

Power Consumption Evaluation for Next-Generation Passive Optical Networks

Serving up to 1Gb/s user demands in a massive deployment

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Abstract—In this paper, we assess the energy efficiency of various optical access solutions including both the telecom operator and the end user side. We compare different next-generation passive optical networks (NG-PONs) to a baseline GPON deployment offering similar bandwidths and Quality of Service (QoS) for best-effort high speed connectivity services. For the operator side, we follow two approaches: first, we consider a fixed split ratio (1:64) in an existing optical distribution network (ODN); next, we consider an upgraded ODN with an optimized split ratio for specific bandwidth and QoS values. For medium bandwidth demands, our results show that legacy PONs can be upgraded to XG-PON without any ODN modification. For future applications that may require access rates up to 1 Gb/s, NG-PON2 technologies with higher split ratios and increased reach become more interesting systems, offering the potential for both increased energy efficiency and node consolidation. For the user side, we consider power consumption of the optical network unit (ONU), installed at the customer premises, incorporating several energy saving mechanisms. Combining our results for the central office and ONU side, we see that XLG-PON (using a bit-interleaving protocol) and TWDM-PON (using a standard protocol) consume the lowest power per user among the different NG-PON2 technology candidates.

Keywords— energy consumption; quality of service; next-generation passive optical networks

I. INTRODUCTION

Fiber-based gigabit passive optical networks (GPONs) are currently being deployed by operators in several countries, offering much higher bandwidths than traditional copper-based access networks. Deployments of 10 Gb/s capable PONs (XG-PON, also denoted as NG-PON1) are expected in the next couple of years. In the long term, increasing bandwidth demands associated with mobile backhaul, content-rich services and the convergence of residential and business access will necessitate the deployment of even faster next-generation PONs beyond 10 Gb/s, referred to as NG-PON2s [1].

At the same time, there is a growing interest in reducing the energy consumption and the associated cost of the access network. Due to rising energy prices and the growing awareness of climate change, energy efficiency becomes an

important factor when analyzing the operational expenditures and carbon footprint of different NG-PON2 technologies [1]. In this paper, we assess the energy efficiency of GPON, XG-PON and four NG-PON2 candidates. First of all, we assess how the energy efficiency at the central office (CO) is affected by the chosen network deployment and by the user demand. We consider a deployment scenario in a major European city to get a more realistic estimation than a purely component-based analysis, taking into account the implications of technology-dependent physical reach over a target area with a limited number of COs. This assessment builds further on the work presented in [2] and [3]. Secondly, we also consider the customer premises equipment (CPE) which is independent of the deployment scenario. For some NG-PON2 technologies, we need to consider intelligent power saving mechanisms to reach an acceptable power level [4]. Our results for the CO and CPE combined give a global view on the power consumption of the most important NG-PON2 technologies for different deployment scenarios and user demands.

II. ACCESS NETWORK AND POWER CONSUMPTION MODEL

This section introduces the general power consumption model of an optical access network, gives an overview of the evaluated technologies and describes the considered user demand and quality of service (QoS) parameters.

A. Power consumption model

Fig. 1 gives a schematic overview of our power consumption model for an optical access network.

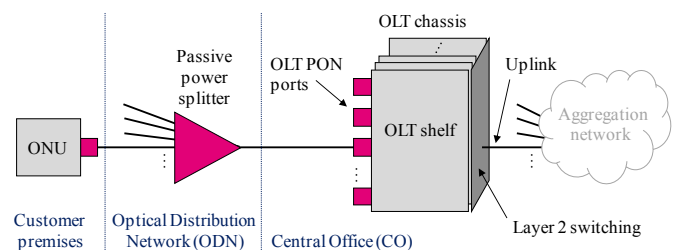


Fig. 1. Schematic overview of the access network and its power consumption components.

The access network power consumption consists of:

- Customer side, i.e. optical network unit (ONU)
- Telecom operator side, the sum of three contributions:
 - Optical line terminal (OLT) PON ports: $\#OLT \text{ ports} \times \text{power consumption per port}$;
 - Layer 2 switching, packet processing, and traffic management: $\#OLT \text{ chassis} \times \text{PONs/chassis} \times \text{bandwidth (DS+US)} \times 1 \text{ W/Gb/s}$;
 - Uplink ports: $\#OLT \text{ chassis} \times \text{uplink energy consumption}$.

