How Sleep Modes and Traffic Demands Affect the Energy Efficiency in Optical Access Networks

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Abstract: An ever-increasing bandwidth demand is the main driver to investigate next generation optical access (NGOA) networks. These networks, however, do not only have to comply with increasing data rates, they should also meet the societal green agenda. As the access part consumes a major fraction of the energy consumption in today's fiber-to-the-home (FTTH) based telecommunication networks, the energy efficiency of NGOA networks should be an important design parameter. In this paper, we present a detailed evaluation of the energy consumption in different NGOA technologies. Furthermore, we analyze the effects of (1) introducing low power modes (e.g., sleep and doze modes) in the various NGOA technologies and (2) using optimal split ratios adjusted to the traffic demands so that the energy consumption is optimized for the desired quality of service (QoS) level.

Keywords: energy efficiency; optical access networks; low power modes; split ratio

1. Introduction

Although most access networks still rely on copper lines, there is a growing number of commercial fiber-to-the-home (FTTH) deployments by several network operators worldwide, offering much higher bandwidths than traditional copper-based access networks. The majority of today's FTTH deployments are based on time division multiplexing (TDM) passive optical networks (PONs). For the moment, 2.5 Gb/s capable PONs (Gigabit PON or GPON) are the most commonly deployed fiber access networks, while 10 Gb/s capable PONs (indicated as XG-PON) are expected in the next couple of years. In the long term, increasing bandwidth demands associated with mobile backhauling, content-rich cloud services and the convergence of residential and business access will necessitate the deployment of even faster next-generation optical access (NGOA) networks. A variety of network technologies have been investigated to meet the demands of NGOA networks. Section 2 provides a comprehensive insight into these technologies.

Due to the rising awareness of climate change and increasing energy prices, there is a growing interest from the telecom sector in energy efficient networks. Reducing the energy consumption and the associated operational cost of the access network is becoming an important factor when evaluating different NGOA systems. Currently, the access segment (including customer premises equipment) consumes a major fraction (60-80%) of the energy consumption in optical access networks, and optical network units (ONUs) at the customers' premises consume about 60% of the energy (Figure 1)[1, 2]. Optical line terminals (OLTs) at the central offices consume about 7% of the energy. Thus, overall significant energy savings can be procured by saving energy in access networks.

ONUs thus consume the major portion of the energy in optical access networks, and several low power modes are actively considered at the ONUs, e.g., sleep modes and doze modes. Low power modes have the potential to save a significant amount of energy at the ONUs [1]. In these modes, whenever there is no traffic to receive/send, non-essential functionalities are turned off at the ONU.

The energy consumption at the OLT could be reduced by using transceivers at a high utilization rate, which can be accomplished by using a high split ratio per transceiver (the split ratio being the number of homes passed by fiber coming from a single OLT transceiver). This leads to higher aggregation levels at the OLT, minimizing traffic bursts and leading to better utilization of the resources. The gains of these effects are evaluated exhaustively in [2] and are omitted in this paper.

The energy efficiency approaches at both the ONU and OLT that we will study here are detailed in Section 3. The evaluation methodology and the corresponding results are presented in Section 4 and in Section 5 respectively, and finally the most important conclusions are given in Section 6.

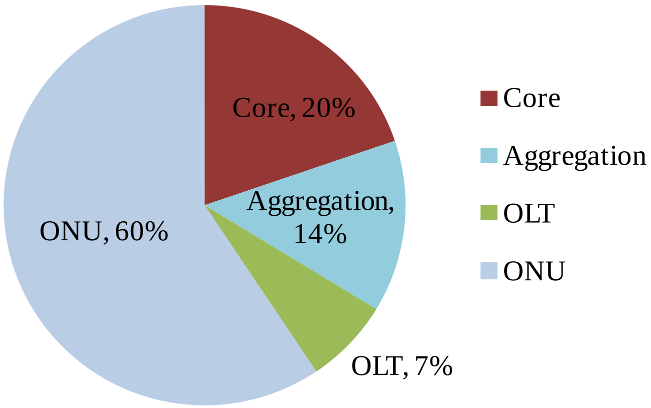

Figure 1: Contributors of the energy consumption in FTTH networks [3].

2. Next Generation Optical Access Networks

Several technologies are currently considered as NGOA candidates[3], such as: 40G- TDM-PON (indicated as XLG-PON), wavelength division multiplexing PON (WDM), time and wavelength division multiplexing PON (TWDM-PON), point-to-point (PtP) and active optical network (AON) [1]. We compare these NGOA solutions with each other and with the current state-of-the-art TDM-PON solutions like GPON and XG-PON.

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[1] In this calculation, a TDM-PON with passive splitters at the remote nodes (like street cabinets) is assumed, meaning that only power is consumed in the ONUs and OLTs. Although some FTTH networks consume power at the remote nodes (like AONs), they only have a minor market share in the current FTTH rollouts.

[2] As aggregation, a 200 Gb/s aggregation switch shared by 100 OLTs is assumed, and as core, several levels of 200 Gb/s IP routers are assumed shared by 4 aggregation switches at the first level [3].

[3] We define NGOA as a next generation compared to the XG-PON standard and in a 2020 time frame, i.e. technologies that potentially could be deployed by 2020. In this way, NGOA corresponds to an extended version of the currently defined NG-PON2 (i.e. TWDM-PON and WDM-PON).

