Dynamic Power Saving in Energy Efficient PONs

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***Abstract*—This paper presents the potentials and challenges of a dynamic power saving technique in optical network units (ONUs) to achieve energy efficiency in passive optical networks. Simulation results show that, at the expense of a limited increase in packet average delay that does not compromise scheduling cycles, a significant reduction of the energy required by ONUs can be accomplished. The paper is concluded with a demonstration of a testbed of the proposed technique.**

Keywords—TDM PON, energy efficiency, sleep mode

I. INTRODUCTION

"Green thinking has been rising in the architectural design of communication networks. It has been estimated that all activities related to information and communication technologies (ICT) contribute to up to 10% of global carbon footprint today [1]. Despite this fact, increasing demands in storage, processing and broadband access are expected to intensify the energy consumption in ICT infrastructure.

Fiber access networks, such as a passive optical network (PON), are expected to connect hundreds of millions of residential and business users to broadband services. Within a PON, most of the energy per bit consumed takes place at the user terminals, called optical network units (ONUs) or optical network terminals (ONTs) [2]. For this reason, a number of initiatives from industry and academia have begun to investigate ONU power saving techniques to effectively lower the energy consumption in PONs.

This paper first presents the ongoing efforts in standards bodies, industry and academia towards the reduction of power consumption in PONs. Then it identifies the challenges to employ a novel dynamic power saving technique in such networks. Lastly, the paper is concluded with simulation results and a testbed demonstration of the power saving technique.

II. ONU POWER SAVE TECHNIQUES AND INIATIVES

In a PON, all transmissions occur between the optical line terminal (OLT) and the ONUs. In the downstream direction, traffic is sent over a point-to-multipoint connection from the OLT to many ONUs. In the upstream direction, traffic is sent from many ONUs to one OLT in a multipoint-to-point fashion. Currently, the great majority of PONs are time division multiplexed (TDM), and the upstream traffic is arbitrated by the OLT through a dynamic bandwidth allocation (DBA) process. DBA uses grant messages from the OLT to allocate upstream time slots to the ONUs, and the ONUs provide the OLT with the state of their upstream buffer by using status report messages. DBA relies on precise synchronized timing among all ONUs to avoid upstream collisions. To achieve and maintain synchronization, ONUs continuously extract the OLT clock from the downstream traffic or idle frames.

A. Overview of ONU Power Saving Techniques

The common objective of ONU power saving techniques is to put ONUs into lower power states. ITU-T G.sup 45 Gigabit capable PON (GPON) power conservation standard [3] classifies ONU power saving states into three categories: power shedding, dozing, and sleeping. The approaches mainly differ in the behavior of the ONU transmitter and receiver. In general, the ONU transmitter is already burst-mode capable, i.e., it can turn on and off quickly during idle time slots to avoid adding noise to other ONU upstream data. On the other hand, turning ONU receiver on and off is much more challenging because the operation will require synchronization overhead to recover the clock from the downstream data.

In power shedding mode, used when the ONU operates under battery power, the ONU powers off or reduces the power of non-essential functions and services. In dozing mode, the ONU keeps all downstream functions operational, but turns off the transmitter and ignores OLT DBA bandwidth requests when the ONU does not have upstream traffic to send. In sleeping mode, the ONU turns off virtually all the functions and services to achieve the highest power saving. ITU-T G.sup 45 further divides sleeping mode into two sub-categories: deep sleep and fast sleep. In deep sleep mode, all ONU functions are turned off and any incoming downstream or upstream traffic is lost. In fast sleep mode, the ONU maintains the timing (free-running clock and synchronized to the OLT) and traffic detection to maintain the ability to wake up from sleep mode whenever new traffic arrives. During the transitional wake up time, the OLT would buffer the downstream traffic until the ONU is fully awake. Table 1 summarizes the key differences among these approaches. The table also contains the characteristics of the dynamic power saving mode, which is presented in this paper. In such a mode, the ONU shares similar transmitter and receiver behaviors to the dozing mode, but the operations of ONU functions and services are more familiar to the fast sleep mode. Details of the dynamic power saving technique will be explained later in this paper.

