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# The Study of Empirical Path Loss Models for Accurate Prediction of GSM Signal for Applications in Microcellular Environments

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**Abstract.** Path loss models are used generally in GSM signal predictions, optimization of coverage and interference analysis. Peculiarity of these models gives rise to high errors in prediction when they are deployed in environments different from the one they are designed for. In this study, the fitness of six path loss models was evaluated using five metrics to gauge their performance. In order to achieve this, empirical prediction models were fitted with the measurement survey data performed on live signals transmission on microcellular service provider in an outdoor propagation in urban, suburban and rural environments of two states in the western part of Nigeria.

The results show that no single model consistently fits the path loss values along the routes. However, Cost-231, Erceg and SPM models provided better fitness in some monitored base stations with RMSE values slightly above 7dB for urban environment and less than 10 dB in some suburban and rural environments. The prediction errors distribution for Erceg model distributes nearly symmetrical around a mean error of 0.71dB for urban, -8.56 dB for suburban and -1.67 dB for rural environments and some of the model prediction error distributions fairly follow a normal distribution curve.

The Gaussian error distribution within the windows of 0 to ±10 dominates the frequency counts. From the analysis, Erceg and Cost-231 presented the closest fit and least RMSE value. However, adjustment of the parameters of the Erceg and Cost-231 models is necessary to minimize the RMSE values to the acceptable ranges suitable for all the environments.

**Keywords:** Root mean square error, Gaussian distributions, Empirical path loss models, frequency count

## Introduction

With the tremendous increase in demand for wireless communication technologies and wireless mobile devices, it is important for wireless regulatory agencies to carry out electromagnetic compatibility analysis to address the issues of interference between users of electromagnetic spectrum in order to accommodate the increasing number of mobile network subscribers and new devices.

Frequencies currently used by cellular systems in Nigeria urban, suburban and rural environments for voice calls are between 0.9 and 1.8 GHz. Path loss parameters from these frequency bands are vital for the determination of base station placement, coverage area of transmitter station, interference and optimization processes. An extensive survey of several propagation models for mobile communications describes the suitable models for micro cell and macro cell appropriate for a particular outdoor environment. To improve the performance of existing Global System for Mobile Communication (GSM) services and to design new network systems, modelling of wave propagation is important. It gives insight of the mechanisms of propagation and phenomena that affects wireless communications. Such insight can be achieved by comparing the existing models with the actual values and modifying the models to conform to the specific conditions of a given site. With this aspect, path loss models are applied in fixed wireless access systems, cellular environment and GSM systems. The peaceful coexistence between the GSM subscribers and operators depends on the propagation characteristics of the channel. The existing path loss models are classified into two categories: theoretical and empirical path loss models. The theoretical models are derived by assumption of physical hypothesis alongside some moderate conditions. For example, the diffraction model is derived by using physical optics, assuming the same space between buildings and constant building heights (Rskesh & Srivatsa, 2012). Empirical models are derived from in-depth measurements of received signal strength (RSS) as a function of distance. It is efficient and the input data are generally quantitative.

Most of the existing path loss models for predicting GSM coverage are built based on measurements carried out in environments/regions different from Nigeria; in terms of usage, these models may differ in their properties with locations due to different environments. Deployment of these models in different environment other than the one they initially designed for gives rise to high prediction errors due to environmental factors and terrain profile. Consequently, these errors may affect the quality of service (QoS) provided by the network operators. For instance, Zia and Mohammed (2014) in their investigation of suitable path loss model for Oman show that using a path loss propagation model not designed for a particular environment can result in over prediction of RSS. This is a challenge as over prediction would increase the cost of design and under prediction would have direct effects on the QoS of the GSM network. Therefore, it is essential to accurately assess path loss propagation models in order to choose a better model or modify a model to attain high accuracy and minimize errors, thus, increasing flexibility in the usage of local spectrum.

In this paper, we investigate the appropriateness of six commonly used empirical path loss models using five metrics measures to gauge their performance. The focus of this research work is on the efficacy of the chosen models at predicting path loss values for safe operation of network operators and GSM subscribers in the chosen environments. The chosen empirical models are Erceg, Cost-231, Standard Path Loss Model, Lee, Ericson and Egli models.

## Related Work

Different researchers have worked on analysing the suitability of GSM path loss models. In most cases, the authors often collect combined sectors measurement data in a particular environment and make assessment of path loss models with the measured values.

Andrej and Tomaz (2013) reported a study of radio propagation models suitable for smart city applications. The measurement campaigns were performed in open area, street canyon and tunnels at three frequency bands 400 MHz, 868 MHz and 2400 GHz using VESNA sensor nodes equipped with wireless transceiver module from Texas instruments. Open area plane earth model, two-slope model and four slope channel models were selected for comparison with the measured data. It was reported that in open areas, the plane earth model performed better than the two-slope model, and four-slope model gave sufficient high accurate prediction of path loss in tunnels than the open earth plane model. Prasad *et al.* (2011) suggested that the design of future generation mobile communication networks are critically dependent on the suitability of path loss prediction models and how appropriate they are to various regions. To investigate radio frequency channel behaviour, they conducted experimental measurements of GSM signal strength in the dense urban region of New Delhi for six GSM base stations transmitting at 1.8 GHz, +45 dBm and antenna height between 22 and 40 m. The results were compared with cost-231 Hata, cost-231 Walfisch Ikegami (WI), roof top diffraction and regression line prediction models. It was observed that the measured regression line exhibited the lowest deviations followed by roof top diffraction propagation model. Following the same method, Prasad *et al.* (2011) emphasize that wireless propagation modelling is an essential component of system design and that testing of various available propagation model values with experimentally generated values helps in identifying a suitable path loss model that can be deployed for the design of mobile communications for future generation. They presented the results of signal level measurements of 11 GSM base stations in the dense-urban, urban and suburban regions of Delhi in northern India. Comparison of the measured path loss was made with values from AWAS, ITU-R, cost-231 Hata, Walfisch-Ikegami and Demitry wireless propagation models. According to their findings, the AWAS electromagnetic code and ITU-R model exhibited good fits with the observed path loss values, compared with the other models based on two evaluation metrics.

Akinyemi *et al.* (2015) investigated the most effective propagation model in South Southern urban part of Nigeria. Two GSM base stations operating at 900 and 1800 MHz bands were monitored. The field measurement results were compared with SUI, Ericsson, Friis and Walficsh-Bertoni models. The results obtained indicated the least variation with Walficsh-Bertoni path loss model.

In assessing the fitness of eight path loss models, the prediction error between the empirical path loss models and actual path loss values of TV propagation signals in Kwara state in Nigeria were distributed in the study by Nasir *et al.* (2013), using Gaussian normal distribution function. CCIR and Davidson empirical path loss models showed better results than the other six path loss models used, based on some metric evaluations. This study is the first of its kind in Southwestern part of Nigeria that carries out an extensive error analysis of path loss models with reference to a large number of GSM data set produced from real time RSS measurements in different microcellular environments using different propagation path loss models.

## Experimental Sites, Materials and Method

With Global System for Mobile Communication (GSM) signal at frequency of 900 and 1800 MHz, propagation measurements were conducted during dry season: November to December 2020 and January to March, 2021 also during wet season months between April and September, 2021. These periods were selected in order to accommodate the two major seasons in Nigeria.

The measurement campaign consisted of three different environments of Southwestern Nigeria. The field measurement survey was performed in the three sectors of the base stations on Isolo environments at 1800 MHz in Akure, the capital of Ondo State and Maryhill in Ado-Ekiti, the capital of Ekiti state. These sites represent typical populated urban environments of the region. The second measurement campaign was carried out in a base station in Mobil a typical commercial suburban environment of Ondo State and a base station in Oye-Ekiti representing a typical suburban environment of Ekiti State. The third measurement survey was performed in base stations in Odigbo and Ilupeju, both representing typical rural environments of Ondo and Ekiti States respectively. Table 1 describes the characteristics of the measurement environments. Figures 1(a) and (b) show the screen shot of one of the measurement routes and a view of one of the environments monitored respectively.

**Table 1: Description of environment type**

| **Environment type** | **Description** | **Distance covered (km)** |
|---|---|---|
| Urban | Populated environments that are typified with blocks of densely constructed buildings, height of buildings between 3 and 20 meters, hills, mountains, parks, schools market places, and trees of average height. Typically, more than 80% of the area is filled with houses constructed with concrete, blocks and tiles. | 0.05 to 1.4 |
| Suburban | These sites comprises lightly constructed buildings of height between 3 and 12 meters, market places, hills, schools, and distributed tall trees. Around 50 to 70% of the areas is filled with houses constructed with concrete and blocks. | 0.05 to 1.2 |
| Rural | These sites reflect rural environments of Ondo state consisting of sparsely constructed buildings, thick vegetation of tall trees, corroded roofs, foot paths, market places and open areas. They are also characterized by some sequence of houses built with muds and planks with less than 60% of houses made of concrete, blocks, wood and sand. | 0.05 to 1.2 |

**Figure 1: One of the investigated environments**

Drive test measurements of the RSS levels of GSM base station transmitters were conducted using a Sony Ericsson Test Mobile System (TEMS). The TEMS device was connected through a Universal Serial Box (USB) cable to a TEMS software equipped laptop. A Global Position System (GPS) receiver was also connected to the laptop to measure the distance between the mobile receiver and the base station, coordinates, location as well as the elevation. A Single Sector Verification (SSV) method was adopted in each site, measurements were carried out at distances ranging from 0.5 km to around 1.4 km along each sector of the base transmitters. Measured data along each sector were also recorded in a log file for each investigated site. The transmitting power of the transmitter at 1800 MHz is 44 dBm and at 900 MHz is 40 dBm, while the height of the mobile receiver is 1.2 meters with maximum sensitivity of -110 dBm. Features of the base stations and the characteristics of each of the sites investigated are shown in Table 2. Figure 2 depicts Isolo base station in Akure.

