ISSN 0511-5728
The West Indian Journal of Engineering
Vol.41, No.2, January 2019, pp.13-21

Determination of Best-fit Propagation Models for Pathloss Prediction of a 4G LTE Network in Suburban and Urban Areas of Lagos, Nigeria

Agbotiname L. Imoize [a,Ψ], Augustus E. Ibhaze[b], Peace O. Nwosu[c], and Simeon O. Ajose[d]

Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Akoka Lagos, Nigeria
[a]E-mail: aimoize@unilag.edu.ng;
[b]E-mail: ibhazea@gmail.com;
[c]E-mail: peacelink345@yahoo.com;
[d]E-mail: solumideajose@gmail.com

[Ψ] *Corresponding Author*

(Received 30 December 2017; Revised 01 June 2018; Accepted 10 July 2018)

Abstract: *Propagation measurements and modeling provide useful information for signal strength prediction and the design of transmitters and receivers for wireless communication systems. In order to deploy efficient wireless communication systems, path loss models are indispensable for effective mobile network planning and optimisation. This paper presents propagation models suitable for path loss prediction of a fourth generation long-term evolution (4G LTE) network in the suburban and urban areas of Lagos, Nigeria. The reference signal received power (RSRP) of a 4G LTE network was measured at an operating frequency of 3.4GHz, and measured data was compared against existing pathloss models. Among the candidate models, the COST 231-Hata and the Ericsson models showed the best performances in the urban and suburban areas with root mean squared errors (RMSEs) of 5.13dB and 7.08dB, respectively. These models were selected and developed using the least square regression algorithm. The developed models showed good prediction results with RMSEs of 6.20dB and 5.90dB in the urban and suburban areas, respectively, and compare favourably with propagation measurement results reported for similar areas. It was found that these models would better characterise radio coverage and mobile network planning, enhancing the quality of mobile services in related areas.*

Keywords: *4G LTE network; Path loss modeling; Propagation models; Suburban; Urban area, Least square regression*

1. Introduction

Propagation modeling has attracted major concerns in the industry and academia in recent years. Path loss models are essential tools for signal strength estimation, a key performance indicator for radio system installation within a wireless communication environment (Athanasiadou, 2009). As electromagnetic waves radiate through space, the signal strength degrades due to the signal path distance, and dynamic terrain characteristics. This results in signal scattering, absorption and reflection among others. It is worthy of note that these models are site specific and are designed based on the propagation terrain of the environment of interest (Mollel and Kisangiri, 2014).

In addition, slight deviations in the characterisation of the area under investigation could affect the efficiency of propagation models designed for the area. This implies that the adoption of models in environments other than those designed for their application could result in severe planning and performance issues. Fourth generation long-term evolution (4G LTE) technology has an undeniable capacity for wireless broadband services due to its enormous benefits. The key features of 4G LTE include higher data rates, greater spectral efficiency, low latency, scalable bandwidth, reduced network complexity and improved quality of service, resulting in user satisfaction (Song and Shen, 2010; Shabbir, et al., 2011; Ramiro and Hamied, 2011; Dahlman, Parkvall, and Skold, 2013; ElNashar, El-Saidny and Sherif, 2014).

However, it is quite challenging to decide on the path loss model applicable to the environment of interest. There are very few proposed models for the 4G LTE contest with a focus on the 3.4 GHz frequency band, but we have not seen any elaborate study on propagation modeling of 4G LTE network with a focus on the Nigerian environment. Therefore, the focus of this paper is to investigate the relationship between measured pathloss and existing propagation models, with a goal to determining the best models for a commercial 4G LTE network in the suburban and urban areas of Lagos, Nigeria. This would be very useful to mobile network planners and engineers in ensuring greater accuracy and better quality of service deployment in the suburban and urban areas of Lagos, Nigeria. The results presented in this paper could be very useful in predicting and characterising propagation path loss in the Nigerian environment, and our future work will focus on providing correction factors to ease the applicability of the proposed models in different areas.

This paper is organised as follows. Section 2 presents an overview of related works on propagation measurements and channel modeling. Section 3 covers the measurements campaigns, experimental set-up, and modeling parameters. Section 4 presents the results of the study and useful discussions. Finally, the conclusion to the paper is given in Section 5.

