigma_i\, p^a(k+i,1)p^d(i,1)$ for above cases. If the case happens in the z cycles of *Sleep* state, the transition probability from S_k to Ah_k equals to $\Sigma_i\, p^a(k+i,z)p^d(i,z)$. Conversely, when the number of arrival packets is smaller than the departures by k during a cycle, the transition probability from Ah_i to Ah_{i-k} is $\Sigma_i\, p^a(i,1)p^d(k+i,1)$.

We assume that the power consumption of Ah, Af and Aw states follow W(Ah)=W(Af)=W(Aw)=W(A).Thus the average energy consumption can be calculated as:

$$E[P_{sw}] = W(\mathrm{A})\Big[\sum_i P(\mathrm{Ah}_i) + P(\mathrm{Af}) + \sum_{j=1}^{x}\mathrm{Aw}_j\Big] + W(\mathrm{L})\Big[\sum_{k=1}^{n}\sum_{l=1}^{y} P(\mathrm{L}_{kl})\Big] + W(\mathrm{S})\sum_{k=1}^{n} P(\mathrm{S}_k) \tag{3}$$

The average transition delay (TD) for the packets that arrive at the ONU when it stays in Ah, Af, Aw, L and S states are respectively denoted as $E[\delta|\mathrm{Ah}]$, $E[\delta|\mathrm{Af}]$, $E[\delta|\mathrm{Aw}]$, $E[\delta|\mathrm{L}]$ and $E[\delta|\mathrm{S}]$. The total TD can be calculated as:

$$\begin{aligned} E[D] &= E[\delta|\mathrm{Ah}]\cdot\sum_{i=1}^{\infty} P(\mathrm{Ah}_i) + E[\delta|\mathrm{Af}]\cdot P(\mathrm{Af}) + E[\delta|\mathrm{L}]\cdot\sum_{k=1}^{n}\sum_{l=1}^{y} P(\mathrm{L}_{kl}) \\ &+ E[\delta|\mathrm{S}]\cdot\sum_{k=1}^{n} P(\mathrm{S}_k) + E[\delta|\mathrm{Aw}]\cdot\sum_{j=1}^{x} P(\mathrm{Aw}_j) \end{aligned} \tag{4}$$

Those packets that arrive when an ONU is sleeping have to wait until the ONU wakes up from the *Sleep* state before be transmitted. Thus, the average TD includes the queuing time in buffer and the "wait-to-wakeup" time. On average, the "wait-to-wakeup "time for a packet is $z/2$ cycles in ONU which stays in *Sleep* state with z cycles. For the other states, the average TD can just consider the queuing time, which is expressed as follow.

$$E[\delta\,|\,\pi] = \sum_{i=1}^{\infty}\big[p^a(i,\tau)\cdot(i-1)\cdot(1/\mu)\big], \quad \text{any } \pi\in\Phi \tag{5}$$

where τ is the scheduling time (e.g. τ=z for *Sleep* state, τ=1 for the other states), $1/\mu$ is the average TD for a packet.

Using Eq. 3 and Eq. 4, we can define the following *Cost* function with the similar concept as [5]. The cost means the expenditure which should be paid to achieve the goal value P_g of the energy consumption and the D_g of the transition delay, that is, the difference between the estimated $E[P_{sw}]$ and $E[D]$ and these goal values.

$$Cost = \Sigma_{\lambda\in S_\lambda}\Sigma_{\mu\in S_\mu}\left\{\alpha\frac{\max\big[\big(E[P_{sw}]-P_g\big),0\big]}{P_a-P_g} + \beta\frac{\max\big[\big(E[D]-D_g\big),0\big]}{D_{\max}-D_g}\right\} \tag{6}$$

where S_λ and S_μ are the set of λ and μ respectively. $D_{\max}$ is the maximum TD for all of λ and μ. α and β are the weights for two conflict performance indexes respectively which follow the constraints of $\alpha+\beta=1$ ($0\le\alpha\le1$, $0\le\beta\le1$).

3. Sleep Period Variation Pattern

In order to study the time duration and variation pattern of the sleep period on the two conflicting performances based on the Markov chain of ONU state machine, we designed 4 different variation patterns as follows to get the optimal tradeoff between the energy-saving efficiency and the transition delay. The 4 different variation patterns can be expressed with two parameters: the duration $\mathrm{T_S}$ of *Sleep* state and the number n of the state pairs. Specifically, i) the $\mathrm{T_S}$ is fixed ($\mathrm{T_S}$=1 cycle) with the increase of n (n=1,2,…), which was denoted as *constant* pattern; ii) the $\mathrm{T_S}$

increases linearly as the n increases and satisfies the equation $T_S = n$, which was marked as *linear*_1 pattern; iii) the T_S and n follow the equation of $T_S=2*n$, which was denoted as *linear*_2 pattern; 4) the T_S increases exponentially as the n increases and follows the constraint $T_S=2^{n-1}$, which was denoted as *exponential* pattern.