**Table 2: Details of the base stations and characteristics of each of the sites**

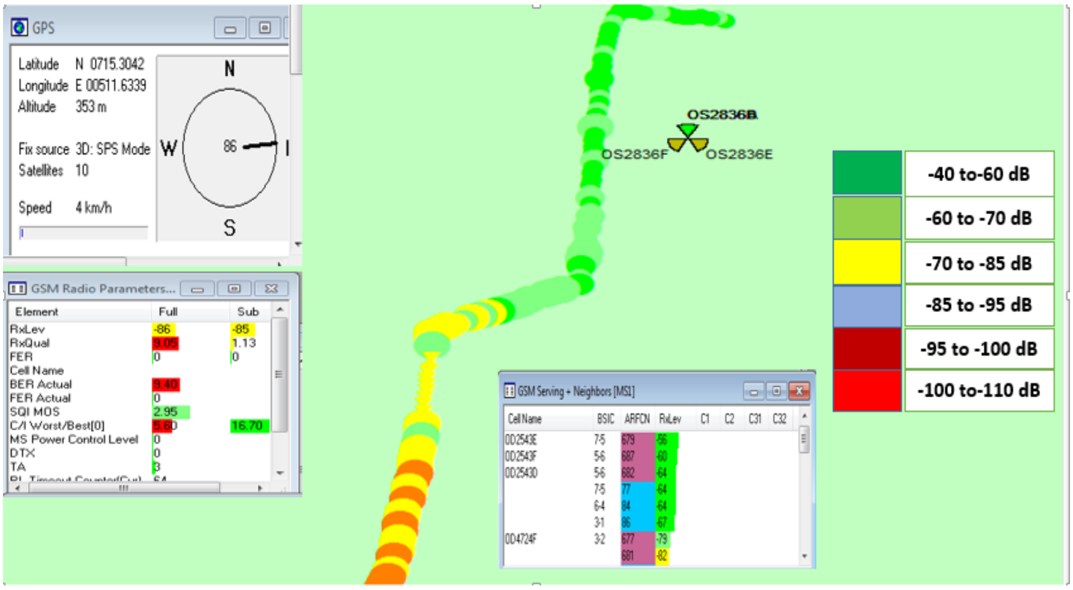
| Environment | Cell identity code | Coordinate | | Elevation (m) | Antenna height (m) | Antenna type | Frequency (MHz) | Tx Antena gain (dB) |
|---|---|---|---|---|---|---|---|---|
| | | °N | $^{0}$E | | | | | |
| Maryhill | EK2225 | 7.629 | 5.231 | 547 | 36 | Sectorial | 1800 | 17 |
| Isolo | OD2543 | 7.254 | 5.197 | 352 | 36 | Sectorial | 1800 | 17 |
| Oye-Ekiti | EK4406 | 7.784 | 5.329 | 543 | 34 | Sectorial | 1800 | 17 |
| Mobil | OD4727 | 6.765 | 4.842 | 93 | 34 | Sectorial | 900 | 14 |
| Ilupeju | EK3471 | 7.810 | 5.329 | 632 | 34 | Sectorial | 900 | 14 |
| Odigbo | OD3835 | 6.788 | 4.874 | 129 | 34 | Sectorial | 900 | 14 |

**Figure 2: Isolo base station in Akure, Ondo State**

### Data Collection and Processing

Intensive drive test was carried out along all identified paths in all the proposed environments in Southwestern Nigeria. The drive test process was conducted by initiating calls at the beginning of each experiment using a data gathering investigation device called Test Mobile System (TEMS) at a height of 1.2 m. The reports of acquisition of radio signal level and several other GSM signal parameters were acquired using a high sensitive Sony Ericsson signal measurement phone linked to a laptop with an installed TEMS software and uploaded cell refs of the network provider. The positioning information, elevation and distances between the transmitter and the receiver were gathered through the GPS antenna that communicates directly with GPS satellite, the measuring system takes up to 100 points in one minute. To avoid measuring signal strength from other sectors and base stations.

The measured RSS values for each microcell was recorded in log files. These log files were transferred for more extraction process of the required data to a processing/analytical software known as ACTIX. ACTIX is a drive test software used for further processing of drive test results. It supports troubleshooting and optimization of GSM networks. This tool can automatically troubleshoot for problems in GSM and WCDMA RF system. This tool was applied to convert the acquired log files into excel worksheet format for further analysis. Figure 3.0 show one of the acquired log files distribution. Averaging was done at 50 m interval based on the three sectors of each cell sites. Thus, fast fading due to multipath was averaged out (Rappaport, 2002; Julio, 2008).



Latitude N 0715.3042
Longitude E 00511.6339
Altitude 353 m
Fix source 3D: SPS Mode
Satellites 10
Speed 4 km/h

GSM Radio Parameters...

| Element | Full | Sub |
|---|---|---|
| RxLev | -86 | -85 |
| RxQual | 9.05 | 1.13 |
| FER | 0 | 0 |
| Cell Name | | |
| BER Actual | 9.40 | |
| FER Actual | 0 | |
| SQI MOS | 2.95 | |
| C/I Worst/Best[0] | 5.60 | 16.70 |
| MS Power Control Level | 0 | |
| DTX | 0 | |
| TA | 3 | |

GSM Serving + Neighbors [MS1]

| Cell Name | BSIC | ARFCN | RxLev | C1 | C2 | C31 | C32 |
|---|---|---|---|---|---|---|---|
| 0D2543E | 7-5 | 679 | -56 | | | | |
| 0D2543F | 5-6 | 687 | -60 | | | | |
| 0D25430 | 5-6 | 682 | -64 | | | | |
| | 7-5 | 77 | -64 | | | | |
| | 6-4 | 84 | -64 | | | | |
| | 3-1 | 86 | -67 | | | | |
| 0D4724F | 3-2 | 677 | -79 | | | | |
| | | 681 | -82 | | | | |

| | |
|---|---|
| 🟩 | -40 to-60 dB |
| 🟩 | -60 to -70 dB |
| 🟨 | -70 to -85 dB |
| 🟦 | -85 to -95 dB |
| 🟥 | -95 to -100 dB |
| 🟥 | -100 to-110 dB |

**Figure 3: Acqiured log file of Maryhill base station in Ado-Ekiti (sector B)**

### Path Loss Calculation

The path loss (dB) was estimated from the measured RSS values by the expression (Perez & Marino 2008; Abiodun & Emeruwa, 2020):

$$P_L = EIRP - RSS_m \tag{1}$$

where EIRP is the total power density from the transmitter and it is expressed as (Abiodun & Emeruwa, 2020):

$$EIRP = P_T + G_T + G_R - L_T - L_R \tag{2}$$

Using equation (2) in equation (1) gives the expression for the propagation path loss in decibel.

$$P_L = P_T + G_T + G_R - L_T - L_R - RSS_m \tag{3}$$

where $P_T$ is base station transmitted power; $G_R$ and $G_T$ are gain of mobile receiver and base station transmitter respectively; $L_R$ and $L_T$ are mobile receiver and transmitter cable loses in (dB) and RSS is the received signal strength.

### Models Performance Evaluation

The performance of the various path loss models is evaluated by error analysis. The five major error metrics used in this research to select the best model are; prediction error, Root Mean Square Error (RMSE), Spread-Corrected Root Mean Square Error (SC-RMSE), normalized error probability density function and Spearman's rank correlation. The prediction error, which describes the difference between the observed path loss $(PL_i)$ at Tx-Rx separation of $i$ and the empirical model estimated values of path loss denoted by $PR_i$ is expressed as (Nasir *et al.*, 2013):

$$\in_i = P_{Li} - P_{Ri} \tag{4}$$

Evaluating using the RMSE, The lower the RMSE value, the better the performance of the path loss propagation model, a RMSE value between 0 to 6 dB indicates a better fit for urban environment (Akinyemi *et al.*, 2019) and 0 to 10 dB for suburban and rural environments (Blaunstein *et al.*, 2003). For this study, RMSE value between 0 to 10 dB is the chosen performance evaluation condition for the environments base on the error counts from the normal distribution curve. The expression for the RMSE for n set of value is given as (Nasir *et al.*, 2013):

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(/P_{Li} - P_{Ri}/)^2} \tag{5}$$

Another essential evaluation metric is the SC-RMSE, it helps in extracting the effect of dispersion from the general error. The SC-RMSE has the ability of reducing noise linked related error. The method of computation of this error is similar to that of RSME, the difference between the two is that SC-RMSE is computed as the difference between the absolute value of the error and the standard deviation. The equation of the SC-RMSE is given as

$$SC - RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(/\in_i^{'}/)^2} \tag{6}$$

where:

$$\in_i^{'} = (|\in_i| - \sigma_i) \tag{7}$$

Another metric is the mean prediction error given as (Nasir *et al.*, 2013)

$$Mean = \frac{1}{n}\sum_i^n \in_i \tag{8}$$

The next metric is the error distribution, the PDF of a normal random variable. In this evaluation, the model should follow a normal distribution curve and 0 to 10dB error windows have to dominate the frequency counts based on the chosen RMSE evaluation criteria for this research. The expressions for normal PDF and Cumulative Distribution Function (CDF) are (Krishnamoorthy, 2006):

$$f(\in|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[\frac{-(\in-\mu)^2}{2\sigma^2}\right], -\infty < \in < \infty \tag{9}$$

$$F(\in|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{\in}(\exp\left[\frac{-(t-\mu)^2}{2\sigma^2}\right])dt \tag{10}$$

where $\in$ is the prediction error, μ and σ are normal distribution parameters.