2. Related Work

Long Term Evolution, a 3rd generation partnership project (3GPP), has been designed and developed to meet the requirements of mobile network operation at data rates up to 100Mbps (Dimou et al., 2009). This will enable operators to provide high data rate applications with low latency, thereby culminating into an increased market penetration by mobile operators (Sesia, Baker and Toufik, 2011). Different propagation models have been adapted to different terrains at different frequencies, and the classification of models into urban, suburban and open (rural) areas has been reported in (Abhayawardhana et al., 2005; Ajose and Imoize, 2013). These models include the free space model, Okumura Hata model, COST 231 model, Walfish-Ikegami model, Lee model, Stanford University Interim (SUI) model, ECC-33 model and others (Milanovic, Rimac-Drlje and Beyuk, 2007; Aragon-Zavala, 2008; Molisch, 2012).

The performance efficiency of the existing models when applied to wireless terrains other than those they were designed for falls far from ideal (Chebil et al. 2011). Thus, this prompts the need to determine the models that best predict the signal strength of the wireless channel. Several studies conducted in Nigeria and other parts of the world have revealed that a number of path loss models perform efficiently when tuned with respect to measured data.

On propagation measurements and channel modeling, Ajose and Imoize (2013) reported extensive propagation measurements, and presented a modified COST 231 Hata model for improved pathloss prediction in Lagos, Nigeria. Similarly, Ibhaze et al. (2016) conducted measurement campaign at 1800 MHz in Ikorodu, Nigeria, and proposed the modification of SUI and COST 231 models for signal prediction and network planning in the investigated area.

Chebil, Lawas, and Islam (2013) carried out a set of measurements at frequencies ranging from 1800 MHz to 1900MHz and compared the measured pathloss with six empirical propagation models. It was reported that the SUI and the lognormal models showed superiority over other models, and could be used to estimate the predicted path loss in microcell mobile coverage, in the Malaysian environment.

Kamboj, Gupta and Birla (2011) reported that the SUI path loss model provides the minimum path loss among other path loss models compared under specified conditions, using propagation measurements at 3.5GHz. Similarly, Kale and Jadhav (2013) performed analysis of empirical models for WiMAX in an urban environment in India. It was reported in the study that the Ericsson and the SUI models showed a better performance in the investigated urban environment.

Bola and Saini (2013) carried out measurement campaigns using different empirical models for WiMAX in urban areas. The analysis showed that all models experienced higher path loss due to multipath and non-line of sight (NLOS) environments. It was concluded that there is a slight change in path loss when the operating frequency was changed. Further studies on LTE, WiMAX, WLAN design, and performance analysis are reported in (Korowajczuk, 2011; Katev, 2012).

In another related study, Podder et al. (2012) reported an analytical study on propagation models at 2.5GHz. The comparative analysis revealed that increased multipath in the urban and suburban areas favored the SUI model, which experienced the lowest path loss compared to the rural area. In the rural area, the COST-Hata model provided the lowest path loss compare to the SUI model, and the results showed that no single propagation model is well suited for all the tested areas.

On performance analysis of diverse models for wireless network in different environments, Khan, Eng, and Kamboh, (2012) reported that all models under study in urban areas, due to increased multipath effect and NLOS, experienced higher path loss compared to suburban areas, and that no single model could be recommended for all environments.

Famoriji and Olasoji (2013) used Friis and Okumura - Hata models to predict broadcasting signal strength for a television station in Akure Ondo State, Nigeria. The authors concluded that the performance of Okumura–Hata model showed its suitability for good signal prediction and the mean deviation errors were added to the Okumura-Hata model in order to derive the modified Okumura-Hata model suitable for deployment in the Akure metropolis.

Furthermore, Ibhaze et al. (2017) proposed the modification of Ericsson model at 2100MHz for the Alagbado axis of Lagos, Nigeria. Here, higher degree polynomial was fitted to measured data and the results were compared with some empirical models. Although this model was used earlier in predicting lower frequency ranges other than the investigated spectrum, it predicted the investigated wireless channel with less probability of error in contrast to the previously used Okumura-Hata model, and inappropriate model application was seen to have resulted in marked quality and coverage issues.

3. Measurement Campaigns

Measurement campaigns at 3.4 GHz using a personal computer with Genex probe, a data collection software interface and a GPS unit for the receiving device tracking is presented in the experimental set-up as shown in Figure 1, and a typical eNodeB site is as shown in Figure. 2.

