Energy Efficiency in Optical Access Networks

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***Abstract*— Among the devices that build a communications network, customer premises equipment are the ones that consume the larger quantity of energy per transmitted bit. Some studies have shown that optical access networks have a high energy saving potential due to the utilization of less power-demanding optical equipment. In this paper the ongoing efforts toward decreasing the energy consumption of optical interfaces utilized in optical access networks are first overviewed. Then the proposed protocols capable of reducing the energy consumption of optical access networks are reviewed. Finally the advantages and challenges of implementing dynamic power saving techniques for ONUs (e.g., switching to sleep-mode) are analytically and experimentally shown. Results show that a reduction up to 60% of the energy required by ONUs can be achieved with limited average delay increase.**

***Index Terms*— TDM-PON; sleep mode; synchronization; clock recovery; power and energy consumption.**

I. INTRODUCTION

"GREEN THINKING" is rising in the communications network area. We are currently witnessing a growing, conscientious effort to develop energy-efficient "green" communication network architectures and protocols. It is estimated that all information and communication technology (ICT) related activities contribute to up to 10% of global carbon footprint today. However, the explosive growth in bandwidth, storage, and processing demands are expected to continuously increase the energy consumed by ICT infrastructure [1].

Significant efforts and progresses have already been made to meet the green communication challenge based on actual traffic demand. An important approach to reduce energy consumption is to use as alternatives or in combination sleep mode and power saving mode in network nodes. The set up of IEEE 802.3az Energy Efficient Ethernet Task Force and the recent approval of the IEEE Std 802.3az-2010, for example, exemplifies an industry effort to lower energy consumption in copper based Ethernet links [2] using sleep or power save mode. Depending on the rates of the links, 802.3az reduces link power by either putting into the system into sleep mode (as for 100 Mb/s or 1 Gb/s rates) or slower rates (as for 10 Gb/s rates).

This paper addresses another important energy bottleneck in fixed communication networks, which is the fiber access network. Fiber access network, such as passive optical network (PON), is expected to connect hundreds of millions of residential and business users to broadband services. As a result, PONs will contribute a significant portion (about 70% today [3]) to the fixed communications network energy consumption. Indeed, although individual energy consumption by an aggregation or backbone device is still far greater than the one by ONU and OLT, this estimate reflects the greater aggregate contribution by large number of ONUs and OLTs.

Moreover, within a PON, most of the energy per bit consumed takes place in the user terminals called optical network unit (ONU) or optical network terminal (ONT) [4]. This is due not only to the ratio between the number of OLTs and ONUs installed (e.g., 1:16) but also to the lower traffic aggregation at the ONU. That is, even though the ONU requires slightly less energy than the OLT when on, the ONU handles, on average, far less traffic than the OLT.

Therefore, industry and academia have both begun to investigate ONU power saving techniques to effectively lower PON energy consumption. So far, the investigations converge toward either an ONU deep sleep mode approach or dozing mode approach. However, the former approach puts ONU into lower power consumption states only during fairly long inactive period and the second approach mandates the downstream channel to remain operational. On the other hand, a dynamic ONU power save technique can allow power saving during active ONU periods, i.e. during ONU regular operational activity.

This paper first reviews ONU power save approaches and current initiatives by standard bodies, industry, and academia Then it identifies the challenges to employ the novel dynamic ONU power saving technique. Finally it presents dynamic ONU power saving technique evaluation: both simulation results and a testbed demonstrator are presented. The implications of this study and opportunities for future research are then discussed.

This work was supported in part by the U. S. National Science Foundation (NSF) under Grant no. 0627085, Brazilian National Council for Scientific and Technology Development (CNPq), and OPNET university program.

