The Dominant Role of CPE Energy Consumption in the Transition from DSL to PON Fixed Access Networks

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***Abstract*—The ICT sector accounts for approximately 4% of the global carbon footprint and 7% of the global electricity consumption. Within this sector, communication networks, and particularly internet access networks, account for about one-third of the carbon footprint. Fixed internet access networks are often overlooked compared to mobile access networks due to their superior energy efficiency. However, their consumption is equivalent to that of mobile networks because they offer a higher traffic capacity and include always-on customer premises equipment (CPEs) that are shared with a very limited number of users. Recently, Internet Service Providers (ISPs) have been switching from copper-based access networks (DSL) to fiber-based access networks (PONs), which allow for higher data rates and offer significant energy savings at the access node level. However, PON CPEs consume a significant amount of energy, especially when the ONU is separate from the Wi-Fi router (WR). This could counterbalance the energy savings expected from the transition from DSL to PON. In this study, we propose an energy consumption model using equipment data sheets for DSL, Gigabit PON (GPON), and 10 Gigabit Symmetrical PON (XGS-PON) access nodes. We then compare the consumption results to those of widely distributed CPEs, as a function of the user activity. Finally, we exploit the model to evaluate the consumption of a metropolitan fixed internet access network. Our results show that CPE consumption accounts for over 96% of PON consumption, and for over 78% of the consumption in DSL networks. XGS-PON networks consume significantly more energy than GPON and DSL networks, which have comparable consumption levels when CPEs are included.**

***Index Terms*—GPON, XGS-PON, VDSL2, access network, power consumption, CPE**

I. Introduction

The Information and Communication Technology (ICT) sector contributes approximately 4% to the Global GreenHouse Gas (GHG) emissions [1] and about 7% to global electricity consumption [2]. Within this, communication networks, particularly internet access networks, account for approximately one-third of the GHG emissions, dominated by the use-stage of the network equipment, i.e., by its consumption of electrical energy [3]. Although mobile access uses more energy per bit, fixed access has a comparable consumption level, mostly due to always-on Customer-Premises Equipment (CPE) and high data rates.

Copper-based Digital Subscriber Line (DSL) and fiber-based Passive Optical Networks (PONs) are among the most widespread fixed-access technologies. Although DSL was the prevailing technology for some time, Internet Service Providers (ISPs) have been switching to PON over the last years, since it enables higher data rates with more power-efficient access nodes. Yet, the literature rarely compares the overall consumption of PON versus DSL when considering CPEs. This study aims to address this gap by covering CPEs, from the modem to the wireless access point, with a focus on recent equipment.

In DSL, the CPE has been identified as a consumption hotspot [4]. On the network side, line drivers and digital signal processing account for about 70% of the DSL Access Multiplexer (DSLAM) power consumption [5].

Several studies have quantified the electricity use and GHG emissions of PON [6], [7], and compared them with those of DSL [8], often showing that PON is more energy efficient [9], [10]. Similar to DSL CPEs, Optical Network Units (ONUs) are consumption hotspots that would benefit from more sleep time [11]. Nonetheless, it was shown that with the right optimizations, DSL could achieve a level of efficiency close to that of PON at low data rates [12]. Let us mention here that most of the previously mentioned studies are based on outdated equipment or omit the wireless access point consumption in PON, which limits their scope to the ONU.

In this work, we present a bottom-up model of fixed internet access networks, spanning from access nodes to CPEs, to evaluate the energy consumption in a given geographic region. To illustrate the analysis it enables, we apply our model to the case study of the Brussels Capital Region. Our access node model is based on a power consumption analysis of VDSL2 DSLAMs and Gigabit PON (GPON) and 10 Gigabit Symmetrical PON (XGS-PON) Optical Line Terminals (OLTs). This analysis is derived from equipment datasheets and covers the period from 2001 to 2025. Unlike previous studies, which often disregard or simplify CPEs, our model considers the devices responsible for modem operation, network routing,

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and wireless connectivity at the customer premises in DSL and PON. In PON, we also consider both configurations where the ONU is integrated into the Wi-Fi Router (WR) and where it is a separate device. To this end, we model actual CPE interfaces according to the EU Code of Conduct on Energy Consumption of Broadband Equipment (CoC) [13], [14]. Additionally, we consider both residential and business subscribers with realistic activity patterns, as in [15]. When applied to a metropolitan access network on a given territory like Brussels, this approach allows for a more accurate comparison of DSL and PON. It clarifies the impact of CPEs on the overall consumption of the access network and demonstrates that CPE consumption can offset the power savings achieved by PON access nodes. This conclusion shows that integrating the ONU and the WR in a single CPE is more efficient, and demonstrates the importance of implementing energy-saving mechanisms, such as sleep modes, in PON at the CPE level, where idle power consumption is significant.

