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An energy efficient cyclic sleep control framework for ITU PONs

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ABSTRACT

Cyclic Sleep Mode (CSM) is a widely studied and standard energy conservation technique for Passive Optical Networks (PONs). The energy savings provided by CSM increase with longer *Asleep* and shorter *SleepAware* state periods. However, this also leads to increased communication delays. Moreover, too short *SleepAware* time may degrade dynamic bandwidth assignment (DBA) performance and even may cause delay of urgent PLOAM messages from OLT. Neither CSM standards nor existing studies provide any detailed framework to configure CSM performance and control parameters in accordance to the target delays. Another limitation of existing studies is their assumption of a single traffic class during sleep mode analysis. They do not consider the impact of CSM on Type-1 (T1) to Type-4 (T4) traffic classes defined by International Telecommunication Union (ITU). Most of these studies also neglect the role of DBA by considering a fixed bandwidth assignment. However, upstream delays critically depend on the DBA performance and its impact should not be ignored during CSM studies. Therefore, this study presents an Efficient Cyclic Sleep (ECS) framework to configure all CSM parameters and timers with optimum values in the presence of all traffic classes and DBA scheme. The proposed scheme maximizes the energy savings even at very high traffic loads while satisfying the target average delay limit of 56 ms for both US and DS links. A sleep buffer approach is used to configure the Local Wake Up Indication (LWI) events and all CSM control timers at the OLT and ONU. The proposed scheme is compared with two other reported schemes. Simulation results show up to 84.1% energy savings at very low traffic loads and 43% savings at 80% network traffic load (equal to traffic arrival rate of 550Mbps per ONU). The delay variance results for both US and DS also remain under 1 ms.

1. Introduction

International Telecommunication Union (ITU) 2015 report mentioned a rise of 46% in internet users since 2010. Specifically, a 10.8% increase in fixed broadband and 47% increase in mobile services subscriptions [1] was reported. This expansion of Information and Communication Technology (ICT) sector is leading to higher electrical energy requirements of this sector. In 2015 the global electrical power generation was recorded as 24,000 Tera Watt hours (TWh) and this generation is expected to increase by 69% by 2040 with 36.5 Trillion KWh productions and 59% of it from thermal resources (Coal, Natural Gas and Oil) [2]. These thermal resources contribute heavily to the emission of greenhouse gases due to massive fuel burnings. In ICT networks, the access networks are responsible for up to 70% [3] of the overall ICT power consumption. In addition, due to major amount of the energy consumption, the service providers have to face high maintenance costs in the access network. Therefore, an energy efficient ICT network is not only environmental friendly but also economical for the network operators.

Passive Optical Networks (PONs) are more energy efficient compared to legacy copper based broadband access networks. However, still, there is significant room for improvement because it has been shown in [4] that an energy aware PON equipment can reduce power consumption up to 58%. The Optical Network Units (ONUs) are responsible for 60% of the PON power consumption while the Optical Line Terminal (OLT) consume only 7% [5]. Therefore, ONU energy consumption is more beneficial and this is the reason that most of the current research on PON energy conservation is focused on ONU power reduction.

Various ONU based energy conservation techniques have been reported in literature like Adaptive Link Rate (ALR) [6,7], Bit Interleaved PON (Bi-PON) [8,9,21], ONU buffer elimination [10] and

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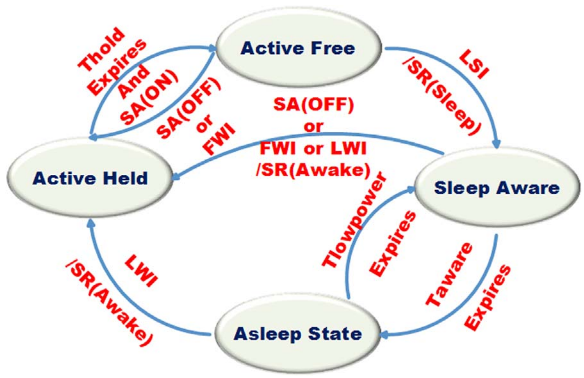

Fig. 1. Cyclic sleep state diagram for ONU.

ONU sleep modes. A detailed review on energy conservation techniques is available in [5,11]. However, ONU sleep mode techniques have gained more popularity due to their simplicity and not requiring extra physical layer changings in existing ONU architecture. It is a widely studied technique, not only for TDM PONs but is also being used in future fiber wireless (FiWi) scenarios [12,13]. In addition to ONUs, sleep mode has also been used for access points (AP) and wireless stations (STA) in FiWi scenario [14]. Out of all the sleep mode techniques, cyclic sleep mode (CSM) has drawn attention of the PON standardizing bodies and has been adopted by ITU and IEEE as a standard energy conservation scheme in their PONs.

In CSM, an ONU switches between four power states namely; *ActiveHeld* (AH), *ActiveFree* (AF), *SleepAware* (SLA) and *Asleep* (AS). The corresponding power states of OLT are; AwakeForced (AWF), AwakeFree (AFR), AlertedSleep (ASP) and LowPowerSleep (LPS). The state transitions mainly depend on Local Wakeup Indication (LWI) events at the OLT and ONU. These events indicate crossing of DS / US traffic queue threshold of an ONU during AS state. Figs. 1 and 2 show the ONU and OLT state diagrams for CSM operation in ITU compliant PONs (GPON and XGPON). OLT maintains a separate CSM process for each ONU. Table 1 shows important parameters and notations used in rest of the paper.

