

# Comparative Evaluation of Path-Loss Models in a Typical African Terrain using Homogenous Grid Outdoor Foot Measurement Technique



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**ABSTRACT:** Several works had been carried out on the comparative analysis of mobile signal propagation path loss at various locations in Africa. The assessments of relevant literature reveal that many, if not all, give no consideration to the peculiar African road networks, irregular building orientations, and patterns that usually prevent the driving of motor cars within when taking the signal strength measurements. This article presents a comprehensive analysis of mobile signal propagation path loss within the Ilorin metropolis. The method adopted for measurement is the homogeneous grid outdoor foot measurement technique; it gives consideration to the peculiar African road networks and irregular building orientations and patterns. GSM signal strengths were measured at various study locations within the Ilorin metropolis and the data obtained were used for path loss calculations. These results were then compared with several widely used and well-established empirical models that are commonly applied in contemporary research and practice. The findings revealed the measured path loss values at all the study locations swing between the COST-231-Hata and Eglis models forecast values. COST-231-Hata model may be adjusted to ensure precise forecasting of radio signals for cellular transmission in Ilorin and identical terrains.

**KEYWORDS:** Loss, RMSE, SD, BTS, FSPLM, PEPLM, EPLM

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## I. INTRODUCTION

Accurate path loss prediction is a key parameter in the design, planning, and optimization of wireless cellular networks, as it directly influences cellular system coverage estimation, interference management, and link budget analysis (Akanni *et al.*, 2023). In practice, especially with a complex terrain characterized by rapidly growing urban centers, signal propagation is significantly affected by features such as irregular building layouts, clustered settlements, undulating terrains, and non-uniform road networks (Ogochukwu *et al.*, 2022; Imoize *et al.*, 2019). These factors introduce additional attenuation through reflection, diffraction, and scattering, making reliable path loss prediction particularly challenging. Path loss may be described as the decline in energy density of a radio signal as it travels across space or barriers (Akanni *et al.*, 2024)

Several works had been carried out on the comparative analysis of mobile signal propagation path loss at various locations in Africa. The study reveals that in order to adequately forecast path loss for better wireless service quality, various propagation path loss models were suggested for different environments. The resulting models are environment-specific (Akanni *et al.*, 2024). The widely adopted models such as COST-231-Hata, Egli, and Walfisch-Ikegami exhibit inconsistent prediction accuracy across different terrains. For instance, Erunkulu *et al.*, (2023) shows that propagation characteristics during measurement campaigns vary

significantly with environmental features, leading to notable deviations between predicted and measured path loss values. Similarly, Azevedo and Mendonça (2024) and Nabaa and Hussain (2024) validated also that conventional empirical models fail to adequately capture the effects of complex urban varying topology, emphasizing the need for environment-specific validation.

Also, comparative analyses of empirical models in African and similar environments further confirm that no single model consistently outperforms others across all environmental topography scenarios. Studies such as Oluwatoki *et al.*, (2023) and Akande *et al.*, (2023) reported that traditional models tend to either underpredict or overpredict path loss depending on the propagation environment, thereby pointing to localized evaluation and adaptation. These findings support the stance that empirical path loss prediction models must be calibrated using real measurement data to improve their predictive reliability. Additionally, Abiodun and Idogho, (2022) compared the path loss prediction between six major statistical path loss models and the observed data obtained in a large city, a medium city, and rural areas of two states in the western part of Nigeria. A driving test was conducted to collect measurement data. The results revealed that three out of the models employed underestimated the path loss prediction in all settings, while only one out of the models employed gave the most appropriate path loss prediction for suburban areas but overpredicted path loss in urban areas. To choose the optimum

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model for cellular service implementation, Enyi *et al* (2021) compared the path loss prediction between some path loss models in urban microcellular regions in Nsukka, Nigeria. The result reveals that COST 231-Hata Model gives the closet path loss perdition to the developed model. While the ECC-33 and the SUI models over predicted and Hata model under predicted the path loss.