## Results and Discussion

Figures 4 to 9 depict the graphical presentation of measured and predicted path losses along the three sectors of the monitored base stations in the environment considered. Figures 4 and 5 presents a comparison between the measured path loss and the predicted path loss as a function of Tx-Rx distance for Maryhill and Isolo base stations. The two environments exhibited similar propagation behaviour, throughout the considered distances; Egli model underestimated the measured path loss values for both environments. Within the first 0.4 km, none of the propagation models follows the measured path loss values. From 0.4 km onwards, Cost-231, Erceg and SPM models show better agreement with the measured path loss values while Lee model underestimating the path loss values from 0.6 km onwards and Ericson model overestimating the measured path loss from closer distances to the transmitter up to about 0.8 km for both Maryhill and Isolo base stations. However, SPM model provided the best result with RMSE of 7.10 dB and 7.12 dB, SC-RMSE of 4.52 and 5.44 dB for Maryhil and Isolo respectively, this is followed by Erceg model with RMSE of 7.27 and 7.71 dB and SC-RMSE of 4.73 and 3.71 dB respectively. Egli, Ericsson and Lee models perform woefully with higher RMSE and SC-RMSE values.

Unlike the urban environments, the suburban environment monitored are not similar in propagation environment as depicted in Figures 6 and 7. Cost-231, Lee and SPM models overestimated the measured path loss up to 0.4 km but give better fits onwards in Oye-Ekiti base station monitored while Lee model has the best RMSE and SC-RMSE values of 6.60 and 3.33 dB when compared the RMSE and SC-RMSE of other models. Erricson model overestimated the measured values from 0.25 km onwards while Erceg model has a better fit with the measured path loss only between 0.4 and 0.8 km. In mobil environment, Lee, SPM, Erceg and Cost-231 models agree with the measured path loss at closer distances from the transmitter; thereafter, Lee, SPM and Cost-231 underestimated the path loss. Ericson model only had a good agreement with the path loss between 0.2 and 0.7 km along the predefined routes. Egli underestimated the measured path loss at all levels in both suburban environments monitored. Erceg model happens to present the best RMSE of 4.69 dB when compared to others in Mobil environment.

Like the monitored urban environments, the rural environments of Ilupeju and Odigbo exhibited similar propagation behaviour as depicted in Figures 8 and 9; this could be because both environments are similar in environmental characteristics. For all the measurement routes followed. Erceg model shows the best results with RMSE values of 4.69 and 4.06 dB when compared with other propagation models. Cost 231, Lee and SPM models at closer distances from the transmitter show better fit but under predict the path loss at 0.5 km onwards while at all distances, the Egli model under predicts the measured path loss with RMSE of 29.36 and 27.80 dB. Tables 2 and 3 present the corresponding error statics in terms of the RMSE and SC-RMSE between the measured path loss and predicted path loss from the various models considered.

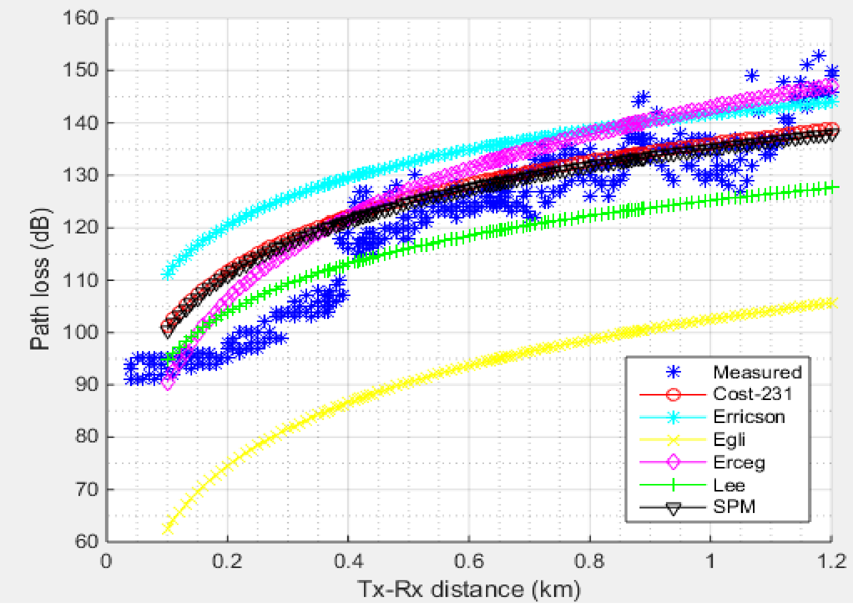
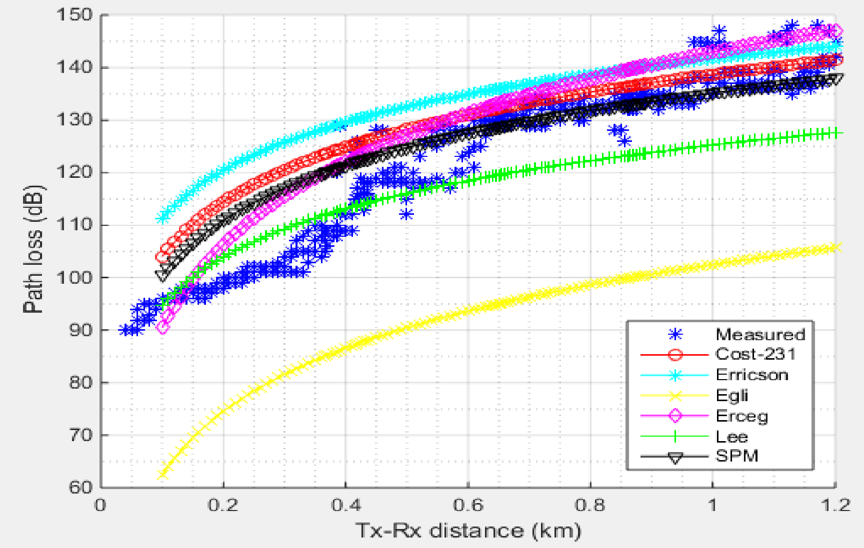


**Figure 4: Comparison of empirical path loss models with measured path loss for Maryhill environment**



**Figures 5: Comparison of empirical path loss models with measured path loss for Isolo environment**

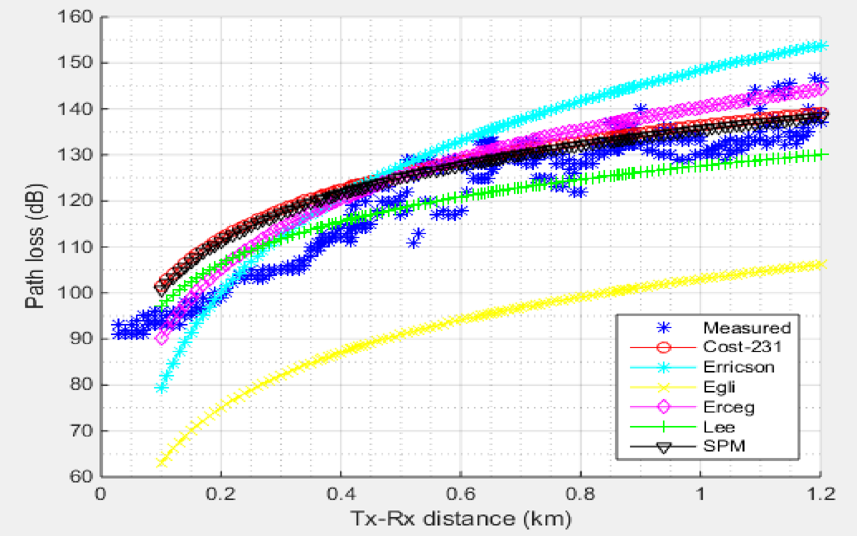


Figure 6: Comparison of empirical path loss models with measured path loss for Oye-Ekiti environment

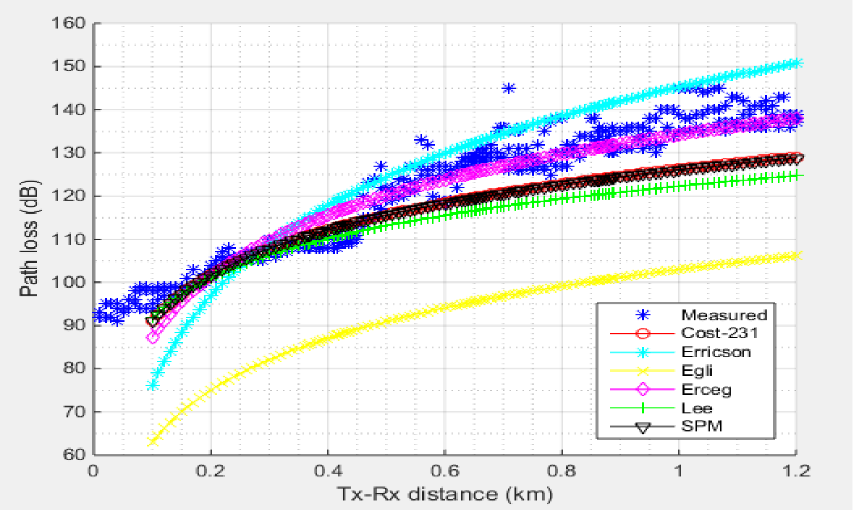


Figure 7: Comparison of empirical path loss models with measured path loss for Mobil environment

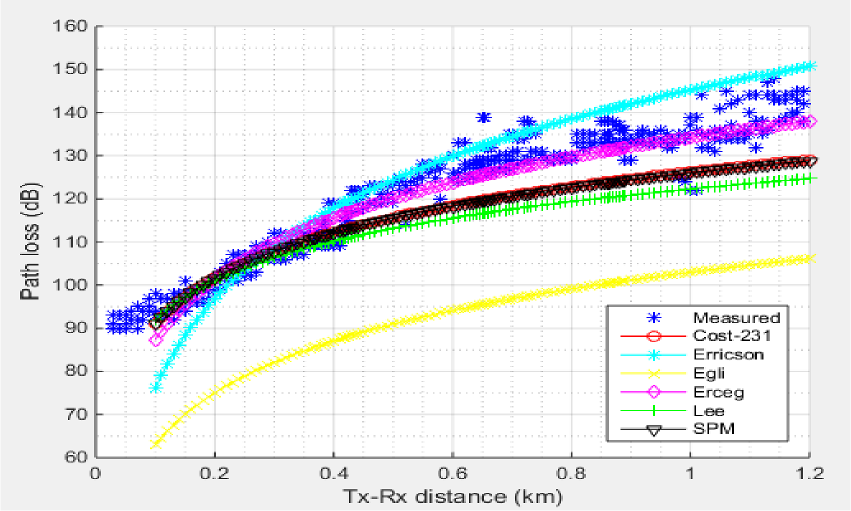


Figure 8: Comparison of empirical path loss models with measured path loss for Ilupeju environment