The paper is structured as follows: in Section II, we propose a power consumption model, first at the component level and then at the network scale. Section III presents an analysis of the Quality of Service (QoS) experienced by the users in PON networks, followed by the impact of user behavior on the consumption, the CPE impact, and a comparison with previous studies. Section IV concludes and opens the path to future research.

II. Proposed model

First, we establish two scenarios to enable fair comparison between VDSL2, GPON, and XGS-PON access networks. In a PON, the network includes the OLTs in central offices, passive splitters in street cabinets, and the ONUs and Wifi Routers (WRs) in subscribers' homes. The WR handles routing between the Wide Area Network (WAN) and the Local Area Network (LAN), and provides wireless connectivity. In DSL networks, the access node is a DSLAM, located in a central office or street cabinet. The CPE performs modem operation, handles local network routing, and serves as a wireless access point. This structure is shown in Fig. 1. User equipment, such as smartphones, tablets, laptops, desktop computers, TVs, etc., is not included in the scope of this study. We also exclude the core network consumption from the study because our focus is on the regional access network.

A. Equipment power consumption

The total power consumption of the access network comes from both the power consumption of the access nodes and the power consumption of the CPEs.

1) Access nodes: We analyzed 105 equipment datasheets for VDSL2 DSLAMs, GPON OLTs, and XGS-PON OLTs to extract their maximum power consumption, typical power consumption values and port count. Since typical values are often not provided, we systematically use the maximum power consumption values and apply a correction factor α_{PON} or α_{DSL} to obtain typical power consumption values from them (see Fig. 2). According to the 17 datasheets that indicate typical power consumption, the difference between maximum and typical consumption is about 20% for OLTs and 40% for DSLAMs. This uncertainty is explicitly shown on the graphs of results in Section III.

Fig. 2 shows that power consumption depends linearly on the number of ports. We therefore approximate the consumption P_{AN} of the access node with a linear equation as follows:

$$P_{AN} = (N_{ppan} \cdot a + b) \cdot \alpha \quad (1)$$

where N_{ppan} is the number of ports per Access Node (AN), a and b are respectively the slope and intercept obtained by performing a linear regression of the maximum power consumption data points, and α is the correction factor between maximum and typical consumption. Applying this methodology to each technology, we obtain the parameters a_{DSL}, b_{DSL}, a_{GPON}, b_{GPON}, a_{XGSPON}, and b_{XGSPON}. The parameter numerical values are given in Table I.

2) CPEs: To model the CPE power consumption, we define P^{s}_{CPE}, the sum of the consumption of each CPE constitutive interface according to the CoC, which are: Central function, WAN, Back-up WAN, LAN Ethernet, Phone, USB, WiFi, and ONU, which is to be included exclusively in the PON case when the CPE consists of two separate devices. Let us notice that we consider two cases. One is that the ONU is a separate device from the WR. An example of this is the CPEs from Proximus ISP, which owns 60-70% of the market share in Brussels [18]. The second case is when the CPE combines the WR and ONU in a single device. This is the configuration used by other ISPs, such as Telenet and Orange, which together represent about 40% of the fixed broadband market in Brussels but have a limited presence in the fiber market [18], [19]. The consumption is defined for the state s, which is either active (denoted *act* in the equations) or idle, and is the same for all the CPE interfaces. The consumption values, provided in Table

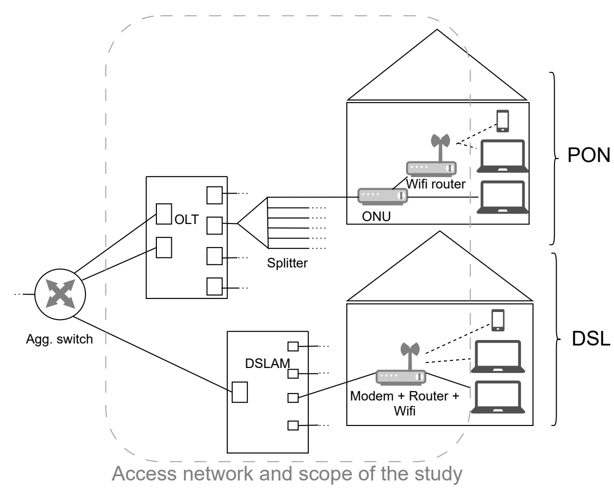

Fig. 1. Schematic of the access network structure in PON and DSL cases. In a PON, several users are linked to a common PON port via a passive splitter, using optical fibers. In a DSL access network, each subscriber is connected to a port via a copper twisted-pair cable.

