The Watchful Sleep Mode: A New Standard for Energy Efficiency in Future Access Networks

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ABSTRACT

The continuously increasing consumption of power to access the Internet has been a major concern for network operators and equipment vendors. Passive optical network (PON) systems are widely seen as the future of broadband access. In 2010, ITU-T standardized a protocol-based PON energy efficiency mechanism that is comprised of two main modes, the doze mode and the cyclic sleep mode, which promise to save significant amounts of energy. However, the use of these two standardized alternative modes requires extra signaling and wastes energy. In this article we present the watchful sleep mode, a new mode that unifies the doze and cyclic sleep modes into a single power management mode. The new mode eliminates the extra control signaling and maximizes the amount of energy saved by keeping only the necessary hardware ON. Recently, the watchful sleep mode has been included in the ITU-T G.984 (G-PON) and ITU-T G.987 (XG-PON) recommendations. It is expected to be operated as the only power management mode in future PON systems.

INTRODUCTION

In the last decade energy efficiency has become a predominant theme in the design and operation of next-generation homes, electronics, software, and machinery. Recent studies show that by the year 2035, at the current power production rate, only 50 percent of the global power need will be satisfied [1]. Furthermore, to ensure human sustainability, global green house gas (GHG) emissions must be reduced by large quantities. This also applies to information and communication technologies (ICT), which are accountable for about 2 percent to 4 percent of the worldwide GHG emissions. More significantly, the power consumption of all ICT equipment, when active, accounts for roughly 40 percent to 60 percent of ICT's GHG emissions, and it is estimated that by the year 2020 these emissions will double if no action is taken [2].

Constituting the "bread-and-butter" of ICT, the Internet is estimated to account for 1 percent to 2 percent of total electricity consumption in broadband-enabled countries; this is expected to grow even further with the data transmission rate trending higher [3]. More importantly, the Internet currently consumes about 10,000 times more energy than the minimum required to operate [1]. Meanwhile, the ever growing increase in Internet traffic (about 20 percent per year) and its impact on network energy consumption have become a growing concern for network operators and equipment vendors. The high electricity costs put pressure on the profitability of Internet service providers and operators, and the increased power consumption is causing heat dissipation problems in network gear. The scientific community reacted to the challenge by analyzing and experimenting with new techniques and tools for reducing the global Internet energy consumption [4].

Accounting for a large portion of modern Internet infrastructure, access networks in general, and optical access networks in particular, such as passive optical networks (which are gradually becoming the de-facto technology for next-generation broadband access networks) have been extensively studied, and many techniques have been proposed aiming at standardizing the energy efficiency mechanism in PON [5].

PON consists of a point-to-multipoint fiber infrastructure connecting a number of optical network units (ONUs) located at the customers' premises to an optical line terminal (OLT) residing at the service provider's central office using a shared fiber. Interested readers can refer to the works in [1] and [6] for a detailed overview of PON. PON systems have matured significantly in the last decade due to the proliferation of several delay-sensitive or bandwidth-intensive applications such as voice over Internet protocol (VoIP), high-definition video (HDTV), and video conferencing, all of which have stringent quality-of-service (QoS) requirements. Gigabit Ethernet PON (EPON) and its counterpart Gigabit PON (GPON) have been accepted as the standard for PON deployments. However, those killer bandwidth-hungry applications have

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made advanced versions of PON systems, such as 10 gigabit-capable PON (XG-PON), 10 gigabit Ethernet PON (10G-EPON), wavelength division multiplexing PON (WDM-PON), and time-wavelength division multiplexing PON (TWDM-PON) to become requisite technologies for the deployment of next-generation PON (NG-PON) [6].

Due to its effectiveness, the watchful sleep mode has been approved to be included in the ITU-T G.984 (G-PON) and ITU-T G.987 (XG-PONs) standards. It is also being considered for the NG-PON2 standard (ITU-T G.989), which aims at standardizing TWDM-PON networks.

Although it was shown in [3] that PON systems consume the least power among all the reported access network technologies, its evolution is expected to significantly increase its power consumption [6]. Therefore, reducing the energy consumption in PON is deemed necessary. To date, putting the ONU into low-energy mode has been considered the most cost-effective and promising method for saving energy in PON [1, 7–10]. Multiple proposals for a low-power mode have been put forward; these have been known as the *sleep* mode, which can either be *fast/cyclic* or *deep*, and the *doze* mode. The low-power modes are expected to decrease ONU energy consumption by almost 80 percent [8]. Interestingly though, the standard does not present a justification for proposing these different independently operated modes. More importantly, in order to achieve maximum energy saving, intelligent, and thus complex, arbitration of the different modes must be implemented at both the ONU and OLT.