Furthermore, a comparison between the Egli and Lee path loss models was carried by Ibe *et al* (2019) based on the measured data obtained along Idoro Road, a dual carriageway that covers both the urban and rural areas of Uyo, Nigeria. The result shows that Egli gives the most accurate forecast with an RMSE of 26.6 dB for the urban area, while the Lee model gives the best prediction result for the rural area. Gadze *et al* (2020) assessed six propagation models to develop an acceptable path loss model for LET in a relatively wide and sparsely populated area of Ghana. The data was acquired using drive testing with a Genex probe attached to cellphones via a computer's USB interface. Finally, redesigned equations that could be employed to improve LET performance in Ghanaian situations were developed.

The reliability of propagation studies is strongly influenced by measurement methodology (Akanni *et al*, 2023). Traditional drive-test techniques, although widely used, often fail to capture signal variations in inaccessible or non-motorable areas, resulting in incomplete datasets and biased model validation (Mollel and Kisangiri 2014; Pawar and Venkatesan 2024). Recent studies emphasize the importance of comprehensive measurement strategies that account for spatial variability across heterogeneous terrains (Erunkulu *et al*, 2023; Azevedo and Mendonça 2024).

The reviews of the many relevant research work available show that all of the authors conducted driving tests to obtain the actual field data (signal strength values) in the study region. Although some of the field data obtained by the car drive test method may be correct, the method may greatly affect the accuracy of many of the measured values because it does not allow access to many important locations due to the unmotorable road networks between the irregular building patterns, low valleys, and high hills in African settings. The objective of this research is to use a more accurate technique that can be used for reliable signal strength measurement values, with the intention of comparing the path loss forecasts between empirical path loss models and the actual field data obtained through measurement in African settings when carrying out a comparative analysis of mobile signal propagation path loss at various locations in Africa.

## II. THEORETICAL ANALYSIS

The two types of propagation models are: deterministic and empirical (statistical). The forecasting of radio path loss and coverage through deterministic means relies on the application of actual concepts governing wave propagation (Pawar and Venkatesan, 2024). When employing this approach, a thorough examination of all environmental factors must be considered. The deterministic approach necessitates complex computations and a substantial quantity of topographical information (Erunkulu *et al*, 2023). If properly configured, the

results can be typically accurate and extremely close to the environment's actual path loss.

Empirical approaches for predicting signal path loss rely on computed average values derived based on signal connection attenuation studies (Erunkulu *et al*, 2023). These average values are subsequently exploited in the anticipated model to provide estimates that depend on the frequency and transmission path span. The Free Space, Plane Earth, Egli, COST-231-Hata, and COST-231-Walfisch-Ikegami (COST-231-WIM) concepts constitute some of the most often used and recognized empirical models that are extensively utilized and acknowledged in contemporary research and practice (Akanni *et al*, 2024).

### A. Free Space Path Loss Model (FSPLM)

The fundamental benchmark for all propagation models is the free space propagation model. In an ideal circumstance, radio transmission in empty space travels in straight lines with no obstruction that can induce attenuation (Ayidu and Elaigwu, 2023; Oguejiofor *et al*, 2013). According to the free space concept, the obtained signal quality is inversely related to the distance that exists between the source and the destination multiplied by two. Eqn. 1 as cited by (Akanni *et al*, 2024) defines FSPLM as:

$$P_{L(FSL)} = 32.40 + 20 \log(f) + 20 \log(r) \quad (1)$$

$P_{FSPL}$  refers to the path attenuation in dB,  $f$  reflects the frequency of radio transmission in MHz, where  $r$  represents the interval of separation between the BTS aerial and the mobile station (MS) aerial.