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II. ONU POWER SAVING TECHNIQUES AND INITIATIVES

Fig. 1 shows a common tree-based PON topology. All transmissions in PON occur between the optical line terminal (OLT) and the ONU. In the downstream direction, traffic is sent over a point-to-multi-point connection from one OLT to many ONUs. In the upstream direction, traffic is sent from many ONUs to one OLT in a multi-point-to-point fashion. Currently, PONs are time division multiplexed (TDM) and the upstream traffic is arbitrated by the OLT through the dynamic bandwidth allocation (DBA) process. DBA uses grant message from OLT to allocate upstream time slots to ONU, and ONU provides the OLT with the state of its upstream buffer by using report message. DBA relies on precise synchronized timing among all ONUs to avoid upstream collision. To achieve and maintain synchronization, ONUs continuously extract OLT clock from downstream traffic or idle frames.

A. Overview of ONU Power Saving Techniques

The common objective of all ONU power save techniques is to put ONU into lower power states. ITU-T G.sup 45 Gigabit capable PON (GPON) power conservation standard [5] categorizes the 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 contribution to the other ONU upstream data. On the other hand, turning ONU receiver on and off is far more challenging because the operation will require synchronization overhead to recover the clock from downstream data.

During lower power states, the ONU also faces the choice to select what part of functions and services to turn off. In the power shedding mode, used when the ONU operates under battery power, the ONU powers off or reduces the power to non-essential part of functions and services only. In the dozing mode, the ONU keeps all the downstream functions operational but turns off the transmitter and ignores OLT DBA bandwidth request when ONU does not have upstream traffic to send. In the sleeping mode, on the other hand, the ONU turns off virtually all the functions and services to gain the greatest power saving potentials. 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 and not synchronized to OLT) and traffic detection functions to maintain the ability to wake up from the sleep mode whenever new traffic arrives. During the transitional wake up time, the OLT would buffer the downstream traffic until ONU is fully awake. Table 1 summarizes the key differences among these approaches. In the table a new mode is referred to as *dynamic power save*. In the dynamic power save mode, the ONU shares similar transmitter and receiver behavior to the dozing mode but the operations of the ONU functions and services are more similar to the fast sleep mode. Details of the dynamic power save technique will be explained later in this paper.

B. Standards and Industry

G.sup45 considers a number of practical issues to incorporate one or more of the proposed ONU power saving techniques in the operators' networks. For example, telcos are required to maintain E911 service regardless of operating ONU states. As a result, modifications are necessary, for example, to ensure that the life-line service remains available during deep sleep.

G.sup 45 also notes the impact of the proposed power saving techniques to existing specifications. In particular, distinctions are made between techniques that will require or avoid changes at the GPON transmission convergence (GTC) layer. GPON GTC frames have very low latency and are transmitted every 125µs. The techniques mentioned in section A will either embed controls in the low latency operation and maintenance (OAM) message or in the physical layer OAM (PLAOM) field. The controls 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 requirement. For example, to implement deep sleep mode in GPON it is sufficient using ONT management and control interface (OMCI); OMCI changes require firmware upgrade only. Note that corresponding GTC and OAM controls in Ethernet PON (EPON) are defined by Multi-Point Control Protocol (MPCP) messages and OAM physical data units (OAMDU), respectively.

Since the rectification of ITU-T G.sup 45, some E/GPON ONU products have added the power saving modes into their features [6]. In general, both fast sleep mode and dozing mode are implemented but not the deep sleep mode, because ONU cannot preserve the serviceability of important traffic such as E911 service when it is in deep sleep mode. On the other hand, fast sleep mode allows ONU to preserve the ability wake up and re-synchronize to the network when it has something to send. The dozing mode gives 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 from the dozing mode.

The key characteristic of fast sleep mode technique is the preservation of the traffic detection function and ability for 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 ONU to wake up from sleep mode to rejoin the network limits network performance [7]. Using existing GPON standard, for example, an ONU must use re-activation procedure (ranging procedure in EPON) to gain access the network. Depending on the reach of the network, the re-activation window can last between 250µs to 1.125ms. The expected re-activation time can be even higher if the multiple awaken ONU compete to gain access to the network.