Note that we consider passive optical networks, which means that no active equipment is needed in the ODN. Further, the equipment count (number of OLT ports & OLT chassis) and required uplink capacity are calculated based on the user demand and expected QoS level.

B. Technologies

A number of relevant candidates for NG-PON2 systems have been recognized by the FSAN (Full Services Access Network) group [1]. In this paper, we focus on the following options:

- 40G (XLG) PON: a time division multiplexing (TDM)-PON offering a capacity of 40 Gb/s downstream and 10 Gb/s upstream. Straightforward scaling of the standard protocol to 40G would result in a large power consumption at the ONU, because functions like frame-synchronisation, de-scrambling and forward error correction are performed at the full line rate. We however assume a new bit-interleaving PON protocol for XLG-PON to minimize the electronic processing [5]. We furthermore assume downstream transmission adjacent to the GPON upstream in the O-band to avoid the need for dispersion compensation and compensate for the higher loss by optical amplification at the OLT.
- Time-shared wavelength division multiplexing (TWDM) PON: four virtual TDM-PONs on different wavelengths – but on a single physical optical distribution network – each deliver 10 Gb/s downstream and 2.5 Gb/s upstream. The tuning principle of the laser is assumed to be coolerless thermal tuning as in [6], hence avoiding the power consumption of a thermoelectric cooler at the ONU.
- Orthogonal frequency division multiplexing (OFDM) PON: multiple orthogonal carriers are multiplexed. The ONU can filter and down-convert a band of 32 subcarriers in the analogue domain, so that subsequent digital signal processing (DSP) and media access control (MAC) functions can be performed at a lower rate and hence power consumption is reduced.
- Coherent ultra-dense WDM (Co-UDWDM) PON: by using coherent detection, a UDWDM-PON can be created using up to 1000 wavelengths, each serving one individual customer.

We will compare the energy efficiency of these solutions with that of two previous PON generations: Gigabit/Ethernet PON (GPON/EPON) with B+ optics and 10G PON (XG-PON E2 class).

TABLE I. OVERVIEW OF CONSIDERED PON TECHNOLOGIES WITH THEIR SYSTEM-SPECIFIC PARAMETERS AND POWER CONSUMPTION.

Technology	Bandwidth / PON DS/US (Gb/s)	PONs / chassis	power / OLT port (W)	power / ONU (W)
G/E PON (B+)	2.5/1.25	128	2	1.8
XG-PON (E2)	10/2.5	64	5	3.1
XLG-PON	40/10	32	17	3.2
TWDM-PON	4x10/4x2.5	32	20	3.4
OFDM-PON	40/10	32	9.5 + $0.5xN_{users}^*$	8.6
Co-UDWDM-PON	1.25/1.25 x N_{users}^*	32	6 + $1.2xN_{users}^*$	4.7

* N_{users} is the maximum number of connected users per OLT PON port (scales with the split ratio and take rate)

The technology-dependent input parameters for the power consumption calculations are given in Table 1. The power consumption per OLT PON port increases as the PON bandwidth increases. For OFDM-PON and Co-UDWDM-PON, the power consumption also depends on the number of users that can be served by the OLT port. To serve more users, more DSP and (in some cases) additional transmitters and receivers are required.

Note that the values for power consumption in Table 1 only include system-specific electro-optical components. To obtain the total power consumption at the CO, we add L2 switching, packet processing, traffic management and uplink energy consumption to the OLT port values from Table 1 (see section II.A).

The total ONU energy consumption is the sum of the system-specific contribution, given in Table 1, and a baseline contribution. The baseline power dissipation of the ONU is estimated to 3.65 W, and consists of contributions from the embedded processor 2.5 W, GbE PHY 0.5 W, dual subscriber line interface circuit (SLIC) 0.25 W, memory 0.12 W, and other miscellaneous components 0.38 W [7]. All digital electronics are assumed to be produced in a 40 nm CMOS technology. The system-specific contribution for the ONU scales with the PON capacity, since faster transceivers consume more power, but the baseline power consumption will reduce the relative importance of these differences.