TABLE I

SUMMARY OF THE PARAMETERS USED IN THE MODEL

Parameter	Description	Value	Unit	Source
β_r	Residential users QoS	Varies	%	/
p_r	Residential activity probability	0.15	/	[15]
p_b	Business activity probability	0.5	/	[15]
$N_{CPE,r}$	Number of residentials CPEs	522000	/	[16]
$N_{CPE,b}$	Number of business CPEs	88000	/	[16]
$N_{ppan,DSL}$	Number VDSL2 ports/DSLAM	768	ports/AN	/[a]
$N_{ppan,GPON}$	Number GPON ports/OLT	256	ports/AN	[7]
$N_{ppan,XGSPON}$	Number XGS-PON ports/OLT	128	ports/AN	[7][b]
M_{GPON}	Maximum GPON splitting ratio	128	/	[10]
M_{XGSPON}	Maximum XGS-PON splitting ratio	256	/	[17]
$R_{GPON,DL}$	GPON DL capacity	2.5	Gbps	[17]
$R_{XGSPON,DL}$	XGS-PON DL capacity	10	Gbps	[17]
γ	Adoption rate of broadband internet	75.5	%	[16]
α_{DSL}	VDSL2 typical/maximum consumption ratio	0.625	/	Section II-A1
α_{PON}	PON typical/maximum consumption ratio	0.805	/	Section II-A1
a_{DSL}	VDSL consumption slope	1.84	W/port	Section II-A1
a_{GPON}	GPON consumption slope	5.5	W/port	Section II-A1
a_{XGSPON}	XGS-PON consumption slope	8.12	W/port	Section II-A1
b_{DSL}	VDSL2 consumption intercept	53.8	W	Section II-A1
b_{GPON}	GPON consumption intercept	26.02	W	Section II-A1
b_{XGSPON}	XGS-PON consumption intercept	149.26	W	Section II-A1

[a] High capacity DSLAMs such as the *Nokia ISAM FD 16* or the *Huawei MA5800C*.
[b] Value initially given for XG-PON1 technology.

II, are extracted from the CoC [13], [14], using the version closest to each device release date. In general, the interface consumption depends on the equipment release year and on the technology.

We then average CPE consumption between active and idle time, using the subscriber probability of activity p:

$$P_{CPE}^{av,p} = \left(\overline{P_{CPE}^{idle}}(1-p) + \overline{P_{CPE}^{act}} \cdot p\right), \tag{2}$$

where $\overline{P_{CPE}^{s}}$ are the average consumption values across the studied CPEs in state s.

Note that even though the *B-Box3V+* and the *Internet Box* could be linked to an XGS-PON ONU (see Table II), they cannot provide speeds higher than 1 Gbps because their WAN interface does not support them. The consumption of an XGS-PON ONU may also be underestimated since CoC V8.0 does not account for ONUs with multi-gigabit Ethernet ports [14].

TABLE II

CPE INTERFACES POWER CONSUMPTION EXTRACTED FROM THE *Code of Conduct on Energy Consumption of Broadband Equipment* [13], [14].

		$P_{CPE}^{s}(W)$		
	s	DSL	GPON	XGS-PON
B-Box3 Proximus[a]	active	11.9	/	/
	idle	6.5	/	/
B-Box3V+ Proximus[a]	active	14.1	17.7	19.7
	idle	8	10.1	11.5
Internet Box Proximus[b]	active	13.2	14.5	17.3
	idle	9.6	10.9	12.5
Internet Box+ Proximus[b]	active	/	/	26.7
	idle	/	/	17.8
Fiberbox 360 Telenet[b] (Combined ONU-WR)	active	/	/	16.1
	idle	/	/	10.3
Livebox Fiber Orange[b] (Combined ONU-WR)	active	/	13.6	/
	idle	/	9.5	/
		$\overline{P_{CPE}^{s}}(W)$		
	s	DSL	GPON	XGS-PON
Average	active	13.07	15.27	19.95
	idle	8.03	10.16	13.03

[a] CoC V5.0 [13], [b] CoC V8.0 [14]

B. Access network power consumption

We now extend the model for individual equipment developed in Section II-A to cover the entire region. We distinguish two types of subscribers with different requirements: business and residential users [15]. To design the network, we model their activity during peak hours, i.e., from 9 a.m. to 11 a.m. for business subscribers and from 7 p.m. to 11 p.m. for residential subscribers [20]. We then assume that network consumption is constant and independent of the number of active subscribers. Business subscribers must always receive their subscribed downlink (DL) data rate ($b_{target,b}$) and are active with a prob-

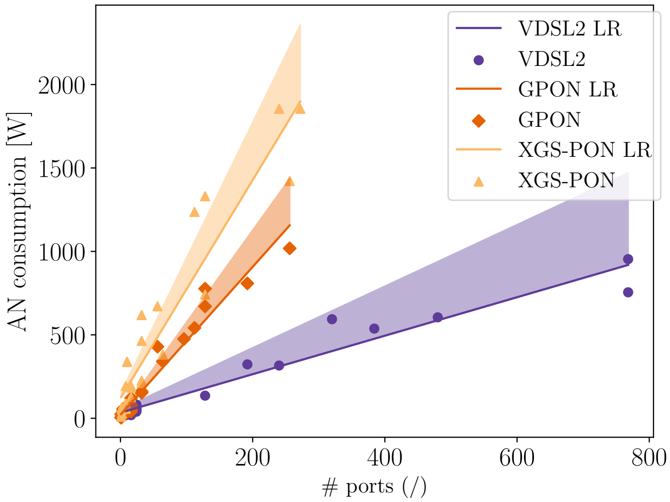

Fig. 2. Typical power consumption values as a function of the number of ports in an access node from vendor datasheets. The linear regression (LR) serves as a basis for the power consumption model. The left axis indicates the consumption of the VDSL2 DSLAMs. The left axis indicates the consumption of GPON and XGS-PON OLTs. The shaded areas represent the uncertainty between typical (plain lines) and maximum consumption values.

