ONU power saving modes in next generation optical access networks: progress, efficiency and challenges

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Abstract: The optical network unit (ONU), installed at a customer's premises, accounts for about 60% of power in current fiber-to-the-home (FTTH) networks. We propose a power consumption model for the ONU and evaluate the ONU power consumption in various next generation optical access (NGOA) architectures. Further, we study the impact of the power savings of the ONU in various low power modes such as power shedding, doze and sleep.

OCIS codes: (060.4250) Networks; (060.4252) Networks, broadcast.

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1. Introduction

Expected global energy demand is growing faster than 2% per annum [1], and will most likely become unattainable in the years to come. Among others, one of the factors leading to the upsurge in the energy needs of society is the continuous colossal growth in the information and communication technology (ICT) sector, particularly the Internet. Today, the ICT and the Internet are the important constituent factors of power consumption (*PC*); and they account for approximately 5 and 1% respectively of the total electrical *PC* in developed economies [2]. Out of the total Internet *PC*, access networks consume about 60 to 80% of power and an optical network unit (ONU), installed at a customer's premises, accounts for about 60% of the energy consumed in current fiber-to-the-home (FTTH) technologies [3]. Thus, significant energy savings can be attained by low energy consuming ONU architectures, and the ONU *PC* has remained as a key parameter in the conception of next-generation optical access (NGOA) networks.

While the design of low power consuming ONU architectures should be considered in the first place, the *PC* at ONUs can be further reduced by operating ONUs in low power modes. Low power modes have been discussed in ITU-T Rec. G.Sup45 and have potential to impart significant energy savings [4]. While all NGOA networks will likely benefit from low power modes, the amount of savings that can be procured vary significantly [5]. A holistic view on the *PC* of various NGOA architectures can only be derived by counting in the possible power savings at the ONUs. In this paper, we evaluate the *PC* of various NGOA architectures in active state and in low power modes. The results show that the architectures that have higher active state *PC* may achieve lower *PC* in low power modes.

The remainder of this paper is organized as follows. Section 2 discusses the considered NGOA networks. Section 3 proposes the ONU *PC* model. Section 4 discusses power saving modes, progress and challenges. Section 5 presents the evaluation methodology, and section 6 presents the results. Finally, section 7 presents the conclusions.

2. Optical access technologies

As the NGOA candidate, different system concepts are actively considered such as: high data rate time division multiple access (TDMA) passive optical network (PON) such as 40G-TDMA-PON, wavelength division multiplexing (WDM) PON, hybrid TDMA/WDM PON (TWDM-PON), point-to-point (PtP) and active optical network (AON) [6]. We will also compare these NGOA solutions with present state-of-art solutions like Ethernet PON (EPON) and 10G-EPON (10G-EPON).

The basic differences among various system aspects are the ways in which a user (or an ONU) connects to the optical line terminal (OLT) at the central office, and accesses network resources. While the network architecture of these solutions is quite different; in addition, these solutions require a different set of functionalities at the ONU. This different set of functionalities drives the *PC* of the ONU. First, the upstream and the downstream line rate of the technologies impact the *PC* as they influence the transceiver design and processing requirements; second, the need of tunability at the transmitter influences the *PC*, as either the laser needs to be thermo-electrically controlled or is a high power consuming uncooled tunable laser; third, if the ONU receives more than one wavelength, there is the need of a tunable filter, which increases the *PC*; and lastly, every TDMA based solution requires burst mode electronics, which increase the *PC*. We distinguish the important functionalities that influence the *PC* in the ONU in Table 1, and discuss them in the perspective of each architecture:

- TDMA-PONs: In TDMA-PON, the OLT accesses ONUs using a TDMA protocol over a power splitter. The architectural configuration of 40G-TDMA-PON is same as EPON and 10G-EPON but with the support of a much higher upstream and downstream rate using a non-return to zero (NRZ) on-off keying. It, however, suffers from reach limitations posed by serious dispersion issues with high data rate (e.g., 40G NRZ) transmission. Hence, special functionalities like electronic dispersion compensation (EDC) and optical amplification (OA) are required along with burst mode electronics.

- ***WDM-PON:*** WDM-PON offers the most straightforward way of capacity increase compared with TDMA-PON, where each user is given a separate wavelength. Since, users are on a separate wavelength, WDM-PON does not require the complexities of TDMA. Either the WDM-PON ONU is equipped with a tunable laser (TL) to tune to a separate wavelength or it may use the downstream signal wavelength to transmit on a separate upstream wavelength. For the second case, the ONU requires reflective semiconductor optical amplifiers (RSOA) and frequency shift keying (FSK) modulators for the simultaneous transmission of the upstream and the downstream signals. We consider these two variants of WDM-PON: with tunable lasers (WDM-TL) and with RSOA (WDM-RSOA).