The basic differences among the various technologies are the ways in which a user (or an ONU) connects to the OLT, and accesses the network resources. The network architecture of these solutions is quite different and employs a diverse set of functionalities, giving rise to system-specific power consumptions. Below, we elaborate on the different architectures.

2.1. TDM-PON

In TDM-PONs, the OLT accesses the ONUs using a TDM protocol over a power splitter. All ONUs receive the same signal, from which each ONU selects the data in its allocated time slots. Examples of TDM-PONs are: XLG-PON (40 Gb/s downstream (DS) and 10 Gb/s upstream (US)), XG-PON (10 Gb/s DS and 2.5 Gb/s US), 10G-EPON (10.3 Gb/s DS and 1.25 Gb/s US), GPON (2.5 Gb/s DS and 1.25 Gb/s US), and EPON (1.25 Gb/s DS and 1.25 Gb/s US)[4]. The latter four are current state-of-the-art solutions, while XLG-PON is a NGOA candidate.

XLG-PON supports the highest DS and US line rate. It, however, suffers from reach limitations posed by serious dispersion issues with a high data rate transmission. Nevertheless, paper [4] points out that dispersion can be limited by using the zero-dispersion wavelength (1.3 μm, O band) and duo-binary modulation for the transmission, and hence, special functionalities like electronic dispersion compensation (EDC) can be avoided. Nevertheless, attaining a high power budget remains a challenge for 40G-PONs, and thus they will need optical amplification (OA) and efficient forward error correction (FEC) designs. Furthermore, XLG-PON requires electronic processing at 40 Gb/s of the incoming traffic bursts at the ONU, which results in a high power consumption. To deal with this limitation, the bit-interleaving protocol was proposed [5] to transmit DS traffic. By interleaving the bits for different ONUs, the electronic processing speed of the ONU receiver can be reduced, resulting in a lower ONU energy consumption. We consider two variants of XLG-PON: without bit-interleaving (XLG-GEM, i.e. using the GPON Encapsulation Method (GEM) to package user traffic) and with bit-interleaving (XLG-Bi, where the electronic processing will be reduced by a factor of 4, i.e. 10 Gb/s).

2.2. WDM-PON

WDM-PON uses multiple wavelengths (e.g., each at 1 Gb/s) and offers the most straightforward way of capacity increase. WDM-PON is assumed to use an arrayed waveguide grating (AWG), which is a static wavelength router that routes incoming wavelengths to different output ports. Each user gets a separate wavelength. Since users are on a separate wavelength, WDM-PON does not require the complexities of TDM. The simplest solution is to use a colored transceiver at the ONU, in which every ONU gets a transceiver of a different color (or wavelength) [6]. Consequently, the vendors have to stock an inventory of different colored transceivers, which will shrink the cost reduction that can be attained by mass production. Thus, colorless transceivers are preferred at the ONUs. There are many approaches for colorless transceivers [7]. However, either the WDM-PON ONU must be equipped with a tunable laser (TL) to tune to a separate wavelength or it may use the DS signal wavelength to transmit on a separate US wavelength. For the second case, the ONU requires reflective semiconductor optical amplifiers (RSOA) and frequency shift keying (FSK)

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[4] There are other possible configurations of the line rates for XG-PON, 10G-EPON and GPON in the US direction. Here, a typical example is given.

modulators. We consider these two variants of WDM-PON: with tunable lasers (WDM-TL) and with RSOA (WDM-RSOA).

2.3. TWDM-PON

TWDM-PON combines the flexibility of TDM-PON with the increased overall capacity of WDM technology. TWDM-PON uses stacked XG-PONs, where each XG-PON is at a different DS and US wavelength. Here, again a power splitter is used which broadcasts all wavelengths to all users. The ONU needs a tunable transmitter and a broadband receiver; the frequency range of a broadband receiver is typically narrower than in the case of WDM-PON as it uses a fewer wavelengths. The ONU also needs a tunable filter (TF), as multiple wavelengths are available at its input. We assume four wavelengths in each direction with a DS line rate of 10 Gb/s and an US line rate of 2.5 Gb/s.

2.4. PtP

In PtP, each ONU is connected directly via a fiber to the OLT, for example at a symmetrical 1 Gb/s line rate. It has the simplest ONU, but comes at the cost of a large amount of fiber that needs to be deployed.

2.5. AON

AONs use an active remote node in the field, which requires powering and maintenance. In an active star deployment, a single fiber is connected from an aggregation switch at the CO to an active access switch at the RN, which is connected to the ONUs. The active switch in the remote node selects and forwards the relevant information for each ONU, hence the ONUs do not require TDMA functionality and tunable optics. The ONU is assumed to use a 1 Gb/s transmitter (TX) and a 1 Gb/s receiver (RX), whereas the OLT uses a 10 Gb/s TX and a 1 Gb/s RX. A high data stream from the OLT is adapted to multiple low data streams by the active switch. Due to different technical backgrounds, different practical and geographical constraints, AON networks differ from each other. The active switch itself may be pure open systems interconnection (OSI) layer 2, or layer 2 with some layer 3 features (e.g., ICMP snooping), or layer 3 devices (i.e., IP routers).

3. Energy efficiency

The power consumption of the different NGOA technologies can be decreased by using sleep modes and applying an optimal split ratio such that a maximal traffic aggregation can be achieved. In this section, first we present the potential of an energy efficient design, and then we discuss the low power modes and the optimal split ratio.