ability $p_b = 0.5$ during peak hours. Residential subscribers must receive their downlink target rate ($b_{target,r}$) at least $\beta_r\%$ of the time (e.g., 40, 60, or 80%) during peak hours. They are active with a probability $p_r = 0.15$ [15]. The total number of users in Brussels is denoted as $N_{CPE} = N_{CPE,r} + N_{CPE,b}$, where $N_{CPE,r}$ and $N_{CPE,b}$ are the respective numbers of residential and business subscribers, as given by the Belgian Institute for Postal Services and Telecommunications (BIPT) [16]. When dimensioning the network, we define γ as the proportion of households with a broadband connection in the region [7], to account for households that may join the network and subscribe to a broadband connection in the near future. For simplicity, we assume that it exists for both residential and business users. We also define N_{ports}, the total number of ports needed to cover Brussels. In the DSL case, $N_{ports} = N_{DSL}$ is simply equal to the number of users. In the PON case, $N_{ports} = N_{PON}$, whose computation depends on the number of users per PON port, and is detailed in Section II-C. Based on this, the number of access nodes on the network is

$$N_{AN} = \lceil \frac{N_{ports}}{N_{ppan} \cdot \gamma} \rceil, \tag{3}$$

which is rounded to the upper integer. The generalized access network power consumption for PON and DSL is written as

$$P_{tot} = P_{AN} \cdot N_{AN} + \underbrace{P_{CPE}^{av,p_r} \cdot N_{CPE,r} + P_{CPE}^{av,p_b} \cdot N_{CPE,b}}_{P_{CPE}^{tot}}, \tag{4}$$

where P_{CPE}^{av,p_r} and P_{CPE}^{av,p_b} are the average power consumptions of the CPEs according to (2), for the residential and business subscribers, respectively. Note that these quantities depend on the residential and business subscriber probability of activity. This implies that the average CPE consumption is influenced by subscriber type and behavior, which may vary geographically. The parameter values are given for each technology in Table I.

C. Capacity planning for dual subscriber types in PON

We now want to compute the number N_{PON} of PON ports needed on the network, to satisfy the user QoS constraints while minimizing the network power consumption. Our approach is based on [7], but we include a dual-consumer type as in [15], and we consider that the users are spread homogeneously across the region. Additionally, we assume that the number of users per PON port is not restricted to powers of two and that some splitter outputs can be empty.

Since the power consumption is linear in the number of ports, up to rounding to the next integer (see (4)), minimizing it reduces to minimizing the number of ports. Thus, the objective is to minimize N_{PON} by selecting the optimal number of residential and business subscribers per port (N_r and N_b). This minimization is subject to three constraints:

The first constraint limits the number of subscribers per port to the splitting ratio M_{PON} of the technology (see Table I). This is written as

$$N_r + N_b \leq M_{PON}. \tag{5}$$

The second constraint is the business data rate. Since the bandwidth is first allocated to the business subscribers, the constraint is

$$N_b \leq \lfloor \frac{R_{PON,DL}}{b_{target,b}} \rfloor, \tag{6}$$

with $R_{PON,DL}$ being the downlink data rate associated with either GPON or XGS-PON.

The third constraint is the residential QoS, which we define as the probability that a residential subscriber receives its target data rate $b_{target,r}$ at least $\beta_r\%$ of the time (at peak hours). We know that the residential subscribers receive their target data rate if the number of active residential subscribers does not exceed

$$k_{max,r} = \lfloor \frac{R_{PON,DL} - k_b \cdot b_{target,b}}{b_{target,r}} \rfloor, \tag{7}$$

where k_b is the number of active business subscribers in the PON. The probability of having exactly k_b active subscribers among N_b, which is based on the subscriber probability of activity p_b [7], is

$$p(k_b; N_b) = \frac{N_b!}{(N_b - k_b)!k_b!}(1 - p_b)^{N_b - k_b} p_b^{k_b}. \tag{8}$$

Therefore, the constraint on the probability of residential subscribers receiving their target data rate is

$$\sum_{k_b=0}^{N_b} \sum_{k_r=0}^{k_{max,r}} p(k_r; N_r) \cdot p(k_b; N_b) \geq \beta_r, \tag{9}$$

where $p(k_r; N_r)$ is defined similarly to $p(k_b; N_b)$, but for residential subscribers.