In this article we present the *watchful sleep* mode, a new mode that unifies the doze and cyclic sleep modes into a single power management mode [11]. In the new mode, an ONU periodically turns off its receiver and transmitter, as in the cyclic sleep mode, and performs infrequent bidirectional handshakes, as in the doze mode. The watchful sleep mode not only simplifies the implementation of the power management scheme at the ONU and OLT, but also combines the advantages of the cyclic sleep and doze modes, and outperforms both of them. More interestingly, a PON system supporting the watchful sleep mode can actually emulate the cyclic sleep or doze mode as a special case.

Due to its effectiveness, the watchful sleep mode has been approved to be included in the ITU-T G.984 (G-PON) and ITU-T G.987 (XG-PONs) standards. It is also being considered for the NG-PON2 standard (ITU-T G.989), which aims at standardizing TWDM-PON networks.

The rest of the article is organized as follows. We present an overview of the main standardized (or considered for standardization) power saving techniques in PON systems. We describe the watchful sleep mode. We also discuss its practical implementation details, and present a comparative study to highlight its advantages. We discuss the future outlook and how the new mode can be operated under NG-PON2 systems. We summarize the article and present our conclusions.

PON ENERGY SAVING TECHNIQUES

In general, energy efficiency in PON systems can be achieved through improvements in components and module designs, one-sided power management techniques (i.e. either at the OLT or ONU), and protocol-based power management mechanisms. As an example of improvements in component and module design, the use of vertical cavity surface emitting lasers (VCSELs)-based ONUs, as proposed in [12], can minimize the power consumed in both the active and power saving modes, and it can maximize the time the ONU spends in the power saving phase.

One-sided power management techniques are specific to either the OLT or ONU, thus they do not involve signaling between them. An example of an ONU-sided technique is *power shedding*, which is supported autonomously by the ONU [5]. With power shedding, the ONU turns off some of its components to reduce power consumption, while keeping the optical link in full function. An OLT-side power management technique has been proposed in [13], in which working ONUs of a TWDM-PON are organized to send and receive traffic over a minimum number of wavelengths, allowing the OLT to turn off some of its transceivers so as to save power.

Protocol-based power management techniques do require signaling between the OLT and ONU. Well known examples of such techniques are the doze and cyclic sleep modes, which have been standardized by the ITU-T [14]. In both modes, the ONU alternates between active and power saving phases, which are initiated and terminated through the exchange of signaling information between the OLT and ONU. During a power saving phase, the ONU swaps between two states: a full power state, referred to as the *aware state* for both modes; and a low power state. In doze mode, the low power state is known as the *listen state*, in which the ONU transmitter is OFF and the ONU receiver is ON. In the cyclic sleep mode, the low power state is known as the *sleep* state; here, both the ONU's transmitter and receiver are OFF.

To enable the doze and cyclic sleep modes in PON, the ONU and OLT implement the state machines illustrated in Fig. 1. Due to the centralized nature of PON systems, the OLT maintains a different state machine for each ONU. As shown in Fig. 1a, in the ONU state machine, the *active held* and *active free* states constitute the active phase of an ONU, while in the active held state, the ONU cannot enter a power saving phase. Meanwhile, in the active free state, the ONU can freely enter a power saving phase as soon as a local doze indication (LDI) occurs, which initiates the doze mode operation. Similarly, a local sleep indication (LSI) will initiate the cyclic sleep mode operation. The *doze aware*, *sleep aware*, *listen,* and *asleep* states comprise the power saving phase of the ONU. The transition from a power saving phase to an active phase is triggered by:

- A local wake-up indication (LWI).
- A message from the OLT.
- A forced wake up indication (FWI) bit in the bandwidth allocation map from the OLT.

The implementation of the LWI, LDI, and LSI is left to the ONU vendor and/or PON operator.

In the OLT state machine, the *awake forced* and *awake free* states correspond to the ONU in the active phase, whereas the *low power doze/sleep* and *alerted doze/sleep* states corre-