3.1. Potential of energy efficient designs

There are large possibilities to save energy due to the following reasons:

1) The traffic in the access link is bursty and follows the Pareto principle, which states that 80% of the network load is generated by 20% of the users [8]. This means that many users remain idle for most of the time, and therefore they can sleep.

2) Access links are heavily under-used with an average utilization rate of only 15% [9].
3) In TDM-PONs, an access link is shared by an ONU for a time fraction inversely proportional to the total number of active ONUs. For example, in a system with 32 ONUs, the access link is shared by an ONU for a time fraction of 3.125% (1/32). Even at very high traffic loads, an ONU can thus theoretically sleep for 96.875% of the time. Note that a legacy ONU, is reachable all the time and in this case there are no sleep possibilities. The sleep potential, however, could be enabled by a sleep mode aware (SMA) dynamic bandwidth allocation (DBA) protocol as proposed in [1], [2] and discussed in section 4.2.2.

3.2. Low power modes

To reduce the power consumption of ONUs, a whole range of low power states have been considered (Figure 2): power-shedding, dynamic power save, doze and sleep state [10], [11].

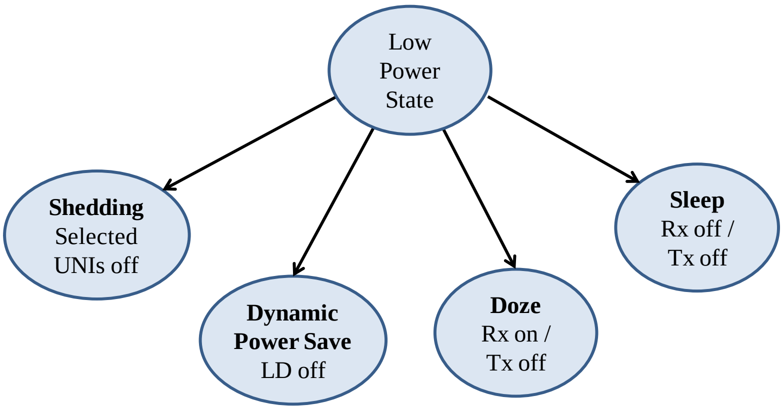
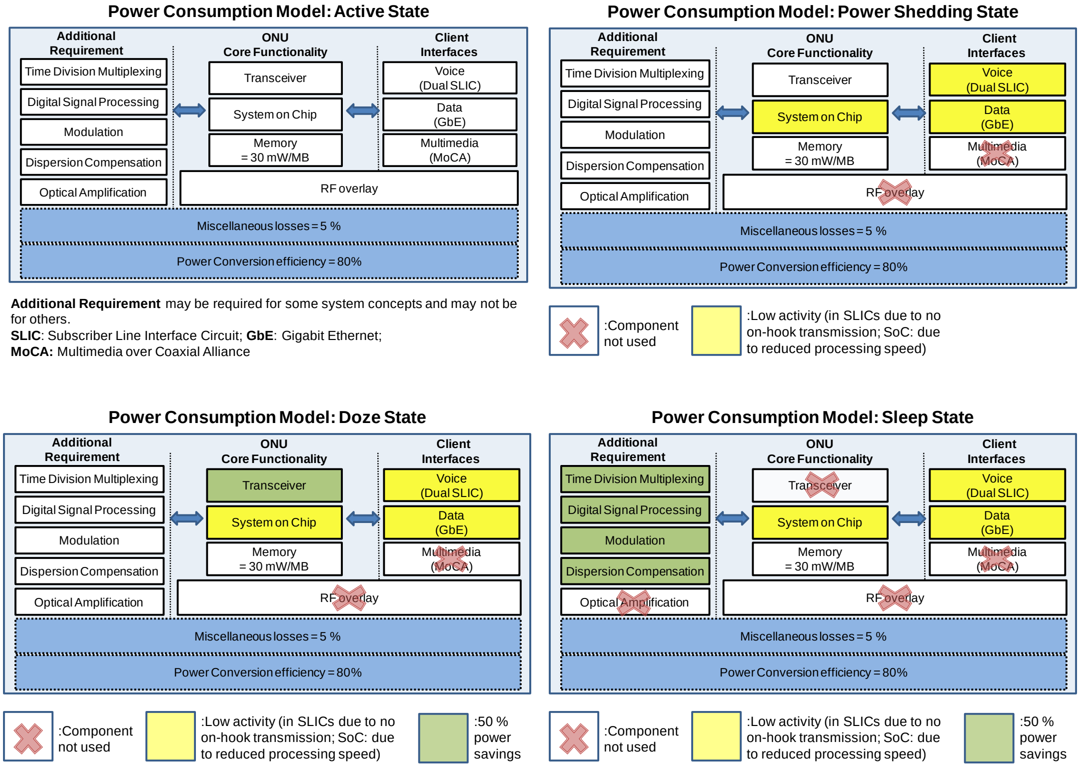


Figure 2: Low power states

The above approaches differ based on the parts of the ONU that are switched off [10], as illustrated in the ONU power consumption model of Figure 3.

- *Power-shedding* − The power-shedding state shuts down the unused user network interfaces (UNIs).
- *Dynamic power save* – In this state, along with the non-essential UNIs, the laser driver (LD) of the transmitter block is switched off (not shown in Figure 3, as this method is not largely used).
- *Doze* − In doze state, non-essential functions are powered off with an additional powering off of the ONU transmitter while the receiver remains on.
- *Sleep* − In sleep state, non-essential functional blocks and both the ONU transmitter and the receiver are turned off.