For each pair (N_r,N_b) meeting the constraints, we start by filling the ports with N_r residential subscribers and N_b business subscribers. If there are still subscribers that are not linked to a port after this step, we fill the remaining ports exclusively with one subscriber type until all subscribers are served. The pair (N_r,N_b) minimizing the total number of active ports is retained. As an example, solving the problem for $b_{target,r} = b_{target,b} = 50$ Mbps and $\beta_r = 60\%$, the PON ports are filled with an average of 125 subscribers (business and residential subscribers combined), before accounting for the take rate γ. This number becomes 20 subscribers at $b_{target,b} = 500$ Mbps. We note that the subscriber probability of activity p_r and p_b, together with the residential QoS β_r, are network design parameters. Once they are fixed, the network power consumption is considered constant.

III. Results and Discussion

Thanks to the proposed model, we can now examine the power consumption of the Brussels internet access network. Let us mention that all the results in Watts (W) have been converted to Wh/year.

A. Power consumption of the access nodes

1) PON case: analysis with only residential users: To gain insight into the efficiency of GPON and XGS-PON, we examine the subscriber QoS of residential users in a single PON port. Analytically, the QoS is defined using (9) when $N_b = 0$, which gives

$$QoS = \sum_{k_r=0}^{k_{max,r}} p(k_r; N_r), \tag{10}$$

where $k_{max,r} = \lfloor \frac{R_{PON,DL}}{b_{target,r}} \rfloor$. This is illustrated in Fig. 3, where the QoS is represented at $b_{target,r} = 200$ Mbps and $b_{target,r} = 500$ Mbps as a function of the number of users per port N_r and per watt of consumption, meaning the X-axis is normalized as

$$N_r/(a_{PON} + \frac{b_{PON}}{N_{ppan,PON}}). \tag{11}$$

We consider that users are active with a probability $p_r = 0.15$ First, the higher splitting ratio allows more users per XGS-PON port than per GPON port with a higher QoS. Notably, at 200 Mbps, increasing the XGS-PON splitting ratio further would be beneficial since, with 256 users per port, the QoS is still close to one, meaning more users could be served well. Additionally, XGS-PON appears to be more efficient than GPON per watt of consumption at the access node level.

2) Impact of subscriber activity on the network design and consumption: We now include business subscribers and vary the target data rates $b_{target,b}$ and $b_{target,r}$ for both PON technologies from 50 Mbps to 2 Gbps. We use the first term of (4) to compute the power consumption of the access nodes for the entire region (see Fig. 4). Residential subscribers require a QoS that ranges from $\beta_r = 40\%$ to $\beta_r = 80\%$. The lines represent the typical consumption values, and the shaded areas show the difference between typical and maximum consumption values. As expected from the previous section, the marginal cost due to an increasing data rate is lower for the XGS-PON network than for the GPON network, which highlights the efficiency of XGS-PON access nodes. As the data rate increases, the influence of β_r on the consumption increases. At 1 Gbps, the GPON consumption is multiplied by 185% between $\beta_r = 40\%$ and $\beta_r = 80\%$. The Brussels GPON network consumes typically 1.4 GWh and a maximum of 1.77 GWh yearly at 500 Mbps and $\beta_r = 60\%$, whereas the XGS-PON network consumes typically 0.56 GWh and a maximum of 0.72 GWh under the same conditions. The plateau effect that appears in the graphs is due to the fact that the number of subscribers per port varies as an integer.

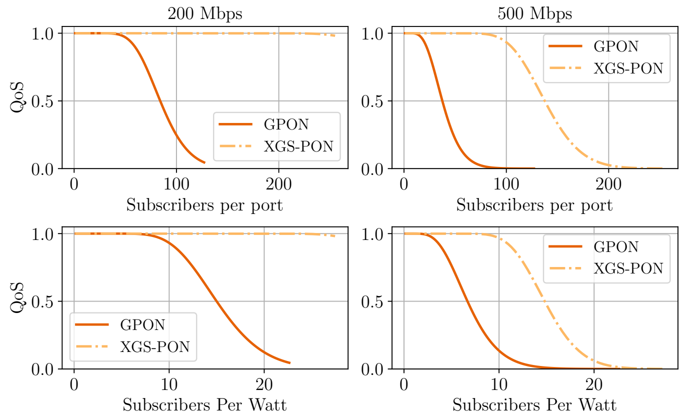

Fig. 3. Comparison of the subscriber QoS when only one type of subscriber is present on the network, for GPON and XGS-PON networks. The QoS is evaluated as a function of the number of subscribers per port and the number of subscribers per Watt.