### B. Plane Earth Path Loss Model (PEPLM)

The open space model signal prediction makes the assumption that there are no impediments in the way that might potentially weaken the signal. In reality, such a perfect condition does not occur; hence, a different wave propagation model called plane earth path loss (PEPL) that accounts for wave reflection was created (Nadir and Ahmad, 2010). In this scenario, a radio wave hits a surface and is sent back in the same way that light rays bounce back, with the amount of reflection fluctuating depending on what percentage of the wave is absorbed by the reflecting surface. The characteristics of the surface determine the intensity of the reflected wave (ITU-R P.525-2, 2000). The Plane Earth Propagation equation is given in Eqn. 2 (Leonard and Nnamani, 2015) as:

$$P_{PEPL} = 40r - 20 \log h_b - 20 \log h_m \quad (2)$$

$P_{PEPL}$  refers to the path attenuation in dB,  $r$  reflects the gap in meters linking the BTS and MS aerials, and  $h_b$  and  $h_m$  denote the elevations in meters of the BTS and the MS aerials, respectively.

### C. Egli Path Loss Model (EPLM)

The Egli model was launched in 1957 (Abu *et al*, 2020). It is a semi-empirical model that assumes a smoothly rolling landscape. As a result of this presumption, no topographical elevation information is needed between the broadcast and receiving stations. In this model, the open-air broadcasting signal attenuation is corrected to account for broadcaster and reception aerials' elevation beyond the ground's level (Akande

*et al*, 2023). It is appropriate in mobile communication when one of the antennas is stationary and the other is movable not when any kind of vegetation gets in the way of the connection (John and Yekeen, 2013). Eqn. 3 describes the Egli Path Loss Model as follows:

$$P_{EPLM} = \begin{cases} 6.3 + 20\log f + 40\log r \\ -20\log h_b - 10\log h_m \end{cases} \quad (3)$$

$P_{EPLM}$  stands for power in decibels,  $r$  represents the gap in kilometers linking the base station transceiver and mobile unit aerials,  $h_b$  stands for the elevations (m) of the base transceiver station aerial,  $h_m$  for the mobile unit aerial, and  $f$  for transmission rate (MHz).

#### D. COST-231-Hata Path Loss Model

A group of committees constituted by the European Cooperation in the discipline of Scientific and Technical Research (EURO COST) increased the frequency ban in the Hata-Okumura model to 2 G (Igbonoba, 2021; Enyi *et al*, 2021). It is an empirical model that is most frequently employed (Abraham *et al*, 2013). In this model, an area type factor was incorporated, and the system frequency was raised to 2G (Raturi *et al*, 2014). As shown in Eqn. 4 (Enyi *et al*, 2021) Cost-231- Hata Path loss Model is given as:

$$P_L = \begin{cases} 46.3 + 32.4 \log_{10} f - 18.82 \log_{10} h_b \\ -a(h_m) + (44.9 \\ -6.55 \log_{10} h_b) \log_{10} d + C_m \end{cases} \quad (4)$$

$$a(h_m) = \begin{cases} 3.2(\log(11.7554h_m))^2 \\ \text{for large cities } f \geq 300 \text{ MHz} \end{cases} \quad (5)$$

$$C_m = 3 \text{ dB for large cities} \quad (6)$$

$r$ ,  $h_b$ , and  $h_m$  represent the gap (in kilometers) linking the base transceiver station and the mobile unit aerials, the elevations (m) of the base transceiver station and the mobile unit aerials, respectively; the transmission frequency is given as  $f$  (MHz), and the adjustment modification factor for the optimal mobile unit aerial elevation is  $a(h_m)$ .

#### E. COST-231-Walfisch-Ikegami (COST-231-WIM) Path Loss Model

It is a hybrid of two models (Seker *et al*, 2010). It is an amalgamation of experimental and statistical methods designed to quantify wireless signal degradation in a particular landscape using frequencies that span 800 to 2000 MHz. The model has three components: roof-to-street diffraction dispersion loss, multi-screen, and open-air loss. Cost-231 WIM took into account two distinct instances, as stated in Eqns. 7 and 8 (Seker *et al*, 2010) this order:

Line of Sight (LOS):

$$L_{50} = 42.60 + 26 \log r + 20 \log f \quad (7)$$

Non-Line-of-Sight (NLOS):

$$L_{50} = L_f + L_{rts} + L_{msd} \quad (8)$$

$L_{50}$  denotes the mean path degradation (dB) decibel;  $L_f$  implies open-air loss (dB);  $L_{rts}$  indicates bending and scattering loss in (dB) from rooftop to street, and  $L_{msd}$  implies multiple-screen loss in (dB).