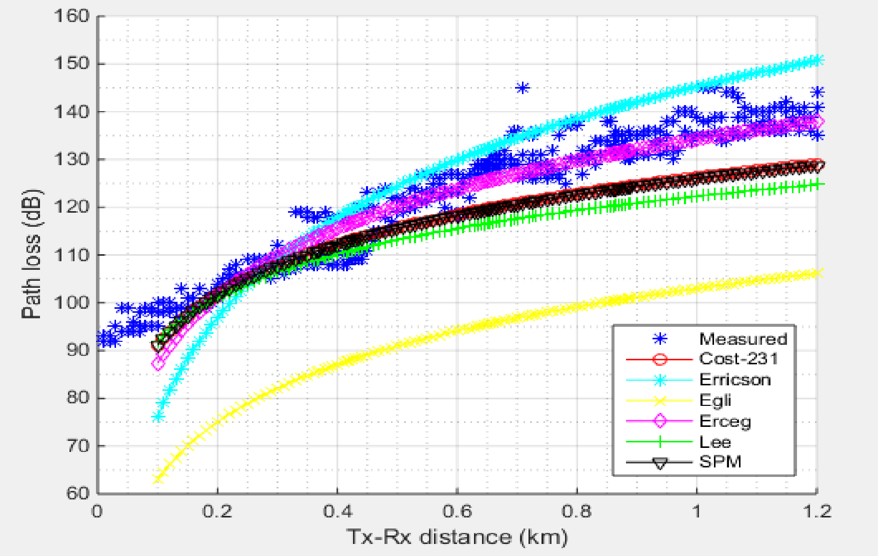


**Figure 9: Comparison of empirical path loss models with measured path loss for Odigbo environment**

**Table 3: Root mean square error (RMSE) for the six monitored environments**

| Environment | Cost-231(dB) | Erricson(dB) | Egli(dB) | Erceg(dB) | Lee(dB) | SPM(dB) |
|---|---|---|---|---|---|---|
| Maryhill | 7.63 | 10.262 | 35.52 | 7.27 | 12.27 | 7.10 |
| Isolo | 9.34 | 12.84 | 32.38 | 7.71 | 10.32 | 7.12 |
| Oye-Ekiti | 10.21 | 13.28 | 26.78 | 9.35 | 6.60 | 9.49 |
| Mobil | 7.22 | 8.93 | 28.51 | 4.69 | 9.62 | 9.34 |
| Ilupeju | 7.49 | 8.02 | 29.36 | 4.06 | 10.08 | 7.63 |
| Odigbo | 6.58 | 9.59 | 27.80 | 4.69 | 8.88 | 6.69 |

**Table 4: Spread corrected root mean square error (RMSE) for the six monitored environments**

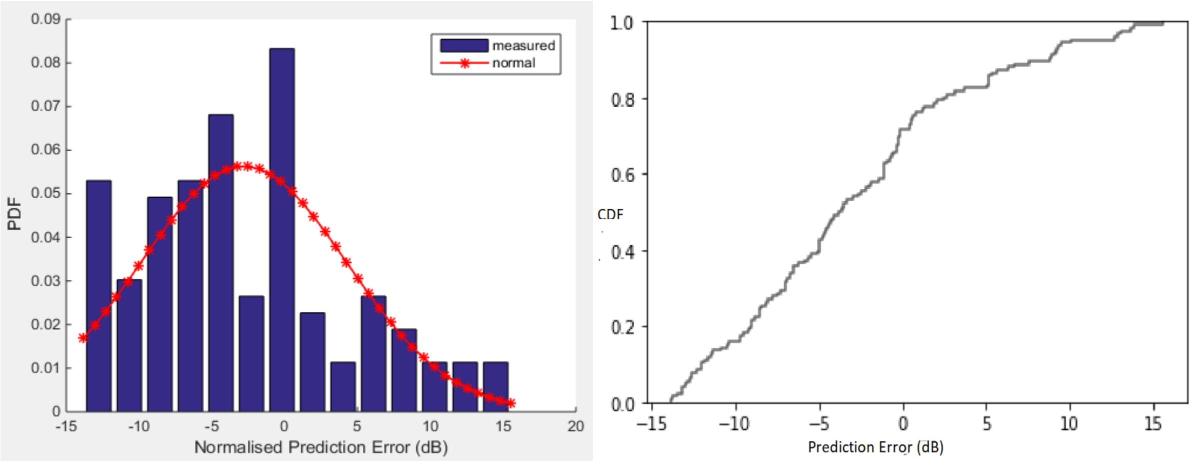
| Environment | Cost-231(dB) | Erricson(dB) | Egli(dB) | Erceg(dB) | Lee(dB) | SPM(dB) |
|---|---|---|---|---|---|---|
| Maryhill | 4.47 | 5.25 | 6.72 | 4.73 | 7.81 | 4.52 |
| Isolo | 6.08 | 7.06 | 7.08 | 3.71 | 5.10 | 5.44 |
| Oye-Ekiti | 5.26 | 4.73 | 10.41 | 3.75 | 3.33 | 5.10 |
| Mobil | 3.59 | 3.62 | 9.15 | 3.27 | 5.54 | 3.68 |
| Ilupeju | 4.01 | 3.89 | 8.59 | 2.67 | 5.60 | 4.10 |
| Odigbo | 6.58 | 9.59 | 27.80 | 3.69 | 8.88 | 6.69 |

Figures 10 (a) to (e), 11 (a) to (e) and 12 (a) to (e) depict the distributed histograms and CDF of the prediction errors between the measured and model predicted path loss for base station considered in urban, suburban and rural environments of the states considered. The solid lines indicate the probability distribution function (PDF) of a Gaussian random variable. The errors were normalized to fit into the Gaussian distribution.

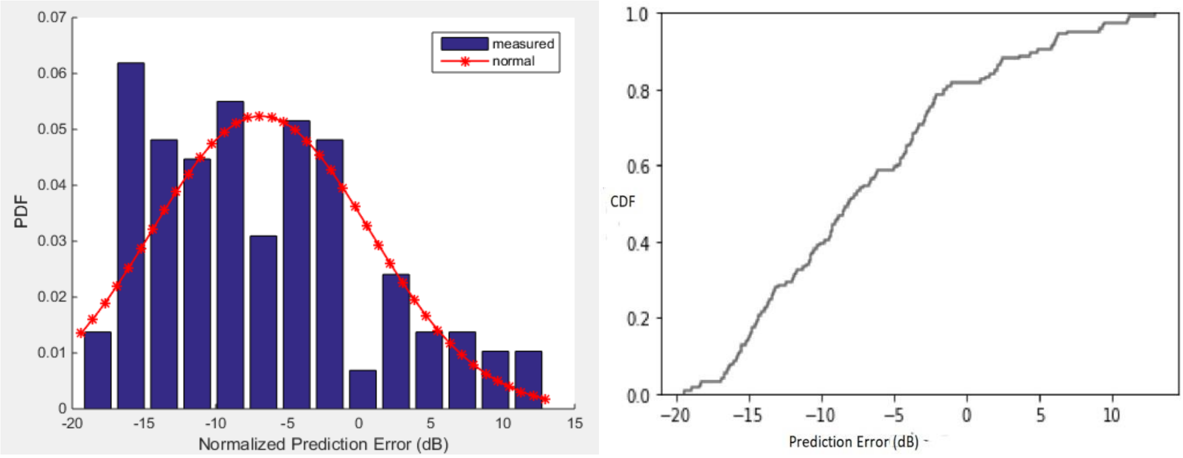
Figure 10(a) represents the prediction error distribution for Cost-231 model for urban environment, the distribution is negatively skewed with a mean error of -2.83 dB, this does not indicate a better prediction of path loss in the environment. Ericson model error distribution follows the same pattern of Cost-231 as shown in Figure 10 (b) but with higher mean error of -6.92 dB while Erceg prediction error distribution in Figure 10 (c) is slightly positively skewed with mean error of -2.55 dB and -8 to 2 dB windows dominating the frequency counts. Figure 10 (d) represents the Lee model prediction error distribution, though skewed positively with mean error of 9.68 dB, Lee model does fit better with the measured path loss of the environment, 0 to 10 dB windows dominates the frequency counts. The SPM prediction error distribution is presented in Figure 10 (e) with 5 to 10 dB windows dominating the frequency counts and a mean error of 0.71 dB indicating a better fit with the measured path loss.

Figure 11 (a) is the Cost-231 prediction error distribution, from all indications, the model underestimated the path loss since the model is found to have a negative skew with a mean error of -8.55 dB. Figure 11(b) is Ericson model prediction error distribution with mean error of -11.82 dB and the distribution is dominated between windows of -20 to -10 dB frequency counts, indicating a poor fit with measured path loss. The error prediction distribution of Erceg model, the model follows fairly a normal distribution curve despite the fact that the distribution is negatively skewed with mean error of -8.58 dB and negative dominance frequency counts, which is an indication of poor fit with the measured values of path loss. Lee and SPM model prediction error distributions are presented in Figures 11(d) and (e) respectively with error counts spreading along the distributions.