C. Research

Efficient sleep mode techniques must eliminate the use of re-activation or ranging procedure. An efficient sleep mode technique uses GPON PLOAM or EPON MPCP message to allow ONU to gain access within the 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. propose the use of a sleep and periodic wake-up (SPW) method that puts the ONU into sleep mode and periodically exchanges messages between OLT and ONU to determine if the ONU should wake up depending on its traffic status [8].

The proposed SPW control protocol is shown in Fig. 2. In SPW, OLT sends downstream *Request* message to request the ONU to enter into sleep mode when it detects there is no downstream traffic for it. The *Request* message specifies the length of sleep period. The ONU sends either an ACK or NACK message to indicate the reception of *Request* message. 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 *Confirmation* message, the OLT can decide to send another *Request* message or not, depending on the status of downstream traffic. The ONU can also respond to a *Request* message with NACK, in which case the ONU does not enter into 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 [9]. Current ONU clock recovery circuit takes 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 an Ethernet pre-amble and subsequently read 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 ONU and the technique is the most efficient in terms of energy saving when the ONU has very light traffic.

More recently, there have been also works proposed to consider power save technique in next generation EPON scenario where the system adopts a dual 10 Gigabit and 1 Gigabit data rates. In this 10G/1G NG-EPON scenario, a link speed adaptation is further incorporated to switch EPON ONU from 10G to 1G interface when a light traffic load is detected [10].

D. Dynamic ONU Power Save

While fast sleep technique can offer significant power reductions, physical limitations prevent the ONU to enter and exit power saving states within the same DBA grant cycle. As a result, fast sleep technique is not an efficient way to conserve energy when ONU has non-trivial traffic loads. In order to conserve energy when the ONU is active, dynamic power save techniques are here proposed to enable the ONU to dynamically enter and exit the power save states.

To realize the potentials of dynamic power saving, a fully dynamic ONU power save scheduler is desired in addition to equip the ONU with the ability to dynamically enter and exit power save states. Because OLT has to buffer incoming packet for the power saving ONUs, downstream traffic sees additional queuing delays to wait for the power saving ONUs to exit from power save states. The tradeoff between OLT buffering and overall energy saving is not unique to dynamic power save. In fast sleep technique, the OLT also has to buffer the downstream traffic for sleeping ONUs. While sleeping ONU takes a longer lead time to wake up, power saving ONU can wake up in response to traffic demand and waste little energy waiting for clock recovery or OLT update. This is possible because OLT can utilize existing DBA table to determine the power save period for each power saving ONU and buffers traffic accordingly. The objective of the dynamic power save scheduler, therefore, is to strike a balance in the 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/power saving, not just the amount of power ONU saves when it enters sleep/power save modes.

The following sections present recent works on enabling dynamic ONU power save technique including details of the dynamic ONU power save architectures, traffic scheduler, testbed, and evaluation of the traffic impacts.

III. CHALLENGES FOR DYNAMIC ONU POWER SAVE

A. Evolution of ONU Architecture

The switch-on time for a power saving ONU to exit power save states includes both clock recovery time and network synchronization time [9]. In current commercial system, ONU employs 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 system. The latter requirement has much shorter duration (less than 125μs) than the clock recovery time.

Therefore, ONU hardware changes are necessary to enable the ability to dynamically enter and exit power save states within the single milliseconds-long DBA grant cycle. While an evolutionary change can meet the timing requirement and significantly lower the power consumption, a conservative approach with minor tweaks to the hardware can be more acceptable at the early adoption stage. Therefore, dynamic power save techniques are further divided into two sub-categories: *burst mode* and *continuous mode*. Fig. 3 shows the two dynamic ONU power save architectures. 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 save state and uses a burst mode receiver to quickly recovery OLT clock from the downstream traffic when it awakes. The continuous mode option, on the other hand, keeps the clock recovery part of the downstream channel active, including the photo-detector and the clock recovery circuit.

The latter approach consumes marginally more power in the power save state but requires only trivial circuit control path changes [9]. 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. This paper would later demonstrate the inter-working of a burst mode ONU prototype.