$$L_f = 32.4 + 20 \log(f) + 20 \log(r) \quad (9)$$

$r$  is transmitter-to-receiver geographical separation,  $r$ , ranges between 200 and 5.0 km, whereas  $f$  represents the transmission frequency.

$$L_{rts} = \begin{cases} 16.9 + 10 \log(b) + 20 \log(\Delta d) \\ -10 \log(w) + L_{ori} \end{cases} \quad (10)$$

The roadway width is indicated by the character "w" (in meters);  $h$  denotes the elevation of the mobile unit aerial beneath rooftops (in meters);  $b$  denotes the building spacing (between 20 and 50 meters); and  $L_{ori}$  serves as the roadway-orienting feature.

### III. METHODOLOGY

#### A. Description of the Study Environment

The study was conducted in Ilorin metropolis located within latitudes 8.410 N and 8.550 N and longitudes 4.490 E and 4.650 E and covers an area of about 89 km<sup>2</sup> Aremu *et al* (2015), a typical urban environment in North-Central Nigeria characterized by heterogeneous terrain features including irregular building layouts, clustered settlements, undulating topography, and non-uniform road networks. This location is a typical realistic representation of many rapidly developing African cities, where propagation condition varies different from most of the assumption made in existing conventional empirical models. Multiple measurement locations were selected to capture diverse terrain characteristics, ensuring that the dataset reflects spatial variability in signal propagation. Figure 1 shows the Google Map of Ilorin Metropolis (Google Map, 2024), while Figure 2 shows the Contour Map and region (A1 to A9) of the Study Location

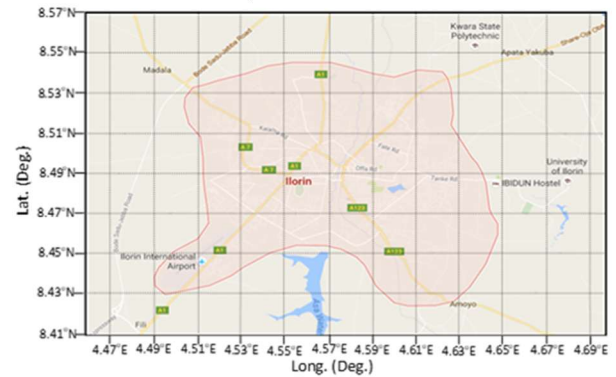


Figure 1 Google Map of Ilorin metropolis (Google Map, 2023)

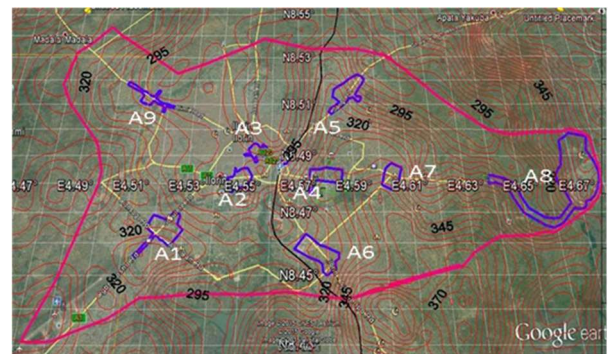


Figure 2 The Contour Map and Regions (A1 to A9) of the Study Location

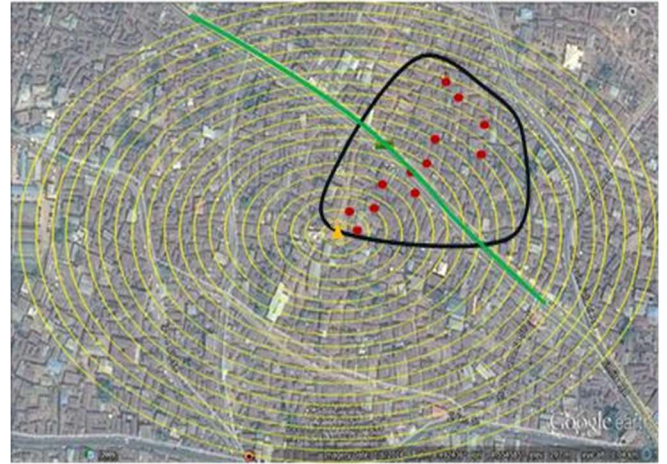
#### B. Data Collection

The measurement approach adopted in this study follows the grid-based outdoor technique previously proposed in