4. Performance Evaluation

In this Part, we assumed the average service time of each packet is a scheduling cycle (T=2ms), that is μ=1, The normalized power consumption of ONU in *Active* (e.g. Ah, Aw, Af), *Listen*, and *Sleep* states are set to be 1, 0.4, 0.05, respectively. The number of cycles of Aw and L are selected as x=4 and y=3, respectively. In order to equally consider the energy consumption and transition delay, we assumed the α=β=0.5.

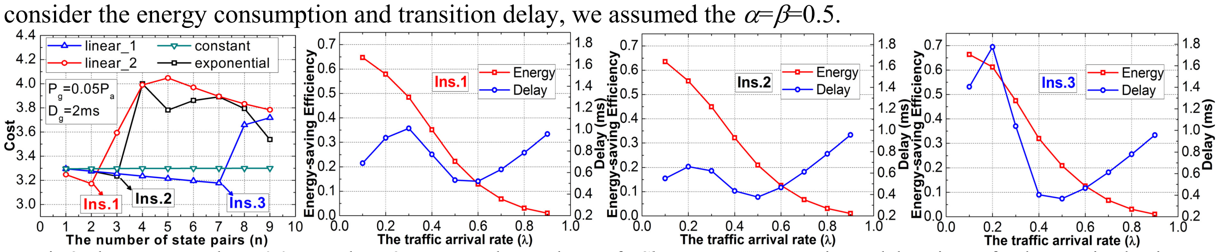

Fig.3 The cost to reach P_g=0.05P_a and D_g=2ms versus the number n of <*Sleep*, *Listen*> state pairs, and three insets for three optimal points

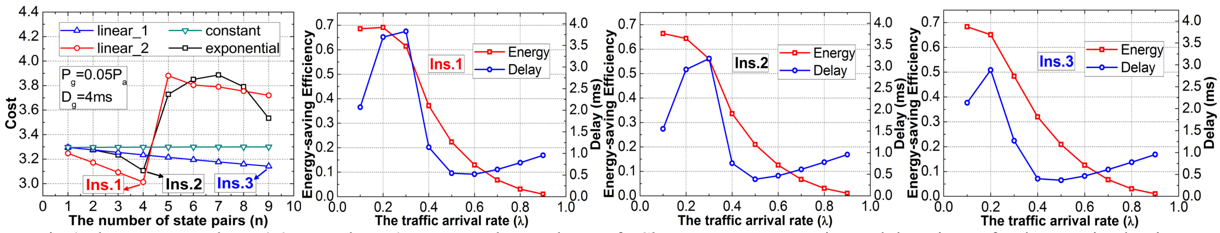

Fig.4 The cost to reach P_g=0.05P_a and D_g=4ms versus the number n of <*Sleep*, *Listen*> state pairs, and three insets for three optimal points

Fig.3 and Fig.4 illustrate the relationship between the cost and the number of state pairs (n) using the different goal values of transition delay (e.g. D_g=2ms or 4ms), and give out some special case in three insets about the energy-saving efficiency and the transition delay performances for three optimal points. Fig.3 reveals that the *linear*_1, *linear*_2, and *exponential* mode would obtain the optimal cost values of 3.2, 3.2 and 3.25, when the n is 7, 2 and 3 respectively for the goals of P_g=0.05P_a and D_g=2ms. And the insets (1), (2) and (3) show the similar variation of energy-saving efficiency as the traffic rate increases, while the transition delays are different from each other and the minimum delay can be obtained when the arrival rate λ=0.5 for the *exponential* and *linear*_1 patterns, and λ=0.6 for *linear*_2 pattern. Fig.4 reveals that the *linear*_1, *linear*_2, and *exponential* patterns would obtain the optimal cost values of 3.2, 3.1 and 3.2, when the n is 9, 4 and 4 respectively for the goals of P_g=0.05P_a and D_g=4ms.

5. Conclusion

In this paper, we have modeled the watchful sleep mode based on Markov chain to analyze the system performances represented by the cost functions. We proposed four different variation patterns of the sleep period to get the optimal tradeoff between the energy-saving efficiency and the transition delay. From the numerical analysis, we can find that *linear*_1, *linear*_2, and *exponential* patterns are better than *constant* pattern, and these optimal cost values can be achieved when the state pairs of n is 7, 2, 3 and 9, 4, 4, and the delay goal value of D_g is 2ms and 4ms, respectively.

6. Acknowledgements

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