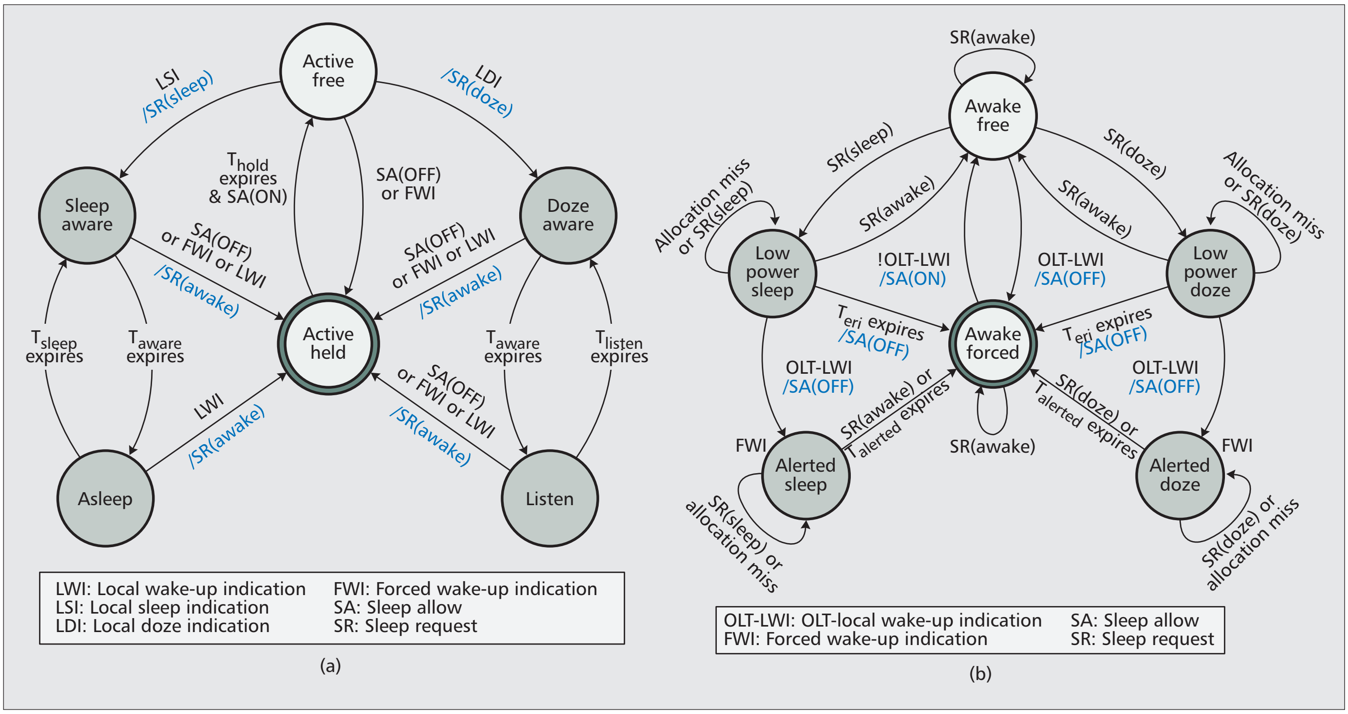


Figure 1. Cyclic sleep and doze modes state machines: a) ONU state machine; b) OLT state machine. The notation MESSAGE(ARG) represents the command and its corresponding argument as defined in the ITU-T standard. For example, SA(ON) is an OLT message that "allows" the ONU to start a power saving phase.

spond to the ONU in the power saving phase. The awake forced state indicates that the ONU cannot enter a power saving phase. In the awake free state, the ONU can enter a power saving mode, which is either the low power doze or low power sleep state. Finally, the *alerted doze* and *alerted sleep* states correspond to the period in which the OLT attempts to wake up the ONU. The transition from the awake forced state to the awake free state, which grants permission for the ONU to start a power saving phase, occurs upon the cessation of the LWI at the OLT, denoted by !OLT-LWI. The OLT stimulus OLT-LWI always triggers a transition to the awake forced or alerted doze/sleep states; this revokes the ONU permission to be in a power saving phase.

The sojourn time of the ONU in the aware, listen, and sleep states is represented by the notations T_{aware}, T_{listen}, and T_{sleep}, respectively, and they are set by the OLT according to the following criteria:

- To configure T_{aware}, the OLT should keep track of the time required to perform at least one handshake between the OLT and ONU; meanwhile the ONU would be in the active state. Therefore, the period T_{aware} is configured to be bigger than the duration of one handshake.
- To configure T_{listen}, the OLT should know how often the periodic bidirectional handshakes between the OLT and ONU occur. These may include, for example, an adjustment margin to account for keep-alive maintenance and ranging periods. Therefore, the period T_{listen} would be configured to be smaller than the maximum interval between these periodic handshakes. The ONU remains in the listen state for the period T_{listen} unless there is a local or an external wake-up stimulus, which forces it to transition to the aware state.
- To configure T_{sleep}, the OLT must primarily take into consideration the tolerable latency of the external wake-up stimulus, that is, the elapsed period between the time to wake up the ONU and the time needed to restore bidirectional communication (i.e., between the OLT and ONU). Therefore, T_{sleep} shall be smaller than the tolerable latency of the external wake-up stimulus. The ONU remains in the sleep state for the period T_{sleep} if it is not interrupted by the arrival of a local wake-up stimulus.

The minimum ONU sojourn time in the active held state is denoted as T_{hold} (Fig. 1a). In the OLT state machine, the timing parameters T_{eri} and $T_{alerted}$ denote the timeout for the low power doze/sleep state, and the timeout for the alerted doze/sleep state, respectively.

Even though the doze and cyclic sleep modes can improve the energy efficiency in PON, they impose several limitations. First, the OLT and ONU need to negotiate and agree upon the operated power saving mode (i.e., either the doze mode or the cyclic sleep mode). Second, in the Doze mode, the ONU keeps the receiver always `ON` even when there is no traffic destined for that ONU. Finally, in the cyclic sleep mode, in order to probe for external wake-up stimulus, the ONU must periodically turn `ON` both its receiver and transmitter, even though turning the receiver `ON` only is sufficient to achieve the foregoing goal.