Akanni *et al.*, (2024). Field measurements of received signal strength were obtained across multiple locations using a structured grid-based outdoor sampling approach. Measurements were collected at incremental distances from selected base transceiver stations (BTSs), typically ranging from 0.1 km to 1 km. At each measurement point, the received signal strength indication (RSSI) was recorded under active communication conditions to ensure continuous connectivity with the serving BTS. The measurement dataset includes: BTS parameters (frequency, antenna height, location), measurement distance from BTS and recorded RSSI values using Tecno Pouvoir 3 Plus Android cell phone equipped with the Network Signal Info software (Kaibits Software GmbH). Figure 3 depicts the Google Earth aerial image of the first research zone, which comprises of clusters irregular building patterns, regular grid lines, and non-motorable road networks.

The antenna height of the mobile unit was 1.5 m. Table 1 shows each of the BTS specifications employed to determine the appropriate path loss for the various study locations. The experimental outcomes of the recorded signal strength and distances associated with the various BTS 1–9 at the specified

study zones (locations) throughout the Ilorin metropolis were recorded. The recorded signal strengths and distances were utilized to calculate the signal path loss from the measured signal data using Microsoft Excel's statistical "Ad-in" feature (Akanni *et al.*, 2023).



**Figure 3** The Google Earth Aerial Image of the First research zone with the Cluster Irregular Building Patterns, homogeneous grid Line and Non-motorable Roads Networks

**Table 1** The Chosen Base Station Parameters

BTS No.	Study Location	Freq. (MHz)	Long. (m)	Lat. (m)	Elevation (m)	Height (m)
1	Tanke	1855.4	4.61	8.49	356	28
2	Offa-Garage	1841.4	4.61	8.49	326	30
3	G. R. A	1820.4	4.58	8.49	335	28
4	Post Office	1826.4	4.56	8.50	264	25
5	Saw-mill	1820.6	4.53	8.47	328	30
6	Unilorin	1851.2	4.67	8.48	342	30
7	Oloje	1820.2	4.52	8.52	294	30
8	Edun/Emir's Rd	1854.4	4.56	8.49	281	28
9	Taiwo Rd.	1826.2	4.56	8.49	290	33

### C. Data Analysis

The path loss is calculated using Eqn. 11.

$$P_{Loss}(dBm) = P_t(dB) - R(dBm) \quad (11)$$

$P_{Loss}(dBm)$  is the calculated path loss,  $P_t(dB)$  is the BTS output power in dB, and R is the measured signal strength in dBm.

In addition, comparison of the actual measured to the predicted path losses was also carried out based on the RME and SD as given in Eqns. 12 and 13.

$$RMSE = \sqrt{\left\{ \frac{1}{N} \left[ \sum_{i=1}^{i=N} (PL_{mi}) - PL_{pi} \right]^2 \right\}} \quad (12)$$

$$SD = \sqrt{\left\{ \frac{1}{N-1} \left[ \sum_{i=1}^{i=N} (PL_{mi}) - PL_{pi} \right]^2 \right\}} \quad (13)$$

Where,  $PL_{mi}$  is the measured path loss at position i in decibel,  $PL_{pi}$  is the calculated path loss at position i in decibel, and N is the number of measured path loss samples.

## IV. RESULTS AND DISCUSSION

The measured signal strength obtained from the experiment carried out was used to calculate the actual signal path loss. Also, the prediction models (empirical models) discussed in section II had been used to estimate the signal path losses. Signal path losses were computed for distances from about 0.1 km to 1 km. The approach used to obtain the signal strength measurements (homogeneous grid outside foot technique) provides several benefits over the customary common drive-test approach as it gives room to cover important unmotorable locations that could not be navigated by using motor car drive test method. Another benefit beyond the driving test approach is the decrease in systematic errors caused by appropriately data windowing and averaging ascribed to the steady measurement at the same spot being recorded.