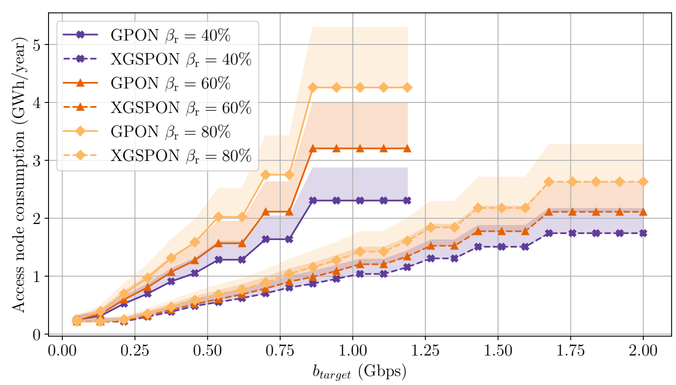

Fig. 4. The annual energy consumption of the Brussels fixed-access network, excluding the CPEs, in function of the subscribed data rate, for several QoS requirements for the residential subscribers for GPON and XGS-PON networks. We consider $p_r = 0.15$, $p_b = 0.5$. The subscribed data rate appears on the X-axis and is identical for both residential and business subscribers. The shaded areas show the difference between typical and maximum consumption values.

B. Power consumption of the different access network types

Fig. 5 shows the annual consumption of the Brussels internet access network at 50 Mbps and 500 Mbps for PON and DSL, comparing cases where the CPE is a combined WR-ONU device, indicated by $C.$ on the x-axis label, and the cases where the CPE consists of two separate devices, indicated by $S.$. The consumption is computed using CPE consumption values from Table II. To highlight the impact of CPE idle consumption, we separate Brussels CPE consumption P_{CPE}^{tot} into two components: idle consumption $P_{CPE}^{idle,tot}$ and transmission overhead consumption when the CPEs are transmitting $P_{CPE}^{data,tot}$. The average transmission overhead consumption per CPE $\overline{P_{CPE}^{data}}$ is defined as

$$\overline{P_{CPE}^{data}} = \overline{P_{CPE}^{act}} - \overline{P_{CPE}^{idle}}. \tag{12}$$

Extended to the whole region, the total overhead consumption when transmitting is

$$P_{CPE}^{data,tot} = \overline{P_{CPE}^{data}} \cdot (p_r \cdot N_r + p_b \cdot N_b). \tag{13}$$

Therefore, the total CPE idle consumption for all users is written as

$$P_{CPE}^{idle,tot} = \overline{P_{CPE}^{idle}} \cdot N_{CPE}. \tag{14}$$

In this simulation, it is assumed that the number and density of DSLAMs are sufficient to ensure that no subscriber receives a downlink data rate lower than 50 Mbps. It is also assumed that PON users are served with a target data rate of 50 or 500 Mbps and a residential QoS $\beta_r = 60\%$ during peak hours. The results presented in Fig. 5 highlight the significant impact of CPEs on all technologies. From an access node perspective, the DSL access node is 27 to 55 times and 31 to 65 times more power-hungry than GPON and XGS-PON access nodes, respectively, at 50 Mbps. In the presented scenarios, the GPON configuration is more efficient than the XGS-PON configuration. However, CPE consumption accounts for over 96% of the power consumption for all PON configurations and between 78% and 85% of the consumption in the DSL case. This means that the CPE configuration in the PON case negates the benefit of PON efficiency entirely, highlighting the necessity of promoting the use of more efficient CPEs. For the studied CPE models, combined ONU-WR devices enable energy savings of 9.8% and 25% for GPON and XGS-PON CPEs, respectively, compared to separate ONUs and WRs. From the graph, we notice that CPE idle consumption represents about 90% of total CPE power consumption for all configurations. This aligns with observations in [21], where 98% of total CPE consumption was idle consumption, indicating that CPE consumption depends minimally on the user activity.

C. Impact of CPE idle power consumption on the access network consumption

Fig. 6 is based on (4) and (2), where we vary the CPE idle power, denoted by $\overline{P_{CPE}^{idle}}$, between 0 and 15 W. This is illustrated by the DSL, GPON, and XGS-PON lines. The DSL line is horizontal because no further development of the technology is expected. The figure shows that the idle consumption of a GPON or XGS-PON CPE must be no greater than 9.43 W or 8.28 W, respectively, for a PON network to consume less power than a DSL network at 50 Mbps. The CoC DSL, CoC GPON, and CoC XGS-PON markers represent the values obtained using (4) with the average idle power consumption from Table II. The idle consumption of the Orange Livebox, reported by the company to be 7.6W, is represented by a dotted vertical line [22], the standard consumption of the Telenet 360 fiberbox [23] is also reported as a horizontal line, as well as the average Proximus CPE consumption measured in [21]. Generally, the figure demonstrates that reducing CPE idle power greatly reduces access network consumption. CPEs are indeed in idle mode most of the time, so implementing power-saving features, such as sleep modes, would greatly benefit their consumption, as has been widely studied in the literature. For example, ONU idle consumption could be reduced to 0.6 W by implementing cyclic sleep modes with short durations (tenths of milliseconds) to limit communication latency, as studied in [24]. The study also presents the possibility of deeper sleep modes with sleep consumption of 0.1 W and longer sleep durations. Other sleep modes are proposed in ITU standards, such as doze mode and watchful sleep mode [25]. Regarding Wi-Fi, sleep modes have been widely studied to reduce power consumption on the UE side. However, implementation on the WR side is still limited, despite being discussed in standard working groups [26]. One possibility is the use of the adaptation of the Wi-Fi TWT feature, in which an AP negotiates an appointment with a UE. Although this mode was initially designed to save power at the UE, the AP could also benefit from intermittent transmission to enter sleep mode [26], [27].