B. Dynamic ONU Power Save Scheduler

Lowering energy conservation and reducing traffic latency are usually competing objectives because an ONU forfeit the transmission or reception opportunity while sleeping or power saving. Therefore, a good traffic scheduler must find a balanced tradeoff between gaining energy savings and minimize traffic delays

Currently, PON employs a DBA process to schedule upstream traffic. The most recognizable form of PON DBA is called interleaved polling and adaptive cycle time (IPACT). IPACT dynamically allocates upstream transmission slots to ONU according to their last reported upstream queue size. EPON uses MPCP gate message to send bandwidth grant message, so this strategy is also called gated service. 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 save operations [11]. 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 the ONU to enter or exit the sleep mode. This can cause some detrimental effects in the delay performance. For example, the OLT can underestimate the downstream traffic loads and incur unwanted delays for downstream traffic by requesting a long sleep period. And vice versa 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. These activities are detrimental to the energy saving objective.

In addition to SPW, other sleep mode schedulers have been proposed for sleeping and/or dozing mode ONUs. These schedulers focus on the difference between periodic ONU wake-up and OLT induced downstream wake-up [12]. However, the most advantageous feature of dynamic power save mode is the ability for an ONU to enter and exit power save state within the millisecond-long traffic cycle. Therefore, we proposed an efficient traffic scheduler specifically for dynamic power save ONUs [13]. The scheduler, called adaptive lock-step (ALS) scheduler, couples the sleep request and wake up message with the DBA grant and report messages. Fig. 2 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 save 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 circuit is always on. After the ONU wakes up from power save state and regain 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 upstream DBA, ALS also locks the downstream scheduling with upstream bandwidth allocation.

IV. TESTBED AND PERFORMANCE EVALUATION

A. Dynamic ONU Power Save Testbed

A testbed has been constructed to demonstrate the burst mode dynamic power save ONU and the control protocol used by 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. OLT implements the ALS scheduler and puts ONU^1 into power save states. The demonstration aims to show the proper protocol working and that ONU^1 successfully enters and exits the power save 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 initiate 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 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 the lead time is trivial (few hundredth ns) comparing to the power save period because burst mode ONU architecture is used.

B. *Performance and Traffic Impact Evaluation*

The proposed ALS scheduler and burst mode dynamic power save ONU are implemented it in OPNET simulator. The latency and the energy saving performance are evaluated. The considered scenario consists of 16 ONUs and one OLT. Downstream packets destined to the ONUs have exponentially distributed interarrival times. An EPON system is simulated with 1Gbps downstream data rate. The packet size is uniformly distributed between 46 to 1500 bytes. ALS policy with fixed gate size is shown here. In the fixed gate size, the TDM cycle time is set to 2ms. Each of the 16 ONU shares an equal share of the cycle time and the packets are not segmented. Propagation delays are not considered because ALS policy do not impact the propagation delays. In addition, downstream propagation delays will only add another 12.5µs to 50µs delays, assuming ONU are located between 5km to 20km away from the OLT.

Fig. 5 shows the average queuing delays for the downstream traffic. The results are averaged over all 16 ONUs. Results show that the average latency is limited to 1ms until very high loads, which is the expected waiting time for a packet in 2ms cycle time. Using the power consumption estimate in [9], which finds burst mode ONU to operate at 35% of peak power consumption, it can be computed that the minimum energy saving in the example is 60%.

V. CONCLUSIONS

This paper reviews ongoing efforts toward decreasing the energy consumption of optical interfaces utilized in passive optical networks. Then the architectures and control protocols capable of reducing the energy consumption of optical access networks are presented. Finally, the advantages and challenges of implementing dynamic power saving techniques for ONUs are analytically and experimentally shown. Results show that a reduction up to 60% of the energy required by ONUs can be achieved with limited average delay increase using an adaptive and lock-step (sleep period and traffic cycle) scheduler.