Figures 4 through 12 depict the path loss variance plotted versus distance linked with the BTSs regards to each study location for the observed and computed path losses. It is noticed that the path loss escalates with distance for all the BTSs in all the study locations. This increase in path losses

can be traced to GSM signals being reflected, diffracted, and scattered by obstacles. It is also established that the observed path-loss data are not always consistent with any of the investigated models, and this proves the fact that no one model is appropriate for all settings.

Further analysis shows that for all places tested, the observed path loss falls between the Cost-231-Hata and Egli models. The WIM model appears to forecast significantly larger path losses in all scenarios, and this can be traced to the fact that there were no real uprising buildings in the metropolis. For this reason, the WIM model is an unsuitable technique for forecasting path losses in settings identical to Ilorin City.

Furthermore, for most of the study areas investigated, the FSPLM and PEPLM underperform when employed in the path-loss evaluation. The outcome shows that when forecasting the path losses for places that are identical to the Ilorin setting, which describes the majority of Nigerian cities, the FSPLM and PEPLM will underestimate the path losses, resulting in layouts that may accomplish below-desired outcomes because true path losses are guaranteed to be low. However, the WIM has a tendency to overestimate path loss, which might lead to overdesign when building mobile network configurations.

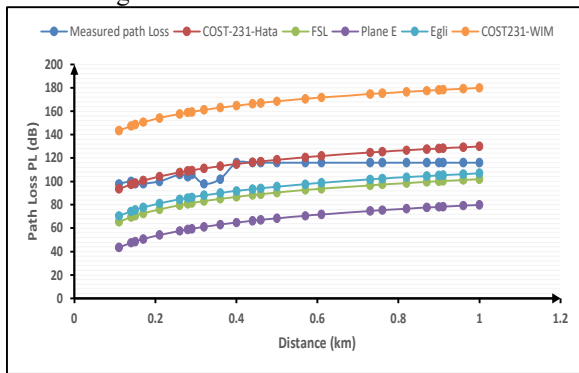


Figure 4 The Plot of path loss (dBm) against distance (km) for BTS 1 at Edun/Emir's Rd, Ilorin, Nigeria

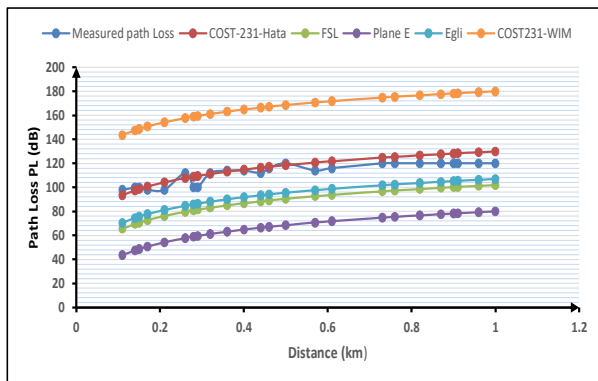


Figure 5 The Plot of path loss (dBm) against distance (km) for BTS 2 at Tanke, Ilorin, Nigeria

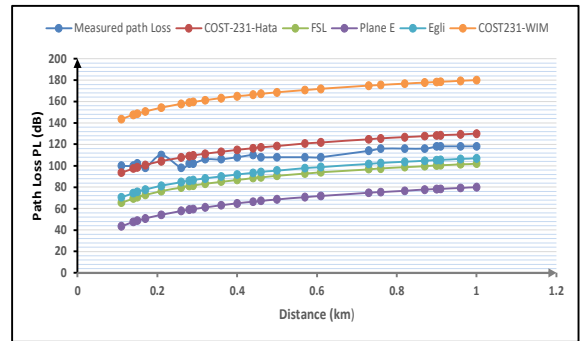


Figure 6 The Plot of path loss (dBm) against distance (km) for BTS 3 at Offa Rd, Ilorin, Nigeria

