Digital Innovations & Contemporary Research in SCIENCE, ENGINEERING & TECHNOLOGY
Vol. 13. No. 3, 2025 Series

Article Citation Format
Osunniyi A.S., Adeleke, O.A., Abdulsalam, T.G. & Ajao, W. (2025): Comparative Evaluation of Path Loss Prediction Models for Wireless Communication within Tropical Rainforest of Ile-Ife, Nigeria. Journal of Digital Innovations & Contemporary Research in Science, Engineering & Technology. Vol. 13, No. 3. Pp 17-26
www.isteams.net/digitaljournal
dx.doi.org/10.22624/AIMS/DIGITAL/V13N3P2

Article Progress Time Stamps

Article Type: Research Article
Manuscript Received: 18th July, 2025
Review Type: Blind Peer
Final Acceptance: 19th September, 2025

Comparative Evaluation of Path Loss Prediction Models for Wireless Communication within Tropical Rainforest of Ile-Ife, Nigeria

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ABSTRACT

Accurate radio propagation modeling is vital for effective wireless network planning, especially in forested environments with significant signal degradation. As vegetation becomes harder to avoid in outdoor wireless channels, the limitations of existing models due to location-specific dependencies challenge general applicability. This study evaluates and compares three widely used path loss prediction models: Free Space, Stanford University Interim (SUI), and Electronic Communication Committee-33 (ECC-33) within a tropical rainforest in Ile-Ife, Southwest Nigeria. Field measurements were conducted at Aba Iya-Gani and Ajigbona using a 3-axis Radio Frequency field strength meter (TM-196) and a mobile phone equipped with G-NetTrack Lite, Google Maps, and Keyhole Markup Language files. Signal strength data, including electric field strength and power density, were collected over distances ranging from 0.1 km to 1.5 km, with an antenna height of 1.5 meters. MATLAB R2021a was used to simulate the results obtained from the two regions, the Standard Deviation (SD), Mean Square Error (MSE), and Root Mean Square Error (RMSE) for each model were computed. The Free Space model had the highest RMSE of 31.55, indicating poor predictive accuracy. ECC-33 showed moderate performance with a RMSE of 23.29. The SUI model, however, performed best with an RMSE of approximately 19.13, along with the lowest MSE and SD values. These findings demonstrate that the SUI model provides the most accurate and consistent path loss predictions in tropical forest environments. It is thus a reliable tool for network design and planning in similar climatic settings.

Keywords: Propagation, Attenuation, Path Loss Models, Tropical Rainforest, Root Mean Square Error.

1. INTRODUCTION

The evolution of wireless communication has significantly changed and influenced every area of modern life. The discovery has paved the way for more meaningful and valuable research in communication in general (Obot *et al*., 2011).

Wireless mobile communication networks have become much more pervasive than anyone ever dreamt of when the cellular concept was first developed (Nadir *et al*., 2008). Today with high-quality and high-capacity networks in demand; estimated coverage has become exceedingly important. Therefore, filed measurement must be considered for the signal strength for a more accurate design of modern cellular networks. The cellular concept came into the picture and made a significant difference in solving the problem of spectral congestion and user capacity (Surajudeen *et al.,* 2011).

In terrestrial cellular radio systems, radio signal propagation uses any combination of these three basic propagation mechanisms: diffraction, scattering, and reflection. One of the most distinct characteristics of the propagation environment is path (propagation) loss (Stubber, 2001; Sharma, 2007). Path loss may be due to many effects, such as free-space loss, diffraction, reflection, refraction, aperture-medium coupling loss, and absorption (penetration) loss. Terrain contours, propagation medium (dry or moist air), environment (urban or rural, vegetation and foliage), the distance between a base transceiver station (BTS) and mobile station (MS), and the height and location of transmitting and receiving antennas are other factors that influence path loss (Obot *et al.,* 2011).

In this research, comparative evaluation of a path loss prediction models for wireless communication the effects of tropical rainforest on wireless communication system in Ife tropical rainforest were look into. The specific objectives are to conduct field measurement in Ife tropical rainforest environment at 2.6 GHz using field strength meter; derive empirical data from the measurements taken for the selected empirical model (Free space, Stamford University Interim and Electronic Communication Committee-33 models); and perform evaluation using standard deviation (SD), mean square error (MSE), and root mean square error (RMSE). The remainder of this pages is as follows: Section 2 review the literature while section 3 presented the materials and methods used. Section 4 highlights results and discussions and section 5 draws the conclusion.

