

Empirical ONU Power Consumption Modeling and Verification for Integrated Optical-Wireless Access Networks

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Abstract—Energy efficiency has become a fundamental requirement in next-generation broadband access networks, particularly in integrated optical-wireless deployments. Optical Network Units (ONUs) constitute a major share of energy consumption in Gigabit Passive Optical Network (GPON) systems, yet most existing studies rely on simulation or oversimplified static models. This paper presents an experimentally validated power consumption model for commercial ONUs deployed in Brunei's live access network. A developed power meter equipped with an INA260 voltage and current sensor was implemented to measure real-time ONU power draw under dynamic traffic loads injected ranging from 0 to 1 Gbps. The findings show a nonlinear power-rate relationship, where the power initially increases with traffic up to approximately 200–300 Mbps, then saturates at higher rates. A logarithmic empirical model is derived and validated using the coefficient of determination (R^2) and the root mean square error (RMSE), confirming its suitability for accurate real-world ONU power estimation. This model enhances energy-efficiency analysis for integrated optical-wireless networks and challenges the legacy linear assumptions commonly used in the prior literature.

Keywords—GPON, ONU power consumption, energy efficiency, empirical modeling, developed power meter, Brunei broadband network.

I. INTRODUCTION

The growing demand for broadband traffic, driven by video streaming, cloud services, and emerging 5G applications, has made energy efficiency a critical design objective in modern access networks. Passive optical networks, particularly GPON, are widely deployed due to their high capacity and low operational cost. However, ONUs located on customer premises account for a significant portion of the total energy consumption of the network. According to [1], among all the network elements in an access network, the ONU exhibits the highest power consumption, accounting for approximately 60% of the total. Although the power consumption of a single ONU is relatively low, ranging from 5 W to 15 W (ONU available in the current Brunei market), cumulative power consumption becomes substantial due to the large number of

installed ONUs, surpassing 10 million worldwide [2]. Taking into account a median ONU power consumption of 10W, the daily power usage of a single ONU amounts to 240 Wh (10W x 24 hours/day). Based on the Brunei Population and Housing 2022 Census report [3] in 2021, the total number of occupied houses with internet connection is 68,102 houses. With each houses having at least one ONU installed, the collective annual power consumption reaches 5.884 GWh. In Brunei, the electricity tariff is at BND 0.01 per kWh for the first 1 to 600 kWh [4]. Based on this tariff, the annual energy cost attributed to the ONUs alone is approximately BND 58,840.15.

Advancing toward greener technologies requires understanding how much power an Optical Network Unit (ONU) consumes, as it is the dominant energy user in optical access networks. In many cases, people assume that changes in traffic load has very little impact on the ONU's power usage. Because of this, the power consumption of the whole access network is often estimated simply as the power used per user or subscriber. However, having an accurate understanding of how an ONU consumes energy and how its power use changes with different traffic loads is crucial. This knowledge can help reduce overall energy consumption and improve the way energy efficiency in the network is measured. With this motivation, this work aims to experimentally measure and study the power consumption patterns of an ONU using a real Gigabit Passive Optical Network (GPON) testbed under real network conditions in Brunei and formulate a verified power consumption model.

Prior studies [5]–[7] have often assumed a constant or traffic-independent ONU power profile, relying heavily on simulation-based models and analytical models. Such simplifications risk misestimating real network energy requirements, especially in integrated optical-wireless scenarios where accurate load-dependent behaviour is crucial.

II. METHODOLOGY

To accurately measure ONU power behavior, a live GPON testbed in Unified National Networks (UNN), Brunei's national broadband operator was used. Measurements were collected under realistic operating traffic profiles to ensure that the observed behaviour was representative of actual field conditions. Fig.1 shows the experimental GPON testbed setup for ONU power measurement.

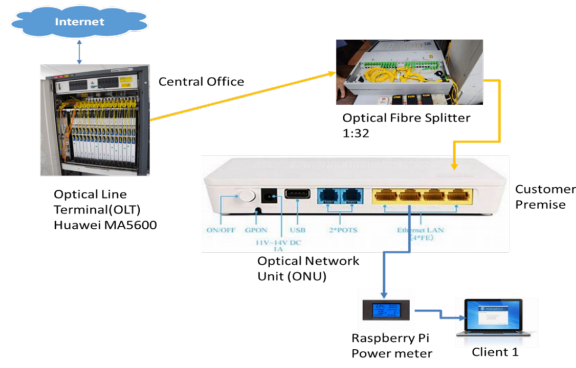


Fig. 1. Experimental GPON testbed for ONU power measurement

A. Hardware Configuration

The testbed comprises three primary components:

- 1) Optical Line Terminal (OLT) — Huawei MA5600 series
- 2) Passive Optical Networking Splitter — 1:32 optical splitter, 20 km link
- 3) Optical Network Units (ONUs) — Huawei SmartAX MA5675 and EchoLife HG8245H5

The ONU DC power was monitored using a developed high-precision metering setup. The developed power meter sampled voltage and current at 100ms intervals, enabling fine-grained capture of instantaneous power fluctuations driven by traffic and device state transitions.