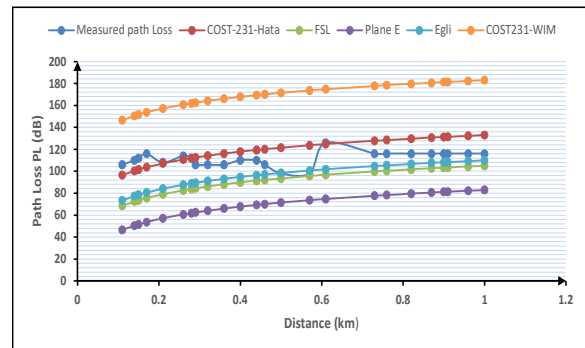


Figure 7 The Plot of path loss (dBm) against distance (km) for BTS 4 at G. R. A., Ilorin, Nigeria

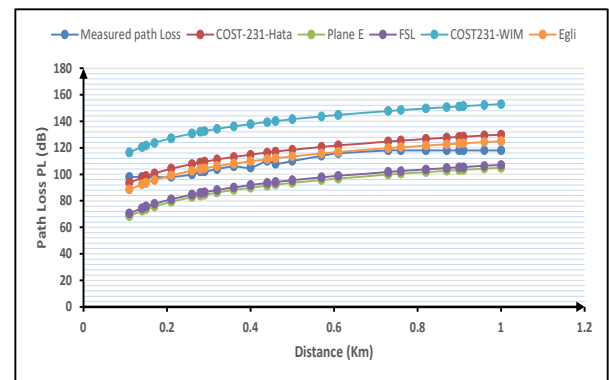


Figure 8 The Plot of path loss (dBm) against distance (km) for BTS 5 at Post Office., Ilorin, Nigeria

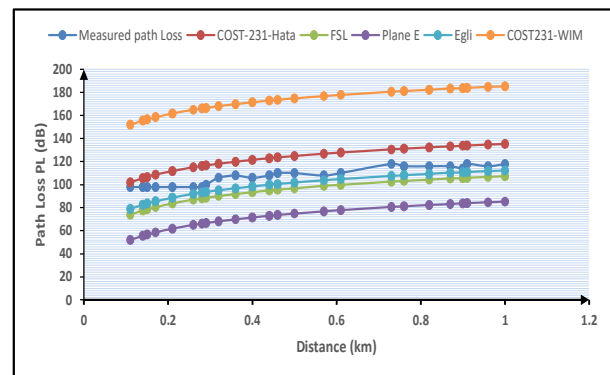
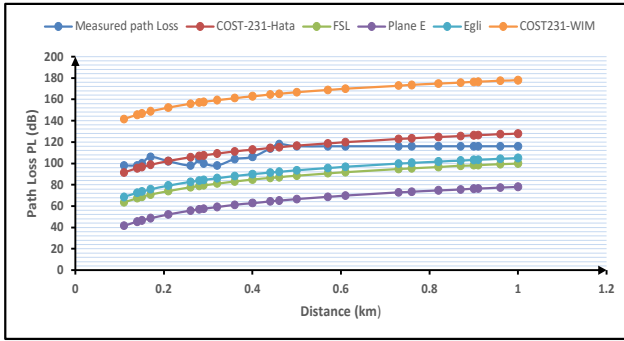
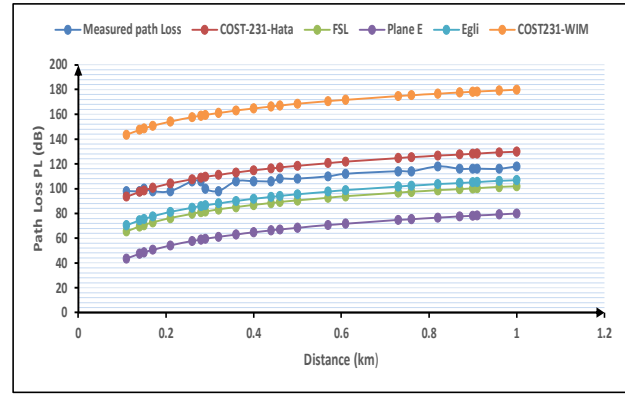


