Malaysian Journal of Computing, 11 (2): 2686-2698, 2026
eISSN: 2600-8238

FIELD ASSESSMENT OF POWER LINK BUDGET ACCURACY IN A RESIDENTIAL FTTH GPON DEPLOYMENT

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ABSTRACT

Fiber to the Home (FTTH) based on Gigabit Passive Optical Network (GPON) is widely used for residential broadband access because of its high bandwidth capacity, scalability, and efficient use of passive optical infrastructure. During FTTH network planning, Power Link Budget (PLB) analysis is commonly applied to estimate cumulative optical losses and received optical power. However, differences may occur between theoretical PLB calculations and actual field measurements due to practical deployment conditions. This study assesses the consistency of PLB predictions using field measurements from a residential FTTH GPON deployment. Measurements were conducted at two Fiber Access Terminal (FAT) points using an Optical Power Meter, with the evaluated network employing cascaded 1:4 and 1:8 passive optical splitters. Theoretical received optical power was calculated using fiber attenuation, connector loss, splice loss, splitter loss, and a safety margin, and was subsequently compared with field measurements. The theoretical received power was −17.498 dBm at FAT 1 and −17.509 dBm at FAT 2, while the measured values ranged from −17.19 dBm to −17.66 dBm. The absolute difference between theoretical and measured values ranged from 0.139 to 0.319 dB, with a Mean Absolute Error (MAE) of 0.1905 dB and a Root Mean Square Error (RMSE) of 0.2046 dB. The mean absolute percentage error was 1.09%, while the original percentage comparison between measured and theoretical values ranged from 98.2% to 99.2%. These results indicate close agreement between the theoretical PLB estimates and field measurements for the investigated residential GPON deployment. The findings provide field-based evidence that standardized PLB parameters can reasonably estimate received optical power under the evaluated network configuration, while the limited number of measurement points restricts broader generalization to larger deployments.

Keywords: *Fiber To The Home, GPON, Optical Power Measurement, Passive Optical Network, Power Link Budget.*

Received for review: 18-05-2026; Revised: 17-09-2026; Accepted: 25-09-2026; Published: 01-10-2026
DOI: 10.24191/mjoc.v11i2.11747



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1. Introduction

Fiber to the Home (FTTH) technology has become one of the primary solutions for delivering high-speed broadband services in residential environments due to the increasing demand for stable and high-capacity internet access (Elfrida et al., 2025). Among various optical access technologies, Gigabit Passive Optical Network (GPON) is widely adopted because it enables efficient bandwidth distribution using passive optical splitters while maintaining relatively low deployment and operational costs (Lorincz et al., 2025; Obinna & Eze, 2024; Saliou et al., 2024). The scalability and efficiency of GPON architecture make it suitable for dense residential deployments requiring reliable downstream and upstream transmission performance.

In FTTH GPON network planning, Power Link Budget (PLB) analysis is commonly used to estimate cumulative optical attenuation across transmission paths. The PLB model considers multiple loss components, including fiber attenuation, connector loss, splice loss, splitter loss, and safety margins, to ensure that the received optical power remains within the acceptable sensitivity range of GPON receivers (Takahashi et al., 2024; Ulfah & Irtawaty, 2025; Hidayah & Atmoko, 2024). Recent FTTH-GPON studies have also applied PLB calculations together with practical network implementation or field measurement to evaluate optical loss and received power ((Muzaki Wayoi et al., 2024) . Accurate PLB estimation is important because underestimation of optical losses may result in insufficient optical margin, whereas overestimation may lead to unnecessarily conservative network planning.

Several previous studies have investigated FTTH GPON performance from different perspectives, including optical loss analysis, network feasibility evaluation, Quality of Service (QoS) assessment, and splitter-based attenuation modelling (Ramadan et al., 2024). Obinna and Eze (2024) analyzed power budget feasibility for passive optical network deployment, while Ulfah and Irtawaty (2025) and Ikhwan et al. (2023) evaluated FTTH feasibility using link budget and rise time budget approaches. In addition, Yustini et al. (Yustini et al., 2021) evaluated FTTH-GPON implementation using PLB and optical attenuation measurements, Habib et al. (Muzaki Wayoi et al., 2024) evaluated a 1:8 splitter configuration using PLB calculations and Optical Power Meter measurements. These studies demonstrate the practical relevance of comparing theoretical optical-budget calculations with measured network performance.