B. ONU Device Specifications

Table I summarises key physical specifications of the tested ONUs.

TABLE I
SPECIFICATIONS OF TESTED ONUS

Model	SmartAX MA5675	HG8245H5
Input Voltage	11–14.2V	11–14V
Rated Power	Max 15.5W	15W
Ethernet Ports	4x GE	4x GE
PON Standard	ITU-T G.984 GPON	ITU-T G.984 GPON

C. Developed Power Meter

A Raspberry Pi 4 was programmed in Python to continuously read and log INA260 power sensor data. The system recorded Instantaneous voltage (V), Instantaneous current (mA) and Computed power (W).

The INA260 provides built-in power calculation with high sensitivity and resolution, making it suitable for access network device monitoring.

D. Traffic Load Profile

User Datagram Protocol (UDP) traffic was generated and progressively increased from idle to 1 Gbps from the operator's network management system. Each test configuration was repeated multiple times to verify stability and repeatability. Power samples were recorded every 100 ms to capture instantaneous variations.

Traffic loads were injected in progressive increments:

0, 50, 100, 200, 300, 500, 1000 Mbps

For each level, measurements were repeated four times to ensure statistical consistency.

This produced robust and repeatable power consumption values across diverse traffic scenarios. Power readings were processed to derive average power for each traffic load condition. MATLAB was used to curve-fit the empirical dataset and estimate the model parameter.

III. RESULTS

Measurements were conducted in four independent runs for each ONU model. The average power consumption values were computed across all repetitions to ensure statistical reliability.

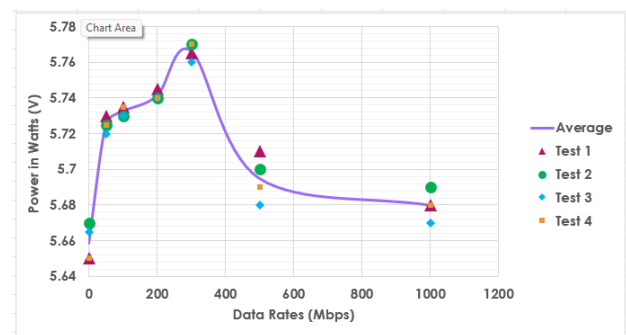


Fig. 2. Power consumption of ONU1 (SmartAX MA5675) across varying data rates.

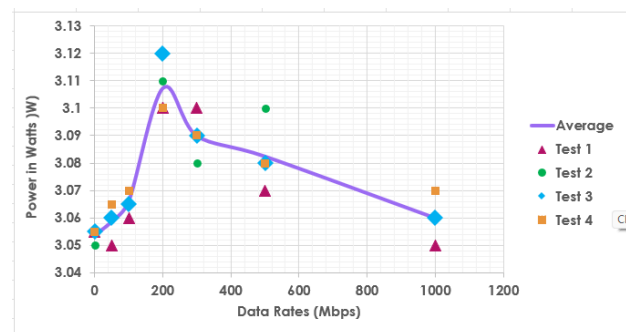


Fig. 3. Power consumption of ONU2 (HG8245H5) across varying data rates.

As shown in Fig. 2 and Fig. 3, power consumption increased steadily with traffic load up to 200–300 Mbps and then stabilised at higher rates. This phenomenon corresponds to

internal queue activation and processor scheduling thresholds within the ONU hardware.

ONU1 exhibited slightly lower power usage than ONU2 across all traffic conditions, indicating higher hardware efficiency. The nearly flat region above 300 Mbps suggests that resource allocation remains constant once saturation is reached. Fig. 4 shows the average power consumption comparison between ONU1 and ONU2.

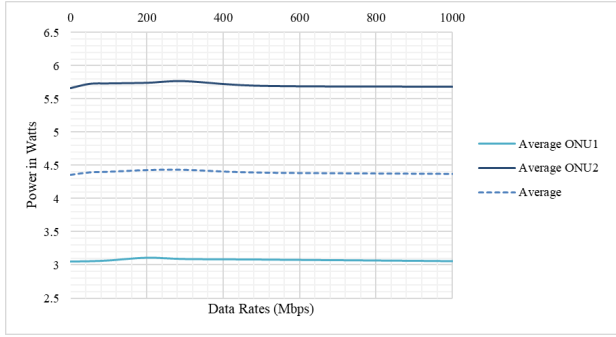


Fig. 4. Average power consumption comparison between ONU1 and ONU2.