- ***TWDM-PON:*** TWDM-PON combines the flexibility of TDMA-PON with the increased overall capacity of WDM technology. They use the TDMA functionality and tunable optics at both the transmitter and the receiver.

- ***PtP:*** In PtP, each ONU is connected directly via a fiber to the central office. It has the simplest ONU architecture.

- ***AON:*** AONs use an active remote node in the field, which requires powering and maintenance. Since, ONUs are accessed over the active switch, they do not require TDMA functionality and tunable optics.

Table 1. NGOA system concepts and key required functionality

System	Data Rate		Tunable TX	Tunable Filter	Burst mode	Special functionality
	Upstream	Downstream				
EPON	1 G	1 G	/	/	√	NA
10G-EPON	1 G	10G	/	/	√	NA
40G-TDMA	10 G	40 G	/	/	√	OA, EDC
WDM-RSOA	1 G	1 G	/	/	/	FSK modulators for upstream
WDM-TL	1 G	1 G	√	/	/	NA
TWDM	2.5 G	10 G	√	√	√	NA
PtP	1 G	1 G	/	/	/	NA
AON	1 G	1 G	/	/	/	NA

/ = does not require, √ = requires

3. ONU power consumption (*PC*) model

In Fig. 1, we present the *PC* model of the ONU. The model takes data from [5–10] and the large survey of component datasheets. To compare the technologies fairly, the power consumption data of components are scaled relative to the power consumption value of 1.2 W of the GPON TRX as adopted in [7]. For example, the value of uncooled tunable TRX of WDM-PON and the GPON TRX are adopted as 0.75 W and 0.45 W respectively by [8]; these values are scaled up to 2 W and 1.2 W. Note that, the value of 1.2 W adopted in [7] was according to the maximum power consumption value found in the survey of component data sheets. For the analysis, we divide the ONU *PC* model in three main parts: user network interfaces (UNIs), core functional blocks (CFBs) and specific functional blocks (SFBs).

- ***UNIs:*** The interfaces towards client sides are referred as UNIs. Depending on the feature set of the ONU, the ONU can host different UNIs such as voice interfaces, data ports, multimedia over coax alliance (MoCA) interface, or video overlay interfaces. Voice interfaces are assumed to provide plain old telephone service (POTS). Dual subscriber line interface circuit (SLIC) modules are used to interface with the analog telephone line. The gigabit Ethernet (GbE) interface is considered for the support of data traffic, and RF video and MoCA for video and multimedia data.

- ***CFBs:*** The core functional block represents the power consumed by an optical transceiver (TRX), digital processing and memory. The optical TRX consists of a transmitter

(TX) and a receiver (RX) block. The TX includes the *PC* for a laser diode (LD) and a laser diode driver (LDD). The RX consists of an avalanche photodiode (APD) or a PIN photodiode, transimpedance amplifiers (TIA) and limiting amplifiers (LA). Digital processing functions are considered to be implemented in a system on chip (SoC). The SoC includes the *PC* for a medium access control (MAC), a serialiser, a deserialiser, forward error correction (FEC), etc. The memory requirement in different concepts may vary (cf. section 6.3), and we have assumed the *PC* of 30 mW per MB of memory.

- ***SFBs**:* For a specific NGOA system concept, we add the *PC* for special functionalities like TDMA, EDC, and OA. For example, we add TDMA *PC* for EPON, 10G-EPON, and TWDM-PON, and TDMA, EDC and OA functionality for 40G-TDMA-PON.

Miscellaneous and power conversion losses are assumed at 5% and 20%, respectively. Note that, the power conversion efficiency consists of AC to DC and DC to DC conversion, which are both assumed to be 90%, resulting in the overall power conversion efficiency of 80%. In the model, we also show *PC* values used for the components in active (A), power shedding (PS), doze (D), fast sleep (FS) and deep sleep (DS) state. These states are discussed in the following section.