The distinction between theoretical calculation and field measurement is relevant because PLB calculations represent the expected optical loss based on specified fiber, connector, splice, and splitter parameters, whereas field measurements reflect the actual condition of the installed transmission path. The differences reported in previous FTTH-GPON measurements indicate that calculated and measured values may not be identical under practical deployment conditions (Muzaki Wayoi et al., 2024) . Such differences can be associated with the actual characteristics of the installed optical path and passive components. Therefore, comparing calculated and measured received optical power provides a practical means of assessing the consistency of the PLB calculation with the conditions observed in an operational network.

Therefore, this study focuses on the field assessment of PLB predictions in a residential FTTH GPON deployment at Cluster Mutiara Persada Residence. The investigated network consists of an Optical Line Terminal (OLT), a Fiber Distribution Terminal (FDT), and two Fiber Access Terminal (FAT) points serving ten users. The optical distribution network employs cascaded 1:4 and 1:8 passive optical splitters. Optical power was measured at the network points using an Optical Power Meter and compared with theoretical PLB calculations for FAT 1 and FAT 2.

The contribution of this study is empirical rather than methodological. The study does not propose a new PLB formulation or a new FTTH GPON architecture; instead, it provides field-based evidence regarding the consistency between conventional PLB calculations and

measured optical power in an operational residential FTTH GPON deployment. The analysis also examines the difference between theoretical and measured values using quantitative error metrics. Because the investigation covers two FAT points within a single residential deployment, the findings are interpreted within the scope of the evaluated network configuration rather than generalized to all FTTH GPON deployments.

2. Methodology

This study employed a quantitative experimental approach to evaluate the consistency between theoretical Power Link Budget (PLB) calculations and actual optical power measurements in a residential Fiber to the Home (FTTH) network based on Gigabit Passive Optical Network (GPON) architecture. The evaluation was conducted by comparing theoretical received optical power with optical power measurements obtained directly from the deployed network. The methodology consisted of network topology identification, parameter-based PLB calculation, field measurement using an Optical Power Meter (OPM), and quantitative error analysis between theoretical and measured optical power. and validating the system.

2.1 Research Environment

The study was conducted in a residential FTTH-GPON network consisting of one Optical Line Terminal (OLT), one Fiber Distribution Terminal (FDT), and two Fiber Access Terminal (FAT) points serving ten active users. The network employed a multi-stage splitter configuration consisting of 1:4 and 1:8 passive optical splitters.

The two FAT points were selected because they constituted the two operational FAT points available in the investigated residential FTTH network. Both FAT points served active users during the measurement period and represented the distribution points included within the defined measurement scope. In addition, the two FAT points had different optical transmission distances, allowing the theoretical and measured optical power to be compared under different transmission conditions within the same network deployment.

The measurement dataset consisted of ten active users distributed between FAT 1 and FAT 2, with five users associated with each FAT point. The users were selected based on their active connection status and availability during the measurement period. Therefore, the measurements represent the operational conditions of the investigated residential network and are not intended to statistically represent FTTH networks in general.

A clear understanding of the evaluated network structure is essential for interpreting both the calculated and measured results. Therefore, the FTTH GPON topology used in this study is illustrated to show the relationship between network elements and measurement points.

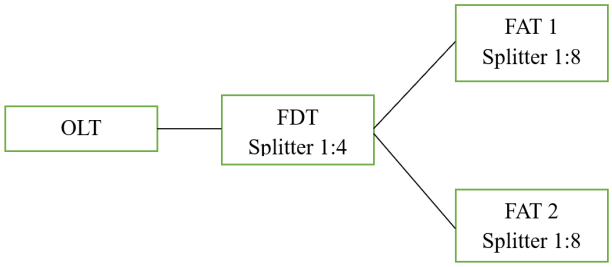


Figure 1. FTTH GPON network topology in the residential environment

Figure 1 illustrates the end-to-end FTTH-GPON topology, starting from the Optical Line Terminal (OLT), passing through the Fiber Distribution Terminal (FDT), and terminating at FAT 1 and FAT 2. The multi-stage splitter configuration consisting of 1:4 and 1:8 passive

optical splitters is included in the optical transmission path. This topology forms the basis for both the PLB calculation and the field measurement strategy.

2.2 Measure Equipment

Field measurements were performed using an Optical Power Meter (OPM) at the OLT, FDT, FAT 1, and FAT 2 points. Measurements were conducted under both working-day and holiday conditions to observe the optical power characteristics under different observation periods.