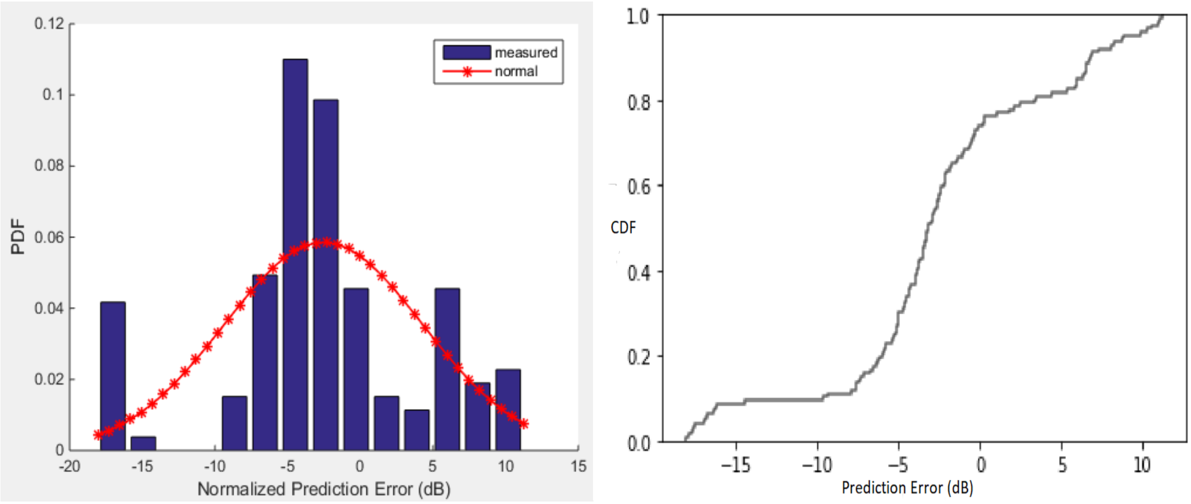
Figures 12 (a), (d) and (e) are the prediction error distribution of Cost-231, Lee and SPM models, the three models show similar shape in their PDFs with mean error of 3.41, 6.19 and 3.56 dB respectively. Erceg prediction error distribution in Figure 12 (c) follows the normal distribution curve with a mean error of -1.64dB and a frequency count of ±2 dB window dominating. This indicates a better fit with the measured path loss values. Eriction prediction error distribution is presented in Figure 12 (e), the distribution is negatively skewed the prediction error is nearly distributed around the mean error of -7.03 dB.



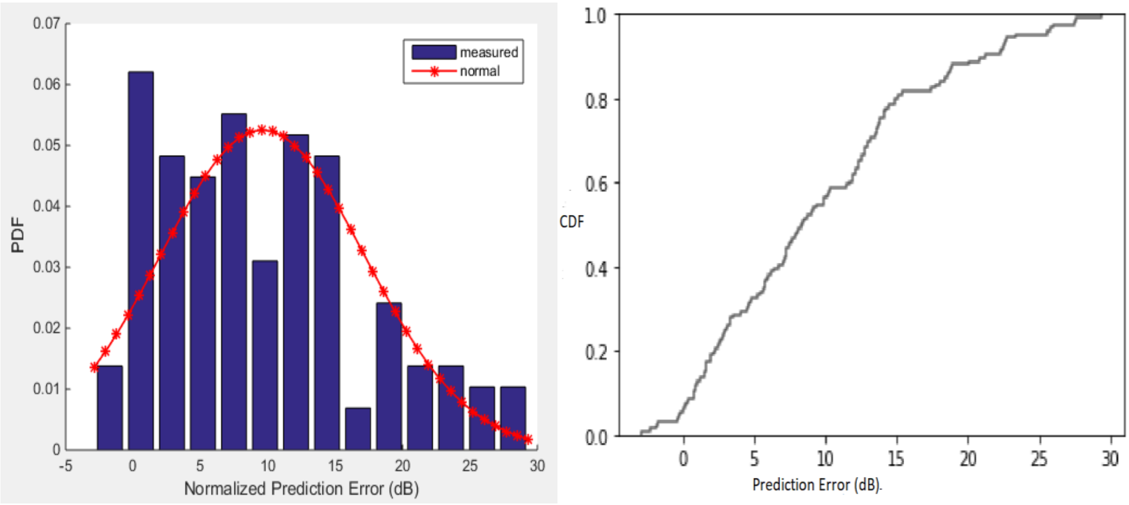
(a)



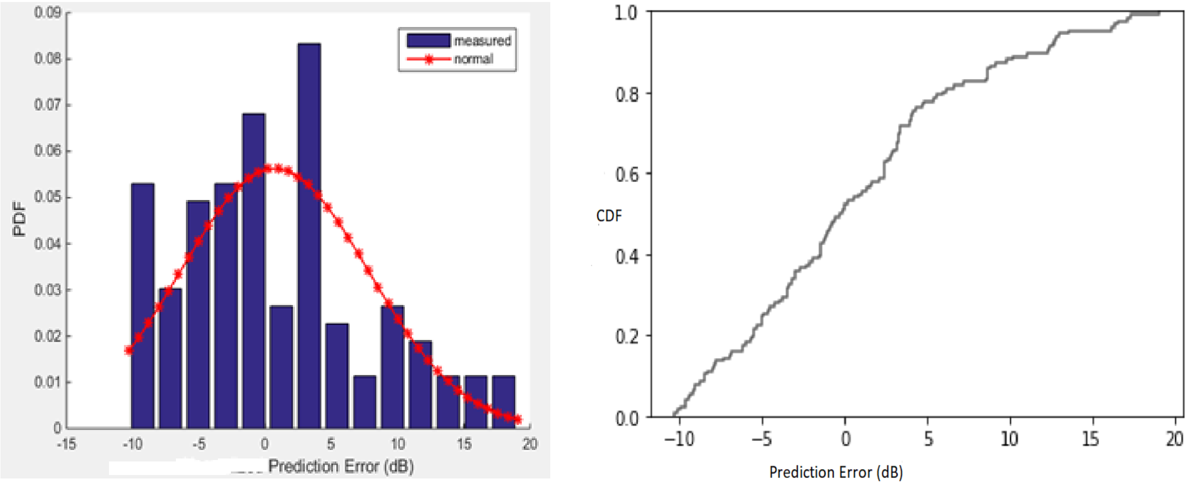
(b)



(c)



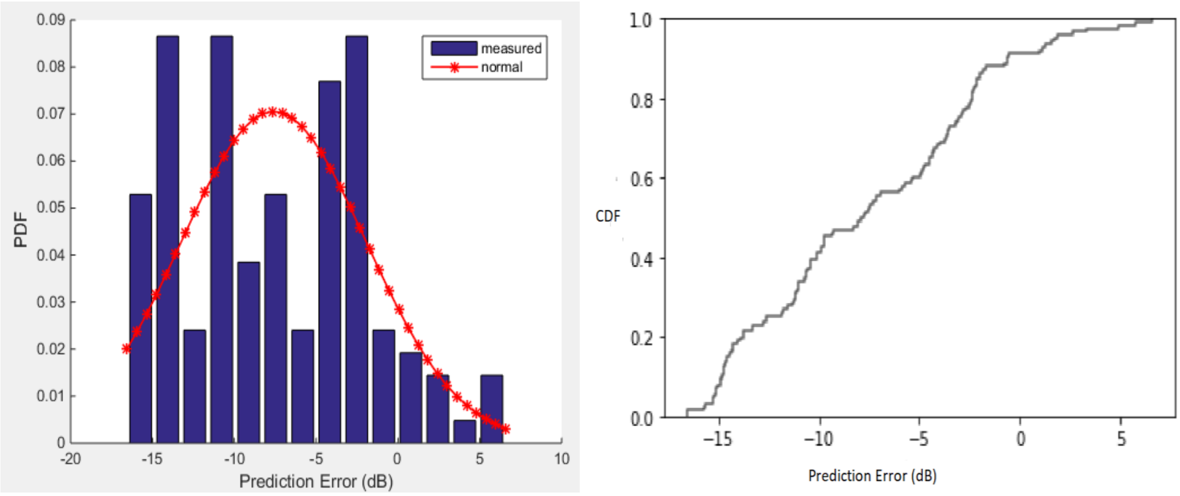
(d)



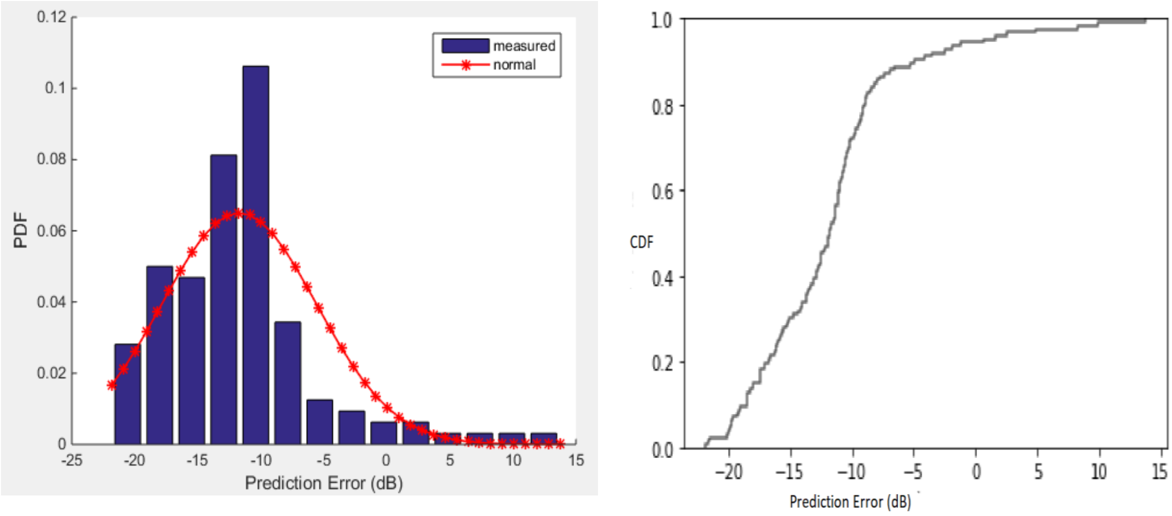
(e)