Note that a low power mode represents the combination of low power states according to the traffic load. For example, doze mode is referred to as the cyclic transitions between active, power-shedding and doze state, and sleep mode as the cyclic transitions between active, power-shedding, doze and sleep state. Sleep modes can be classified further as deep and fast (cyclic) sleep mode based on the periods of sleep, where the deep sleep approach has comparatively longer periods of sleep.



Additional Requirement may be required for some system concepts and may not be for others.
SLIC: Subscriber Line Interface Circuit; **GbE**: Gigabit Ethernet;
MoCA: Multimedia over Coaxial Alliance

Figure 3: ONU power consumption model illustrating four different power states (active, power shedding, doze and sleep).

3.3. Optimal split ratio

Different technologies have a different DS and US capacity per OLT transceiver. Since this capacity is shared by all the end users connected to a single transceiver, changing the split ratio will change the available capacity per user. The split ratio should be optimized independently for each technology to satisfy user demands, taking into account technology-specific physical constraints such as reach and capacity.

First of all, the split ratio is restricted by the available optical power budget, as higher split ratios result in more loss of the optical signal strength. The higher the power budget of a technology, the higher the split ratio can be. Moreover, the split ratio should be chosen such that the desired quality of service (QoS) can be assured to users, taking into account bandwidth and availability requirements. Normally, the same average bandwidth per customer is assumed to select the split ratio. However, this does not take into account the advantages that can be accrued due to the statistical multiplexing of demands from a large number of users. For example, a system with a higher fan out will be able to deliver a better QoS performance compared to a system with a lower fan out even with the same average bandwidth per customer. Thus, choosing an optimal split ratio requires modeling the architecture performance, taking into account user traffic profiles and the potential for dynamic bandwidth allocation. Paper [12] provides insight into deriving such optimal split ratios for various technologies. Note that we assume a maximum split ratio 1:256, with additional restrictions imposed by the technology-dependent reach.

4. Evaluation Methodology

In this section, we first outline the input parameters for evaluation of the optimal split ratio and then discuss the calculation of the power consumption of the different components in active and sleep mode.

4.1. Calculation of the optimal split ratio

The optimal split ratio is calculated for each technology such that the QoS requirements are fulfilled. First we define a target bandwidth, referred to as B_{target}, which is the bandwidth requested by an active user. Further, we vary the probability p_{act} of a user being active. Based on B_{target} and p_{act}, we can vary the bandwidth requests in the scenario. For the evaluation in this paper, we define two scenarios:

1) Low demand scenario: B_{target} = 100 Mbps, p_{act} = 10%.
2) High demand scenario: B_{target} = 1 Gbps, p_{act} = 50%.

For each technology, we select the split ratio such that the target bandwidth is provided with an availability probability p_{av}. p_{av} is fixed at 20%, this means when users request the target bandwidth they will get full B_{target} only 20% of the time, while the other 80% of the time they will get a lower bandwidth. The details of this calculation can be found in [12]. The optimal split ratio calculated for each technology is given in Table 1. Once a split ratio is chosen for a certain deployment, there is no easy way to upgrade it. This means that the user demand of the area should be estimated with a sufficient margin to allow future demand growth considering the expected lifetime of the fiber deployment.

Table 1: Maximum power budget, OLT power consumption and split ratios per transceiver of various NGOA technologies

Technology	Maximum Power Budget (dB)	Transceiver power consumption (W)	Digital Processing power consumption (W)	Total power consumption per transceiver (W)	Split ratio (in low demand scenario)	Split ratio (in high demand scenario)
GPON (B+)	28	1.8	2.0	3.8	64	8
XG-PON	35	5.0	7.0	12	256	32
XLG-PON (GEM)	28	16[5]	25	41	128	128
XLG-PON (Bi)	28	16	25	41	128	128
WDM-PON (Tunable Lasers)	38	1.9	1.2	3.1	1	1
WDM-PON (RSOA)	25	1.9	1.2	3.1	1	1
TWDM-PON	38.5	6	7	13	64	32
Ethernet PtP	31	1.0	1.2	2.2	1	1
AON	35	4.0	7.0	11	256	128

4.2. Calculation of the power consumption in sleep mode

To calculate the power consumption in sleep mode, several assumptions have to be made, and first we outline them for the various components of the different NGOA technologies considered in this paper. Next the sleep periods are

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[5] Including SOA power consumption.

calculated by using a specific DBA algorithm. By combining the power consumption of the components and the calculated sleep periods, the ONU's power consumption in sleep mode is defined.

4.2.1. Assumptions of the power consumption of the components

In this paper, we consider the power consumption[6] due to the transceivers and digital processing at the OLT and the ONUs. For the OLT, the power consumption of the uplink interfaces to the aggregation network, layer 2 switching, packet processing and traffic management are not included (together they would add less than 0.2 W for the low demand scenario, or about 3 W for the high demand scenario). Similarly, for ONUs, the power consumption due to the user network interfaces (UNIs), RF overlay, and memory[7] is the same for all technologies (approximately 5 W) and is thus excluded. For details about the total power consumption of an ONU, we encourage readers to refer to [1].