As noted, the foregoing limitations may either downgrade the system performance (e.g., due to extra sophisticated signaling overhead), or waste energy due to keeping some of the devices unnecessarily `ON`. Furthermore, the ITU-T stan-

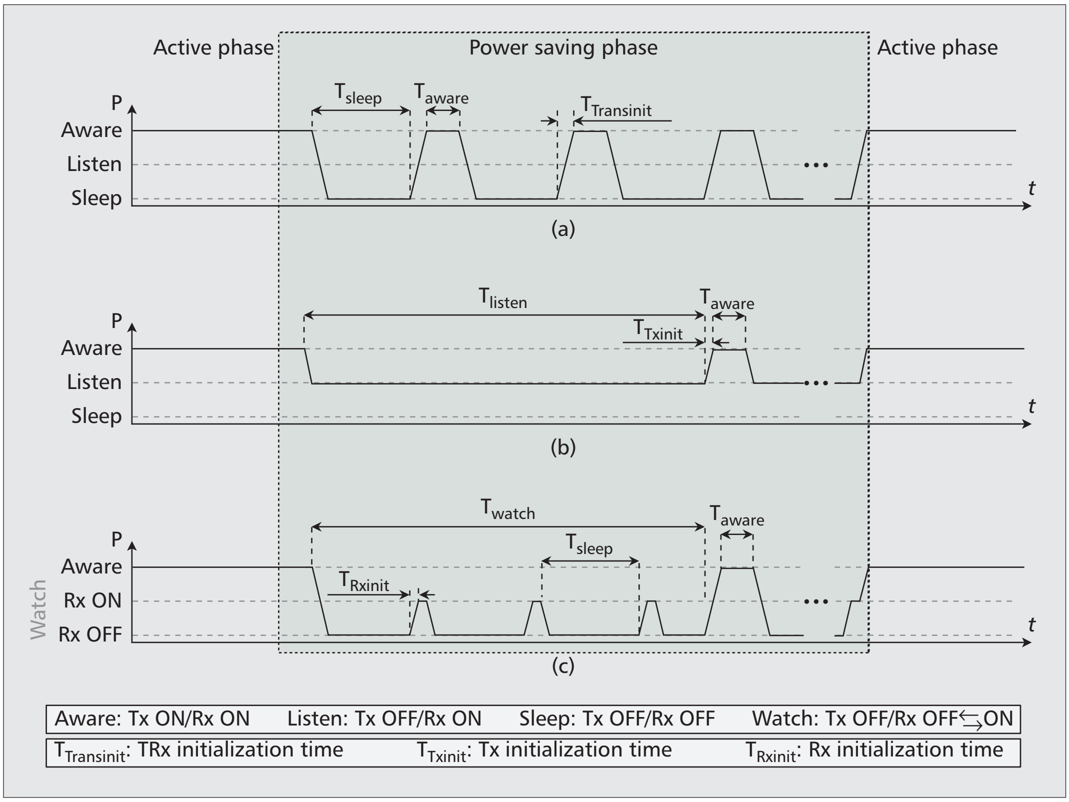


Figure 2. Power consumption in a) cyclic sleep mode; b) doze mode; c) watchful sleep mode.

Like the doze and cyclic sleep modes, the watchful sleep mode alternates between the active and power saving phases. In addition, during the power saving phase, it switches between the full power state and the low power state. The difference between the watchful sleep mode and the other two modes lies in the semantics of the low power state.

dard does not present a justification to maintain a separation of the two aforementioned power saving modes. Thus, the complexity of implementing and operating these two modes is not justified.

THE WATCHFUL SLEEP MODE

The *Watchful Sleep* mode is a new mode that unifies the doze and cyclic sleep modes into a single power saving mode. The new mode mitigates the drawbacks imposed by the operation of the doze and cyclic sleep modes by eliminating the need for negotiation of the employed mode between the OLT and ONU. It also maximizes the amount of energy saved in the ONU by keeping only the required devices ON, while the rest will be OFF.