D. Comparison with other studies in the field

In Table III, we compare the per-subscriber power consumption of the fixed-access network when the subscribers are paying for 500 Mbps with $\beta_r = 60\%$, to the results obtained in previous studies. For the previous studies that did not consider any wireless connectivity and disregarded the WR consumption, we added P_{WR}^{tot}, which is equal to $P_{CPE,GPON}^{tot}$ minus the ONU contribution, to the CPE consumption. The considered values are indicated in italics. The main hypotheses of each study are also presented to allow for fair comparisons. For the GPON and DSL access nodes, our evaluation of the consumption is slightly lower than in other studies. Indeed, as far as DSL is concerned, the difference ranges from 18% to 54%, while for GPON it ranges from 41% to 88%.

This can be explained by several differences in assumptions. First, AC/DC and DC/DC conversion efficiencies were not included in this study. We also excluded external cooling consumption for equipment, which was considered a factor of 2 for central offices in [12]. Network equipment age in previous studies also explains differences in access node consumption. For example, [8] considers a single datasheet from before 2009, while [6] uses a single OLT datasheet from 2012. Equipment size varies between studies as well. With small access nodes, the port-independent power component (the intercept b in our model) is divided among fewer ports, reducing efficiency. In [6], the OLT connects only 512 users. Similarly, [10] uses small peripheral access nodes. Our study

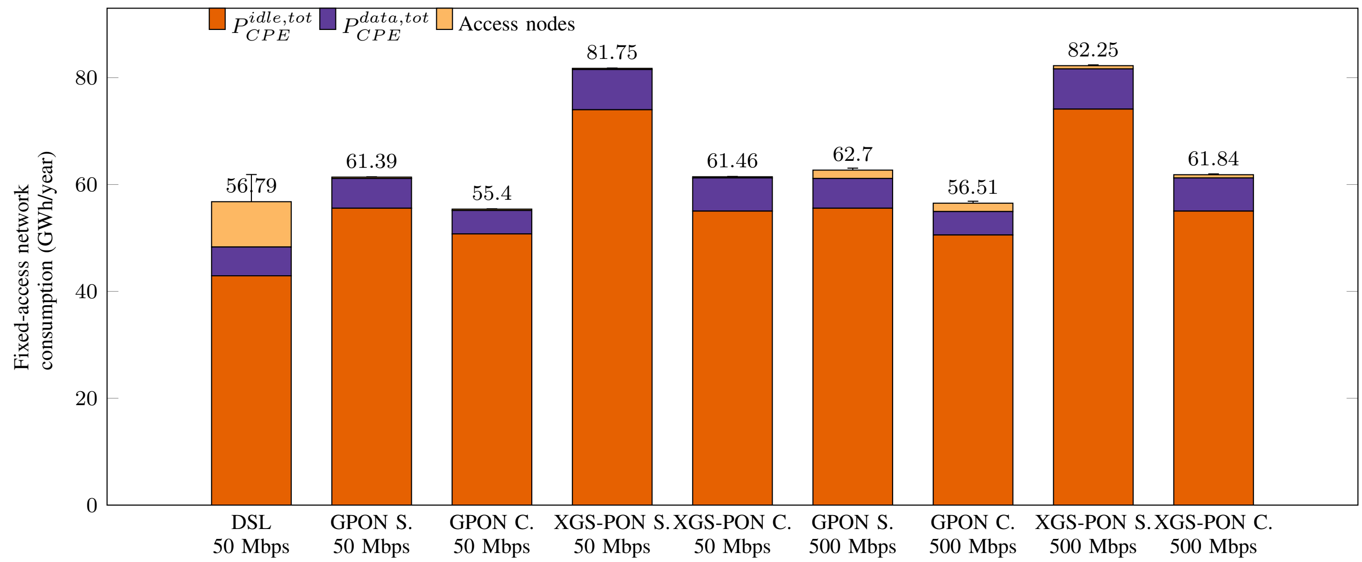

Fig. 5. Total electricity consumption results of Brussels fixed-access network under various deployment scenarios, for 50 and 500 Mbps of downlink data rate, with $\beta_r = 60\%$. The S. and the C. in the x-axis labels indicate if the PON CPEs are two separate devices or a single ONU-WR combined device, respectively. The $P_C^{data,tot}PE$ legend indicates the power overhead compared to the idle power consumed by the CPEs while they are in an active transmission. The error bars show the difference between typical and maximum consumption values.