REFERENCES

[1] The climate group, "SMART 2020: Enabling the low carbon economy in the information age", http://www.smart2020.org

[2] http://www.ieee802.org/3/az/index.html

[3] C. Lange, D. Kosiankowski, C. Gerlach, F.J. Westphal, A. Gladish,"Energy Consumption of Telecommunications Networks", paper 5.5.3, ECOC 2009, 20-24 Sep., 2009, Vienna, Austria

[4] R. Tucker, "Switching and Energy", Keynote Speech, PS2009, Pisa, Italy, Sep. 15-19, 2009, Pisa, Italy

[5] "GPON Power Conservation", ITU-T G-series Recommendations – Supplement 45 (G.sup45), ITU-T, 05/2009

[6] http://www.pmc-sierra.com/products/details/pas7401/

[7] T. Smith, R. S. Tucker, K. Hinton, and A. V. Tran, "Implications of sleep mode on activation and ranging protocols in PONs," in Proceedings of IEEE LEOS 2008

[8] R. Kubo, J. Kani, Y. Fujimoto, N. Yoshimoto, K. Kumozaki, "Proposal and Performance Analysis of a Power-Saving Mechanism for 10 Gigabit Class Passive Optical Network Systems", NOC 2009, 10–12 June 2009, Valladolid, Spain

[9] S.-W Wong, L. Valcarenghi, S.-H Yen, D. R. Campelo, S. Yamashita, and L. Kazovsky, "Sleep Mode for Energy Saving PONs: Advantages and Drawbacks," *Globlecom Second International workshop on Green Communication*, November 2009

[10] R. Kubo, J. Kani, Y. Fujimoto, N. Yoshimoto, and K. Kumozaki , "Sleep and Adaptive Link Rate Control for Power Saving in 10G-EPON Systems", IEEE Globecom 2009, Honolulu, HI.

[11] R. Kubo, J. Kani, Y. Fujimoto, N. Yoshimoto, and K. Kumozaki, "Adaptive Power Saving Mechanism for 10 Gigabit Class PON Systems," IEICE Transaction on Communications, Vol. E93-B, No. 2, Feb. 2010.

[12] Y. Yang, S. Wong, L. Valcarenghi, S. Yen, D. Campelo, S. Yamashita, L. Kazovsky, and L. Dittmann, "Energy Management Mechanism for Ethernet Passive Optical Network (EPON)," ICC, May 2010.

[13] S. Wong, S. Yen, P. Ashfar, S. Yamashita, and L. Kazovsky, "Demonstration of Energy Conserving TDM-PON with Sleep Mode ONU Using Fast Clock Recovery Circuit," OFC, March 2010.

TABLE 1
Comparison of ONU Power Saving Techniques

	Shedding	**Sleeping**		**Dynamic Power Save**[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 operational**	**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 save 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 *ms* of switch-on time [9] and this paper experimentally demonstrates an enhanced ONU receiver requiring only *ns* of switch-on time using burst mode CDR circuitry.

[c] Continuous power save ONU receiver keeps both photo-diode receiver and clock recovery parts of the circuit active. Although it consumes more energy during power save states than burst mode power save ONU, continuous mode power save ONU offers a simpler implementation option and can still achieve substantial energy saving [9].