**Figure 10: Normalized Prediction Error between measured and predicted models for urban Environment, Maryhill**

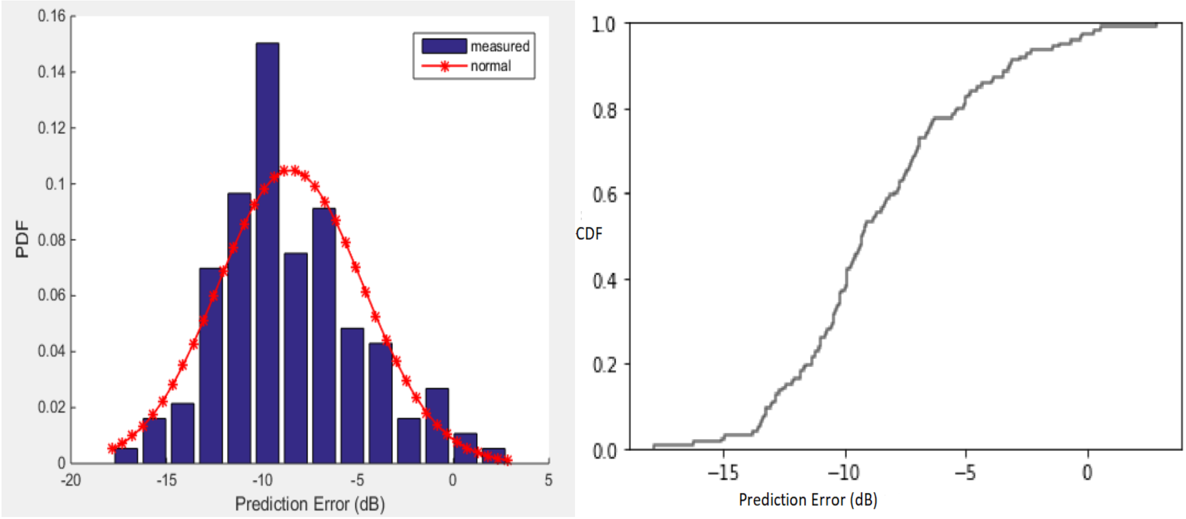
(a) Cost-231 model (b) Ericson model (c) Erceg model (d) Lee model (e) SPM model


PDF
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-20
-15
-10
-5
0
5
10
Prediction Error (dB)
measured
normal
CDF
1.0
0.8
0.6
0.4
0.2
0.0
−15
−10
−5
0
5
Prediction Error (dB)

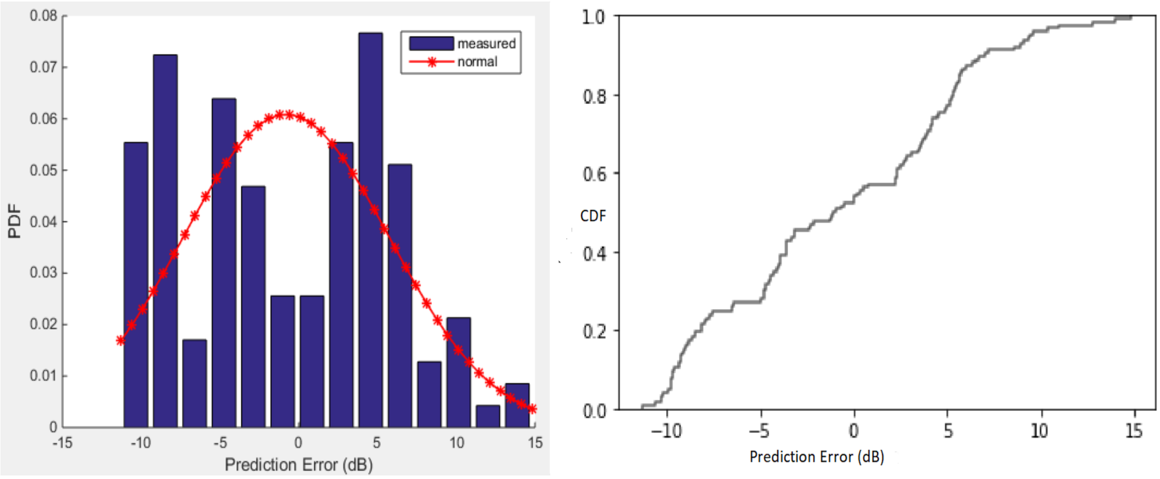
(a)


PDF
0.12
0.1
0.08
0.06
0.04
0.02
0
-25
-20
-15
-10
-5
0
5
10
15
Prediction Error (dB)
measured
normal
CDF
1.0
0.8
0.6
0.4
0.2
0.0
−20
−15
−10
−5
0
5
10
15
Prediction Error (dB)

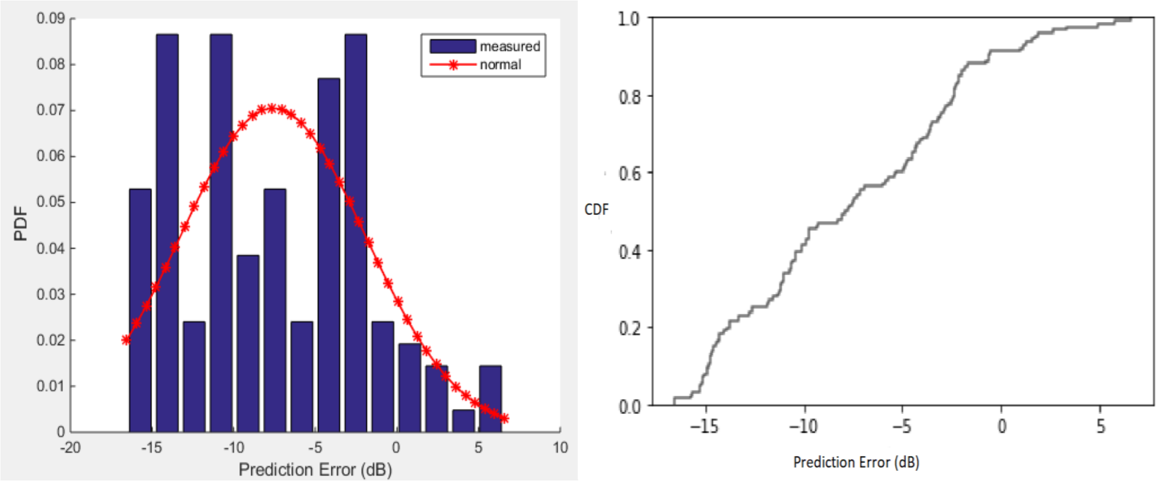
(b)


PDF
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-20
-15
-10
-5
0
5
Prediction Error (dB)
measured
normal
CDF
1.0
0.8
0.6
0.4
0.2
0.0
−15
−10
−5
0
Prediction Error (dB)

(c)

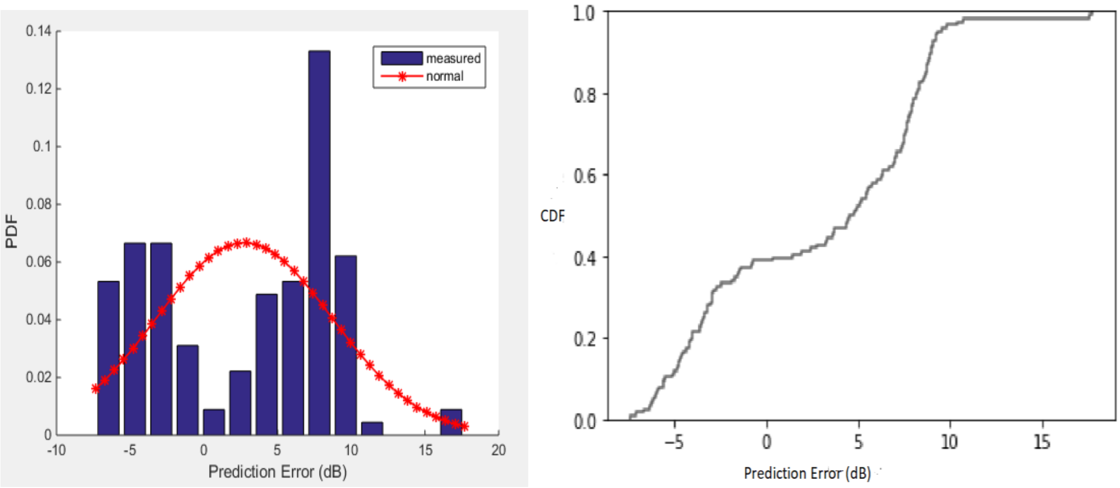


(d)

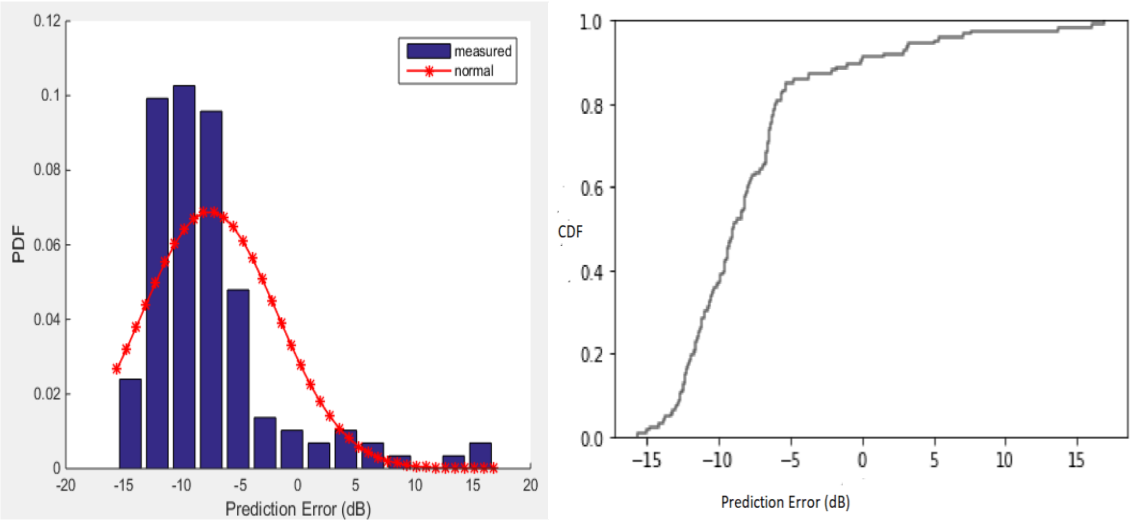


(e)