In the AH state, ONU is fully active and not allowed by OLT to exercise CSM. The corresponding power state of the OLT is AWF. If the $LWI_{OLT} = 0$, the OLT allows sleep mode operation by sending a SA (ON) message to ONU and transitions to AWF state. On receiving this message, the ONU sets its local flag variable $SA_{ON} = 1$. In AH state after the expiry of T_{HOLD} if $SA_{ON} = 1$, then ONU transitions to AF state. In this state if the ONU is willing to avail low power mode, indicated by the flag LSI=1, the ONU transitions to SLA state and sends SR (Sleep) message to OLT. This leads OLT to the LPS state and it starts the timer

Fig. 2. Cyclic sleep state diagram for OLT.

T_{ERI}. The maximum sojourn in SLA state is for a period of T_{AWARE} and during this time the LWI_{ONU} and LWI_{OLT} are monitored. If both these events are not asserted during the T_{AWARE} time, then the ONU transitions to AS state. The OLT remains in LPS if continuously no valid optical signal is being received from the ONU in the contiguous allocation slots assigned to it. This event is termed as Allocation Miss. On every Allocation Miss or SR(Sleep) message from OLT, the timer T_{ERI} is reinitialized. OLT switches from LPS to AWF state in two different conditions. First, if it finds $LWI_{OLT} = 1$ then OLT transitions to ALS state and sends a SA (OFF) message to ONU and starts the timer $T_{Alerted}$ as well as starts forcing ONU to wake up by setting the forced wake up indication (FWI) flag in the bandwidth map (BWmap) field of every DS frame. During this time if ONU switches to AH state and sends SR (Awake) message or the $T_{Alerted}$ expires, the OLT transitions to AWF state. In the second condition, if the T_{ERI} timer expires and no Allocation Miss event or SR (Sleep) message is received, the OLT declares a handshake violation and transitions to AWF state. This condition actually happens when an ONU goes offline like in case of a fiber cut. In the normal case, in the SLA state, at the expiry of T_{AWARE}, if LWI_{ONU}=0, $LWI_{OLT} = 0$ and $SA_{ON} = 1$, the ONU transitions to AS state for a period of $T_{LowPower}$. In the AS state ONU can only quit this state if the LWI_{ONU}=1. In that case $T_{LowPower}$ timer is cancelled and the ONU immediately switches to AH state and sends the SR (Awake) message to OLT. Once in the AS state, if the LWI_{ONU} and LWI_{OLT} are not asserted, indicating absence or very low traffic, the ONU keeps on switching periodically between AS and SLA states (with OLT being in LPS mode, termed as sleep cycle). Practically, ONU cannot immediately switch to AH state from AS state as it requires a transceiver initialization time (T_{Init}). The ONU sojourn in AS sate is more commonly indicated by T_{AS} instead of $T_{LowPower}$ and we adapt the same notation in this study.

The choice of LWI_{OLT}, LWI_{ONU}, T_{AWARE} and T_{AS} characterizes the performance of CSM in terms of energy savings and Quality of Service (QoS). In most of the studies, only the impact of T_{AS} and T_{AWARE} on cyclic sleep performance is considered. These studies force ONU to switch to AH state by setting $LWI_{OLT} = 1$ or $LWI_{ONU} = 1$, as soon as a single traffic frame arrives at OLT or ONU and thus terminate sleep cycle immediately. We call this approach as Quick Release (QR) which provides energy savings only when traffic arrival rates are very low [15,16]. Another approach is proposed by Hirafuji et al. [17] and Skubic and Hood [18], in which the LWI_{OLT} and LWI_{ONU} events are delayed for a fixed time before they are set to '1' on DS / US traffic arrivals during AS state. We call this approach as Delayed Release (DR). Although, DR provides better energy savings even at higher traffic loads but this is not an optimized approach to configure CSM to obtain maximum energy savings at low traffic loads. To the best of our knowledge no comprehensive study on this subject is available., Therefore, this paper presents a comprehensive energy efficient CSM framework (ECS) for XGPON using a sleep buffer approach used in [19] for computing the optimized values of all CSM parameters and control timers; T_{AWARE}, T_{AS}, T_{ERI}, T_{Hold} and $T_{ALERTED}$. The proposed frame work can work with any ITU compliant DBA scheme and considers all ITU defined T1 to T4 traffic classes. For a definition of these traffic classes, the reader is referred to Table 1 of [20]. By following this frame work, the CSM provides maximum energy savings while adhering to the target US and DS average delay limits D_{DS} and D_{US}.

Rest of this paper is organized as follows. Related work is discussed in Section 2. Section 3 presents the proposed frame work. Section 4 explains the simulation setup to test the proposed framework with existing reported work. In Section 5, the results are discussed and finally, Section 6 concludes this paper with future research direction.

2. Related work

The main cause of higher power consumption in PON is broadcast nature of traffic in the DS link. Due to this, every ONU has to receive and process all frames from OLT and check for relevancy. This