

A Power Consumption Model for Customer Premise Equipment: Methodology and Application

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Abstract—Given today’s fast increase in data transfer volumes over fixed access networks, it becomes critical to have an accurate evaluation of the power consumption of access networks for environmental sustainability concerns. However, the current literature shows a high sensitivity of fixed-access network environmental impacts to the customer premise equipment (CPE) power consumption and do not offer accurate power data nor hotspot analysis capabilities. This paper presents a hybrid methodology combining measurements of up-to-date CPEs and datasheet analysis to develop a parametric power consumption model separating the contribution of the interfaces, enabling hotspot analysis. Applied to nine CPEs across different WAN technologies (xDSL, DOCSIS, PON, EoTP), the results reveal a significant power consumption variability—up to an order-of-magnitude between CPEs and a factor of 2.2 for the same CPE with different operating modes. The model highlights that idle power contributions represent more than 98% of the average power consumption and demonstrates that the power consumption of a typical configuration of PON CPE is marginally higher than for a DOCSIS CPE. These insights offer a robust basis for enhanced analyses of the environmental impacts of access networks.

Index Terms—Customer Premise Equipment (CPE), power consumption, access networks, DOCSIS, PON, xDSL, Wi-Fi

I. INTRODUCTION

Despite years of attention and growing pressure to reduce its environmental impact, the information and communications technology sector accounted for an estimated 2–4% of global greenhouse gas (GHG) emissions in 2020, with this share continuing to rise [1], [2]. The wide area networks (WANs), also referred to as access networks, contribute to 20–40% of the sector’s greenhouse gas (GHG) emissions [1], primarily through emissions associated with electricity consumption during the usage phase. In addition, these networks experience a rapid data traffic growth, with annual growth rates of 28% for mobile and 25% for fixed broadband networks between 2019 and 2024 [3]. In this context, passive optical networks (PONs) have been widely promoted as energy-efficient WAN for fixed broadband access compared to copper technologies such as digital subscriber line (xDSL) or data over cable service interface specification (DOCSIS) [4], [5]. Studies assessing the power consumption (PC) of various technologies

of fixed broadband access network highlight that the customer premise equipments (CPEs) are responsible for more than 50% of the PC [4]–[10]. CPEs refer to home networking devices such as home gateways (HGWs), optical network units (ONUs), and local network equipment (LNE) that includes Wi-Fi access point, Wi-Fi extenders and Ethernet switches. HGWs and ONUs connect the access network of the internet service provider (ISP) to a local area network (LAN). The studies assessing the access network PC are highly sensitive to the inclusion of CPEs. Indeed, including the ONUs in the scope of a PON PC study degrades the energy efficiency of data transfers by a factor $3\times$ up to $10\times$ [11]. The aforementioned studies mostly consider fixed CPEs PCs (ranging from 3W up to 14W). A recent work [9] stresses the limited literature related to network device PCs including the CPEs. We conclude that macro-level PC and environmental impact studies of the access networks suffer from a high sensitivity with respect to the CPEs PC, highlighting the need for accurate data and hotspot analysis.

Several studies characterize the PC of CPEs with different objectives and scopes. Starting with PON technologies, the authors in [12] compare active and idle PC for three ONUs and three HGWs, showing that the HGWs typically consume between 3W and 11W while an ONU consumes between 2.5W and 5.8W depending on their configuration and operating mode. For one ONU and one HGW, the author in [13] measures their PC and propose a fixed PC breakdown between the components of the CPEs. The authors in [14] and [15] use a more generic approach based on datasheets to propose component-level ONU PC models for various PON technologies. In addition to PON-related studies, [16]–[19] explore the PC of LNE with Wi-Fi capabilities under different configurations. Likewise, the PC of Ethernet-over-Twisted-Pair (EoTP) technologies are studied in [20], [21]. Beyond the scientific literature, industry-led initiatives such as the U.S. Voluntary Agreement (USVA) and the European Code of Conduct (EuCoC) annually collaborate with manufacturers to improve the energy performance of CPE by establishing configuration-dependent maximum PC targets and standardized reporting practices for every technology of CPEs. The differences in the approaches of the

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scientific literature and the industry-led initiatives illustrate a tradeoff between completeness, transparency and accuracy. While the scientific literature focuses on transparency and accuracy, it lacks completeness regarding the various CPEs technologies. To the best of our knowledge, no study has assessed so far the different CPE technologies using a consistent scope that would allow a fair comparison.