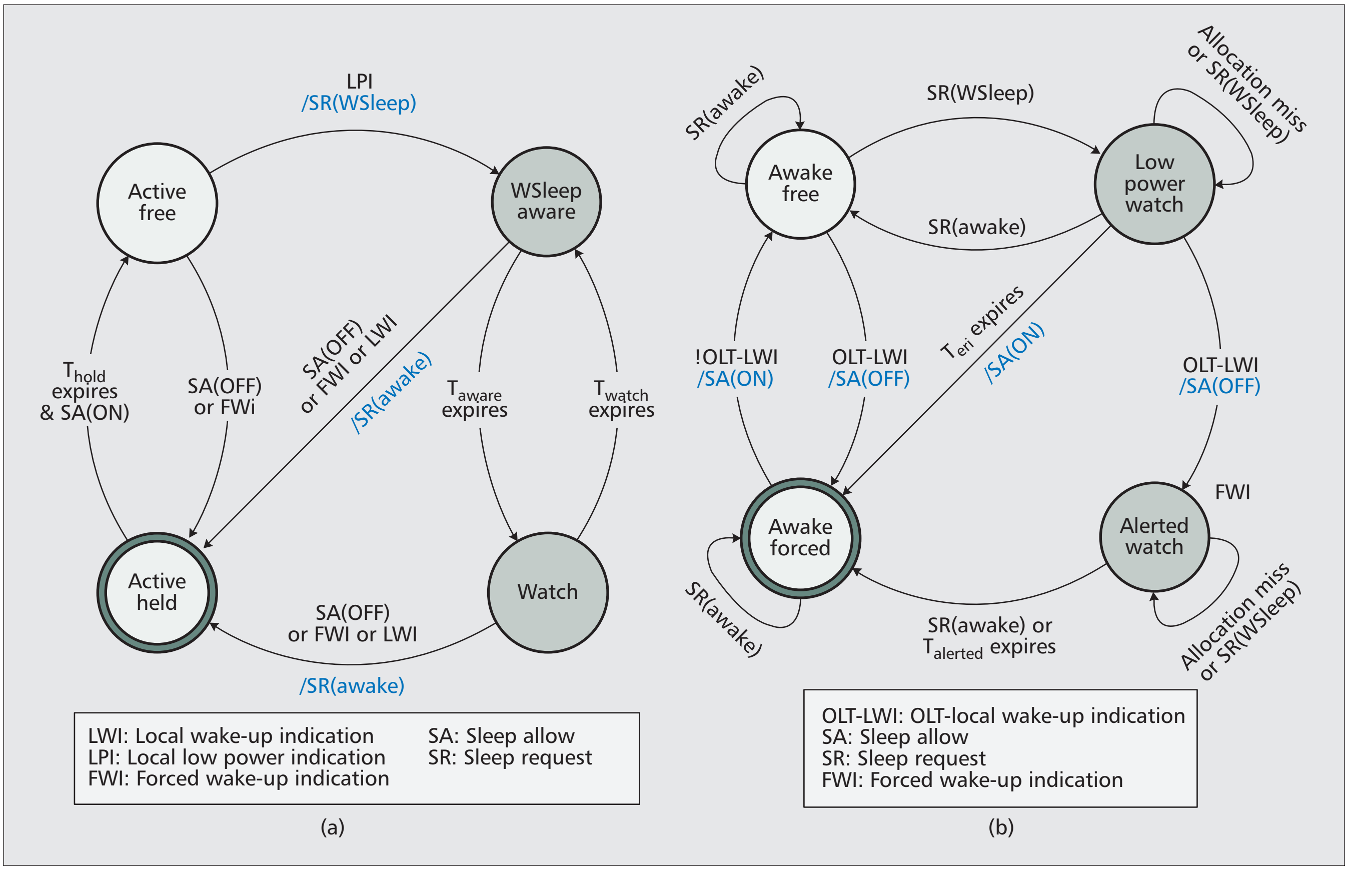
Like the doze and cyclic sleep modes, the watchful sleep mode alternates between the active and power saving phases. In addition, during the power saving phase, it switches between the full power state and the low power state. The difference between the watchful sleep mode and the other two modes lies in the semantics of the low power state, as depicted in Fig. 2.

In the low power state of the watchful sleep mode, referred to as the *watch state*, the ONU maintains its transmitter OFF, but periodically turns the receiver ON for a short time to check for external wake-up stimuli. As a result, during the watch state, the ONU may be in two possible power consumption levels:

- The power level in which both the transmitter and the receiver are OFF.
- The power level in which the transmitter is OFF and the receiver is kept ON.

The ONU remains in the watch state for a period denoted T_{watch}, unless there is a local or an external wake-up stimulus that forces the ONU to transition to the aware state. The ONU sojourns with the receiver OFF for the period T_{sleep} before turning the receiver back ON to check for external wake-up stimuli; the receiver is kept ON until the ONU confirms that there is no external wake-up stimulus. This interval can be as small as one frame (e.g., 125 μs in GPON) if the OLT sends a scheduling grant to the ONU in each frame. The OLT configures T_{aware} and T_{sleep} according to the same criteria used for the choice of these parameters in the cyclic sleep mode, whereas T_{watch} is configured according to the same criteria used to set T_{listen} in the doze mode.