2. REVIEW OF RELATED WORKS

Elechi and Otasowie (2016) developed a model to predict indoor signal penetration using the Fresnel Refraction Coefficient and knife-edge diffraction principles. Their model considered free-space loss, material penetration loss, and environmental factors like human movement and furniture. They found that environmental dynamics significantly influenced indoor signal loss. Notably, plastered walls and curtains each reduced loss by 4 dBm. The model achieved mean squared errors between 1.6–2.1 dBm and a standard deviation of 11.1–11.5, indicating its predictive reliability. Akinlolu and Owolabi (2019) modeled UHF signal propagation from Ekiti State Television using linear regression. Field strength measurements were compared to ITU recommendations. The study assessed three models: Egli, Okumura-Hata, and COST-HATA. COST-HATA had the highest standard deviation (24.11), while Okumura-Hata and Egli yielded lower deviations (22.76 and 23.30), suggesting better alignment with real-world data.

Isaac and Kingsley (2021) evaluated 1800 MHz signal propagation using five models in Osun State: Erceg, Ericson, SUI, Log-normal Shadowing, and Cost-231 Hata. Measurements from a TEMs-equipped Ericson phone showed that the Log-normal Shadowing model delivered the best accuracy with an RMSE below 8 dB and the lowest relative error. However, these findings may not apply directly to forested terrains. Zakaria et al. (2021) applied regression to model wireless path loss using a spectrum analyzer (FSH6).

Measurements confirmed that path loss increases with distance, with 32 m identified as the breakpoint. The study highlighted attenuation as a result of multiple phenomena impacting signal transmission. Akhideno and Eguasa (2023) studied 910 MHz signal loss in suburban Benin using Call Info Lite software. Their results confirmed the widespread application of the Hata model in GSM/CDMA networks. However, the study overlooked critical antenna parameters like height, gain, and polarization, affecting path loss accuracy. Despite these efforts, most path loss models are based on temperate zones and not tailored to Nigeria's tropical rainforest environments. This study addresses that gap by evaluating path loss models under real field conditions in a rainforest setting.

3. MATERIALS AND METHODS

A Base Transceiver Station (BTS) operated by Globacom Nigeria Ltd in Ile-Ife was selected due to its accessibility and data availability. In-field measurements were conducted and compared with established prediction models to predict a reliable path loss model for cellular transmission in a tropical rainforest environment. Measurements were taken using a 3-axis RF field strength meter (TM-196) and a mobile phone preloaded with G-Net Track Lite, Google Maps, and Keyhole Markup Language (KML) files. Two locations were selected for the study: Aba Iya-Gani (IFE042) as a rural area (Region A) with coordinates 7.531389^{o}N and 4.570278^{o}E, and Ajigbona (IFE003) as an urban area (Region B) with coordinates 7.486666^{o}N and 4.535277^{o}E.

The KML file was loaded onto Google Maps to access site information, including site code, coordinates, and proximity. A GPS determined the distance between the BTS and the measuring device. G-Net Track Lite helped identify the serving sector (cell ID) and measure the Reference Signal Received Power (RSRP). The field strength meter was aimed at the signal source, and electric field strength and power density were recorded at intervals from 0.1 km to 1.5 km, maintaining a consistent mobile antenna height of 1.5 meters.

Figure 1. A 3-axis RF field strength meter (TM-196)

3.1 Description of the study area

Ife, also known as Ile-Ife, is a city in Osun state, Southwest Nigeria. It has an undulating terrain under metamorphic rocks and is located between latitude 7.4905°N and 4.5521°E. It comprises two local governments (Ife East and Ife Central) and shares borders with neighboring towns and cities, such as Ifetedo to the South, Ifewara to the Southeast, Osu to the Southwest, and the seven Origbo communities to the north.

3.2 Propagation Path Loss Predictions Models

Works of literature present several propagation models, and different researchers have employed these in analyzing the propagation path losses in their different geographical areas. The other reason for this is that research is environment-specific. Very little or no research has been carried out in this area in the chosen geographical region under consideration in this study.

3.2.1 Free Space Path Loss Model

The power in free space incident on the receiving antenna from the transmitting antenna is then given by (Sharma, 2007).

$$P_{Rec}(d) = \frac{P_{tx}G_{tx}G_{rx}\lambda^2}{16\pi^2 d^2} \quad (1)$$

where $P_{Rec}(d)$ is the power received, which is a function of transmitter and receiver separation distance, P_{tx} is the transmit power of the base station, G_{tx} is the gain of the transmitting antenna, G_{rx} is the gain of the receiving antenna, λ is the signal wavelength, d is the distance between the transmitter and the receiver in km.