In this work, we aim to improve the accuracy of macro-level access network PC or environmental impact studies and to identify hotspots in the average PC of CPEs. Accordingly, our goal is twofold: (1) provide a methodology to estimate the average PC and to analyze the contributions of the different network interfaces for CPEs with different technologies under a consistent scope, and (2) apply the proposed methodology to a subset of CPE to provide up-to-date average PC data. This paper is structured as follows. Section 2 outlines the methodology proposed to develop the average PC model. Section 3 demonstrates how to use the methodology by applying it to nine commercially-deployed CPEs, eventually providing a comparison between the measurements results and the PC breakdown. Finally, Section 4 summarises the key messages of this work.

II. METHODOLOGY

A. General modeling approach

Aligned with the EuCOC, USVA and the work [13], Fig. 1a shows the three type of interfaces we consider: the wireless local area network (WLAN) interface, the EoTP interface, and the WAN interface combined with the central function (WAN+CF). Additional interfaces such as the Bluetooth and Voice over IP (phone) are considered negligible in the PC of CPE [13], [14] and excluded from the scope of this study. Each interface is implemented by one or various active and passive hardware components. The PC of an interface is defined as the aggregated PC of the components implementing the physical and data link layers of the OSI model. We consider four types of WAN technologies for the WAN+CF interface: xDSL, DOCSIS, PON, and EoTP. The latest is used in LNE as they are located within a LAN. The WAN+CF interface also contains the CF, which routes the data packets and controls the various interfaces.

Each interface i can operate in the following states s and related PCs P_i^s : (a) deactivated (P_i^{deact}), (b) active but idle (P_i^{idle}), (c) active with download (DL) ($P_i^{DL} = P_i^{idle} + \Delta P_i^{DL}$), (d) active with upload (UL) ($P_i^{UL} = P_i^{idle} + \Delta P_i^{UL}$), and (e) active with simultaneous DL and UL ($P_i^{DL+UL} = P_i^{idle} + \Delta P_i^{DL} + \Delta P_i^{UL}$). The DL and UL directions for data transfers are also referred to as downstream and upstream in the fixed access network literature. The additional DL (resp. UL) PC ΔP_i^{DL} (resp. ΔP_i^{UL}) occurs when data is being transferred by the interface i towards the user equipment (UE) (resp. the access network). When an interface is active but not associated with UEs, this interface is considered disconnected (disc) and we assume it stays in active but idle state.

Finally, for some interfaces (e.g.: WLAN interfaces), there exists a deactivated state which requires a manual intervention to be entered and left. The average CPE PC including the AC-DC converter efficiency η is expressed as the sum of the interface average PCs \bar{P}_i as

$$\bar{P}_{CPE} = \frac{1}{\eta} \sum_i \bar{P}_i = \frac{1}{\eta} \sum_i \sum_s \tau_i^s P_i^s, \quad (1)$$

with τ_i^s denoting the fraction of time the interface i spends in the state s .

The WLAN interface and EoTP interface PC models developed below are derived as follows. First, we set relevant PC model variables based on the literature. Next, we propose simplified average PC models featuring both linear and nonlinear dependencies on the selected model variables and parameters. We then create a PC database for the interface using datasheet of components to collect the model variables and calculate the PC data for the available operating modes (e.g. by multiplying the current consumptions and operating voltages). Finally, we use these PC data to estimate the model parameters and the degree of non-linear dependencies by minimizing the sum of squared residues. The accuracy of the estimations are then evaluated using the coefficient of determinations (R^2), the RMSEs and the relative error between the prediction and the datasheet value. An R^2 close to one indicates that a large part of the output variability is captured by the model. The development of the WAN+CF interface PC model cannot follow the same approach because this interface is partially integrated with the CF in the main system-on-chip (SoC) of the CPE and the datasheet of such CPE-specific SoCs are not publicly available. For this reason, we propose a measurement-based approach in which we estimate the PC of the WAN+CF interface by subtracting the estimated PC of the WLAN and EoTP interfaces from the measured CPE PC. We can then estimate the average CPE PC and its distribution across interfaces by using these PC models and estimating their variables assuming specific data usage scenario.