Figure 1. Experimental set-up inside a drive test vehicle

Figure 2. Pictorial view of a typical eNodeB site located in Ajah area of Lagos, Nigeria

The reference signal received power measurements were taken and stored on a personal computer (PC) which had GENEX probe drive test (DT) software installed on it, and a Huawei Model E392 (4G compatible). The operating frequency is set from the PC and other readings such as transmitter-receiver distance, received signal level, location (latitude and longitude) are read from the PC. Here the personal computer with GENEX software installed on it, the Huawei modem and the GPS system were set-up in the drive test vehicle. The channel frequency was set to 3.4GHz, and the reference distance used for the measurements is 100m from the fixed base station. Transmitter to receiver distance was varied between 0.1km to 1.0km in steps of 50m at a near constant receiver antenna height of 1.5m. The transmitter-receiver distance was limited to 1km, in order to limit the impact of interference from neighboring transmitting antennas.

3.1 Suburban Areas

Propagation measurements were carried out at two eNodeB sites located in Ajah, typical of a suburban area in Lagos, Nigeria. Ajah is located on Latitude 6.4670N and Longitude 3.5670E. This area is dominantly residential and moderately congested. In addition, there are several schools, banks, and religion worship centers in this area. A typical Ajah area on a Google map is shown in Figure 3. The tested eNodeB sites are as shown in Figure. 4 and for simplicity, these are labelled as eNodeB 1 and eNodeB 2.

Figure 3. Google map showing Ajah (suburban) area of Lagos Nigeria

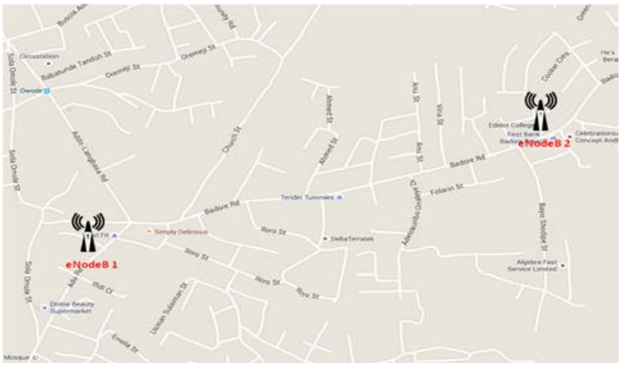

Figure 4. Google map showing the location of eNodeBs in the suburban areas

3.2 Urban Areas

Field measurements were carried out at two sites in Lagos-Island typical of an urban area in Lagos. Lagos-Island is located on Latitude 6.4500N and Longitude 3.4000E and is classified as an urban area. This area is dominantly a business hub with high density of high-rise buildings. A typical Lagos-highland area on a Google map is shown in Figure 5. The eNodeB sites location are as shown in Figure 6 and for convenience, these are denoted as eNodeB 3 and eNodeB 4.