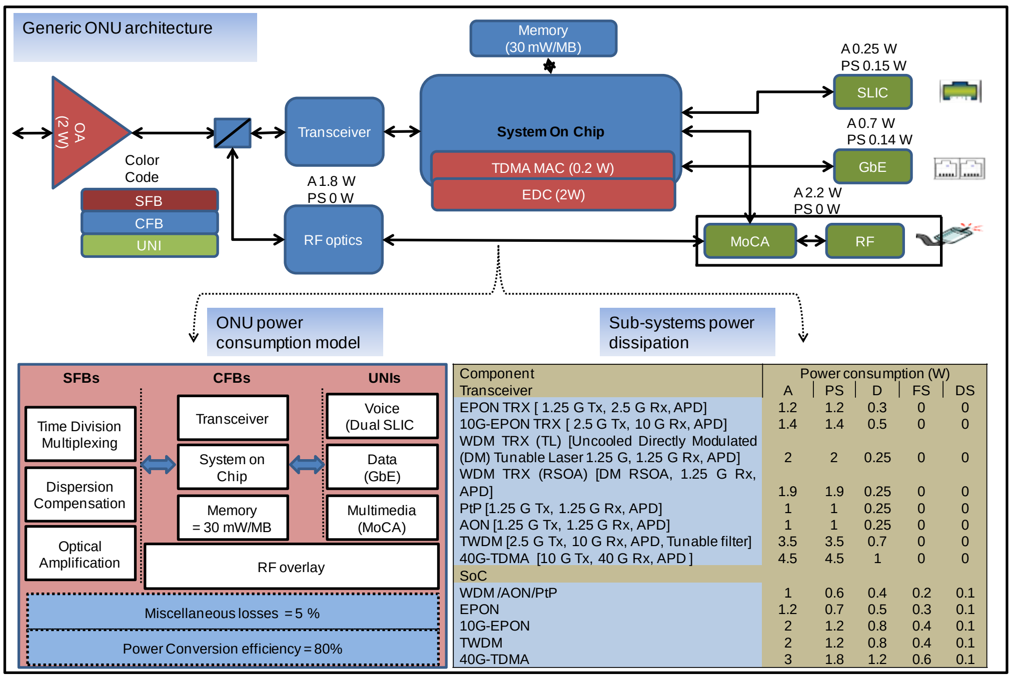


Fig. 1. ONU power consumption model.

4. Power saving modes: definitions, progress and challenges

In this section, we first define the low power modes in section 4.1, and then discuss progress, and challenges associated with powering off the parts of the ONU in section 4.2.

4.1 Definitions

ITU-T G.sup 45 [7] proposes a number of power saving states, namely power shedding, doze and sleep. These approaches differ based on the parts of the ONU that are switched off.

- ***Power shedding:*** The power shedding approach shut down the unused UNIs. Note that there can be many classes of power shedding based on the interfaces that can be shut down. For the analysis, we assume power shedding with MoCA and RF interfaces completely powered down.

- ***Doze state:*** In doze state, non-essential functions are powered off with an additional powering off of the ONU transmitter while the receiver remains on.

- ***Sleep state:*** In sleep state, non-essential functional blocks and both the ONU transmitter and the receiver are turned off.

We digress here to mention the difference between the term ‘state’ and ‘mode’ as used in the paper. Note that a mode represents the combination of states according to traffic load. For example, doze mode is referred to as the cyclic transitions between power shedding and doze state, and sleep mode as the cyclic transitions between power shedding, doze, or sleep state. Sleep mode can be classified further as deep and fast sleep mode based on the periods of sleep.

4.2 Progress and Challenges

In this section, we review progress and challenges for the implementation of power saving modes.

- ***Transmitters:*** The switch on/off time of TXs is important, as a large switch on/off time will increase sleep overheads and guard bands, leading to the decrease in energy efficiency and throughput. The switch on/off time of the TX depends on whether it is a burst mode (BM) TX or a continuous mode (CM) TX. The BM-TX has inherited better ability to switch on/off and can be switched on/off within microseconds. On the other hand, the CM-TX takes about 1 ms to switch on/off [11] and thus cannot support very short sleep cycles. TDMA based technologies like EPON and TWDM-PON use the BM-TX, and WDM-PON and AON use the CM-TX. In addition, switch on/off time depends upon transmission rates; high bit rate TXs have a longer switch on/off time than low bit rate TXs. To minimize further the switching time and the *PC* of the TX, there have been some recent proposals in [12] and [13].

-***Receivers****:* The ONU receiver consists of the APD (or PIN), TIA, and LA. When the RX is powered down, the ONU loses the downstream signal, which is required to recover clock by the clock and data recovery (CDR) circuit, and is used to maintain synchronization between the OLT and the ONU. Paper [14] has shown that CDR can take as long as 5 ms to re-acquire clock. To minimize clock recovery time, there are the proposals of the burst mode CDR that uses a local oscillator to keep the ONU in accord with the OLT. The BM-CDR can reduce recovery time to as low as 10 ns for the 1 G receiver and even less for 10 G, as the higher bit rate CDRs can scan a higher number of bits in a shorter time. Note that, for NGOA architectures, ONUs can employ BM-CDRs, which will lead to negligible overheads associated with switching off a RX, and thus doze mode will not give any additional dividends compared with sleep mode. Doze mode makes sense only for ONUs that are already deployed in the field and are equipped with CM-CDR, wherein overheads associated with sleep mode are high compared with doze mode.