Figure 3 illustrates the OLT and ONU state machines for employing the watchful sleep mode in PON. In comparison to the doze/cyclic sleep-based state machines shown in Fig. 1, the state machines for the watchful sleep mode have fewer states and signaling messages. Specifically, in the ONU state machine, the doze/sleep aware states have been merged into the *single* wsleep aware state, and the listen and asleep states have been merged into the single watch state. Similarly, in the OLT state machine, the low power doze/sleep states have been merged into the single *low power watch state*, and the alerted doze/sleep states have been merged into the single *alerted watch state*. Furthermore, the LSI and LWI stimuli have been merged into the local low power indication (LPI). Clearly, the new "simpler" state machines make the implementation and operation of the watchful sleep mode in



(a) (b)

Figure 3. Watchful sleep mode state machines: a) ONU state machine; b) OLT state machine. The notation MESSAGE(ARG) represents the command and its corresponding argument as defined in the ITU-T standard. To adhere with the ITU-T standard, we define and implement similar commands. For example, SR(WSLeep) is an ONU message sent to the OLT, expressing intent to start a power saving phase in the watchful sleep mode.

Parameter	Watchful sleep mode	Doze mode	Cyclic sleep mode
T_{aware}	5 ms	5 ms	5 ms
T_{sleep}	10 ms	—	10 ms
T_{listen}	—	10 s	—
T_{watch}	10 s	—	—
P_{Active}[1]	100%	100%	100%
P_{Listen}[2]	40%	40%	—
P_{Sleep}[3]	5%	—	5%
T_{Txinit}[4]	3 ms	3 ms	—
T_{Rxinit}[4]	2 ms	—	—
$T_{Transinit}$[4]	3 ms	—	3 ms

[1] P_{Active}: the power consumption when both the receiver and transmitter are ON.

[2] P_{Listen}: the power consumption when the receiver is ON and the transmitter is OFF.

[3] P_{Sleep}: the power consumption when both the receiver and transmitter are OFF.

[4] Refer to Fig. 2.

Table 1. Simulations parameters.

PON systems easier and more efficient. Furthermore, with the watchful sleep mode, the OLT and the ONU do not need to negotiate the power saving mode, since there is only one power management mode. More interestingly, the watchful sleep mode can emulate the doze and cyclic sleep modes in a very simple manner. To emulate the doze mode, the parameters will be simply configured as follows: $T_{watch} = T_{listen}$ and $T_{sleep} = 0$. To emulate the cyclic sleep mode, the OLT simply configures: $T_{watch} = T_{sleep}$.

COMPARATIVE SIMULATION STUDY

To highlight the advantages of the watchful sleep mode over the doze and cyclic sleep modes in terms of energy saving, we have conducted extensive simulations using OMNeT++. We consider an XG-PON system with 16 ONUs. The distance between each ONU and the OLT is set as 20 km, and a self-similar traffic generator is used to inject traffic in the network. The packet size is uniformly distributed between 64 and 1518 bytes. Table 1 shows the set of parameters used in the simulations for the doze, cyclic sleep, and watchful sleep modes. For the sake of generality, the power consumption of the XG-PON transceivers are represented by percentages in lieu of absolute values.

Most of the results in the literature pertaining to energy saving in PON consider the implementation of the wake up stimuli based on the