The assumptions of the power consumption of the transceivers depend upon many factors. To explain this, we first depict the components of a transceiver (Figure 4). A transceiver includes a TX and a RX (separated by a circulator or diplexer), and occasionally a semiconductor optical amplifier (SOA) based booster or a pre-amplifier. A booster is used in the DS direction with a TX, and a pre-amplifier is used in the US direction with a RX. For example, we assume SOA based booster integrated in the TX of an XLG-PON. The TX includes a laser and a laser driver (LD), and the RX consists of a photo-diode (PD), a trans-impedance amplifier (TIA), a limiting amplifier (LA) and a clock and data recovery (CDR) circuit. Besides, other components like a thermal-electric cooler (TEC) and a tunable filter (TF) may also be used depending upon the NGOA technology. Different technologies influence the design of a transceiver and its sub-components in the following ways:

a) *High data rate*: The power consumption of most components is sensitive to the data rates. For example, the power consumption of a TIA and an LA varies as 3 mW and 2 mW per Gb/s, respectively [13]. More significantly, the transceiver with a high data rate may require a completely different design that can consume more power. For example, for high data rate transmission (e.g., 10 Gb/s or more), an externally modulated laser (EML) should be used instead of a directly modulated laser (DML), but EML consumes more power. Thus, XLG-PON (for both OLT and ONU), XG-PON (for OLT) and TWDM-PON (for OLT) use EML and hence consume more power compared to the other technologies.
b) *High insertion loss*: To compensate high insertion loss, the technologies use an avalanche photodiode (APD) instead of a positive-intrinsic-negative (PIN) photodiode in the receivers. APD has better receiver sensitivity, and thus furnishes a higher power budget. However, APDs are also more expensive. Moreover, SOA based boosters and pre-amplifiers can be used to increase the power budget.
c) *Multiple wavelength systems*: The technologies using multiple wavelengths, such as WDM- and TWDM-PON, require a high-wavelength precision in the DS direction so that the wavelengths do not drift into each other's spectrum. Thus, they need temperature control, which requires a

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[6] Power consumption also includes power conversion inefficiency.

[7] For each technology, the memory requirements and thus its associated power consumption may vary. However, its effect is negligible and is thus ignored.

power-hungry TEC. In the US direction, uncooled tunable laser[8] are preferred. Moreover, a receiver will need a tunable filter as well, if multiple wavelengths are fed to it.

d) *TDM based PONs*: for TDM based PONs, e.g., TDM-PON and TWDM-PON, the ONU TX has to be optimized for a fast turn on/off and thus needs a burst mode laser driver (BM-LD).

e) *Logical Point-to-Multi-Point (L-PtMP) technologies*: In L-PtMP technologies, like TDM-PON and TWDM-PON, the OLT RX receives signals from the ONUs, which are located at different distances, and thus it needs a burst mode LA (BM-LA) to adjust to the dynamic range of the received signal power. Note that AON, however, does not require a BM-LA due to the optical-electrical-optical (OEO) conversion at the intermediate active remote node.

f) *Sleep mode requirements*: To support sleep modes, the ONU RX should be equipped with a burst mode CDR (BM-CDR) to resynchronize to the OLT data within negligible (few nano-seconds) time.

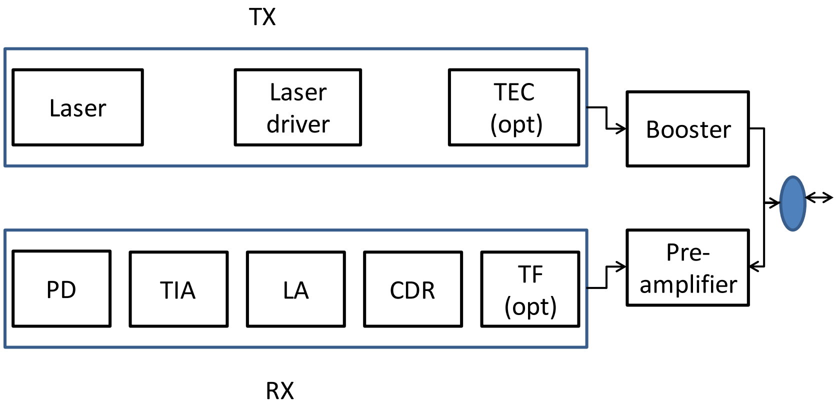

Figure 4: Sub-systems of a transceiver.

The details of the transceiver design are given in Table 2. Based on this design, power consumption values are calculated for the transceivers of the OLT (Table 1) and the ONUs (Table 3) of different NGOA technologies. The sub-components values are taken from [12], [13] and a large survey of component's data sheets. The power consumption of an active remote node in AON is assumed as 4 W. Note that bit-interleaving does not affect the ONU transceiver, as still data rates at 40 Gb/s are offered to the ONU. Only the digital processing is affected by the bit-interleaving protocol as explained below.

The power consumption of the digital components can be linked to their data processing rate, e.g., on DS and US data rate. The higher the data rate, the higher the operation frequency of the system on chip (SoC), leading to a higher power consumption. Further, TDM based PONs require some additional power for the medium access control (MAC) protocol. Based on this, we can compare the power consumption of the digital part for the different technologies, for example the power consumption of TWDM-PON and XG-PON will be identical as they have the same data rate and both require a MAC protocol. The power consumption of GPON will be lower due to lower data rates. Further, the power consumption in WDM-PON will still be lower (compared to GPON) due to reduced line rates and

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[8] Paper [14] achieves tuning by only heating the wavelengths. However, such advanced solutions are not considered.

no requirement of a TDMA based MAC protocol. The bit-interleaving protocol (used in XLG-PON) also reduces the power consumption of the digital part as the processing at the ONU can now be done at a reduced data rate.