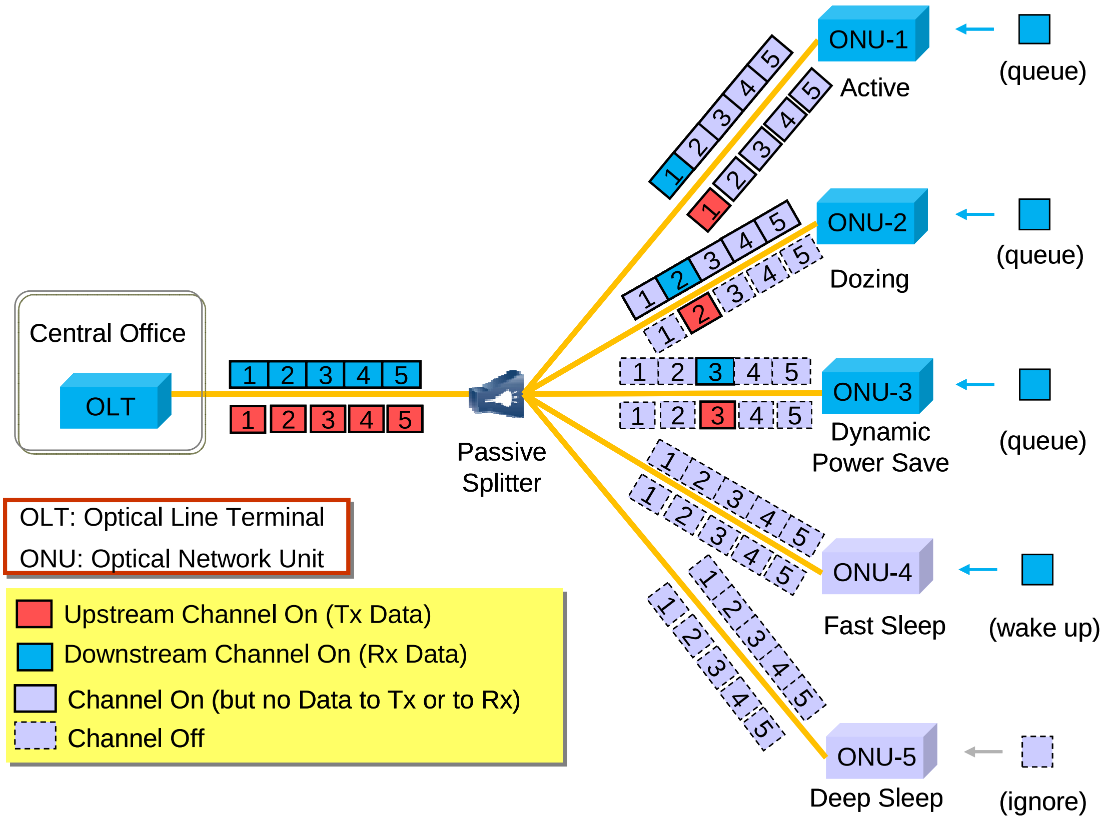

Fig. 1 Common PON architecture is point (OLT) to multi-point (ONU). The figure also illustrates ONUs operating in fiber different modes: active mode, dozing mode, dynamic power save mode, fast sleep mode, and deep sleep mode. The figure uses different colors to represent activity level when enter into one of the possible operation modes.