We also take into account two overhead factors: a factor of 1.25 to include DC/DC conversion losses and a site factor of 1.70 to account for the energy consumption of auxiliary equipment (including cooling, power units, ...). The DC/DC conversion factor is applied to both CO equipment and CPE, whereas the site factor is only applied to CO equipment.

C. User demand and QoS parameters

For the user demand, we consider a best-effort internet access service dominating the traffic in the PONs, described with a simple model consisting of two parameters:

- B_{target} : maximum bandwidth offered to each customer
- p_{act} : probability that a user is active; when active, the user requests a fixed bandwidth B_{target} .

In our analysis we focus on two values of B_{target} (600 Mb/s and 1 Gb/s) and one value for p_{act} (0.5).

QoS is quantified by two parameters:

- $p_{avail,min}$ (%): minimum percentage of time that B_{target} should be available for each connected user.
- PL_{max} (Maximum Packet Loss): maximum ratio of packets discarded over packets offered in the uplink interface of an OLT chassis (from the OLT to the aggregation network).

In our analysis we focus on a best-effort internet service, with moderate QoS requirements: PL_{max} is fixed at 10^{-3} , and $p_{avail,min} = 20\%$.

III. POWER CONSUMPTION RESULTS

Two different approaches for deploying an optical access network are considered: first, the power consumption results of a fixed ODN with a split ratio of 1:64 are shown; next, an ODN with a flexible split ratio is considered to increase the QoS and energy-efficiency of the considered technologies. In all our simulations we assume 50% of the real estate units passed by fiber are connected to the optical network (e.g. a split ratio 1:64 means there are 32 users connected to each OLT PON port).

A. Fixed split ratio of 1:64

In our first analysis, we consider a fixed split ratio of 1:64, allowing operators to re-use the legacy ODN of (X)G-PON solutions without modifications. Fig. 2 shows the total power consumption per user of the various PON solutions for a medium and high offered bandwidth ($B_{target} = 600$ Mb/s and 1 Gb/s respectively). When offering a bandwidth of 600 Mb/s, the availability for G/E PON technologies no longer meets the minimum availability requirement of 20%: due to the limited capacity per PON, users would get the requested target bandwidth less than 20% of the time. A switchover to XG-PON could improve the QoS greatly at a relatively low energy cost compared to the other next-generation technologies. If B_{target} grows even further, up to 1 Gb/s, NG-PON2 technologies will be needed to offer the requested bandwidth at least 20% of the time. The expense of providing these high speed services in a legacy ODN using NG-PON2 technologies is a high increase in the energy demand (as shown in Fig. 2).

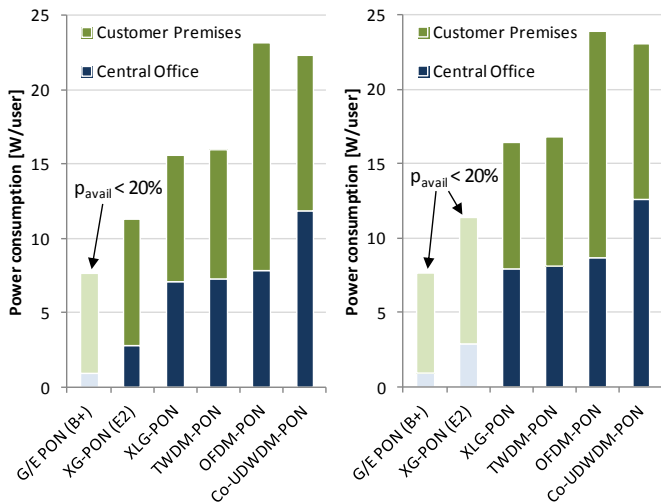


Fig. 2. Power consumption at the CPE and CO of the considered PON solutions for a user activity of 0.5 and a target bandwidth of 600 Mb/s (left) and 1 Gb/s (right) using an ODN with a fixed split ratio of 1:64.