B. Standards and Industry

ITU-T G.sup 45 considers a number of practical issues to incorporate one or more of the proposed ONU power saving techniques in PONs. For instance, operators are required to

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TABLE 1
Comparison of ONU Power Saving Techniques

	Shedding	Sleeping		Dynamic Power Saving[a]		Dozing
		Deep	Fast	Burst	Continuous	
Rx/Tx	on/on	off/off	on-off/on-off	on-off /on-off	on /on-off	on/on-off
Re-synch. needed	no	yes	yes	yes	No	no
OLT buffer	no	no (traffic lost)	yes	yes		no
Lower power states	NA	all functions off	only timing and detection functions on	only timing and detection functions on	timing, detection, and recovery on	all functions on except ignore DBA
Link maintenance	fully operation al	none	need re-synch	need very fast re-synch[b]	fully operational[c]	fully operational
Main challenge	NA	maintain life-line	sleep mode control	fast re-synch circuitry	Scheduler	protocol
Power consumption	basic	least	very low	very low	low	medium
Use case	improve saving	idle or power outage	light traffic load	anytime	anytime	anytime

(a) Dynamic power saving technique is a hybrid sleep/dozing mode and it is not classified in the ITU-T G.sup45 document.

(b) Current commercial ONU receiver consumes milliseconds of switch-on time [7] and this paper experimentally demonstrates an enhanced ONU receiver requiring only nanoseconds of switch-on time using burst mode CDR circuitry.

(c) Continuous power save ONU receiver keeps both photodiode receiver and clock recovery parts of the circuit active. Although it consumes more energy during power saving states than burst mode power saving ONU, continuous mode power saving ONU offers a simpler implementation option and can still achieve substantial energy saving [7].

maintain emergency services regardless of operating ONU states. As a result, modifications are necessary, for instance, to ensure that lifeline services remain available during deep sleep mode. ITU-T G.sup 45 also points out the impact of power saving techniques on existing specifications. In particular, distinctions are made between techniques that will require or not changes in GPON transmission convergence (GTC) layer. GPON GTC frames have very low latency and are transmitted every 125μs. The techniques mentioned in Section II-A will either embed control functions in the low latency operation and maintenance (OAM) message or in the physical layer OAM (PLOAM) field. The control functions will correspond to either a mapped or dedicated field(s) in the header of a GTC frame. Therefore, changes at the GTC layer would require hardware level modifications. On the other hand, some techniques can use control messages with more relaxed timing requirements. For example, to implement deep sleep mode in GPON it is sufficient to use ONT management and control interface (OMCI); OMCI changes require firmware update only. In EPONs, corresponding GTC and OAM control functions are defined by multipoint control protocol (MPCP) and OAM physical data units (OAMDU), respectively.

Since the rectification of ITU-T G.sup 45, some E/GPON ONU products have added power saving modes into their features [4]. In general, both fast sleep mode and dozing mode are implemented, but not the deep sleep mode because of the need of support of lifeline services. The fast sleep mode allows the ONU to preserve the ability of waking up and synchronizing to the network when there is traffic to be sent. The dozing mode provides more flexibility because it always keeps the downstream channel active. In this case, the OLT can send a force report grant at any time to force the ONU to wake up.

The key characteristic of the fast sleep mode technique is the preservation of the traffic detection function and ability of the ONU to wake up from sleep mode if necessary. However, the OLT must know the presence of the awaken ONU in order to allocate data bandwidth. As a result, the lead time for an ONU to wake up from sleep mode to rejoin the network may limit network performance [5]. Using current GPON standard, an ONU must use re-activation procedure (ranging procedure in EPON) to be connected to the network. Depending on the reach of the PON, the re-activation window can last between 250μs to 1.125ms. The expected re-activation time can be even higher if multiple awaken ONUs compete to have access to the PON.