B. WLAN interface power consumption model

The WLANs standardized by the IEEE 802.11 standards are the most common and are also referred to as Wi-Fi. They operate over radio frequencies in the 2.4 GHz, 5 GHz, and 6 GHz bands using the OFDM modulation on bandwidths ranging from 20 MHz up to 320 MHz. Since IEEE 802.11n, the standard has supported multiple-input, multiple-output (MIMO) spatial streams [25].

We propose the simplified WLAN PC model presented in Table I. Its structure is inspired from the mobile networks PC model from [22] and the studies [16], [18] highlight the dependence of the PC of WLAN devices to the number of spatial streams. We propose to use the following model variables: (a) N_L the maximum number of spatial streams, (b) N_{PA}^a the number of active power amplifiers (PA), (c) P_{PA}^{TX} the PA output power, (d) η_{PA} the PA efficiency, and (e)

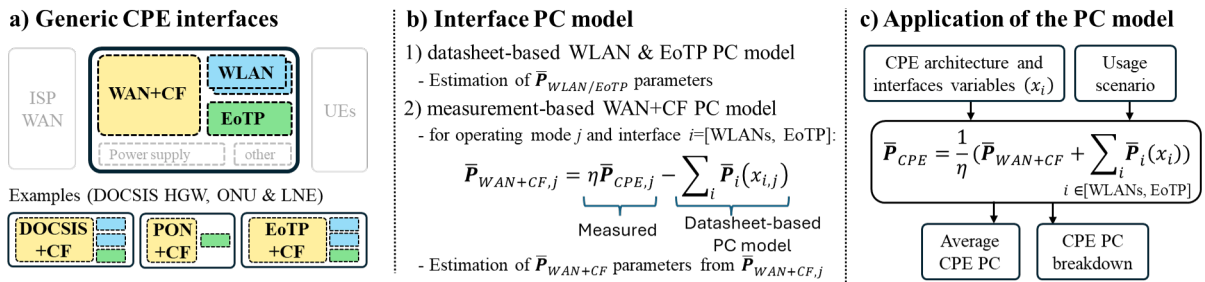


Fig. 1. General modeling approach including the generic CPE architecture, the interface PC model and the average CPE PC estimation

N_{LNA}^a the number of active low-noise amplifiers. The N_{PA}^a and N_{LNA}^a are limited by the MIMO capability of the UE and are maximized in order to achieve the highest throughput to reduce transmission time and save spectrum occupation [17], [19]. For a given MIMO capability and bandwidth, the maximum achievable data rate is primarily constrained by the transmit power, and the channel quality which determine the modulation and coding scheme (MCS) applied on each OFDM subcarrier. P_{PA}^{TX} is estimated under the assumption that the device transmits at the maximum possible level while remaining below the effective isotropic radiated power limits set by regulatory authorities [23], [24]. We then use 128 PC values from datasheets of WLAN active components such as WLAN SoC and front-end modules to estimate the model parameters. The studied datasheets limits the domain of applicability of this model to $N_L = N_{PA}^a = N_{LNA}^a \leq 4$ and $P_{PA}^{TX} \leq 500$ mW. We test different values for α_1 exponent in $[0.5, 1, 1.5, 2]$ and select $\alpha_1 = 1.5$ because the relative errors are minimized and more evenly distributed. Our model achieves an R^2 of 64% with the following estimated parameters: $P_{WLAN}^{idle,ref} = 0.23$ W, $P_{WLAN}^{TRX,ref} = 0.16$ W, and $P_{WLAN}^{deact,ref} = 0.1$ W. Fig. 2a shows a good prediction accuracy and the relative error distribution.

C. EoTP interface power consumption model

The EoTP interfaces standardized by the IEEE 802.3 standards are commonly referred to as Ethernet ports. Using a copper twisted-pair cable, the maximum achievable throughput increased from 10 Mbps to 40 Gbps, driven by advancements in coding schemes and symbol rates.