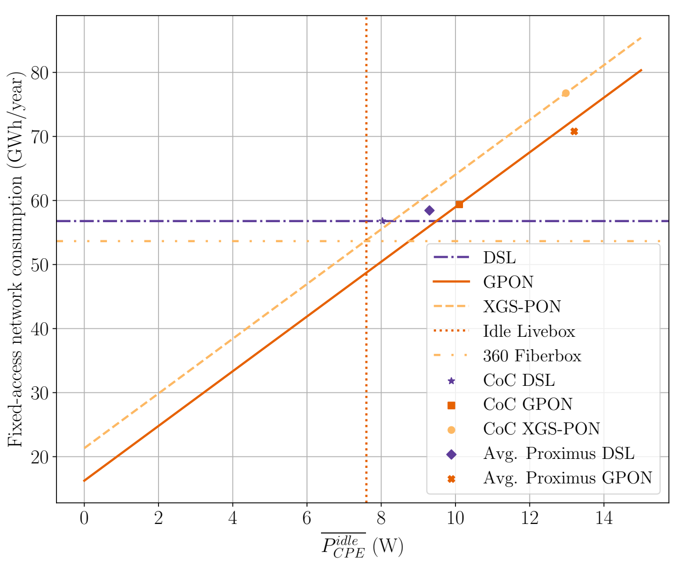

Fig. 6. Impact of the CPE idle power consumption on the access network per subscriber power consumption at 50 Mbps.

assumes *VDSL2* DSLAMs with 768 ports, *GPON* OLTs with 256 ports, and *XGS-PON* OLTs with 128 ports. Some studies include switching between access and core networks at the central office, such as [10]. Since the value was specified as 0.96W per subscriber for DSL networks, it has already been corrected in the table. Moreover, [7] assumed a 50% take rate, compared to $\gamma = 75.5\%$ in this study.

Finally, we note that the total consumption of GPON access networks and VDSL2 access networks are within the same order of magnitude, aligning with our previous observations. The difference between maximum and typical consumption values, however, only significantly impacts DSL, as observed in Fig. 5.

IV. Conclusion

This paper compares the energy consumption of the Brussels access network when using VDSL2, GPON, or XGS-PON technology, taking into account the modem (or ONU in the PON case) and the WR. Since the objective was to assess regional consumption, the core network was excluded from the study. We developed updated models for GPON/XGS-PON OLT and VDSL2 DSLAM power consumption using equipment datasheets. We also accounted for different user profiles, allowing business users to have a higher QoS than residential users. The results show that CPEs are the main source of energy consumption (i.e., the hotspot), accounting for over 96% of PON consumption and for over 78% of the consumption in DSL networks. As such, CPEs could offset the benefits of PON access-node efficiency. Besides, the idle power consumption of CPEs has a significant impact on the overall access network consumption, as CPEs are idle most of the time. Implementing sleep modes for both ONUs and WRs is a promising solution to reduce idle mode power consumption. We found that the VDSL2 network uses a similar amount of energy to the GPON alternative, but less than the XGS-PON alternative at 50 Mbps. At higher data rates, the GPON network consumes less energy than the XGS-PON network. Future research should focus on the development of more energy-efficient CPEs, particularly WRs, as well as the implementation of power-saving features such as sleep modes, to enhance the efficiency of PON access networks.

TABLE III

ENERGY CONSUMPTION IN ACCESS NETWORKS - COMPARATIVE STUDY

Author	**Year**	**Hypothesis**	**Access node (kWh/(year·sub.))**				**Total (kWh/(year·sub.))**			
			GPON	XGS-PON	VDSL2	Mixed	GPON	XGS-PON	VDSL2	Mixed
This study	2025	- PON DR 500 Mbps $\beta_r = 60\%$ - DSL DR 50 Mbps - Bottom-up	2.57	0.98	13.89		99.53	126.45	93.09	
Malmodin [3]	2024	- Ref year: 2020 - Top-Down				40.51				140.93
IBPT [16]	2022	- Probably top-down - No information on ONUs				25.00				125.00
Prysmian [10]	2021	- 32 users/PON - Bottom-up	6.45		21.99		124.71		109.59	
Lambert [7]	2015	- PON DR = 600 Mbps - Optimized # of ONUs/OLT - Only res. users with $\beta_r = 90\%$ - Bottom-up					76.65+*79.91* = 156.56			
Ishii [6]	2015	- Ref years:2000-2030 - 512 users/OLT - Bottom-up	6.84				41.88+*79.91* = 121.78			
Greentouch [28]	2015	- Ref year: 2010	4.38				56.94+*79.91* = 136.85			
Hooghe [12]	2011	- GPON DR = 77 Mbps - VDSL2 DR = 50 Mbps - 32 users/PON	9.02		16.91					
Vereecken [9]	2010	- 32 users/PON - No description of CPEs	7.01		21.90		94.61		109.50	
Baliga [8]	2009	- 32 users/PON - Bottom-up	22.78		23.00		66.58+*79.91* = 146.49		110.60 + *79.91* = 190.51	

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