C. Research

Efficient sleep mode techniques must eliminate the use of re-activation or ranging procedures. An efficient sleep mode technique uses GPON PLOAM or EPON MPCP messages to allow an ONU to gain access with traffic cycles. In addition, the use of PLOAM or MPCP messages can allow ONUs to enter and exit sleep mode according to traffic demands. Kubo et al. have proposed the use of a sleep and periodic wake up (SPW) method that puts the ONU into sleep mode and periodically exchanges messages between the OLT and the ONU to determine if it should wake up according to its traffic status [6].

The SPW control is shown in the upper part of Fig. 1. The OLT sends a downstream *Request* message to request the ONU

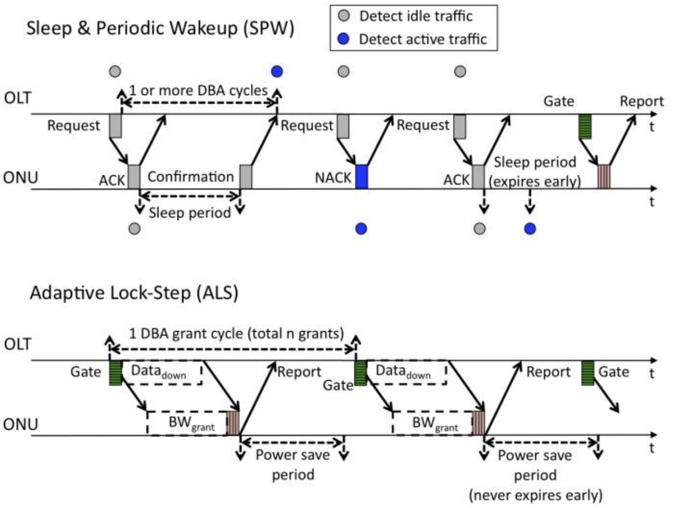

Fig.. 1. The protocol steps for the Sleep and Periodic Wake up (SPW) method and the Adaptive Lock-step method in PONs.

to enter sleep mode when it detects that there is no downstream traffic for it. The *Request* message specifies the length of the sleep period. If the ONU does not have traffic to send when it receives the *Request* message, it responds with an *ACK* message and sends a *Confirmation* message when it enters active mode from sleep mode upon the expiration of the sleep period. Upon the reception of the *Confirmation* message, the OLT can decide to send another *Request* message or not, depending on the status of the downstream traffic. The ONU can also respond to a *Request* message with *NACK*, in which case it does not enter sleep mode. SPW controls can be implemented using MPCP messages in EPON or PLOAM messages in GPON.

To avoid upstream collision, the operation of SPW control requires a lead time between the expiration of the sleep period and the *Confirmation* message. This is because the local ONU clock enters free running mode as the downstream receiver is turned off in fast sleep mode. Therefore, the lead time is subject to the implementation of the clock recovery circuit and the synchronization protocol [7]. Current ONU clock recovery circuits take up to milliseconds of lead time to recover the OLT clock from the downstream traffic. After recovering the OLT clock, the ONU still needs to synchronize to the network before being capable of sending upstream message/traffic without colliding with another ONU. An EPON ONU can synchronize by detecting and Ethernet preamble and subsequently reading the time stamp field in the EPON packet. A GPON ONU can synchronize when it detects the physical synchronization (Psynch) header at the beginning of the GTC frame. In general the length of the sleep period is expected to last several DBA grant cycles in fast sleep mode. The technique is the most efficient one in terms of energy saving when the ONU has very light traffic.

D. Dynamic ONU Power Saving

While the fast sleep technique can offer significant reduction of power consumption in ONUs, physical limitations prevent the ONU to enter and exit power saving states within the same DBA grant cycle. As a result, the fast sleep technique is not an efficient way to conserve energy when the ONU has nontrivial traffic loads. In order to conserve energy when the ONU is active, a dynamic power saving technique is proposed in this paper to enable the ONU to dynamically enter and exit power saving states.