We propose the simplified EoTP PC model presented in Table I. The studies [20], [21] highlight the dependence of the PC of EoTP devices to the maximum data rate achievable per Ethernet port and the actual data rate. We propose to use the following model variables: (a) r_{EoTP}^{max} the maximum data rate achievable on one Ethernet port, (b) r_{EoTP}^{DL} (resp. r_{EoTP}^{UL}) the actual download (resp. upload) data rate transmitting on the connected Ethernet port, (c) N^p the number of Ethernet port of the EoTP interface, (d) $N_{DL}^{p,con}$ (resp. $N_{UL}^{p,con}$) the number of connected Ethernet ports transmitting at r_{EoTP}^{DL} (resp. r_{EoTP}^{UL}). We set the unit-normalizing parameter $r^* = 1$ Mbps and estimate the other model parameters by

minimizing the sum of the squared residuals on 209 PC values obtained from Ethernet SoC datasheets. The studied datasheets limits the domain of applicability of this model to $r_{EoTP}^{max} = r_{EoTP}^{DL/UL} \leq 10$ Gbps and $N^p = N_{UL/DL}^{p,con} \leq 4$. We test different values for α_2 and α_3 exponents in $[0.5, 1, 1.5, 2]$ and select $\alpha_2 = \alpha_3 = 0.5$ because the relative error is more evenly distributed and minimized. Our model achieve an R^2 of 83% with the following estimated parameters: $P_{EoTP}^{idle,ref} = 7.3$ mW, $P_{EoTP}^{TRX,ref} = 6$ mW, and $P_{EoTP}^{deact,ref} = 0.1$ W. Fig. 2b shows a very good prediction accuracy and the relative error distribution.

D. WAN+CF interface power consumption modeling

As explained in Section II.A, we propose a measurement-based approach in which we estimate the PC of the WAN+CF interface by subtracting the estimated PC of the WLAN and EoTP interfaces from the measured CPE PC. Fig. 3 shows the measurement setup with a generic CPE under test located between the WAN of the ISP and the LAN. We use the tool *iPerf2* [26] to simulate data traffic between a client and a server that are either emulated on a device in the LAN or hosted in our university server. This allows us to control the data routed by the CPE. We also use Google speed test tool when the communication with the university server is impossible due to limitations in the firewall configuration. We measure the DC current after the AC-DC converter using a *Keithley DMM7510* digital multi-meter assuming the supply voltage is constant to its rated value.

To isolate every contribution to the PC of the WAN+CF interface, we define seven operating modes that we run for a short time scale (a few seconds) and for which we measure the average PC. We refer to these operating modes as M0 up to M6. The state of the interfaces in these operating modes are summarized in Table II with idle, DL and UL referring to the states active but idle, active with DL, and active with UL. The idle PC P_{WAN+CF}^{idle} is deduced from the operating modes M0, M1 and M2. The DL (resp. UL) additional PC (P_{WAN+CF}^{DL}) (resp. P_{WAN+CF}^{UL}) is deduced from M3 and M5 (resp. M4 and M6) for the respective average data rates $\bar{r}_{WAN+CF}^{DL/UL}$. This average data rate is experienced by one UE during the transmitting operating modes and is

TABLE I
WLAN, EoTP, AND WAN+CF INTERFACE POWER CONSUMPTION MODELS.

Interface i	WLAN	EoTP	WAN+CF
Model variables	$N_L, N_{PA}^a, N_{LNA}^a, P_{PA}^{TX}, \eta_{PA}$	$N^p, N_{DL}^{p,con}, N_{UL}^{p,con}, r_{EoTP}^{max}, r_{EoTP}^{DL}, r_{EoTP}^{UL}, r^*$	-
P_i^{idle} [W]	$(N_L)^{\alpha_1} P_{WLAN}^{idle,ref}$	$\left(\frac{r_{EoTP}^{max}}{r^*}\right)^{\alpha_2} N^p P_{EoTP}^{idle,ref}$	$P_{WAN+CF}^{idle,ref}$
ΔP_i^{DL} [W]	$N_{PA}^a \left(P_{WLAN}^{TRX,ref} + \frac{P_{PA}^{TX}}{\eta_{PA}} \right)$	$\left(\frac{r_{EoTP}^{DL}}{r^*}\right)^{\alpha_3} N_{DL}^{p,con} P_{EoTP}^{TRX,ref}$	$P_{WAN+CF}^{DL,ref}$
ΔP_i^{UL} [W]	$N_{LNA}^a \left(P_{WLAN}^{TRX,ref} + P_{LNA} \right)$	$\left(\frac{r_{EoTP}^{UL}}{r^*}\right)^{\alpha_3} N_{UL}^{p,con} P_{EoTP}^{TRX,ref}$	$P_{WAN+CF}^{UL,ref}$
P_i^{deact} [W]	$P_{WLAN}^{deact,ref}$	$P_{EoTP}^{deact,ref}$	-