Quantitavely, path loss in decibel is given as;

$$PL(dB) = P_t(dB) - P_r(dB) \quad (2)$$

When antenna gains are given, the free space path loss in decibel can be express as;

$$PL(dB) = 100log_{10}\frac{P_t}{P_r} = -10log_{10}\left(\frac{G_{tx}G_{rx}\lambda^2}{16\pi^2 d^2}\right) \quad (3)$$

When the gains of the antennas are unity (isotropic antenna), equation (3) can be written as;

$$PL(dB) = -10log_{10}\left(\frac{\lambda^2}{16\pi^2 d^2}\right) \quad (4)$$

Equation (4) can be rewritten after removing the negative sign and this yield;

$$PL(dB) = 10log_{10}\left(\frac{16\pi^2 d^2}{\lambda^2}\right) \quad (5)$$

According to (Nadir, *et al.*, 2008) substituting λ (km) = 0.3/f (MHz)), and rationalizing equation (5), gives the generic free space path loss formula which is given as;

$$PL(dB) = 32.5 + 20\log_{10}(f_c) + 20\log_{10}(d) \quad (6)$$

where f_c is the carrier frequency in MHz, d is the distance in km and PL(dB) is the path loss in decibel.

3.2.2 Stamford University Interim (SUI Model)

The model was formulated to operate with a cell radius of 0.1 km to 8 km, receiver antenna height of 1 m to 10 m, base station antenna height of 10 m to 80 m, and operating frequency above 1.9 GHz. This model categorized terrain into A, B, and C. The Category A terrain is a region that is densely populated and is associated with maximum path loss. Terrain category B is captured with moderate path loss. The Category C terrain is known for its minimum path loss and flat terrain with light tree densities (Shabir *et al*., 2011). The SUI model path loss is given as;

$$L_{PLSUI}(dB) = F_{FSPL} + 10mlog_{10}\left(\frac{d}{d_o}\right) + X_{fcf} + X_{bshcf} + S_{csf} \quad (7)$$

The free space attenuation parameter is given as,

$$F_{FSPL}(dB) = 20log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (8)$$

where m is the path loss exponent, F_{FSPL} is the free space path loss in decibels, d is the distance between the transmitting and receiving antenna in km, do is the reference distance in km (usually 0.1km), λ is the wavelength in meter, X_{fcf} is the correction factor for frequency above 2 GHz in MHz, X_{bshcf} is the base station height correction factor in meter, S_{csf} is the correction for shadowing in decibel. For shadow fading due to trees and other clutter on mobile radio paths, the log-normally distributed factor (S_{csf}) value is between 8.2 and 10.6 dB (Shabir *et al.*, 2011).

The path loss exponent m is given as;

$$m = a - bh_{bsh} + \left(\frac{c}{h_{bsh}}\right) \quad (9)$$

Where h_{bsh} is the height of the bas e station in meters usually 10 to 80 m.

The frequency correction factor (X_{fcf}) is expressed as;

$$X_{fcf} = 6log_{10}\left(\frac{f_c}{2000}\right) \quad (10)$$

where f_c is the carrier frequency in MHz.

The base station height correction factor (X_{bshcf}) for terrain A and B is given as;

$$X_{bshcf} = -10.8log_{10}\left(\frac{h_r}{2000}\right) \quad (11)$$

For terrain C, the base station correction factor (X_{bshcf}) is given as;

$$X_{bshcf} = -20log_{10}\left(\frac{h_r}{2000}\right) \quad (12)$$

where h_r is the receiving antenna height in meters.

The constant given for each terrain is given in Table 1.

Table 1: Numerical value for the SUI model parameters (Akinwole and Biebuma, 2013)

Model parameter	Terrain A	Terrain B	Terrain C
a	4.6	4.0	3.6
b(m^{-1})	0.0075	0.0065	0.005
c(m)	12.6	17.1	20

3.2.3 ECC-33 Model

The model was extrapolated from Okumura's original measurements and assumptions (Adeyemo *et al.*, 2016). The path loss model is defined as;

$$L_{P(ECC\text{-}33)}(dB) = K_{FSA} + K_{MPL} - G_{THGF} - G_{RHGF} \quad (13)$$

where $L_{P(ECC\text{-}33)}$ is the ECC-33 model path loss in decibels, K_{FSA} is the attenuation due to free space,

K_{MPL} is the basic median path loss, G_{THG} is the transmitter antenna height gain factor, G_{RHGF} is a gain factor for the receiver antenna height. Each specification in (2.13) is stated as follows: (Ekeocha et al., 2016).

$$K_{FSA} = 92.4 + 20\log(d) + 20\log(f) \quad (14)$$

$$G_{THGF} = \log\left(\frac{h_{bsah}}{200}\right)[13.98 + 5.8(\log d)^2] \quad (15)$$

where d is the distance between the mobile and base station in kilometer (km), f is the operating frequency in GHz, h_{bsah} is the transmitter antenna height in meters, h_{mst} is the mobile antenna height in meters.