The measured optical power values were recorded in dBm and, where applicable, converted into milliwatts (mW). The measurement points followed the installed FTTH-GPON topology so that the obtained values corresponded to the actual optical transmission path in the investigated network.

The main characteristics of the evaluated residential FTTH-GPON network are summarized in Table 1.

Table 1. Research object and FTTH GPON network configuration

Parameter	Description
Deployment environment	Residential area
FTTH technology	GPON
Number of FAT points	2
Number of users	10
Splitter configuration	1:4 and 1:8
Measurement points	OLT, FDT, FAT 1, FAT 2

The two FAT points provided different optical transmission distances within the same residential deployment. FAT 1 had an optical path length of 4.91 km, while FAT 2 had an optical path length of 4.94 km. These differences were considered in the PLB calculation and comparison with the corresponding field measurementsFuzzy Inference System (FIS) is the computational framework used to evaluate and predict student dropout risks based on various input factors. and validating the system.

2.3 Power Link Budget Calculation

The Power Link Budget (PLB) was calculated using standard optical loss parameters, including fiber attenuation, connector loss, splice loss, splitter loss, and safety margin, as commonly applied in optical link budget analysis (Giggenbach et al., 2023). The total optical attenuation along the transmission path was calculated using Equation (1):

$$\alpha_{total} = L \,.\, \alpha_f + N_c \,.\, \alpha_c + N_s \,.\, \alpha_s + \alpha_{sp1} + \alpha_{sp2} \quad (1)$$

where α_{total} is the total optical attenuation (dB), L is the fiber length (km), α_f is the fiber attenuation coefficient (dB/km), N_c is the number of connectors, α_c is the connector loss per connector (dB), N_s is the number of splices, α_s is the splice loss per splice (dB), and α_{sp1} and α_{sp2} are the losses of the first stage and second-stage optical splitters, respectively.

The parameters used in the calculation were a fiber attenuation coefficient of 0.35 dB/km, connector loss of 0.25 dB per connector, splice loss of 0.10 dB per splice, a first-stage splitter loss of 7.25 dB for the 1:4 splitter, and a second-stage splitter loss of 10.38 dB for the 1:8 splitter. The calculation was applied separately to FAT 1 and FAT 2 according to their respective optical path lengths.

For FAT 1, the measured optical path length was 4.91 km. The total attenuation was calculated as:

$$\alpha_{total}, FAT1 = (4.91\ x\ 0.35) + (5\ x\ 0.25) + (6\ x\ 0.10) + 7.25 + 10.38 = 21.1985\ dB$$

The theoretical received optical power was calculated from the transmitted optical power and total attenuation using Equation (2):

$$P_{rx} = P_{tx} - \alpha_{total} \quad (2)$$

where P_{rx} is the theoretical received optical power (dBm), P_{tx} is the transmitted optical power (dBm), and α_{total} is the total optical attenuation (dB).

Using the transmitted optical power of 3.70 dBm, the theoretical received optical power at FAT 1 was:

$$P_{rx}, FAT1 = 3.70 - 21.1985$$
$$P_{tx}, FAT1 = -17.4985\ dBm$$

For FAT 2, the optical path length was 4.94 km. Using the same optical loss parameters, the total attenuation was calculated as:

$$\alpha_{total}, FAT2 = (4.94\ x\ 0.35) + (5\ x\ 0.25) + (6\ x\ 0.10) + 7.25 + 10.38 = 21.2090\ dB$$

The theoretical received optical power at FAT 2 was:

$$P_{rx}, FAT2 = 3.70 - 21.2090$$
$$P_{rx}, FAT2 = -17.5090\ dBm$$

The resulting theoretical received optical power values of -17.4985 dBm for FAT 1 and -17.5090 dBm for FAT 2 were subsequently used as reference values for comparison with the field measurements. The calculation parameters applied in this study follow the standardized optical loss values presented in Table 2, which are consistent with the parameters used in FTTH-GPON link budget analysis (Lorincz et al., 2025; Nurus et al., 2023).

Table 2. Parameters used in power link budget calculation

Parameter	**Value**	**Unit**
Fiber attenuation coefficient	0.35	dB/km
Connector loss	0.25	dB/connector
Number of connectors	5	connectors
Splice loss	0.10	dB/splice
Number of splices	6	splices
1:4 splitter loss	7.25	dB
1:8 splitter loss	10.38	dB
Transmitted optical power	3.70	dBm
Fiber length to FAT 1	4.91	km
Fiber length to FAT 2	4.94	km

2.4 Accuracy Evaluation

The accuracy of the PLB calculation was evaluated by comparing the theoretical received optical power with the corresponding field measurement. To make the accuracy evaluation mathematically reproducible, the percentage error was calculated using Equation (3) (Abdellaoui et al., 2022):

$$E(\%) = \frac{|P_{measured} - P_{calculated}|}{|P_{calculated}|} x\ 100 \quad (3)$$

where E is the percentage error, $P_{measured}$ is the received optical power obtained from field measurement (dBm), and $P_{calculated}$ is the theoretical received optical power obtained from the PLB calculation (dBm).