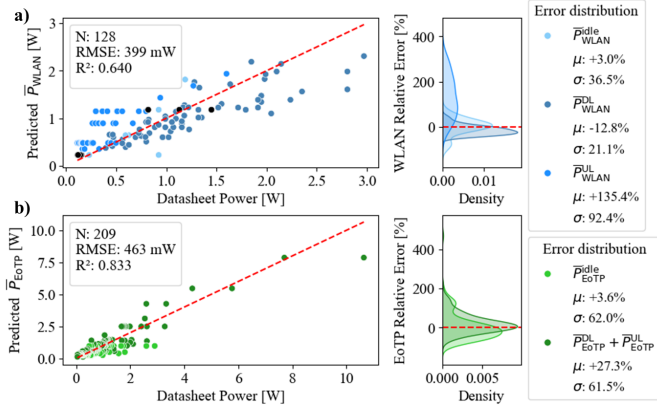


Fig. 2. Predicted PC and relative error distribution of the power consumption model of (a) WLAN and (b) EoTP interfaces

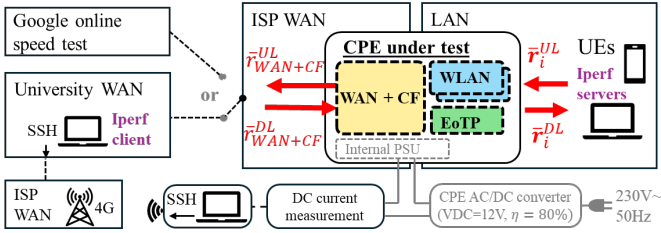


Fig. 3. Power measurement set-up.

limited by the interface with the lowest throughput. After these deductions, a parametric PC model can be defined and fitted to estimate the parameters if the deduced WAN+CF PC data set is large enough and if the values appear to be correlated with technology-specific variables. Otherwise, we recommend the use of a model with constant power as we propose in Table I and propose to differentiate the estimated parameters by WAN technologies. These parameters are estimated by averaging the WAN+CF interface PC values obtained from the corresponding operating modes for the CPEs grouped by common WAN technology.

E. Uncertainty

The main source of uncertainty in the methodology is the estimation of the WLAN and EoTP PC model parameters. To

TABLE II
MEASUREMENT OPERATING MODES AND RELATED STATES OF THE INTERFACES

op. mode	WAN+CF	EoTP	WLANs
M0	Idle	Disconnected	Deactivated
M1	Idle	Idle (1 UE)	Deactivated
M2	Idle	Disconnected	Idle (1 UE)
M3	DL @ \bar{r}_{CPE}^{max}	DL @ \bar{r}_{CPE}^{max} (1 UE)	Deactivated
M4	UL @ \bar{r}_{CPE}^{max}	UL @ \bar{r}_{CPE}^{max} (1 UE)	Deactivated
M5	DL @ \bar{r}_{CPE}^{max}	Disconnected	DL @ \bar{r}_{CPE}^{max} (1 UE)
M6	UL @ \bar{r}_{CPE}^{max}	Disconnected	UL @ \bar{r}_{CPE}^{max} (1 UE)

quantify this uncertainty, we rely on the mean (μ) and standard deviation (σ) of the relative error, as reported in Fig. 2. We apply a bias correction by dividing the predicted typical values from these models by $1 + \mu$. Then, we sum the variances of the WLAN and EoTP PC estimates to calculate the variance of the deduced WAN+CF PC model. Given the precision of the instruments and controlled setup we used, we consider the PC measurement uncertainty to be negligible.