-***Digital Processing circuits:*** Digital processing circuits can be either clock-gated, power gated or can be completely powered off [15]. Clock-gating disables (i.e., gating) the clock signal of the register that feeds a portion of the combination logic that is not performing useful functions. Clocks consume power because they continuously toggle registers and removing clocks from the parts that are not useful saves *PC*. Power gating uses low-leakage transistors to shut off the power supplies of the parts of a design that are not used. The advantage of clock gating and power gating is that the components can be turned on/off in microseconds. On the other hand, powering off a whole digital circuit reduces *PC* to zero, but it takes a longer switching time (depending on the functionality) of up to tens of milliseconds. For the analysis, we assume a power saving between 60 to 90% by using clock gating, or power gating, or both.

-***UNIs:*** UNIs also support power savings. SLIC modules available today support no on-hook transmission. Low power idle (LPI) mode has been recently proposed for the GbE interface [16]. In LPI mode, the transmitter sends out a periodic pulse to keep the receiver in sync instead of the normally required continuous transmission between the transmitter and the receiver. LPI mode can lead to power savings of about 50%. For MoCA interfaces, also power saving modes like "wake-on-MoCA" have been proposed.

Table 2 gives the summary of switching time and power saving tradeoffs in considered mechanisms.

Table 2. Switching time and power saving tradeoffs in considered mechanisms

Mechanisms	Component	Switching ON/OFF time	Power Savings
Doze mode (TRX)	1.25 G CM	1 ms	100%
	1.25 G BM	10 ns	100%
	2.5 G BM	200 ns	100%
	10 G BM	500 ns	100%
Sleep Mode (RX)	CM-CDR	1-5 ms	100%
	BM-CDR	10 ns	100%
Clock Gating	Digital Processing Blocks	5 µs	30-60%
Power switching	Digital Processing Blocks	10 ms	100%
Low Power Idle	GbE	5 µs	0-50%
Wake on MoCA	MoCA MAC	5 ms	0-40%

5. Evaluation methodology

For the evaluation of power saving modes, we first discuss the proposed algorithm, sleep mode aware (SMA). Then in the next section, we discuss the assumptions for the analysis.

5.1 Sleep Mode Aware (SMA) Algorithm

To evaluate sleep mode efficiency, a well-suited dynamic bandwidth allocation (DBA) algorithm is required, which can optimize the cyclic transitions between the states according to the traffic requirement. For this purpose, we apply an Ethernet PON (EPON) based protocol. EPON is chosen as an example; the approaches proposed, however, are generic and can apply to any system concept. Interleaved polling with adaptive cycle time (IPACT) [17] is considered as an important example of an EPON DBA algorithm for scheduling upstream transmission. IPACT, however, does not support sleep mode and thus we propose a new DBA algorithm, which we refer as the SMA algorithm. In traditional approaches, the downstream traffic is broadcasted to all ONUs and each ONU has to continuously hear the broadcasted traffic. This leaves no opportunity for the ONU to sleep and it wastes energy, as the ONU has to remain awake at all the time and process packets that are not destined for it. In the SMA algorithm, the OLT buffers the downstream traffic for each ONU and only transmits it during a pre-determined activity slot of the ONU. The ONU transmits upstream traffic and receives downstream traffic only during this activity slot. This removes the requirement of the ONU to be awake at all times and gives an opportunity for the ONU to sleep. It, however, necessitates buffering even in the downstream direction and increases packet delay. SMA, like IPACT, polls ONUs in a round-robin manner and issues GATE messages to every ONU in each cycle. Now, the OLT computes the transmission slot (TS) as the function of the buffer backlog of the downstream and the upstream traffic of the ONU according to:

$$TS = Min\{\frac{T_{cycle}}{N_u}, Max(\frac{B_u}{R_u}, \frac{B_d}{R_d})\} \qquad (1)$$

where Min/Max represents the minimum and the maximum value of the function, T_{cycle} is the cycle time in which ONUs are polled, N_u is the number of users, B_u and B_d are backlogged upstream and downstream bytes for the ONU, R_u and R_d are the upstream and the downstream data rate, respectively. SMA also safeguards against very frequent polling of the ONU by assuring every ONU a minimum sleeping time (MST). If the TS (calculated by Eq. (1)) is smaller than MST / N_u, then the TS equivalent to MST / N_u is chosen. This insures that even at a very low load, the ONU polling time is not very short and the ONU does not wake up frequently. Note that, the ONU may be allocated a longer upstream TS than it requested, in which newly arrived packets between the time of a previous request and present grant are transmitted. If the ONU, however, has no additional packet arrivals, it goes to doze mode. The ONU sleeps for a period of $T_{cycle} - TS$. The proposed algorithm is adopted to study sleep mode in considered NGOA architectures. For example, for WDM PON, PtP, and AON, N_u is chosen as 1.