For medium size cities G_{RHGF} is given as;

$$G_{RHGF} = [42.57+13.7\log(f)][\log(h_{mst}) - 0.585] \quad (16)$$

While for large cities we have;

$$G_{RHGF} = 0.759(h_r) - 1.862 \quad (17)$$

3.3 Performance Evaluation Metrics

Standard Deviation (SD), Mean Square Error (MSE) and, Root Mean Square Error were used to analyzed and determined the rate at which the measured value deviate from the predicted measurements.

3.3.1 Standard Deviation (SD)

The standard equation formula (σ) is given by equation 3.1;

$$SD(\sigma) = \sqrt{\frac{\Sigma(i-j)^2}{N}} \quad (18)$$

where i is the measured path loss from empirical model, j is the predicted path loss from the field and *N* is the number of samples.

3.3.2 Mean Square Error (MSE)

The mean square error formula is given by the equation below;

$$MSE = \frac{1}{N}\sum_{I=1}^{N}\left(L_m - L_p\right)^2 \qquad (19)$$

where L_m is the measured path loss (dB), L_P is the predicted path loss (dB), N is the number of measured data points.

3.3.3 Root Mean Square Error (MSE)

The root mean square error formula is given by the equation below;

$$RMSE = \sqrt{\frac{1}{N}\sum_{I=1}^{N}\left(L_m - L_p\right)^2} \qquad (20)$$

where L_m is the estimated path loss (dB), L_P is the predicted path loss (dB), N is the number of measured data points

4. RESULTS AND DISCUSSION

Results obtained from field measurements from region A and B were simulated on MATLAB R2021a. The performance evaluation of all the two regions was conducted, and the error metrics were presented as shown in Tables 2 and 3 respectively. The path loss models adopted (free-space, ECC-33, and SUI) for all the regions from a distance of 0.1 km to 1.5 km were computed. The Mean Square Error, Root Mean Square Error (RMSE) and Standard Deviation (SD) were computed for all the regions to evaluate the accuracy of different models.

Table 2: Region A Error metrics

Metric/Model	Free-space	ECC-33	SUI
RMSE	31.5591	23.2927	19.1350
SD	29.7345	24.1407	20.0368
MSE	995.9744	542.5477	366.1483

Table 3: Region B Error metrics

Metric/Model	Free-space	ECC -33	SUI
RMSE	32.0910	24.3863	18.9378
SD	35.8154	27.1488	20.9571
MSE	1029.8316	594.6936	358.6402

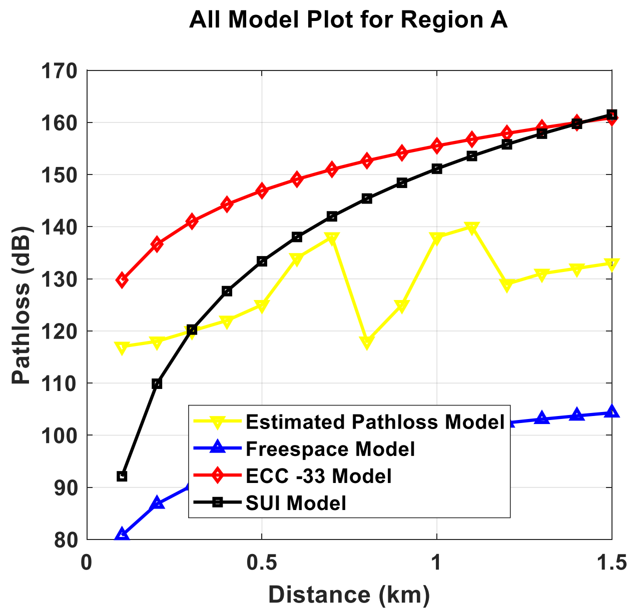

Figure 2: All Model Plot for Region A

The results show that the Free-space model significantly underestimates the path loss compared to the measured data, as shown in Figure 2. The standard deviation measures the spread of errors, indicating the consistency of each model. The Free space model shows the highest SD, of 29.7345, suggesting that its error values vary significantly from the mean. ECC-33 follows closely with a SD of 24.1407, while the SUI model has a lower SD of 20.0368, as shown in Table 2. This means the SUI model's predictions are more stable and consistent than the other two. A high SD in the Free-space model suggests that its errors are not uniformly distributed, leading to unpredictable deviations.