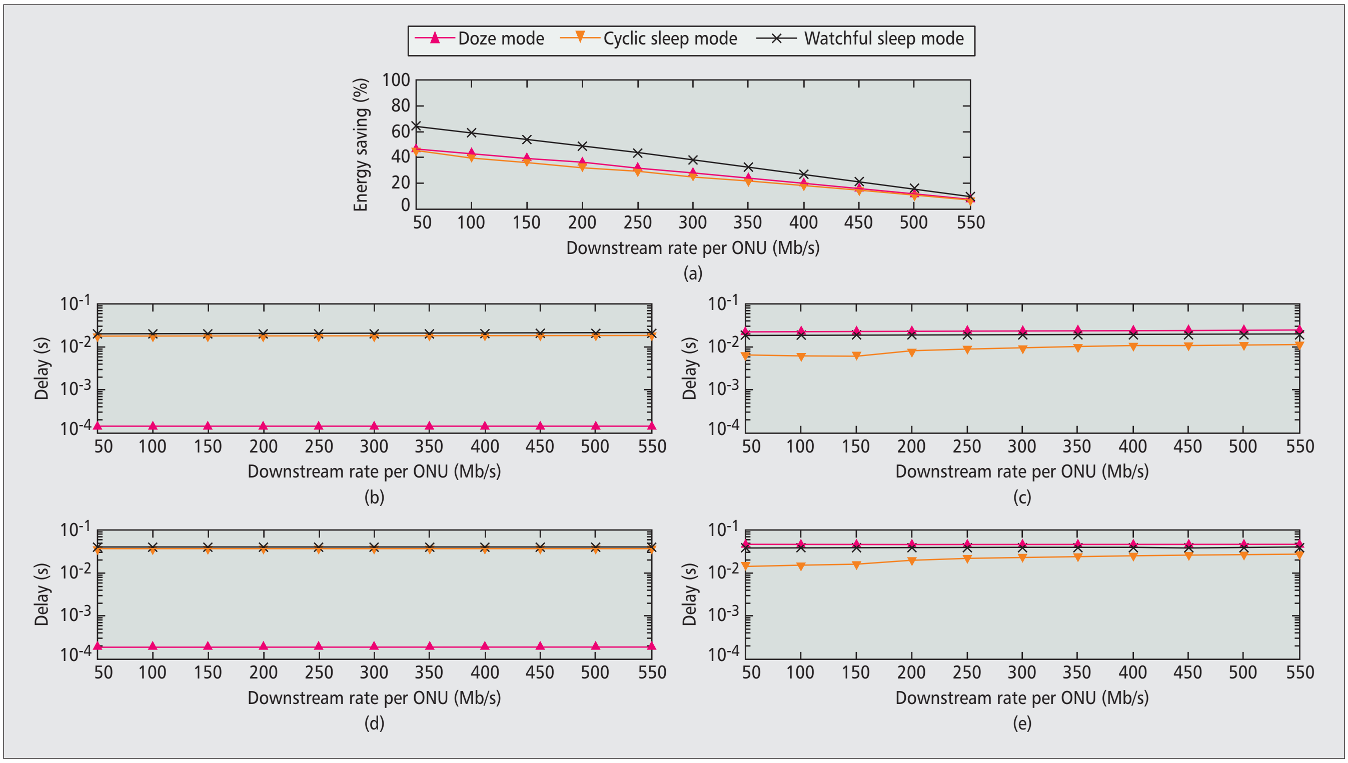


Figure 4. Simulation results with the watchful sleep mode under XG-PON: a) energy saving; b) mean downstream delay; c) mean upstream delay; d) maximum downstream delay; e) maximum upstream delay.

arrival of a user data frame [7, 11]. Consequently, the reported results do not exhibit any energy saving for high traffic loads, since a single frame arrival terminates the power saving phase. Conversely, in this work the wake up indicators are configured to enable energy saving at the ONU even in the presence of intense traffic, while maintaining a maximum end-to-end delay requirement of 56 ms (this value is considered to be acceptable for delay-sensitive applications such as voice over IP [9]).

The LWI indicator is configured to be activated 50 ms after a frame arrival, whereas the OLT-LWI indicator is configured to be activated 40 ms after a frame arrival. This difference of 10 ms between both indicators is due to the value of T_{sleep} = 10 ms in Table 1. Since, in the worst case scenario, the OLT might decide to wake the ONU as soon as the ONU switches to the Rx-OFF level in the aware state, a difference of T_{sleep} (10 ms) is necessary to maintain the maximum delay close to 50 ms. The indicators LDI, LSI, and LPI are configured to be activated once the ONU empties the queue. The !OLT-LWI stimulus is used by the OLT to trigger the ONU to enter the power saving mode when its queue is empty.

Figure 4 compares the performances of the doze, cyclic sleep, and watchful sleep modes in terms of the following: energy efficiency; mean downstream delay; mean upstream delay; maximum downstream delay; and maximum upstream delay. All the results are presented as a function of the packet arrival rate (measured in Mb/s) in the downstream direction. The packet arrival rate for the upstream direction is set to be always 1/4 of the downstream rate. The maximum delay curves look constant due to the 40 ms (at the OLT) and 50 ms (at the ONU) extra waiting time in the queue. Besides, even without the power management modes, these curves would look constant due to the fact that these rates are not even close to the maximum capacity of XG-PON systems. It is worth noting that the watchful sleep mode not only outperforms the other two modes in terms of energy efficiency, but it also achieves about 50 percent energy saving for a downstream rate of 200 Mb/s, as shown in Fig. 4a. Furthermore, under the new mode, the maximum delay in the downstream and upstream directions is 55 ms. This demonstrates the ability of the watchful sleep mode to save more energy than the doze and cyclic sleep modes, without violating the delay requirements.

FUTURE OUTLOOK

THE WATCHFUL SLEEP MODE FOR NG-PON2

Currently, ITU-T is working toward the standardization of a 40-Gigabit-capable passive optical network (NG-PON2), which will be based on the TWDM-PON architecture [15]. Due to its effectiveness, the watchful sleep mode is also being considered to be operated as the default energy management mode in NG-PON2.

To anticipate the performance of the watchful sleep mode under NG-PON2, which may contribute to the foregoing decision of adopting the watchful sleep mode by ITU-T, we conducted a simulation study. Here we consider a TWDM PON with four wavelengths and 64 ONUs, with each wavelength serving 16 ONUs. Each wavelength pair has a downstream rate of 10 Gbps and an upstream rate of 2.5 Gbps. The