In addition, the OLT communicates the next wake up time to the ONU. The next wake up time of the ONU is the time of issuing the next GATE message of the ONU. The time of issuing the next GATE message of the ONU may not be known at the time of issuing the present GATE message; and thus the OLT predicts the time epoch of the issue of next GATE message. Figure 2 (a) explains it more clearly. We have assumed two ONUs for clarity. Let us assume that at time T, the OLT knows the buffer statistics of both ONUs and their round-trip time (RTT). Thus, at the transmission time of the first GATE G_1 to ONU_1, the OLT can easily calculate the grant time of the next GATE message for ONU_1. At the time of issuing the second GATE message for ONU_1, however, the REPORT message from ONU_2 has still not arrived and thus the OLT cannot calculate the time epoch of the next GATE message for ONU_1. In the SMA algorithm, the OLT assumes a minimum TS for the ONUs of which the REPORT messages have not arrived at the time of decision. When the REPORT messages from ONUs arrive, we determine the grant time of the next (in cyclic order) ONU. Using the latest determined grant time of the ONU *k*, we can calculate the minimum time epoch $\left(MT_p[i+1]\right)$ at which the *(i + 1)*th GATE message to the *p*th ONU is transmitted and is formulated by:

$$MT_p[i+1] = GT_k[i+1] + rtt[k] - rtt[p] + \Delta \qquad (2)$$

where *r tt[p]* is the round trip time of the *p*th ONU and Δ is the minimum TS of the remaining ONUs (ONUs for which the REPORT has not arrived) as shown in Fig. 2 (b). Note that, the actual TS of the remaining ONUs is (Δ + ϒ). From Fig. 2 (b), we can see that the sleep percentage (*SP*) of an ONU is T_S / T_G. Logical point-to-point systems like WDM-PON, PtP, and AON will not suffer from the impairments due to wake up time prediction. To the best of our knowledge, for logical point-to-point systems, no other algorithm has been proposed to exploit the sleep mode functionality. Nevertheless, even for the logical point-to-point systems, the SMA algorithm achieves high power efficiency without adding a high complexity. However, for future research, the DBA algorithms focused on logical point-to-point systems can be used for the analysis of their *PC*.

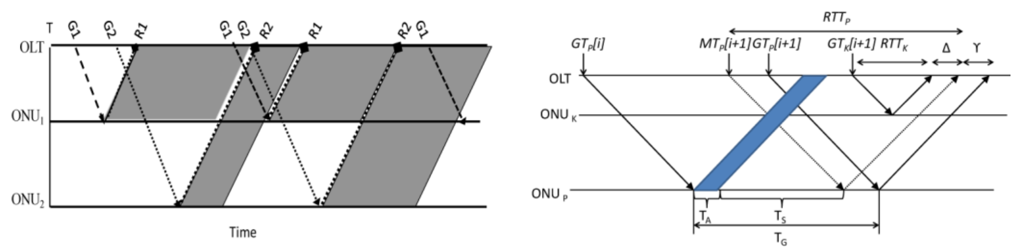


Fig. 2. (a) A TDMA-PON with an OLT and two ONUs showing REPORT (R1 and R2 for ONU1 and 2) and GATE (G1 and G2 for ONU1 and 2) messages transmission. (b) GATE prediction in the SMA algorithm.