Table 2: Transceiver design of the considered NGOA technologies and their key required functionality

System	ONU		OLT	
	Rx	Tx	Rx	Tx
GPON	2.5 G-PIN + TIA + LA + BM-CDR	1.25 G-DML + BM-LD	1.25 G-PIN + TIA + BM-LA + CDR	2.5 G-DML + LD
XG-PON	10 G-APD + TIA + LA + BM-CDR	2.5 G-DML + BM-LD	2.5 G-APD + TIA + BM-LA + CDR	10 G-EML + LD
XLG-PON[9]	40 G-APD + TIA + LA + BM-CDR	10 G-EML + BM-LD	10 G-APD +TIA + BM-LA + CDR	40 G-EML + LD + SOA
WDM-TL	1 G-PIN + TIA + LA + BM-CDR	1 G-uncooled TL+LD	1 G-PIN + TIA + LA + CDR	1 G-DML + LD + TEC
WDM-RSOA	1 G-PIN + TIA + LA + BM-CDR	RSOA + FSK modulators	1 G-PIN + TIA + LA + CDR	1 G-DML + LD + TEC
TWDM	10 G-APD + TIA + LA + BM-CDR + TF	2.5 G-uncooled TL + BM-LD	2.5 G-APD + TIA + BM-LA + CDR	10 G-EML + LD + TEC
PtP	1 G-PIN + TIA + LA + BM-CDR	1 G-DML + LD	1 G-PIN + TIA + LA + CDR	1 G-DML + LD
AON	1 G-PIN + TIA + LA + BM-CDR	1 G-DML + LD	10 G-PIN + TIA + LA + CDR	10 G-EML + LD

4.2.2. *Evaluation of sleep periods*

We use the SMA algorithm [1], to evaluate the sleep mode gains in the various NGOA technologies. SMA uses the GATE message to inform an ONU about the awake period only during which it needs to wake up to receive the DS traffic. This necessitates buffering for both the DS and US traffic. Note that buffering introduces delay in the traffic that has to be within the QoS limits. Further, we maximize the alignment of the reception of the DS traffic and the transmission of the US traffic for an ONU, maximizing the time during which an ONU can sleep. The OLT determines the sleep period according to the DS and US bandwidth backlog of an ONU and grants a transmission slot (*TS*) according to:

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

where *Min*/*Max* represents the minimum and maximum value of the function, T_{cycle} is the cycle time[10] in which ONUs are polled, N_u is the number of users, B_d and B_u are the backlogged DS and US bytes for an ONU, R_d and R_u are the DS and US data rate, respectively. The proposed algorithm is adopted to study sleep modes in all NGOA architectures. For example, for WDM-PON, PtP, and AON, N_u is chosen as 1, and the polling is after a fixed T_{cycle}.

4.2.3. *ONU's power consumption in sleep modes*

The ONU's power consumption is given in active, cyclic sleep and deep sleep states in Table 3. The actual ONU power consumption depends upon the time that an ONU spends in active, cyclic sleep and deep sleep state. For making optimal transitions between these various states, we use the SMA algorithm as discussed in section 4.2.2.

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[9] No difference in the transceiver part between XLG-PON (GEM) and XLG-PON (Bi). Bit-interleaving only affects the digital processing.

[10] Time interval between two successive pollings of an ONU.

Table 3: ONU’s power consumption (W) in various power states for different NGOA technologies

	Power Consumption					Sleep overheads		
Technology	Trans-ceiver	Digital	Active	Cyclic sleep	Deep sleep	Trans-ceiver	Overall Cyclic sleep	Overall Deep sleep
GPON (B+)	1.2	2	3.2	0.6	0.1	100 ns	5 µs	10 ms
XGPON	1.6	4	5.6	1.2	0.1	200 ns	5 µs	10 ms
XLG-PON (GEM)	2.6	5	7.6	1.5	0.1	500 ns	5 µs	10 ms
XLG-PON (Bi)	2.6	3.2	5.8	0.96	0.1	500 ns	5 µs	10 ms
WDM-PON (Tunable Lasers)	1.9	1.5	3.4	0.45	0.1	1 ms	1 ms	10 ms
WDM-PON (RSOA)	1.7	1.5	3.2	0.45	0.1	1 ms	1 ms	10 ms
TWDM-PON	2.3	4	6.3	1.2	0.1	200 ns	5 µs	10 ms
Ethernet PtP	1	1.5	2.5	0.45	0.1	1 ms	1 ms	10 ms
AON	1	1.5	2.5	0.45	0.1	1 ms	1 ms	10 ms

Note that since the power consumption of UNIs is ignored, the power-shedding state is irrelevant. Moreover, for NGOA technologies, doze state does not make sense as NGOA systems can always be assumed to be equipped with a BM-CDR, which makes the penalties associated with switching off a receiver negligible. Whenever a receiver is turned on, it needs to resynchronize to the OLT data. However, by using a BM-CDR [15], which uses a local oscillator to keep the ONU in accord with the OLT, the recovery time reduces to as short as 10 ns for the 1 Gb/s receiver, and is even shorter for 10 Gb/s as the higher bit rate CDRs scan more bits in the same time. Thus, the resynchronization time of the receivers can be neglected.