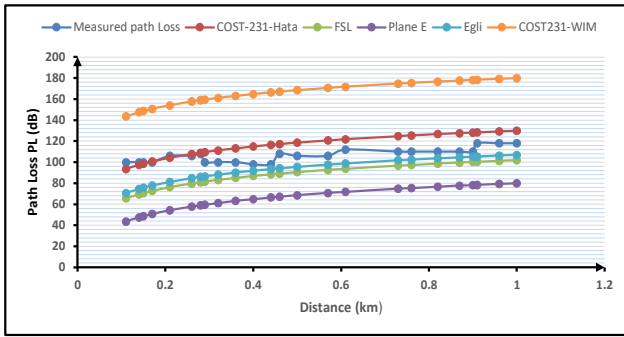
Figure 9 The Plot of path loss (dBm) against distance (km) for BTS 6 at Sawmill, Ilorin, Nigeria



**Figure 10** The Plot of path loss (dBm) against distance (km) for BTS 7 at Unilorin, Ilorin, Nigeria



**Figure 12** The Plot of path loss (dBm) against distance (km) for BTS 7 at Taiwo Rd., Ilorin, Nigeria



**Figure 11** The Plot of path loss (dBm) against distance (km) for BTS 7 at Oloje, Ilorin, Nigeria

Table 2 shows the statistical evaluation of RME and SD between the measured path and the predicted path loss models. From the results obtained (Table 2), The WIM model gave the highest value of the path loss predictions for all the regions (environments), which further proved that they overestimated the measured path loss. COST-231-Hata and EPL models give good prediction values when compared with the minimum acceptable limit for good signal propagation that is within 1 and 15 decibels (Ogbulezie *et al*, 2013).

**Table 2** The Statistical comparison of RME and SD for measured and estimated path loss models

Study Region (Location)	BTS No.	Plane-Earth models		Egli Model		COST-231-Hata		COST 231-WIM	
		RMSE	SD	RMSE	SD	RMSE	SD	RMSE	SD
Tanke	1	24.27	25.67	13.62	14.18	13.16	14.29	39.17	40.17
Offa-Garage	2	21.43	22.62	10.76	11.17	9.35	10.44	39.89	41.40
G. R. A	3	22.61	24.17	12.49	13.17	9.32	10.52	41.04	43.26
Post Office	4	15.87	17.27	6.37	6.67	14.15	15.35	46.23	48.73
Saw-mill	5	17	17.83	8.1	8.35	14.74	15.47	46.6	48.04
Unilorin	6	18.60	19.54	8.49	8.77	12.83	13.55	44.65	46.11
Oloje	7	24.98	26.69	14.63	15.34	14.36	15.16	38-80	40.69
Taiwo Rd.	8	22.49	24.25	12.49	13.17	9.08	10.14	41.29	43.53

**V. CONCLUSION**

A comparative analysis of path loss prediction models for the Ilorin metropolis had been carried out with a improved accurate signal strength measurements technique. The results of the analysis revealed that the COST-231-Hata and Egli models performed satisfactorily with the nearest path loss forecast to the practical measure path loss results across all locations investigated. COST-231-Hata has RMSE and SD that vary between 9.08 and 14.74 and 10.14 and 15.47, respectively, while the Egli model has RMSE and SD that vary between 6.7 and 14.63 and 6.67 and 14.18, respectively. It is recommended that either the COST 231 Hata model or the Egli model be modified (adjusted) for precise radio signal forecast

for cell service transmission in Ilorin and other similar environments, as inadequate execution of service by a network provider could end up in customer complaints and faults, ultimately leading to disappointment with the operator.

**AUTHOR CONTRIBUTIONS**

**J. Akanni:** Conceptualization, Software, Validation, Writing – original draft. **A. A. Isa:** Conceptualization, Methodology, Supervision. **B. J. Olufeagba:** Review & editing.

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