5.2 Assumptions

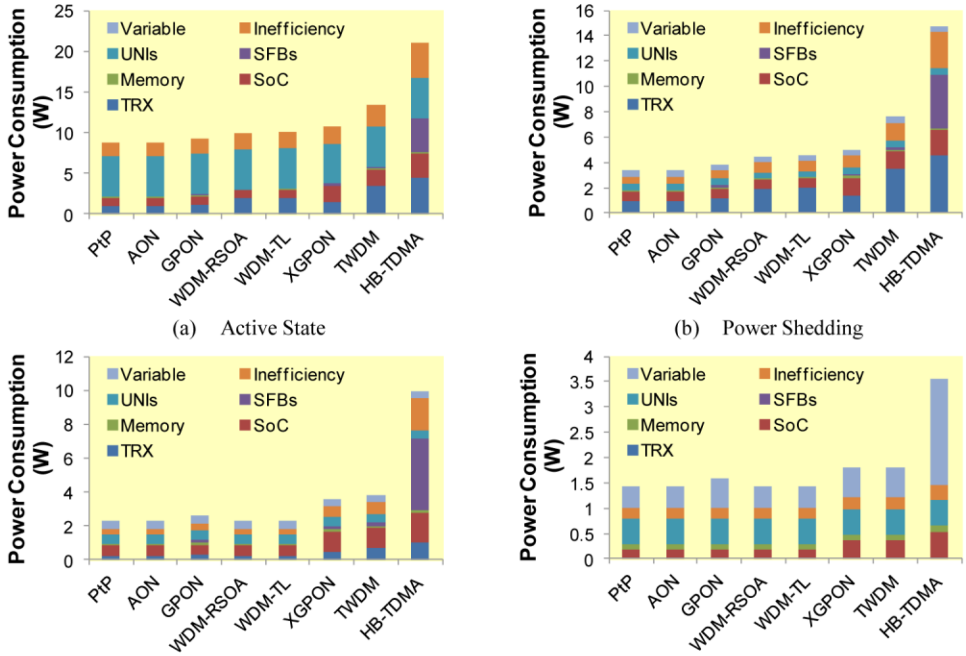
We have simulated considered NGOA architectures using the OPNET simulation environment and employing the DBA algorithm as explained in section 5.1. Service quality is considered as an important requirement with sleep mode scheduling [7] and the SMA scheduling fulfills this requirement. For the study, we have assumed a symmetric upstream and downstream data rate (R_d) between 0 to 100 Mbps, in line with [9]. To meet this end, 1:8, 1:16, and 1:64 split are chosen for EPON, 10G-EPON and TWDM-PON, and 40G-TDMA-PON respectively. We have assumed the reach of 60 km, the buffer size of 5 MB, and three durations of cycle lengths: short (5ms), moderate (20 ms) and long (100 ms). Different cycle lengths are adopted to study the effect of QoS requirements in energy efficiency. The shorter cycle lengths reflect the stringent QoS requirements. For long cycle lengths, we have assumed that digital components can be completely powered off; but at short and moderate cycle lengths, we have assumed the clock gating and the power gating approach. Overheads (T_o) in sleep and doze modes are assumed to vary with a $\pm$ 20% deviation from the switching ON/OFF times given in Table 2. During transition period (i.e. active to sleep state), *PC* is assumed as half in active state. The synthetic user traffic is self-similar with a Hurst Parameter of 0.8 [16] and with a packet size varying exponentially in the form of Ethernet frames (64 to 1518 bytes). All ONUs are assumed to be symmetrically loaded. Note that, though we have employed EPON based multi-point control protocol (MPCP) even for PtP, WDM-PON and AON, the overheads due to the use of MPCP are negligible, as these technologies have considerably higher line rates (1 Gbps) compared to the considered maximum data rate per user, and the overheads in scheduling only become significant at a high network load. Furthermore, the transmission of a MPCP control message requires only 0.512 µs, which is negligible compared to the sleep cycle lengths and the overheads of 1 ms due to continuous mode transmission.

6. Simulation results

In this section, we evaluate the *PC* of considered NGOA system concepts. We first discuss the *PC* in low power states and then in low power modes. Finally, we discuss the effects of low power modes on quality of service (QoS) performance and memory requirements.

6.1 Low power states

Figure 3 gives the *PC* of NGOA networks in low power states, viz. active, shedding, doze and sleep. The *PC* is split into the following parts: TRX, SoC, memory, SFBs, UNIs, power conversion inefficiency and a variable part. The variable part represents the extra *PC* that results from worst assumptions of power saving possible. For example, it represents the extra *PC* due to the worst estimates of the benefits of LPI [16], and the power savings that can be achieved by clock gating or power gating or power switching a digital processing block. For sleep state, the variable component is further divided into two parts to show the influence of fast and deep sleep. In fast sleep, not all the functionalities of a SoC can be turned off, and the SFBs cannot be completely powered off. Whereas in deep sleep, the SoC functionality can be essentially reduced to maintain an internal timer to wake up at its expiry or to respond to local stimuli like the off-hook condition, and all SFBs can be completely powered off. In addition, the contribution of the variable part is highest in 40G-TDMA-PON, as it has a significant power contribution from digital processing blocks like EDC and SoC. Due to variable power savings possible for digital processing blocks, the resulting power saving varies significantly. For example, for 40G-TDMA-PON, the *PC* of digital processing blocks can be reduced to zero if they are completely powered off at long cycle lengths or can be as high as 60% at short cycle lengths, where the large portion of a digital processing block has to remain awake for a faster switch on. The variable part for the best-case scenario will be zero. The system concepts are arranged according to ascending order of the active state *PC*. 40G-TDMA-PON has the highest *PC* in active state because of the use of OA, EDC, and the high downstream and upstream bit rates. The power shedding state minimizes the *PC* due to UNIs. Note that the *PC* of WDM-PON concepts in doze mode is same as PtP and AON, as it has similar receiver and other requirements. In sleep state, the *PC* due to the TRX becomes zero, and the considered technologies achieve a similar power consumption for deep sleep or at long idle conditions.