The absolute value is used because optical power is expressed in dBm and may have a negative numerical value. The percentage error therefore represents the relative deviation between the measured and calculated received optical power. A smaller percentage error indicates a smaller deviation between the theoretical and measured values.

For FAT 1 under working-day conditions, the calculated received optical power was -17.4985 dBm and the measured value was -17.64 dBm. The percentage error was calculated as:

$$E_{FAT1,WD} = \frac{|-17.64 - (-17.4985)|}{17.4985} x100$$
$$E_{FAT1,WD} = 0.81\%$$

For FAT 1 under holiday conditions, the calculated received optical power remained -17.4985 dBm, while the measured value was -17.66 dBm:

$$E_{FAT1H} = \frac{|-17.66 - (-17.4985)|}{17.4985} x100$$
$$E_{FAT,H} = 0.92\%$$

For FAT 2 under working-day conditions, the calculated received optical power was -17.5090 dBm and the measured value was -17.37 dBm:

$$E_{FAT2,WD} = \frac{|-17.37 - (-17.5090)|}{17.5090} x100$$
$$E_{FAT2,WD} = 0.79\%$$

For FAT 2 under holiday conditions, the calculated received optical power was -17.5090 dBm and the measured value was -17.19 dBm:

$$E_{FAT2,H} = \frac{|-17.19 - (-17.5090)|}{17.5090} x100$$
$$E_{FAT2,H} = 1.82\%$$

The comparison between the theoretical and measured received optical power is summarized in Table3.

Table 3. Comparison of Theoretical and Measured Received Optical Power

Distribution Point	**Measurement Condition**	**Calculated Received Power (dBm)**	**Measured Received Power (dBm)**	**Percentage Error (%)**
FAT 1	Working day	-17.4985	-17.64	0.81
FAT 1	Holiday	-17.4985	-17.66	0.92
FAT 2	Working day	-17.5090	-17.37	0.79
FAT 2	Holiday	-17.5090	-17.19	1.82

The percentage error obtained from the four comparisons ranged from 0.79% to 1.82%. These values quantify the deviation between the theoretical PLB calculation and the field measurements at the two FAT points under working-day and holiday conditions. The results were subsequently used to evaluate the consistency of the PLB model with the actual optical conditions of the investigated residential FTTH GPON network.

3. Results and Discussion

This section presents the results of the Power Link Budget (PLB) analysis and field measurements conducted in the residential FTTH GPON network. The analysis focuses on comparing theoretical PLB calculations with actual received optical power values measured at different Fiber Access Terminal (FAT) points. The comparison was performed to evaluate the accuracy and reliability of the PLB model under real deployment conditions involving multi-stage splitter configurations. Furthermore, the discussion examines the factors influencing optical attenuation and analyzes the consistency between theoretical predictions and field measurement results.

3.1 Power Link Budget Calculation Results

Based on the defined parameters, power link budget calculations were performed to estimate the theoretical received optical power at each FAT point. The calculated results represent the expected signal level under ideal installation and operational conditions.

Table 4. Power link budget calculation results

FAT point	**Total Loss (dB)**	**Theroetical Received Power (dBm)**
FAT 1	21.198	-17.498
FAT 2	21.209	-17.509

Table 4 indicates that the total optical loss for both FAT links is approximately 21.2 dB, resulting in theoretical received power values of −17.498 dBm for FAT 1 and −17.509 dBm for FAT 2. The small difference between the two links reflects the similarity in network configuration and link length. These values fall well within the acceptable GPON receiver sensitivity range, suggesting that the network is theoretically feasible from a power budget perspective.

3.2 Field Measurement Analysis

To validate the theoretical calculations, field measurements were conducted at the FAT points under different temporal conditions. Measurements were taken during weekdays and weekends to evaluate the consistency of the received optical power under different network operating conditions.