B. Flexible split ratios

In our second analysis, we consider some flexibility in the ODN: splitters can be modified to adapt the split ratio, and COs can be consolidated by eliminating active nodes. For each technology, we select the highest split ratio at which the availability p_{avail} is still above 20%. By increasing the split ratio, we can fully take advantage of the higher capacities of NG-PON2 solutions. This could make them a more attractive option in case of high user demands. Fig. 3 shows the power consumption of a flexible split ratio scenario, for $B_{target} = 600$ Mb/s and 1 Gb/s. We see that the power consumption per user for NG-PON2 solutions can be decreased significantly by deploying higher split ratios. This would allow for CO consolidation and thus easier network management, while offering similar QoS at a comparable energy cost. The split ratios for G/E PON and – in case of $B_{target} 1$ Gb/s – XG-PON need to be lowered in order to obtain the desired availability, thus making them a less attractive option for practical deployments.

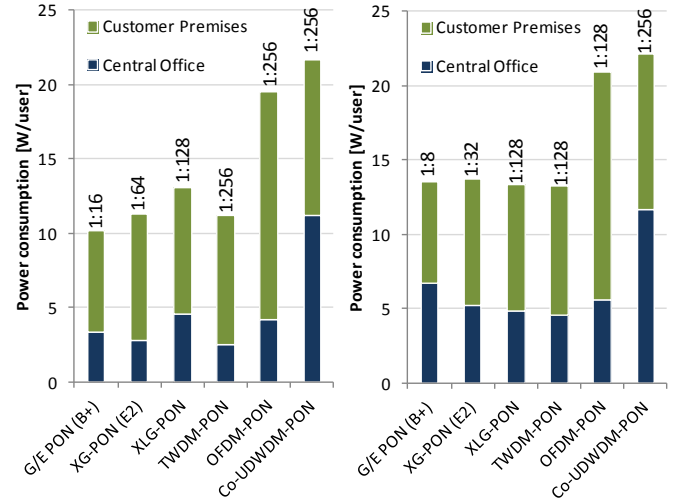


Fig. 3. Power consumption at the CPE and CO of the considered PON solutions for a target bandwidth of 600 Mb/s (left) and 1 Gb/s (right) using an ODN with a flexible split ratio.

From our results at the operator side, it is clear that Co-UDWDM-PON has a higher power consumption per user at the CO in every scenario; however, it must be noted that this solution offers the advantage of 100% bandwidth availability and lowest traffic latency, which may be useful for specific applications such as business services or mobile backhauling. The power consumption values for the other technologies are close to each other.

Significant differences can be observed for the power consumption of the ONU at the customer side of the network. The power consumption typically increases proportional with the line rate. However, the ONU of an 40G XLG-PON consumes about the same power as XG-PON, despite a four times higher line rate, thanks to the by using an energy efficient bit-interleaving protocol in the downstream direction (see section II.B). The TWDM-PON ONU consumes slightly more power than XG-PON because it is based on the same standard MAC protocol, but consumes a slightly higher power for the tuning of the laser and receive filter. The ONU in a coherent

WDM-PON consumes more power due to the coherent receiver requiring two balanced receiver pairs and the optical field modulator for upstream transmission. OFDM-PON is highly inefficient due to the need for DSP and optical amplification to meet the stringent signal to noise ratio across a standard ODN. We assumed the possibility to select a subset of carriers and as such reduce the power consumption of the DSP and MAC processing, but the ONU power consumption remains high. Additional savings can be obtained by applying sleep mode to each of these technologies, this is however not included in the current figures.

IV. CONCLUSIONS

We have studied the energy efficiency of various PON technologies for best-effort high-speed connectivity services up to 1 Gb/s, by considering a deployment scenario in a major city. To a certain extent, increasing demands up to 600 Mb/s can be met without changes to presently deployed networks with a split ratio of 1:64, by using XG-PON, consuming less power than NG-PON2 technologies. For future user demands up to 1 Gb/s, it's more interesting to move to NG-PON2 technologies with higher split ratios and increased reach, which offer the potential for CO consolidation (simplifying network management) in addition to enhanced energy efficiency. Among the different NG-PON2 technology candidates, XLG-PON (using a bit-interleaving protocol) and TWDM-PON (using a standard protocol) consume the lowest power per user in the central office and at the ONU side.

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