(a) Active State (b) Power Shedding

(c) Doze State (d) Sleep State

Fig. 3. Power Consumption of NGOA architectures in low power modes

6.2 Low power modes

We investigate the *PC* of considered NGOA contenders in doze and sleep mode. Note that, the analysis corresponds to busy hour traffic conditions. Due to the continual increase in online behavior of users and the requirement that the lifeline telephone services should always be available [7], it is essential to evaluate the *PC* in busy hour traffic conditions. In the long idle periods, the *PC* of various contenders is same as in deep sleep state shown in Fig. 3(d).

We show the *PC* as the split of four parts: 1) primary part, which includes the *PC* of TRX, SoC, memory, SFBs, and power conversion inefficiency; 2) data rate, which shows the variation in *PC* due to the variation in data rate; 3) overheads, which include the *PC* because of the variation in overheads assumptions; and 4) a variable part, which includes the *PC* because of the variation in the *PC* of UNIs and digital processing blocks. Figure 4 shows the *PC* of various NGOA system concepts in doze mode. The *PC* performance is shown for short, moderate and long cycle lengths. The *PC* contribution due to overheads in NGOA system concepts employing the CM-TX is only significant at short cycle lengths. No significant *PC* variation is observed for the variation in cycle lengths. The power savings in doze mode are limited between 50 and 75%. It is easy to see that the *PC* in doze mode (P_{DM}) is a function of the *PC* in shedding state (P_{PS}), doze state (P_{DS}) and doze period (T_D) as:

$$T_D = T_{cycle}.(1 - \frac{R_d}{R_u} - \frac{T_o}{T_{cycle}}) \tag{3}$$

$$P_{DM} = P_{PS}.(\frac{R_d}{R_u} + \frac{T_o}{T_{cycle}}) + P_{DS}.(1 - \frac{R_d}{R_u} - \frac{T_o}{T_{cycle}}) \quad (4)$$

Figure 5 shows the *PC* and the power savings in sleep mode. The power savings in sleep mode are found to vary between 72 and 92%. The *PC* in sleep mode is largely impacted by the cycle lengths. The *PC* for all technologies will drop down with the increase in the cycle length. All technologies, however, will benefit differently. The technologies with BM transmission and reception are found to benefit more. At short cycle lengths, CM-TX technologies will have an increased *PC* because of the effects of overheads. As the cycle length increases, the impact of overheads reduces. 40G-TDMA-PON has the highest *PC* at short and moderate cycle lengths because of the use of EDC and a high power consuming SoC. At long cycle lengths, the *PC* in sleep state is reduced as the large number of functional blocks can be powered off and the SoC functionality reduces significantly. Note that, at short or moderate cycle lengths, the functionalities, like phase locked loop (PLL), are still maintained because of the requirement of shorter wake up times. Furthermore, because of the high downstream and upstream rate, 40G-TDMA can transmit and receive packets in the minimum time and can, thus sleep for the maximum period. Because of the combination of the maximum sleep time and the low *PC* in sleep state for long cycle lengths, 40G-TDMA-PON has a minimum *PC* at the long cycle lengths.

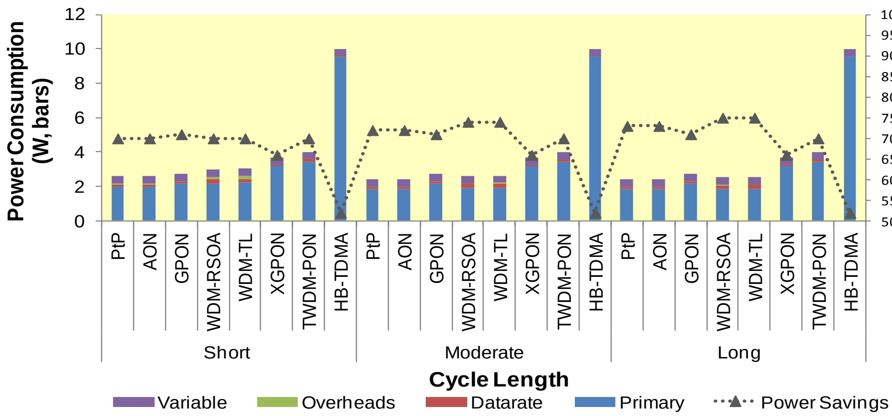


Fig. 4. Power Consumption (W) of various NGOA systems in doze mode during busy hours with three values of the cycle length: short (5 ms), moderate (20 ms) and long (100 ms). The bars representing variable, overheads, and data rate components will be zero for the best case scenario.