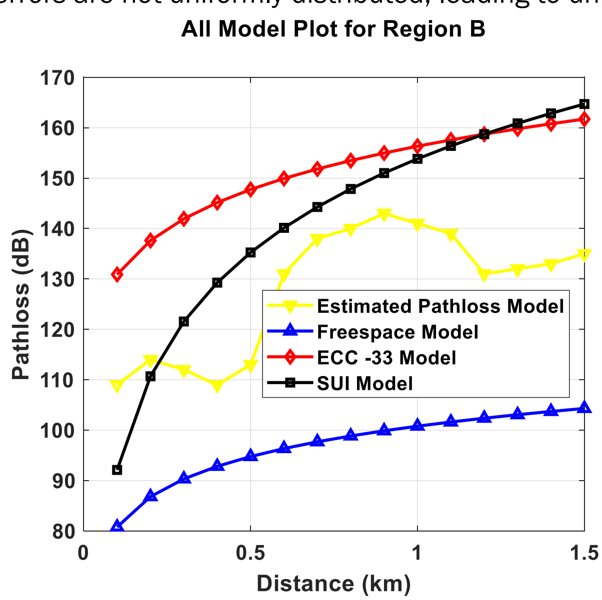

Figure 5: All Model Plot for Region B

The RMSE in Table 2 indicates that the Free-Space model has the highest error, with a RMSE of 32.0910. The ECC-33 model follows, with a RMSE of 24.3863, while the SUI model has the lowest RMSE of 18.9378. A lower RMSE suggests better prediction accuracy, implying that the SUI model outperforms the other two in minimizing error. The Free-Space model, having the highest RMSE, suggests significant deviations between predicted and actual values, making it the least accurate in this region.

Figure 5 shows all three models with the measured path loss data. The plot clearly shows that the SUI Model best fits the measured data, with the predicted path loss values closely matching the estimated path-loss. The Free-space and ECC-33 Models show significant discrepancies from the estimated result. While the Free-space model underestimates path loss significantly, particularly at larger distances, the ECC -33 model also predicts a steeper increase in path loss than observed in the actual measurements. This over/under estimation by both models indicates that they are less suitable for environments with non-line-of-sight conditions, complex terrain, or varying interference patterns.

The Standard Deviation (SD) comparison in Table 3 for the three path loss models, ECC-33, Free-space, and SUI, reveals significant differences in their prediction consistency. The Free-Space Model shows the highest SD of 35.8154, indicating that the model exhibits considerable variability in its predictions. This variability suggests that the model's predictions are inconsistent and likely to deviate significantly from the measured data, making it less reliable in this specific environment. In contrast, the ECC-33 Model has a moderate SD of 27.1488, which indicates a somewhat better consistency than the Free-Space model but still demonstrates considerable variability in predictions. The SUI Model, however, shows the lowest SD of 20.9571, reflecting the highest level of consistency in its predictions. This suggests that the SUI model most accurately tracks the measured path loss values, providing reliable and stable predictions that closely match the real-world data.

The Root Mean Square Error (RMSE) metric reinforces the findings from the MSE comparison. The Free-Space Model exhibits the highest RMSE of 32.0910, which indicates significant discrepancies between the predicted and measured path loss values. This result suggests that the Free-Space model is significantly less accurate, as the RMSE value indicates substantial deviations from the real-world measurements. The ECC-33 Model follows with a RMSE of 24.3863, reflecting considerable inaccuracy in its predictions. Although this value is lower than that of the Free-Space model, it still indicates that the ECC-33 model overestimates the path loss, especially in environments where real-world factors such as obstacles and interference are present. On the other hand, the SUI Model presents the lowest RMSE of 20.9571, demonstrating the least error in its predictions and making it the most accurate of the three models. The lower RMSE confirms that the SUI model better fits the measured data, offering more realistic and reliable path loss predictions, as shown in Table 3.

5. CONCLUSION

The results of the comparison between the three models, ECC-33, Free space, and SUI, have shown apparent performance discrepancies across various metrics, including Standard Deviation (SD), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). The SUI model demonstrated superior performance, with the lowest SD, MSE, and RMSE values, indicating higher accuracy, reliability, and consistency than the other models.

On the other hand, the Free-space model displayed the highest error values and variability, suggesting that it is less reliable and more prone to inconsistent predictions. ECC-33, while performing better than Free space, still exhibited moderate levels of error and variability, positioning it between the extremes of SUI and free space. The findings strongly suggest that the SUI model is the most effective for predictive accuracy and reliability.

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