To accomplish dynamic power saving, a fully dynamic ONU power save scheduler is desired in addition to equip the ONU with the ability of dynamically entering and exiting power saving states. Because the OLT has to buffer incoming packets destined for the power saving ONUs, the downstream traffic suffers additional queuing delays to wait for those ONUs to exit power saving states. The tradeoff between OLT buffering and overall energy saving is not exclusive to dynamic power saving, as one can expect. In the fast sleep technique, the OLT also has to buffer downstream traffic destined for sleeping ONUs. While a sleeping ONU takes a longer lead time to wake up, a power saving ONU can wake up in response to traffic demands and waste little energy waiting for clock recovery or OLT update. This is possible because the OLT can utilize existing DBA table to determine the power saving period for each ONU, and buffer traffic appropriately. The objective of the dynamic power saving scheduler is, therefore, to obtain a tradeoff between traffic latency and energy conservation. Note that we use energy conservation to quantify the effectiveness of the techniques because it takes into account the amount of time an ONU is sleeping/saving power, and not just the amount of power an ONU saves when it enters sleep/power saving modes.

III. CHALLENGES FOR DYNAMIC ONU POWER SAVING

A. Evolution of ONU Architecture

The switch-on time for an ONU to exit power saving states includes both clock recovery time and network synchronization time [7]. In current commercial systems, ONUs employ low-cost receiver that would require up to milliseconds of switch-on time. On the other hand, network synchronization time depends on the interarrival time of Ethernet preamble or PLOAM Psynch field for E/GPON systems. The latter requirement has much shorter duration (less than 125μs) than the clock recovery time.

As a result, ONU hardware changes are necessary to enable an ONU to dynamically enter and exit power saving states within a single milliseconds-long DBA grant cycle. While an evolutionary change can meet the timing requirements and significantly lower power consumption, a conservative approach with minor tweaks to the hardware can be more acceptable at the early adoption stage. In this direction, the dynamic power saving technique is further divided into two sub-categories: burst mode and continuous mode. Fig. 2 shows both architectures of dynamic power saving ONUs. The two types mainly differ in the implementation of the ONU time recovery circuit. The burst mode option turns the receiver circuitry off during power saving states and uses a burst mode receiver to quickly recovery the OLT clock from the downstream traffic when it awakes. On the other hand, the continuous mode option keeps the clock recovery part of the downstream channel active, including the photodetector and the clock recovery circuit. The

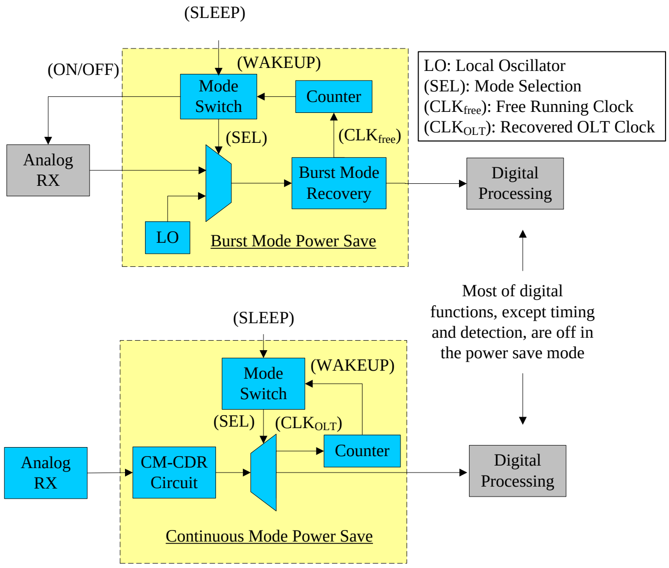

Fig.. 2. Architectures for ONU with dynamic power save capability including the burst mode and continuous mode architectures. The figure uses color (highlighted vs. grayed) to indicate part of functions that are turned on or off during sleep mode.

latter approach consumes marginally more power in the power saving state but requires only trivial circuit control path changes [7]. The former approach saves more power and can therefore save more energy if the time for the burst mode recovery circuit to recover clock is negligible when compared to the overall power save time.