III. RESULTS

In this section we apply the methodology to nine CPEs, present the measured CPE PCs, and deduce the WAN+CF PC model. In these nine CPEs, there is five different CPE models from three different Belgian ISPs. We measure the *G-010G-R* ONU and *CGA4233V00* DOCSIS HGW under different WAN subscriptions that limits the maximum WAN+CF throughput. Additionally, the two xDSL HGWs are also used as LNE with ONUs to provide HGW services even if they are not directly connected with the ISP WANs. We then use the complete CPE PC model to estimate the average PC of three CPE configurations under realistic usage scenarios.

A. WAN+CF power consumption model

Fig. 4.a shows the short-time scale average CPE PC measured for the nine CPE under test and the different operating modes. For the short-time scale average PC, we observe an order-of-magnitude of difference between the different CPE and up to a factor $2.2\times$ of difference for the same CPE between the different operating modes. In addition,

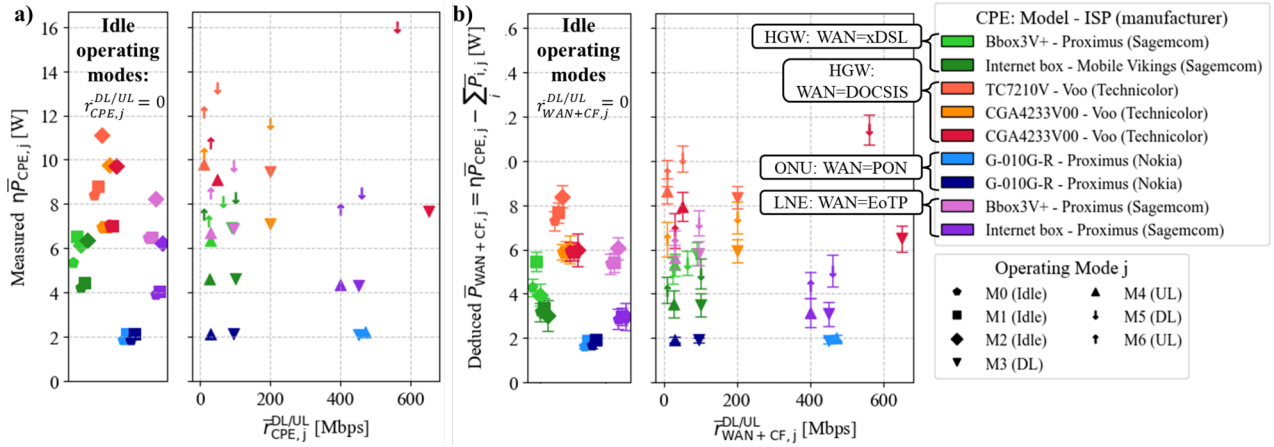


Fig. 4. (a) Measured average power consumption of nine CPEs under the defined operating modes. (b) Deduced average power consumption and related uncertainty for the WAN+CF interface of the measured CPEs over the defined operating mode

DOCSIS HGWs seem to consume more power than xDSL and LNEs independently of the operating mode. The ONU PC is significantly lower due to their simplified functions and architecture. Nevertheless, they require an LNE to provide WLAN services. Fig. 4.b summarizes the deduced WAN+CF PC across all measured CPEs. We observe that the idle PC of the WAN+CF interface is significantly higher for DOCSIS HGWs. This is consistent with the DOCSIS standard, which requires continuous demodulation across the entire allocated downstream spectrum [27]. Finally, the estimation and related uncertainties for the WAN+CF PC model parameters of Table I are calculated by averaging the value obtained from the different devices classified by WAN interface type.