For this analysis, we assume that the ONUs can be inducted sometimes in cyclic sleep and the other times in deep sleep. The percentage of time an ONU can be inducted in cyclic sleep is assumed as P_{active}. This means that the percentage of time an ONU can be inducted into deep sleep is $1\text{-}P_{active}$. This means that the OLT senses the traffic request of an ONU, and shifts it into one of the sleep modes based on the traffic request of an ONU.

For cyclic sleep, we assume a scheduling cycle of 20 ms, whereas for deep sleep, we assume a scheduling cycle of 100 ms. The assumptions of the transceiver’s sleep overheads are from [1] and are given in Table 3. The sleep overheads are due to the finite time taken by the transmitter to wake up and sleep. For TDM based technologies, the transmitter is a burst mode transmitter and hence takes negligible time to wake up and sleep. However, technologies like PtP, WDM-PON and AON use a continuous mode transmitter and hence they experience longer overhead times. In cyclic sleep, the power consumption of the digital circuits is assumed to be reduced by 60% using clock gating. The time taken in clock gating the digital circuits is assumed as 5 µs. The overall sleep overhead in cyclic sleep is the maximum of the overhead penalty due to the transceivers and clock gating.

In deep sleep, the digital circuits are completely switched off. This saves more power but increases the wake up overheads. The wake up time to completely power off digital circuits is assumed as 10 ms. This means in deep sleep, the overall overhead is dominated by the time to power on/off digital circuits and is the same for all technologies. The power consumption in deep sleep is in essence to maintain an internal timer to wake up the ONU at its expiry or to respond to local stimuli like the off-hook condition, and is thus the same for all technologies.

5. Results

We evaluate the power consumption of GPON (B+), XG-PON, XLG-PON (GEM), XLG-PON (Bi), WDM-PON with tunable lasers, WDM-PON with RSOA, TWDM-PON, Ethernet PtP, and AON. The optimal split ratios are calculated as described in section 4.1, and they are influenced by the target bandwidth B_{target} and the availability probability p_{av}. Further, OPNET is used as a simulation environment to evaluate the ONU sleep mode potential (based on the amount of sleep time during the simulation period[11]) of the different technologies. We generate packets in the form of Ethernet frames (64 to1518 bytes) and the packets arrive at each ONU from the end user. The simulated end user traffic is self-similar by aggregating 32 sub-streams [16], each consisting of alternating Pareto-distributed on/off periods, with a shape parameter of 1.4 for the on period and a shape parameter of 1.2 for the off period. In the on period, the packet arrivals are exponentially distributed with a mean arrival rate of $B_{target} \times p_{act}$, where p_{act} is the active user probability. As mentioned in section 4.1, a low and a high demand traffic scenario are defined by varying B_{target} and p_{act}.

Figure 5 depicts the power consumption of different technologies in the low demand scenario without and with sleep modes at the ONUs. The presented power consumption values are instantaneous values per user, averaged over the simulation period. Without sleep modes, we see that an ONU has the maximum influence on the power consumption of the technologies. XLG-PON (GEM) is found to consume the highest power and this is due to the high ONU's power consumption because of a high data rate transceiver and OA. XLG-PON (Bi) already reduces the power consumption due to the reduced power consumption in digital processing. Note that the digital components of a bit-interleaved PON work at a much lower rate and hence consume less power.

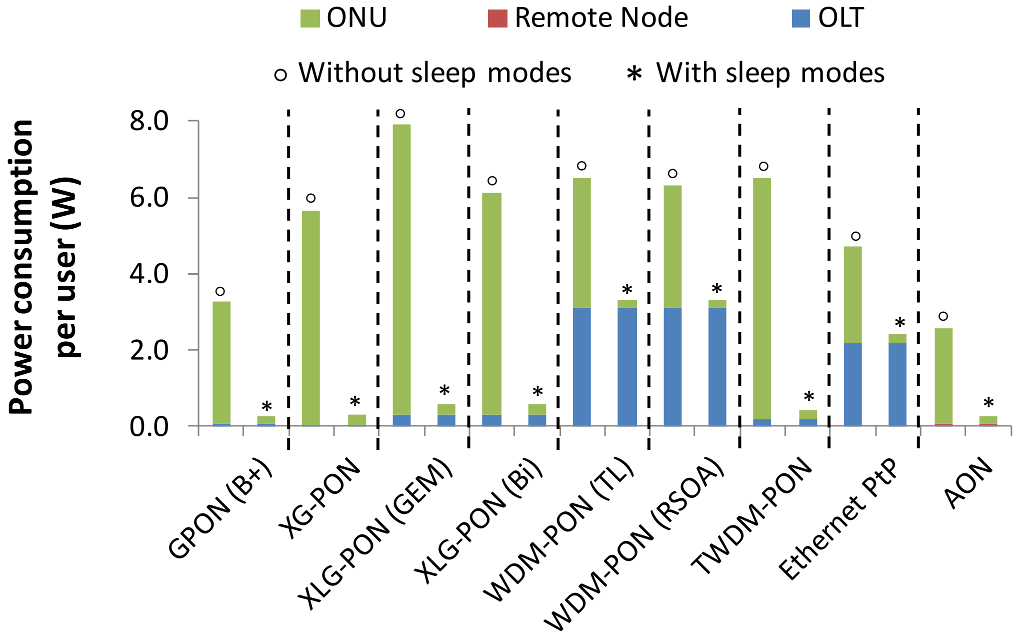

Figure 5: Power consumption per user of different optical access technologies at a low demand scenario with and without sleep modes at the ONUs. Note that at the ONU and OLT only the power consumption of the transceivers (both optical and digital components) is included. For the remote node (in AON), there is an Ethernet switch included.