Table 5. Field measurement results of received optical power

FAT Point	Weekday (dBm)	Weekend (dBm)
FAT 1	-17.64	-17.66
FAT 2	-17.37	-17.19

The measurement results in Table 5 show that the received optical power ranged from −17.19 dBm to −17.66 dBm. For FAT 1, the measured received optical power was −17.64 dBm on the weekday and −17.66 dBm on the weekend. Meanwhile, FAT 2 recorded −17.37 dBm on the weekday and −17.19 dBm on the weekend. The difference between weekday and weekend measurements was relatively small for FAT 1, while a larger variation was observed at FAT 2.

These variations do not necessarily indicate changes in the passive optical path itself because optical attenuation in a passive GPON distribution network is primarily determined by physical components such as fiber length, connectors, splices, and optical splitters. Differences between repeated measurements may also be associated with practical installation and measurement conditions, including connector condition, fusion-splice imperfections, fiber bending, and measurement uncertainty. Therefore, the measured values should be interpreted as field observations that may exhibit small deviations from theoretical PLB values.

To visually evaluate the relationship between theoretical predictions and field measurements, a scatter plot with a linear regression trendline was used. The theoretical received optical power was plotted on the x-axis, while the measured received optical power was plotted on the y-axis.

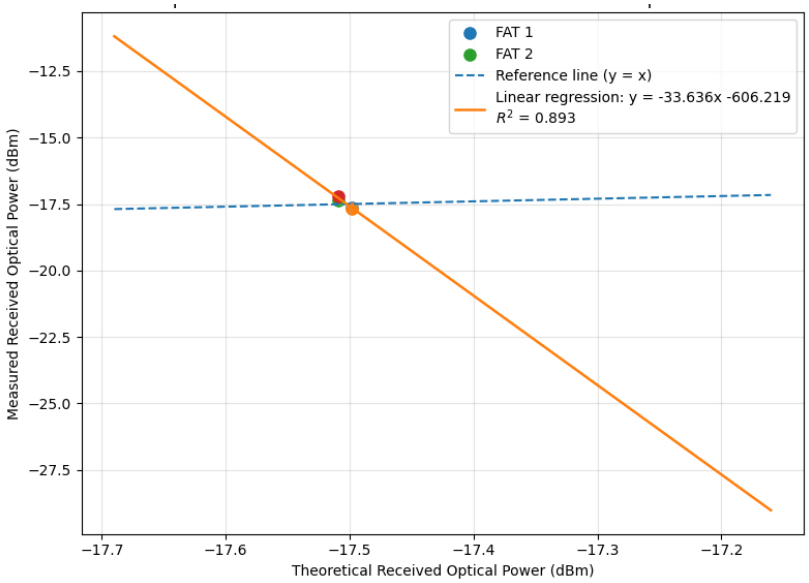


Figure 2. Comparison between theoretical and measured received optical power

Figure 2 presents the relationship between the theoretical and measured received optical power values. The reference line (y = x) represents an ideal condition in which the measured value is identical to the theoretical value. In addition, the linear regression trendline is included to quantify the relationship between the theoretical and measured values. Based on the four measurement observations, the regression equation is:

$$y = -33.636x - 606.219$$

with a coefficient of determination of:

$$R^2 = 0.893$$

The (R^2) value indicates a strong linear relationship between the theoretical and measured values within the limited dataset evaluated in this study. However, the regression result should be interpreted together with the point-by-point accuracy analysis presented in Section 3.3 because the dataset consists of measurements from only two FAT points. The deviations of individual measurements from the (y = x) reference line demonstrate that practical field conditions can produce differences from the ideal theoretical PLB calculation.

3.3 Model Accuracy Evaluation

To quantitatively assess the validity of the power link budget model, a direct comparison between theoretical and measured received power values was conducted. The accuracy level was calculated to evaluate how closely the model represents real field conditions.

Table 6. Accuracy evaluation between theoretical calculation and field measurement

FAT Point	Accuracy (%)	Deviation (%)
FAT 1	99.0-99.1	0.9-1.0
FAT 2	98.2-99.2	0.8-1.8

Table 6 demonstrates that the accuracy of the power link budget model ranges from 98.2% to 99.2%, with maximum deviations below 1.8%. These results indicate a strong agreement between theoretical predictions and field measurements. The small deviation observed can be attributed to installation tolerances, connector conditions, and minor measurement uncertainties. Overall, the results confirm that the power link budget model provides a reliable representation of actual optical performance in residential FTTH GPON networks.

In addition to point-by-point comparison, the overall accuracy of the power link budget model is summarized to emphasize its reliability as a planning tool.