B. CPE power consumption estimation

To illustrate the application of our model, we compare the average PC of CPEs for xDSL, DOCSIS and PON internet access during 24h. The PON technology requires an ONU and an LNE with WLAN capabilities to provide a typical internet access while the xDSL and DOCSIS CPE are single HGWs. We then define a *light* and a *heavy* usage scenario detailed in Fig. 5 which influence the respective times spent by interfaces in each state τ_i^s . In addition, we study the impact of an impairment of the WLAN channels (e.g. due to a reduced SNR or high interferences) for the xDSL HGW under the heavy usage scenario. We simulate a generic impairment by assuming a reduction of the MCS index from 11 to 2 changing the OFDM modulation from QAM1024 to QPSK. This limits the maximum instantaneous WLAN data rate $r_{WLAN}^{DL/UL,max}$ and thus make the WLAN interfaces transmit for a longer period of time. Each variable of the PC models from Table I are estimated accordingly.

Fig. 5 shows that idle power contributions across the various interfaces accounts for more than 98% of the average CPE PC. The impact of the *heavy* usage scenario and degraded WLAN signal-to-noise ratio (SNR) is marginal, increasing the average

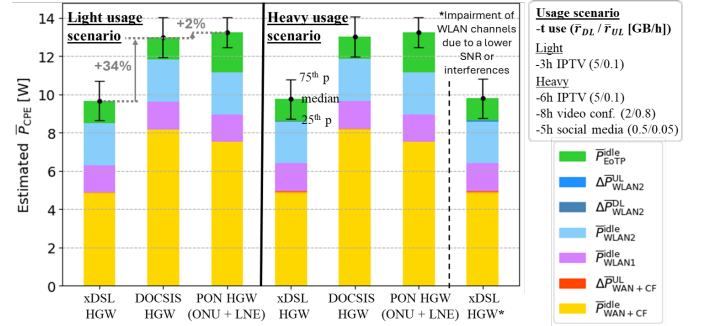


Fig. 5. 24h average CPE power consumption for different usage scenarios including the uncertainty and the power consumption breakdown.

CPE PC by less than 1% regardless of CPE type. This is explained by the fact that the cumulative transmission time remains on the order of a few minutes per day, during which the CPE consumes a few additional Watts. When averaged over a 24-hour period, this translates to an increase of just a few tens of mW. Lastly, the PON HGW has an average PC that is 2% and 36% higher than its DOCSIS and xDSL counterparts, respectively, mainly due to its reliance on two separate CPE devices (ONU and LNE). It is worth noting that the xDSL HGW supports a lower maximum data rate than the DOCSIS and PON HGWs due to technology limitations.

IV. CONCLUSION

Studies assessing the PC of the access networks suffer from a high sensitivity with respect to the PC of CPEs, emphasizing the need for accurate PC data and hotspot analysis. This paper introduced a novel methodology that combines measurements and datasheet-based modeling to estimate the PC of CPEs. This hybrid approach enables consistent cross-technology comparisons while accounting for configuration and usage-dependent behavior.

Applied to nine commercially deployed CPEs spanning several technologies, the results reveal up to a factor of 2.2 of difference in the short-time scale PC of a given CPE under different operating modes. Across different technologies and configurations of CPE, we observe an order-of-magnitude of difference in short-time scale PC. However, the 24-hour average PC for a given CPE under typical usage scenarios does not depend much on its usage as the idle PCs of its interfaces account for more than 98% of the average PC. Therefore, it is the technology and the configuration of a CPE that drives its average PC. For this reason, we demonstrate that a PON HGW (comprising an ONU and a LNE) consumes 2% and 36% more power than a DOCSIS and a xDSL HGW, respectively. This emphasizes the importance of minimizing baseline PC. However, reducing the interface idle PCs must be balanced against the need for low-latency service: shutting down the CPE or deactivating the WLAN interface introduce wake-up delays of several minutes or few seconds, respectively. Future work should investigate this trade-off across the WAN+CF, WLAN, and EoTP interfaces, and explore dynamic power management strategies that adapt to the throughput and the user activity. Additionally, the proposed WLAN and EoTP datasheet-based power consumption models would benefit from an extended domain of applicability and the incorporation of ongoing technological advancements.

This work contributes to improving the accuracy of macro-level access network PC assessments by providing both a methodology and empirical data for developing up-to-date, CPE PC models. In addition, it offers actionable insights to support the energy-efficient design of future CPEs. However, these findings should be complemented by a comprehensive, multi-indicator life cycle assessment to fully capture potential environmental trade-offs and to validate eco-design priorities.

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