The laboratory measurement was conducted to evaluate accuracy of the developed power meter. The current and voltage measured are compared with the current and voltage generated and measured by the Siglent DC power supply. Fig. 5 and Fig. 6 illustrate the setup used for validating the power meter. The voltage of the DC power supply was varied from 0 V to 10 V, in steps of 1V/sample and the output was compared with that of the power meter. It was found that the values measured by the power meter were matching well with the outputs generated and measured with the power supply as in Fig. 7 and Fig. 8.

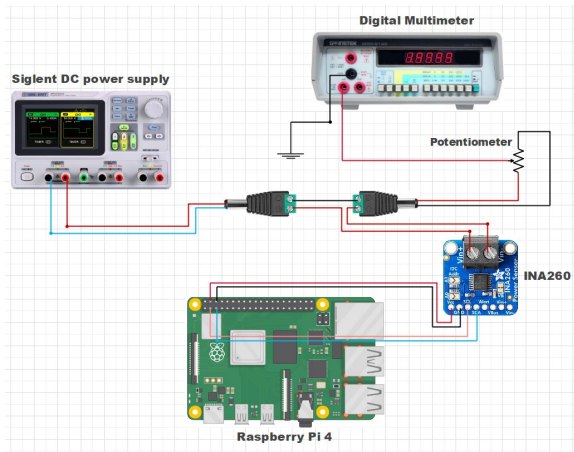


Fig. 5. Schematic diagram of the measurement setup

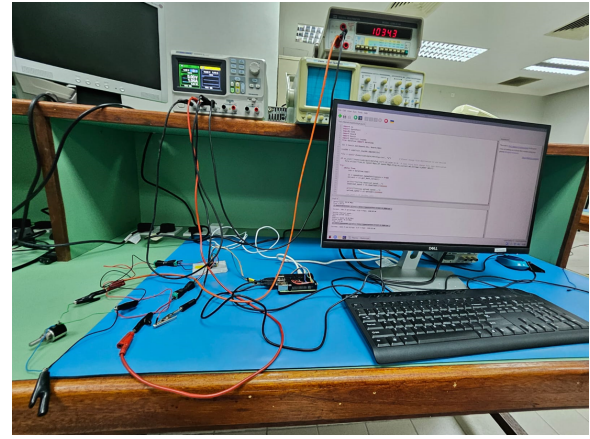


Fig. 6. Physical measurement setup.

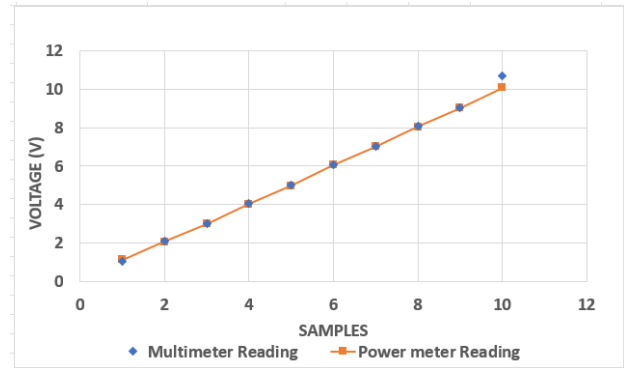


Fig. 7. Voltage validation: multimeter vs developed power meter.

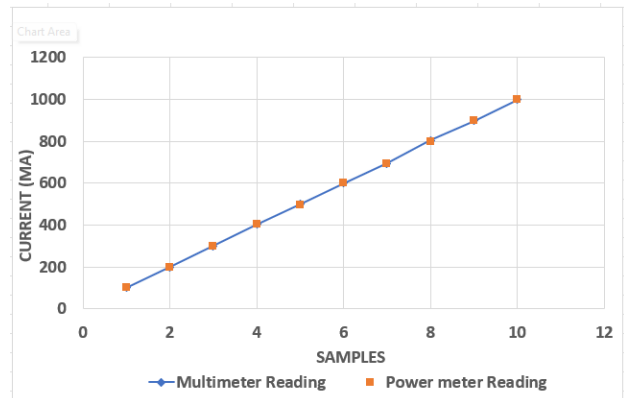


Fig. 8. Current validation: multimeter vs developed power meter.

IV. LOGARITHMIC POWER MODEL DERIVATION

To analytically express the measured relationship, a logarithmic curve was fitted to the empirical data. The proposed model is given by:

$$P_{\text{ONU}} = a_0 \log_{10}(r + 1) + b_0 \quad (1)$$

where:

- P_{ONU} = ONU power consumption (W),

- r = data rate (Mbps),
- a_0, b_0 = model coefficients.