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[11] A simulation period of 30s is used, corresponding to a steady-state situation.

However, there is a large effect of sleep mode on the power consumption of the technologies: XLG-PON (GEM), which consumes the highest power without sleep mode, consumes very little (less than 0.5W) power with sleep mode. In sleep mode, the components can be switched off for a long time and thus large savings are possible. What is more, it benefits the technologies with a more bursty transmission as they have a longer switch-off time.

We also notice that the reduced power consumption by applying bit-interleaving disappears if sleep modes are used. Both XLG-PON (GEM) and XLG-PON (Bi) consume roughly the same amount of power in sleep mode. XLG-PON (Bi) is using less power in active state than XLG-PON (GEM), but due to the bit-interleaving, its ONU will have shorter sleep periods as bits are offered at a reduced data rate. Both effects are compensating each other in the low demand scenario.

Further, with sleep modes, the OLT's power consumption becomes dominant, and logical PtP (L-PtP) technologies, like Ethernet PtP and WDM-PON, perform worse due to a low sharing of the OLT components.

Figure 6 gives the power consumption of different technologies in the high demand scenario without and with sleep modes at the ONUs. The effect of sleep modes is similar to the scenario with low demand. However, the power consumption of the L-PtMP technologies increases due to the reduced split ratio at the RN and thus lowered sharing. Moreover XLG-PON (Bi) even consumes more power than XLG-PON (GEM) if sleep modes are used in combination with a high demand. Because of the high demand, the sleep periods will be reduced, and this will mainly affect the bit-interleaved solution.

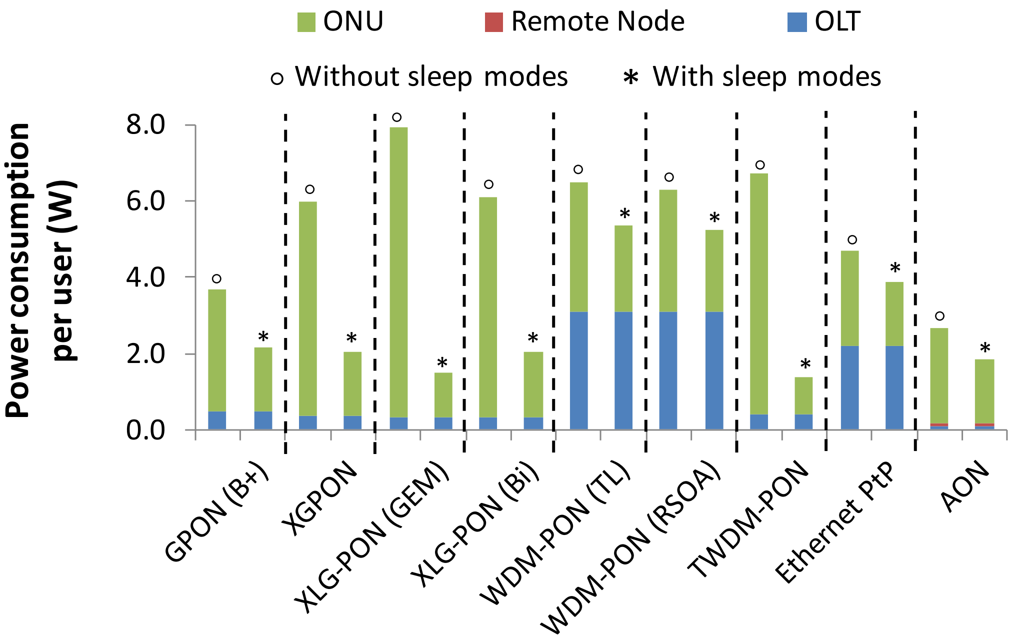

Figure 6: Power consumption per user of different optical access technologies at a high demand scenario without and with sleep modes at the ONUs. Note that at the ONU and OLT only the power consumption of the transceivers (both optical and digital components) is included. For the remote node (in AON), there is an Ethernet switch included.

6. Conclusions

We need to keep innovating broadband access to satisfy increasing user demands. In this paper we focused on optical access technologies, and in order to know which technology we should move forward with, we need to be able to compare them by evaluating a number of metrics, including energy efficiency (given the current economic and ecological context). Compared to previous studies, this paper especially investigated how the introduction of sleep modes and varying traffic demands affect the conclusions on energy efficiency. We analyzed the power consumption of different technologies like GPON, XG-PON, XLG-PON with and without bit-interleaving, WDM-PON with tunable lasers and with RSOA, TWDM-PON, Ethernet PtP and AON. This evaluation was done for a low and a high traffic demand scenario, respectively. The results indicate that technologies with a more bursty transmission like TWDM-PON and XLG-PON benefit more from sleep modes. When sleep modes are taken into account, the OLT's power consumption becomes a dominant factor in determining the overall power consumption of the technologies, and the logical PtMP technologies become a clear winner over the logical PtP technologies, thanks to the sharing of the OLT's transceivers and other digital processing components. It is also shown that the advantages of an energy-efficiency technique like bit-interleaving are partly cancelled out when using sleep modes as the reduced power consumption of bit-interleaving in active state is (partly) lost by the reduced sleep periods.

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