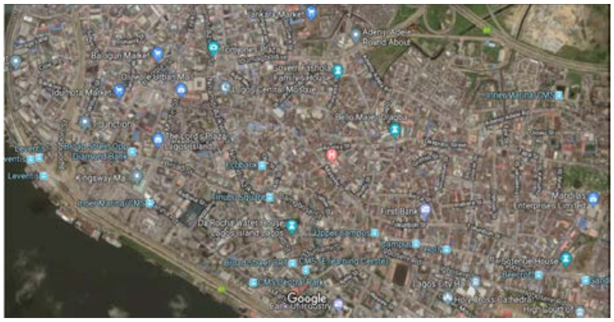

Figure 5. Google map showing Lagos-highland (urban) areas of Lagos Nigeria

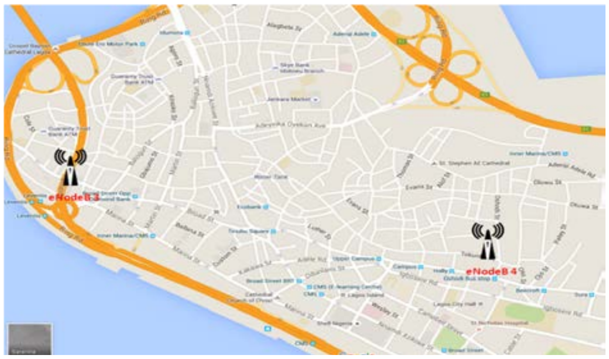

Figure 6. Google map showing the location of eNodeBs in the urban areas

4. Modelling Parameters

In this study, the operating frequency is fixed at 3400 MHz, distance between the transmit antenna and the receiver is limited to 1km with a transmitter height of 20m in urban area and 24m in sub-urban areas. Evidence shows that 1km is a reasonable antenna separation distance to limit the impact of interference from adjacent base stations (eNodeBs). For the Lagos environment, average inter-building distance is about 20m and street width is about 10m. Correction factors for shadowing effects are given as 10.6 dB in urban and 8.2dB in sub-urban areas, respectively (Sesia, Baker and Toufik, 2011; Shabbir et al., 2011). The modeling parameters are as shown in Table 1.

Table 1. Modeling Parameters

Parameters	Values	
	Suburban area	Urban area
Transmitter power	43 dBm	43 dBm
Operating frequency	3.4GHz	3.4GHz
Max. distance between Tx and Rx	1km	1km
Transmitter antenna height	20m	24m
Receiver antenna height	1.5m	1.5m
Building to building distance	20m	20m
Average building height	9m	18m
Street width	10m	10m
Street orientation angle	40^o	30^o
Correction for shadowing	8.2dBm	10.6dBm

5. Results and Discussion

The mean reference signal received power measured from the suburban and urban areas was converted to the equivalent pathloss values for further analysis. Results shown as tests eNodeB 1 and eNodeB 2 are used for analysis to reflect a suburban area, and tests eNodeB 3 and eNodeB 4 are typical of an urban area. The path loss is calculated using Eq. (1) as in Rappaport (1996).

$$PL(dB) = \mathrm{P_T + G_T + G_R - P_R - L_T - L_R} \qquad (1)$$

where,

$$\mathrm{P_T + G_T + G_R - L_T - L_R} = EIRP \qquad (2)$$

From Equations (1) and (2),

$$PL(dB) = EIRP - P_R \qquad (3)$$

Equation (1) gives the gains and losses in the signal strength from the transmitter to the receiver, and Table 2 presents the LTE downlink gains and losses (Mishra, 2004). The total effective isotropically radiated power (EIRP) includes the transmitter EIRP, and other gains and losses. The values of the test eNodeB parameters are observed from the equipment manufacturers' manual, actual measurements and from the data reported in (Mishra, 2004; Holma and Toskala, 2007). From Table 2, the total EIRP is given as shown in Eq. (4). Hence, from Equations (3) and (4), the corresponding path loss at a distance *d* km from the transmitter is given by Eq. (5). Correspondingly, the calculated path loss in the suburban and urban areas, compared with free space loss is as shown in Figure 7. Here, it is observed that the pathloss for the urban setting is higher than the suburban setting for about 80% of the measurements period. This is expected because pathloss in suburban area is supposed to be less compared with pathloss in the urban area.

$$EIRP = 58.75\ dB + (-22.5)\ dBm = 36.25dBm \qquad (4)$$

$$PL = 36.25dBm - P_R \qquad (5)$$

Table 2. Base stations (eNodeBs) downlink parameters

Parameters	Values
Maximum Transmitter Power	43dBm
Multi-Antenna Combining Gain	3dB
Transmitter Antenna Gain	17dBi
Radio Frequency Filter + Cable Loss	3dB
Pilot Power Boosting	3dB
Transmitter Duplexing Loss	0dB
Loss Due to Pilot Powers	-1.25dB
Total Transmit EIRP	58.75dBm
Handoff Gain	2.5dB
HARQ Gain	3dB
Coding Gain	0dB
Interference Margin	2dB
Penetration Loss	20dB
Log normal Fading Margin	6dB
Other Losses and Gains	-22.5dB