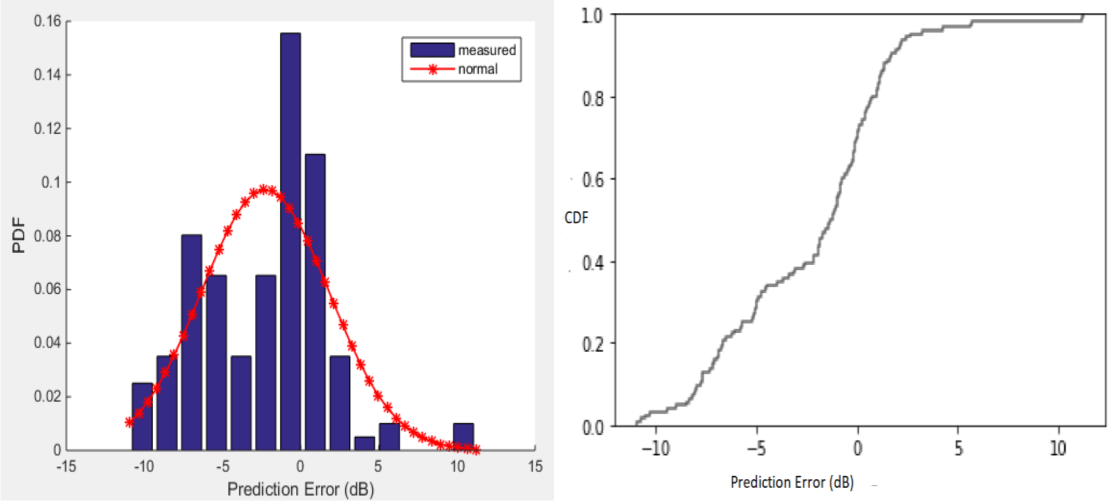
**Figure 11**: **Normalized Prediction Error between measured and predicted models for suburban Environment, Oye-Ekiti**
(a) Cost-231 model (b) Ericson model (c) Erceg model (d) Lee model (e) SPM model



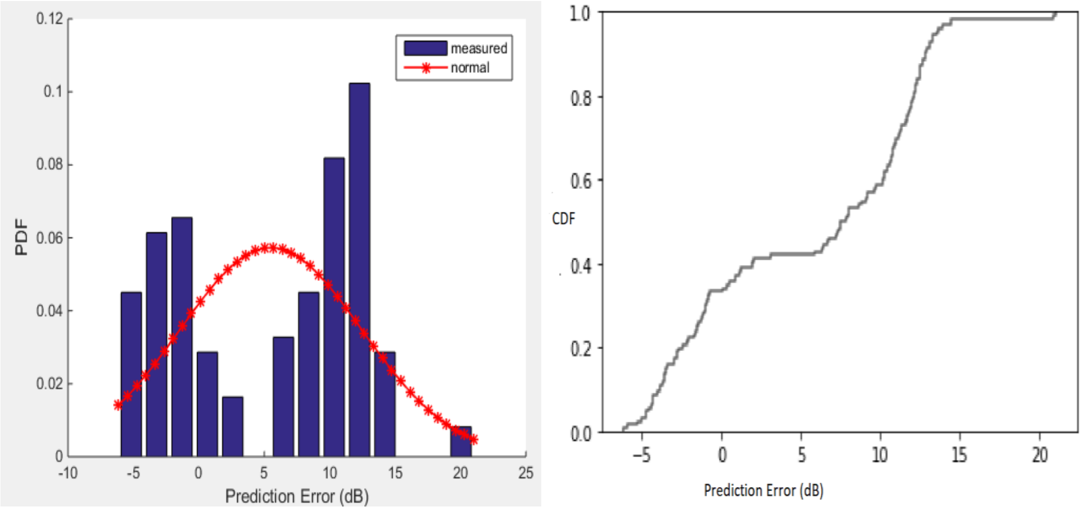
(a)


measured
normal
PDF
0.12
0.1
0.08
0.06
0.04
0.02
0
-20
-15
-10
-5
0
5
10
15
20
Prediction Error (dB)
CDF
1.0
0.8
0.6
0.4
0.2
0.0
−15
−10
−5
0
5
10
15
Prediction Error (dB)

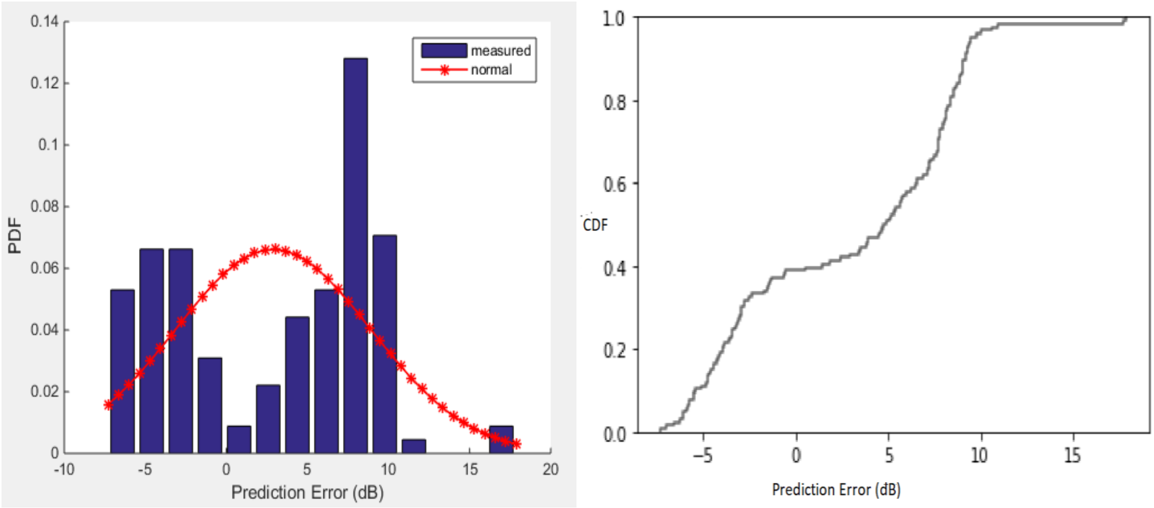
(b)


measured
normal
PDF
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-15
-10
-5
0
5
10
15
Prediction Error (dB)
CDF
1.0
0.8
0.6
0.4
0.2
0.0
−10
−5
0
5
10
Prediction Error (dB)

(c)


measured
normal
PDF
0.12
0.1
0.08
0.06
0.04
0.02
0
-10
-5
0
5
10
15
20
25
Prediction Error (dB)
CDF
1.0
0.8
0.6
0.4
0.2
0.0
−5
0
5
10
15
20
Prediction Error (dB)

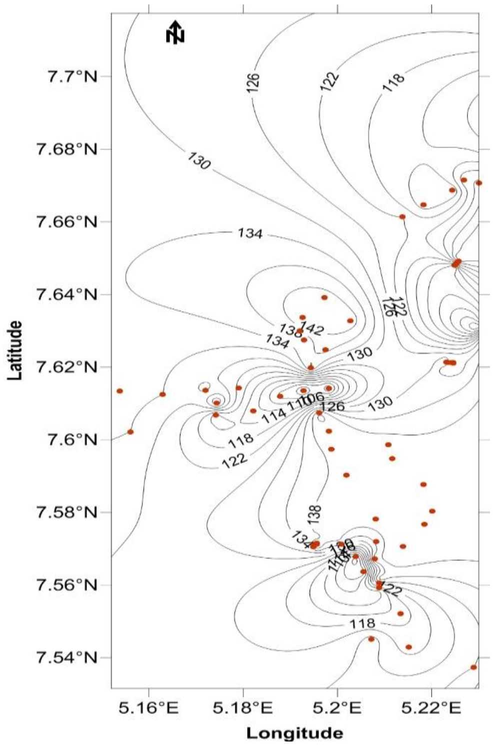
(d)



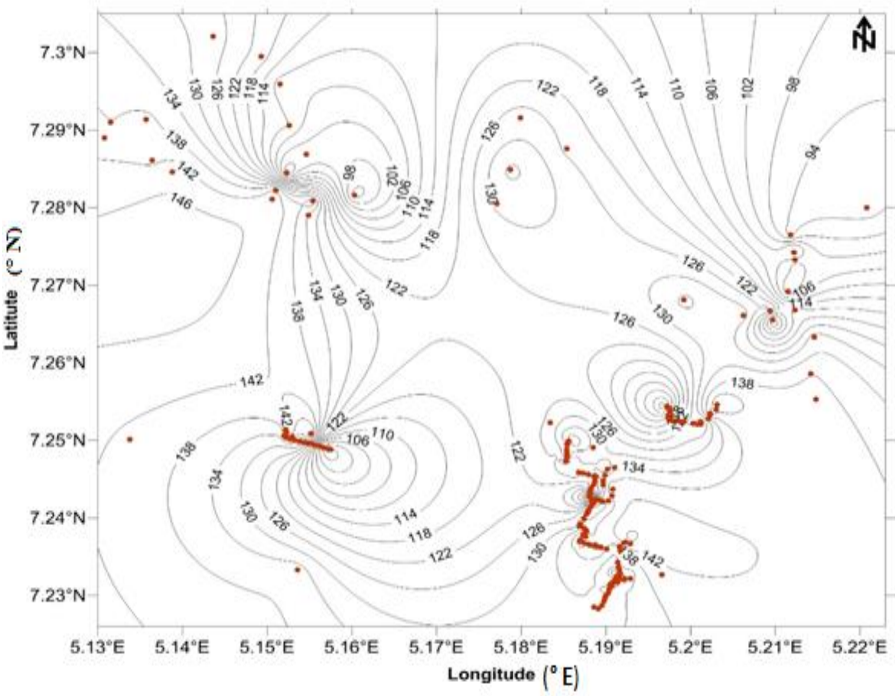
(e)

**Figure 12**: **Normalized Prediction Error between measured and predicted models for rural Environment, Odigbo**
(a) Cost-231 model (b) Ericson model (c) Erceg model (d) Lee model (e) SPM model

The measured path loss values estimated from the received signal strength in all the sectors of the base stations considered based on different microcellular environments are used to generate contour plots for both seasons. In order to make the path loss contour map to cover a wide area over southwestern Nigeria, some other locations within the region studied were also incorporated. The contour lines were developed using kriging spatial interpolation technique. Figures 13(a) and (b) present the path loss contour plots for urban environments of Maryhill and Isolo. Figures 14(a) and (b) also depict the contour plots of path loss over suburban environments of Oye-Ekiti and Mobil. Similar results were also observed in the rural environments investigated and the contour maps are presented in Figures 15(a) and (b).