B. *Dynamic ONU Power Saving Scheduler*

Currently, PONs employ a DBA process to schedule upstream traffic. A well-known DBA algorithm is the interleaved polling and adaptive cycle time (IPACT). IPACT dynamically allocates upstream transmission slots to ONUs according to their last reported upstream queue size. Since access traffic can be very bursty, a modified strategy called limited gate service is more often used because it ensures fairness and lower average packet delays for the perspective of multiple ONUs. Limited gate service still grants the requested ONU slot size but only up to a pre-defined limit. IPACT is simple, effective, and does not rely on the use of any predictive traffic filters.

The aforementioned SPW method has been recently shown to be compatible in supporting dynamic power saving operations [8]. The advantage is that it does not interfere with the existing DBA process. However, it relies on the use of traffic filter to determine the traffic loads and initiate request to an ONU to enter or exit sleep mode, what can cause some detrimental effects in the delay performance. For instance, the OLT can underestimate the downstream traffic loads and incur unwanted delays for downstream traffic by requesting a long sleep period. Conversely, it can overestimate the traffic loads and have ONU awaken but without fully utilizing the downstream bandwidth. Moreover, SPW independently determines the length of the sleep period without using information from the upstream reports. As a result, SPW may require very frequent sleep and wake up occurrences. These activities are detrimental to the energy saving objective.

An efficient traffic scheduler has been proposed specifically for dynamic power saving ONUs [9]. The scheduler, called adaptive lock-step (ALS) scheduler, couples the sleep request and wake up message with the DBA grant and report messages. The lower part of Fig. 1 shows the steps in the ALS scheduler in an EPON system. The OLT sends enhanced *Gate* messages containing the allocated slot size and the explicit end time of the sleep period. The start of the sleep period is implicit and begins with the end of the allocated slot. The end of the sleep period is specified to leave sufficient lead time to account for the free running clock drifts and subsequent clock recovery time for the burst mode dynamic power saving ONU. The maximum clock drift can be calculated because the ONU clock is required by the standard to be within ±100ppm frequency accuracy to the OLT clock. It is not necessary to reserve the lead time for continuous mode ONU because its downstream clock recovery part of the circuit is always on. After the ONU wakes up from the power saving state and regains synchronization with the network, it is ready to receive the next gate message in a just-in-time fashion, without wasting time and energy waiting for the next transmission and or reception opportunity. The principle of the ALS scheduler is to lock the dynamic sleep period to the DBA grant cycle, since the ONU is not expected to send any upstream traffic between two consecutive upstream grants. As a result of the coupling between the sleep period and the upstream DBA, ALS also locks the downstream scheduling with upstream bandwidth allocation.

IV. PERFORMANCE EVALUATION AND TESTBED

A. *Performance and Traffic Impact Evaluation*

The proposed ALS scheduler and the burst mode dynamic power saving ONU have been implemented in OPNET simulator with the purpose of evaluating latency and energy saving performance. The considered scenario consists of an EPON network with one OLT, 16 ONUs, and 1 Gbps of downstream data rate. The size of downstream packets is uniformly distributed between 46 and 1500 bytes, and interarrival times of packets are exponentially distributed. The ALS policy with fixed gate size has been considered, in which the TDM cycle time is set to 2ms. Each of the 16 ONUs equally shares the cycle time and the packets are not segmented. Propagation delays have not been considered because the ALS policy does not impact such delays. In addition, downstream propagation delays will only add another 25µs to 100µs delay, assuming the ONUs located between 5km to 20km away from the OLT. Fig. 3 shows the comparison of latency in the dynamic power saving mode versus one without power saving (first-come-first-serve) mode. In the dynamic power saving mode, additional latency is introduced by the ONU switch-on time and the ALS scheduling cycle. It can be seen that the added latency in no greater than 2ms, i.e. the