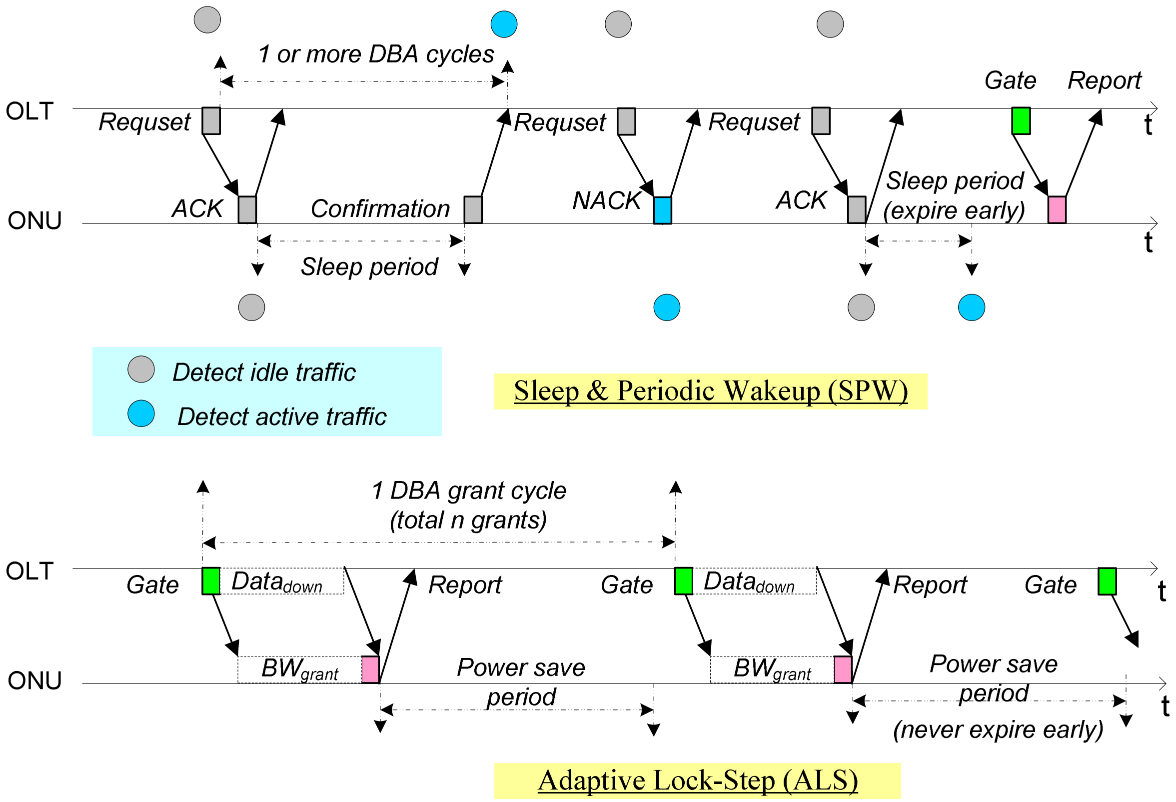

Fig. 2 The protocol steps for the sleep and periodic wakeup (SPW) method and for the adaptive lock-step (ALS) method.

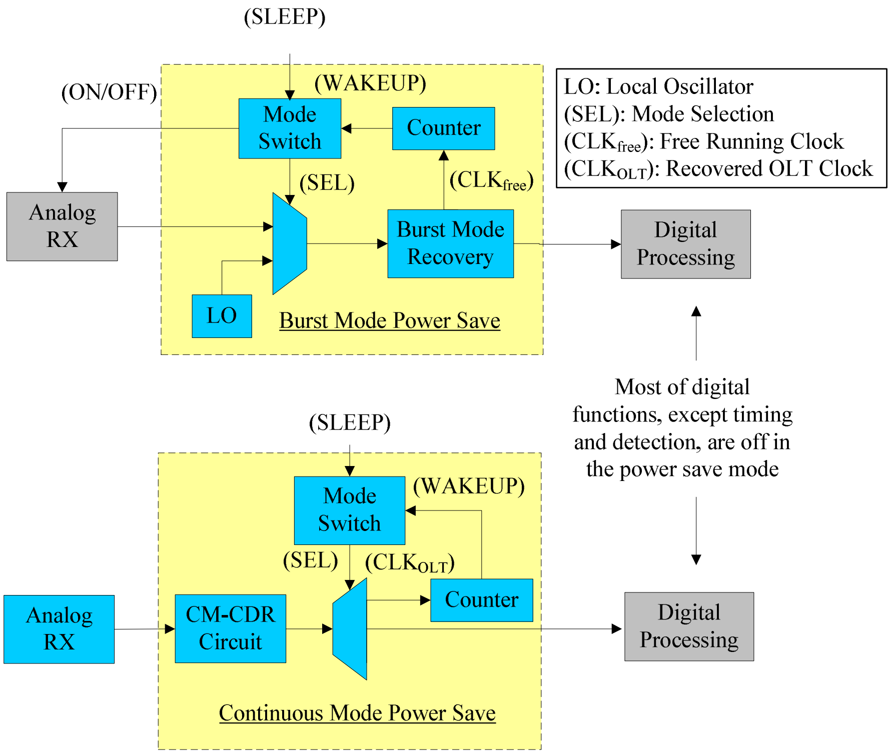

Fig. 3 Architectures for ONU with dynamic power save capability including the burst mode and continuous mode architectures. The figure uses color (highlighted vs. grayed) to indicate part of functions that are turned on or off during sleep mode.