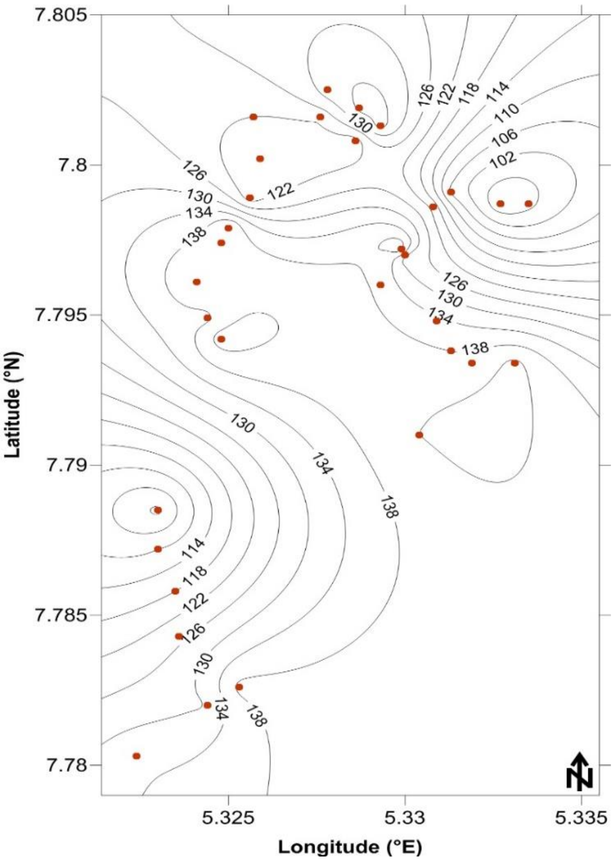


(a)

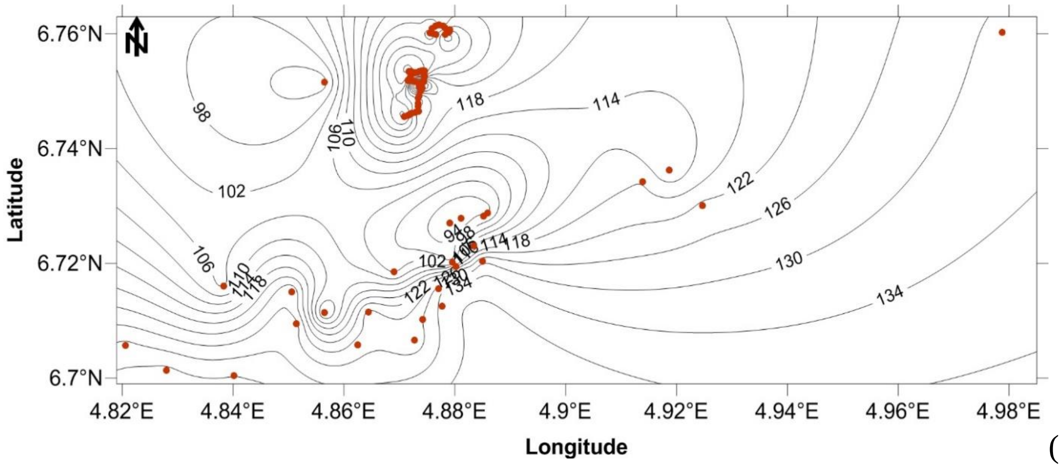


(b)

**Figure 13**: **Contour plots of urban environments** (a) Maryhil (b) Isolo

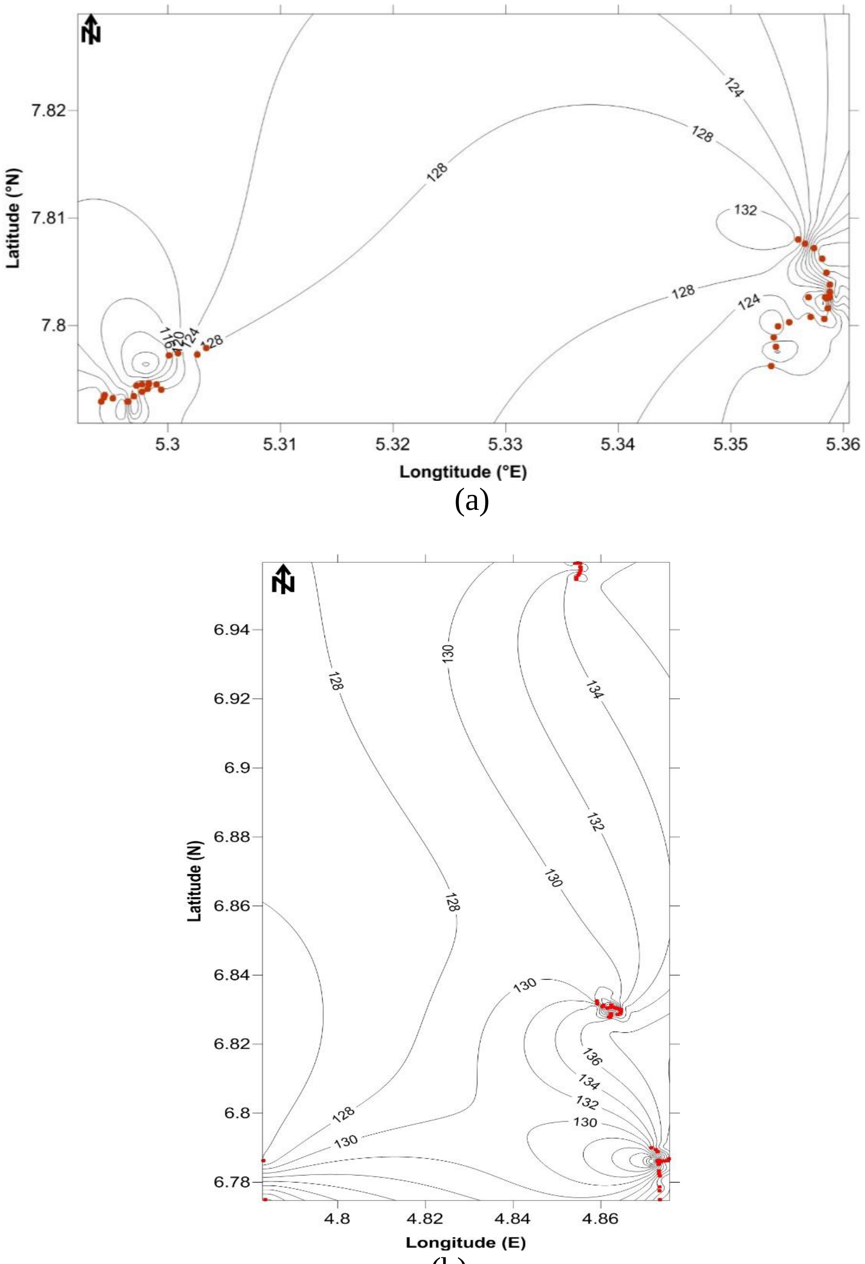


(a)



(b)

**Figure 14**: **Contour plots of suburban environments** (a) Oye-Ekiti (b) Mobil



(a)

(b)

**Figure 15**: **Contour plots of rural environments** (a) Ilupeju (b) Odigbo

## Conclusion

In this paper, the fitness of six widely used empirical path loss models has been evaluated using five metrics to gauge their performance based on field received signal strength measurements along the three sectors of six base stations located in urban, suburban and rural environment of Ekiti and Ondo States, Nigeria. The performance measures were based on RMSE, SC-RMSE, prediction error, normalised error probability function and mean prediction error. From the outcomes of the error analysis, no single model consistently fit the path loss values along the routes. The criteria for fitness is when the RMSE value is 0 to 7 dB for urban environment and 0 to 10 dB for suburban and rural environments. However, Cost-231, Erceg and SPM models provide better fitness in some monitored base stations in urban environments with RMSE values slightly above 7 dB. In suburban and rural monitored base stations, some of the models performed better in terms of RMSE analysis, apart from Egli and Ericson models that perform woefully with higher RMSE and SC-RMSE values.

The introduction of normalized probability density function has helped in studying the prediction error distribution counts for each of the empirical models across the link and has aided in evaluating which model fit into Gaussian distribution better. The provision of prediction error bounds for models and contour plots will serve as guidelines for researcher and practising engineers in choosing the appropriate path loss models for interference analysis and coverage optimization of wireless devices operating in the GSM frequency bands in similar environments in Nigeria.

However, tuning of the parameters of Erceg and Cost-231 models is essential to minimize the RMSE values to the acceptable ranges suitable for all the three environments.

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