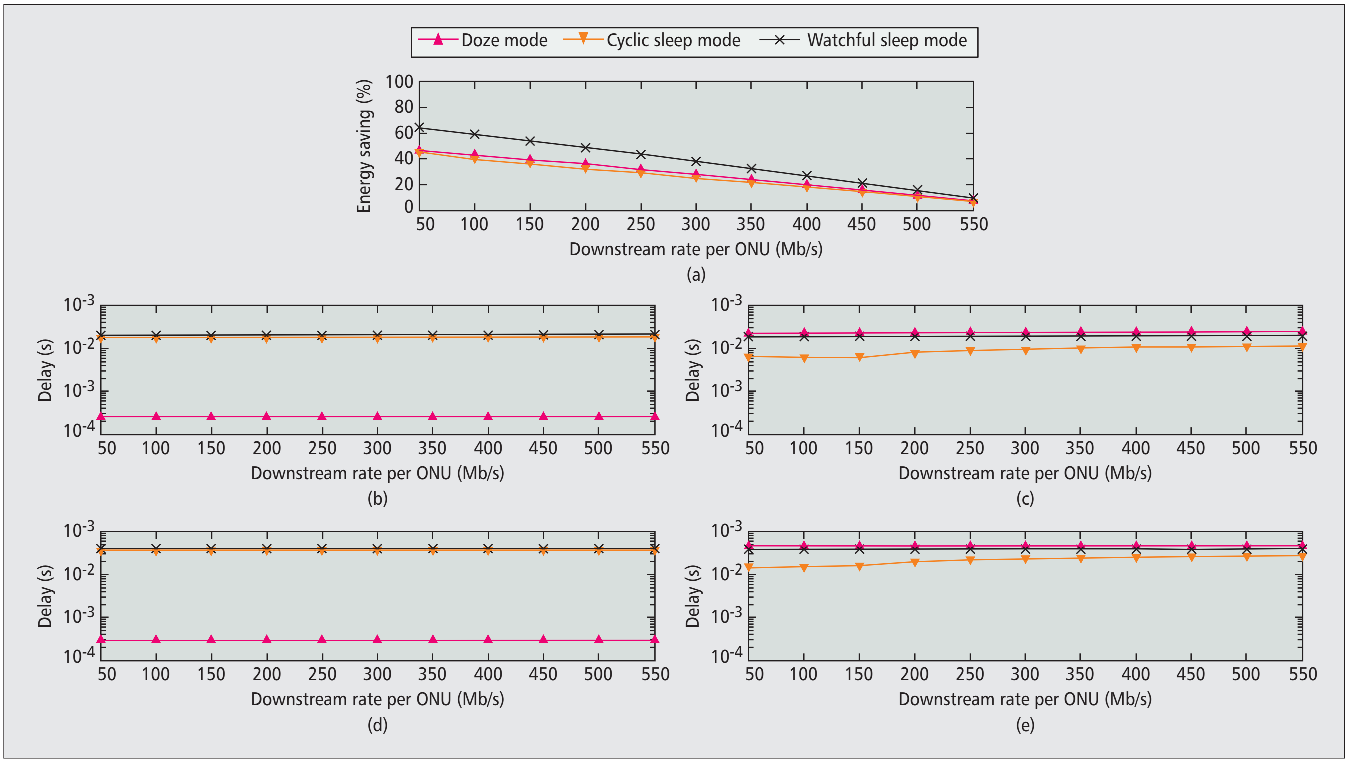


Figure 5. Simulation results with the watchful sleep mode under TWDM-PON: a) energy saving; b) mean downstream delay; c) mean upstream delay; d) maximum downstream delay; e) maximum upstream delay.

distance between the ONUs and the OLT is assumed to be 40 km, resulting in a propagation delay of 200 μs. The same parameter set used for the XG-PON scenario is used here (Table 1).

Figure 5 compares the performance of the watchful sleep mode to that of the doze and cyclic sleep modes under the simulated TWDM-PON network. As noted, with the unified mode, the energy saved at lower rates is significantly larger than that at higher rates, due to the ONU spending more time in the power saving phase at lower rates. The results in Fig. 5 are quite similar to those presented in Fig. 4 since the TWDM-PON system is formed by four staked XG-PON systems. In terms of delay, it can be seen in the figure that the delay requirement for delay-sensitive applications is not compromised. These results show that the watchful sleep mode can indeed by employed for NG-PON2, as it can effectively save more energy than the other two modes without impairing the services delivered to end users.

CONCLUSIONS

Energy efficiency is central to the design and operation of next-generation broadband access networks such as passive optical networks. Several effective techniques have been proposed to reduce the energy consumption of the network elements in PON systems, especially the customer premises equipment, without impairing the services delivered to end users.

In this article we present a novel power saving mode, namely the watchful sleep mode, which unifies two standardized alternative PON power saving modes (i.e., the doze and cyclic sleep modes) into a single power management mode. The watchful sleep mode combines the advantages of the doze and cyclic sleep modes and outperforms them in terms of energy efficiency and simplicity of implementation. Due to its efficacy, the watchful sleep mode has been included in the ITU-T G.984 (G-PON) and G.987 (XG-PON) Recommendation suites, and is currently being considered for adoption in the ITU-T G.989 Recommendation series, which standardizes TWDM-PON systems.

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