Curve fitting was performed in MATLAB R2020b using nonlinear least-squares regression. The derived parameters were:

$$a_0 = 0.01273 \text{ W/Mbps}, \quad b_0 = 4.517 \text{ W} \quad (2)$$

The resulting curve is plotted in Fig. 9, showing strong agreement between predicted and measured values.

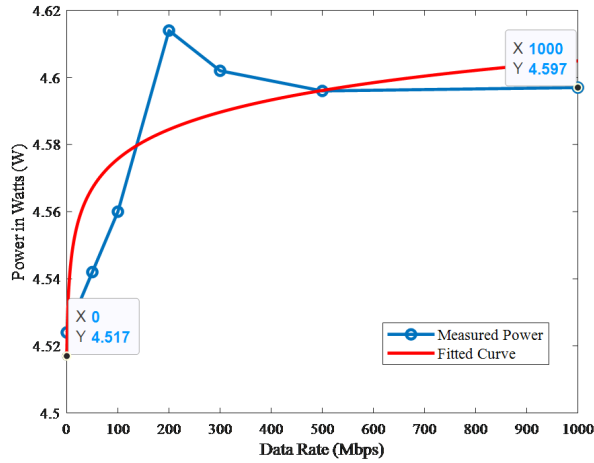


Fig. 9. Measured vs fitted logarithmic power model for ONU.

This model accurately captures the nonlinear behaviour of ONU power with respect to traffic load, particularly the saturation effect beyond 300 Mbps, which cannot be explained by linear models.

V. MODEL VALIDATION AND STATISTICAL ASSESSMENT

To evaluate accuracy, the proposed model was validated using two performance metrics [8], [9]: Coefficient of Determination (R^2) and Root Mean Square Error (RMSE).

The R^2 value indicates the proportion of variance in measured power explained by the model, while RMSE quantifies the average prediction error in watts.

$$R^2 = 0.7159, \quad \text{RMSE} = 0.0169 \text{ W} \quad (3)$$

The relative RMSE is calculated as:

$$\text{Relative RMSE} = \frac{0.0169}{4.614 - 4.524} \approx 18.8\% \quad (4)$$

This value falls within the 10–20% range commonly accepted for power consumption modelling of physical access systems [10], [11]. Thus, the model is statistically consistent and physically realistic.

VI. DISCUSSION

The experimental results confirm that modern GPON ONUs do not follow the traditional assumption of linear or constant power consumption. Instead, they exhibit a hybrid characteristic:

- 1) Initial Rising Region (0–200 Mbps) — Power increases as the ONU activates higher layers of its internal processing pipeline, such as packet scheduling, buffer management, and queue handlers.
- 2) Saturation Region (300 Mbps–1 Gbps) — Beyond a threshold, resource allocation remains fixed, resulting in minimal increases in power consumption.

This behaviour is aligned with energy-efficient chipset design principles implemented in newer ONU hardware.

A. Implications for Integrated Optical–Wireless Access Networks

In Integrated Optical–Wireless Access networks, ONUs operate along side wireless equipment such as femtocells. Accurate modelling of ONU power consumption is therefore essential for Energy-efficient scheduling algorithms, Hybrid network energy budget estimation, ONU sleep/wake optimisation and Green ICT policy alignment for Brunei.

The experimental model derived in this work provides a realistic foundation for such analyses. The proposed logarithmic model outperforms traditional models because it is built directly on real-world measurements collected from Brunei's national network infrastructure.

VII. CONCLUSION

This paper presented an empirical study of ONU power consumption using a live production GPON network in Brunei. A custom high-resolution metering system was developed to record instantaneous ONU power under traffic loads up to 1 Gbps. Results show that power increases initially with traffic but saturates beyond 200–300 Mbps. A logarithmic model fits measured behaviour with high accuracy ($R^2 = 0.7159$) and the derived model significantly improves realism compared to traditional linear or constant assumptions.

The findings support additive energy modeling in integrated optical–wireless networks, and can be extended into machine-learning predictive frameworks and multi-vendor ONU analysis.

ACKNOWLEDGMENT

The author thanks Unified National Networks (UNN) Brunei Darussalam for support to conduct real network measurements. Special appreciation is also extended to Universiti Teknologi Brunei (UTB), School of Electrical and Electronic Engineering, for research guidance and academic support.

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ISBN: 979-11-88428-14-4



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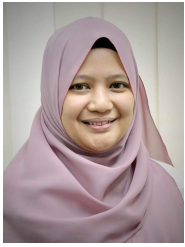
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