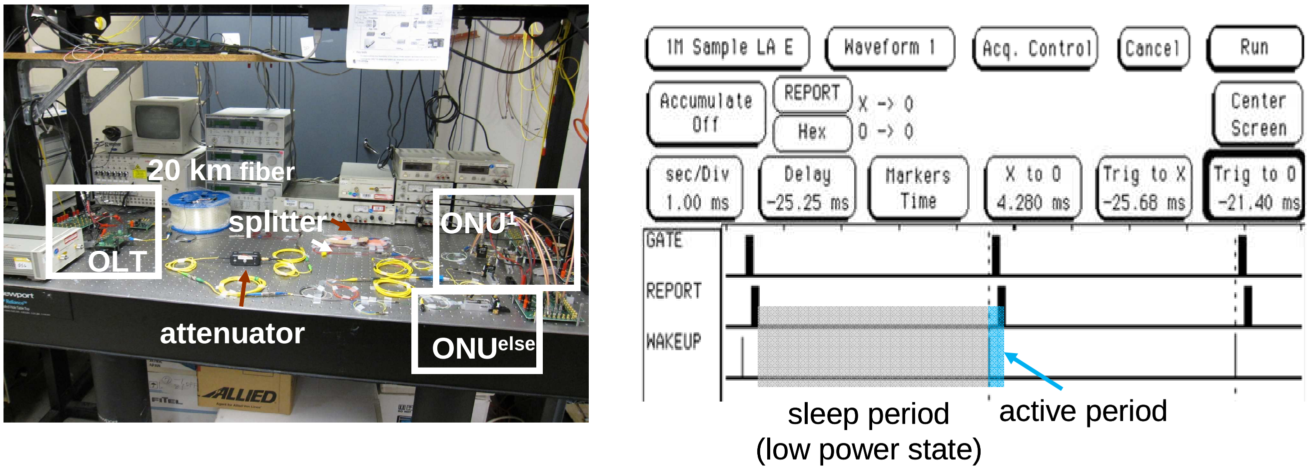

Fig. 4 (Left) Picture of the testbed setup. (Right) Steps of adaptive and lock step (ALS) captured on a logic analyzer [13].

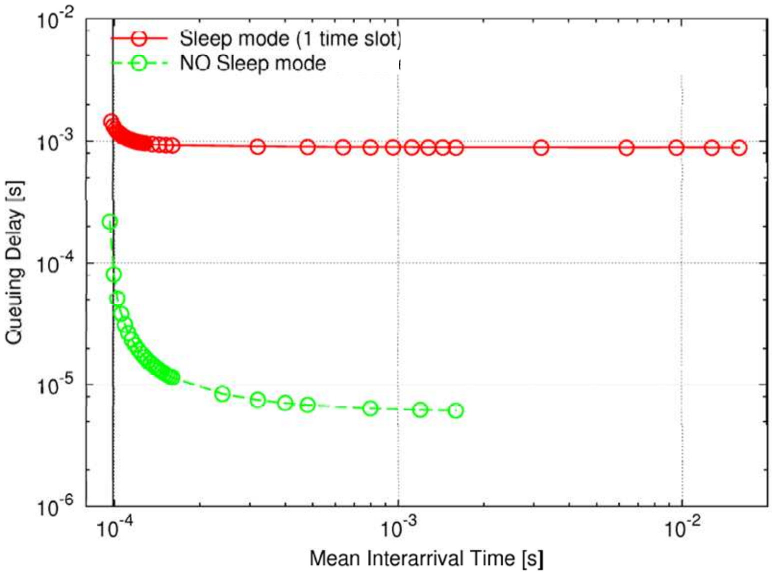

Fig. 5 Downstream packet buffering latency in the OLT. Simulation results compare the latency suffer in dynamic power save mode versus one without power saving (first-come-first-serve) mode. In the dynamic power save mode, additional latency is introduced by the ONU device switch-on time and the ALS scheduling cycle. Note the added latency is no greater than 2*ms*, or the maximum length of one ALS scheduling cycle plus switch-on time in the system.