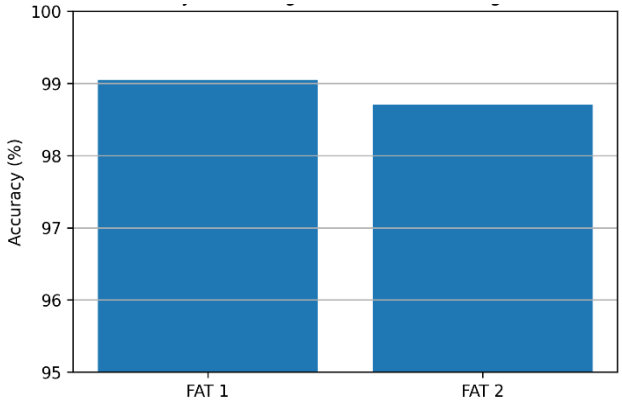


Figure 3. Accuracy percentage of the power link budget model

Figure 3 shows that the accuracy percentage for both FAT points exceeds 98%, demonstrating the robustness of the power link budget model in representing real network behavior. Such high accuracy indicates that the model can be confidently used during the planning and evaluation stages of residential FTTH GPON deployments, provided that standard installation practices are followed.

The small deviation between theoretical and measured values confirms that the PLB model accurately represents real network conditions in residential FTTH GPON deployments. The dominant loss contribution was caused by splitter components, while traffic load variations

did not significantly affect optical attenuation, as expected in passive optical networks (Grigoraș et al., 2021; Farid & Nugroho, 2025).

Overall, the results demonstrate a strong agreement between the theoretical power link budget model and field measurement outcomes in the evaluated residential FTTH GPON network. The consistently high accuracy, exceeding 98% across all evaluated links, indicates that the model reliably captures the dominant optical loss mechanisms, particularly those introduced by multi-stage splitter configurations. Minor deviations between calculated and measured values can be attributed to practical installation factors and measurement tolerances rather than limitations of the model itself. These findings confirm that the power link budget approach remains a robust and dependable tool for evaluating and planning residential FTTH GPON deployments under comparable network configurations.

4. Conclusion

This study evaluated the accuracy of the Power Link Budget (PLB) model by comparing theoretical calculations with field measurements obtained from a residential FTTH GPON network employing multi-stage splitter configurations. The comparison results demonstrate that the PLB model achieved an accuracy level exceeding 98%, with maximum deviations below 1.8% between theoretical predictions and measured received optical power values.

The findings confirm that the power link budget model provides a reliable representation of actual optical performance in residential FTTH GPON networks and are consistent with previous optical access network studies involving advanced PON architectures (Putra et al., 2025). The close agreement between calculated and measured values indicates that standardized PLB parameters are capable of representing real operational conditions with high consistency.

The results also show that splitter components contribute the dominant portion of optical attenuation within the evaluated network architecture, while variations in traffic conditions between weekdays and weekends do not significantly affect received optical power levels. This behavior is consistent with the characteristics of passive optical network architectures, where attenuation is primarily determined by physical transmission components rather than traffic intensity.

Compared with previous studies that mainly focused on simulation or theoretical feasibility analysis, this study contributes empirical validation using real field measurements from an operational residential FTTH GPON environment. Therefore, the study strengthens the practical applicability of the PLB model as a reliable planning and evaluation tool for optical access network deployment.

Nevertheless, this study is limited to a relatively small-scale residential GPON network with specific splitter configurations and transmission distances. Future studies may incorporate additional performance parameters such as Rise Time Budget, Bit Error Rate (BER), Quality of Service (QoS), and larger-scale deployment scenarios to provide more comprehensive evaluation of FTTH GPON network performance under broader operational conditions.

Acknowledgement

The authors would like to acknowledge the support provided by Universitas Bung Hatta.

Funding

The author(s) received no specific funding for this work.

Author Contribution

Arnita conducted field measurements, collected network data, and performed preliminary analysis. Zulfadli supervised the research process, validated the methodology, and reviewed the manuscript. Tiara Resti Indah Rahmawati contributed to data processing, figure preparation, and result visualization. Aswan Muhammad Azizi and Sangkot Wahyu Pulungan assisted in network configuration analysis, technical validation, and interpretation of optical transmission performance results.

Declaration of generative AI in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, grammar improvement, and manuscript preparation. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data Availability/Supplementary Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universitas Bung Hatta.

Conflict of Interest

All authors state that they have no conflict of interest.

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