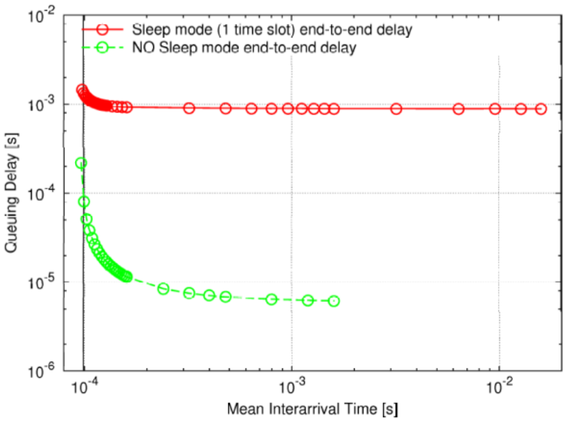

Fig.. 3. Comparison of the latency in the dynamic power saving mode versus one without power saving (first-come-first-serve mode). The added latency does not compromise the length of one scheduling cycle.

maximum length of one ALS scheduling cycle plus switch-on time. Using the power consumption estimate in [7], which finds burst mode ONU to operate at 35% of peak power consumption, it can be computed that the minimum energy saving in this scenario is 60%.

B. Dynamic ONU Power Saving Testbed

A testbed has been constructed to demonstrate the burst mode dynamic power saving ONU and the control protocol used by the ALS sleep scheduler. Fig. 4 shows the testbed setup and a picture of the protocol captured on a logic analyzer. In the setup, two ONUs are connected to the OLT. The OLT implements the ALS scheduler and puts ONU^{1} into power saving states. The objective is to show that ONU^{1} successfully enters and exits the power saving states without either losing traffic or interfering with the upstream transmission from ONU^{else}.

In the protocol steps, the OLT employs the ALS scheduler and initiates the sleep period using enhanced *Gate* message. The ONU^{1} first transmits upstream data according to the gated slot size and responds with the *Report* message, which is the standard approach for IPACT DBA process. At the same time, the ONU^{1} continues to receive downstream data until the clock reaches the start of the sleep period, as indicated in the enhanced *Gate* message. The power saving ONU^{1} wakes up as the sleep period expires using its local free running clock. The scheduler ensures that enough lead time is reserved such that the ONU^{1} will be just-ready to receive the next *Gate* message. Note that the lead time is trivial (few hundredth ns) compared to the power saving period because a burst mode ONU architecture has been used.

V. CONCLUSIONS

In this paper, the architectures and control protocols capable of reducing the energy consumption of passive optical networks have been presented. The advantages and challenges of the implementation of a dynamic power saving technique for ONUs have been analytically and experimentally discussed. Results have shown that, at the expense of a trivial increase of packet delay incurred by an adaptive and lock-step scheduler, a significant reduction of the energy required by ONUs can be obtained.

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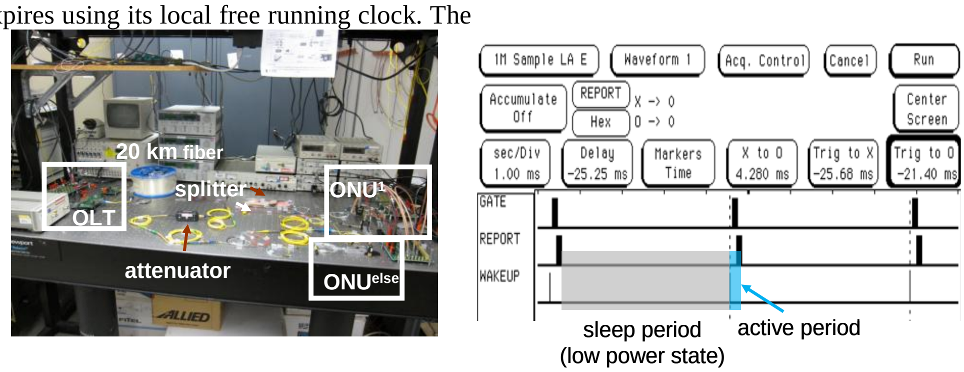

Fig.. 4. (Left) Picture of the testbed setup. (Right) Steps of adaptive and lock step (ALS) captured on a logic analyzer [9].