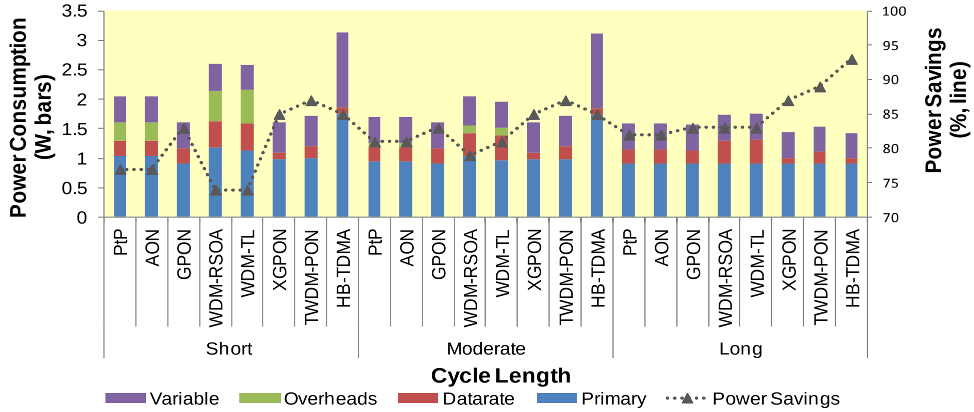


Fig. 5. Power Consumption (W) of various NGOA systems in sleep mode during busy hours with three values of the cycle length: short (5 ms), moderate (20 ms) and long (100 ms). The bars representing variable, overheads, and data rate components will be zero for the best case scenario.

6.3 Effect on QoS parameters and Memory requirements

We have seen that large power savings can be obtained by increasing the cycle length but the increase in cycle length also impacts the quality of service (QoS) performance. The queuing delay is an important QoS parameter, which increases with the cycle length. The increase in the cycle length also enlarges the queue size, which scales the memory requirements. From the simulations, we found out that the delay and the queue size increase linearly with the cycle length, and all NGOA systems exhibited the same increase in the delay and the queue size. Figure 6 shows the upstream queuing delay and the queue size (for upstream traffic at the ONU) variation with the cycle length and the data rate (H = high (100 Mbps), L = low (1.5 Mbps)).The queuing delay and queue size requirement for downstream traffic at the OLT was also found to be the same. There is another difference among the technologies. 40G-TDMA, TWDM, and 10G-EPON have a higher downstream data rate (> 1 Gbps), but have UNIs with only 1 Gbps capability. Hence, either UNIs need to be scaled to higher bit rates or the downstream traffic has to be buffered at the ONU. The UNIs with higher bit rates have significantly higher power dissipation, and hence buffering is a preferred solution. For 40G-TDMA, where the effect of buffering is most severe, there is the additional queuing delay of 2 ms and the increase in buffer size of 0.05 MB, which will have insignificant additional *PC*.

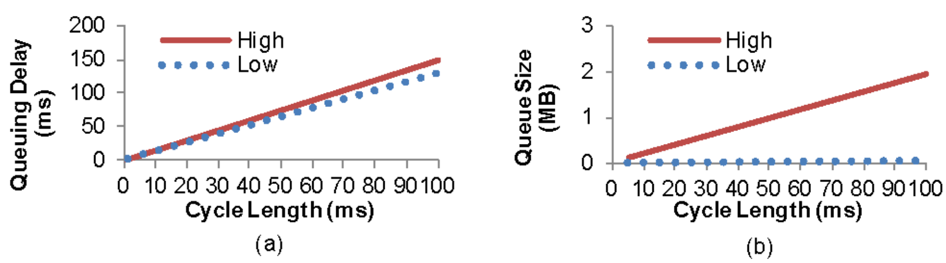


Fig. 6. (a) Queuing delay vs. cycle length (b) Queue size vs. cycle length. H (high = 100 Mbps) and L (Low = 1.5 Mbps) data rates are evaluated.

7. Conclusions

Sleep and doze mode, which are proposed as a promising mechanism to reduce the power consumption of the customer premises equipment, are investigated for next generation optical access (NGOA) technologies like 40G time division multiple access (40G-TDMA) passive optical network (PON), wavelength division multiplexing (WDM) PON, hybrid TDMA/WDM PON (TWDM-PON), point-to-point (PtP) and active optical network (AON). In active state, the power consumption profile of the considered technologies varies significantly and is shown in Fig. 3(a). By application of low power modes, the power consumption of the technologies can be reduced significantly. For long idle periods, the considered technologies achieve similar power consumption. However, during busy hours, the power consumption of the technologies depends upon the cycle length. During busy hours, doze mode can reduce energy consumption between 50 and 75%, whereas sleep mode can reduce energy consumption between 72 and 92%, and technologies with burst mode transmission and reception, like 40G-TDMA-PONs, TWDM-PONs, 10G-EPON, and EPON achieve a better power saving compared to continuous mode transmission and reception technologies like WDM-PON, AON and PtP.

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 249025 (ICT-OASE) and grant agreement n° 257740 (Network of Excellence TREND). We would also like to thank the GreenTouch consortium for its valuable feedback and suggestions.