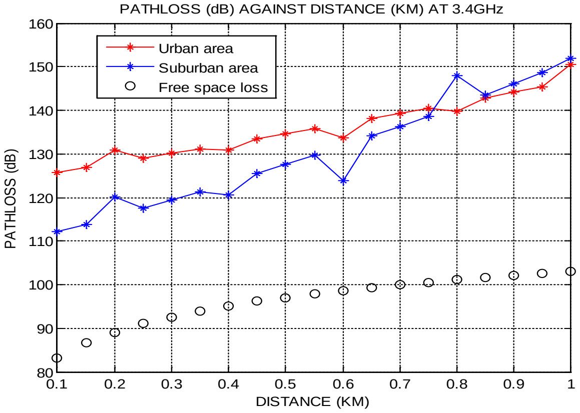

Figure 7. Comparison of path loss of measured data in suburban and urban areas

5.1 Results - Typical of a Suburban Area

The mobile receiver height was maintained at 1.5m, Tx-Rx distance increases in steps of 50m from 100m to 1.0km and a transmitter antenna height of 20m was used. Results typical of a suburban area are as shown in Fig. 8. Here, the predicted and the measured path loss vary logarithmically with propagation distance. It can be seen from Figure 8 that the SUI and the COST 231/WI models showed alarming deviations from the measured path loss. On the other hand, the Ericsson model showed the best match to measured data whereas the COST 231-Hata and ECC-33 models show close agreement with measured data.

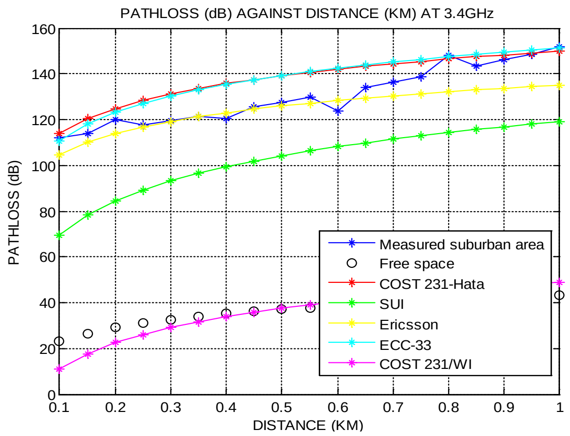

Figure 8. Predicted and measured pathloss in a suburban area

5.2 Results - Typical of an Urban Area

In the urban area, the operating frequency was set at 3400 MHz, the transmitter height at 24 m, transmitter (Tx)-receiver (Rx) distance was varied between 0.1km to 1.0km in steps of 50m at a near constant receiver antenna height of 1.5m. Variations in the predicted and measured path loss values are as shown in Figure 9. It shows that the COST-231 Hata model is the best fit to measured pathloss, and the Ericsson model show close relationship with the measured data, while the COST 231 Walfisch Ikegami (COST-231/WI), SUI and the ECC-33 models showed reasonable deviations from the measured data.

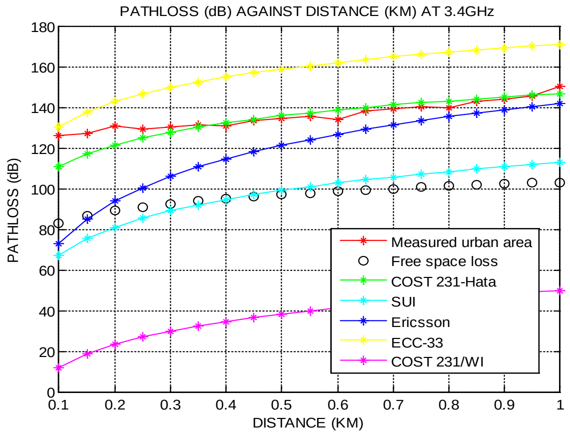

Figure 9. Predicted and measured path loss in an urban area

5.3 Root Mean Squared Error Analysis

The root-mean-squared error (RMSE) is used for error estimation between measured data and referenced or standardised data set. The RMSE represents the mean standard deviation between the measured and predicted values (Chebil et al., 2011; Ajose and Imoize, 2013).

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(PL_{M,i} - PL_{P,i}\right)^2}{N}} \quad (6)$$

Where,

$PL_{M,i}$ is the actual sample values
$PL_{P,i}$ is the predicted sample values
N is the number of data points

From Eq. (6), the RMSE for the measured and predicted path loss is given as shown in Eq. (7);

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(PL_{measured,i} - PL_{predicted,i}\right)^2}{N}} \quad (7)$$

where

$PL_{measued,i}$ = Path loss of measured data in dB
$PL_{predicted,i}$ = Predicted path loss measured in dB
N = 19 depicting the number of measured data points

The RMSE values follows directly from Eq. (7) with the resulting values for the suburban and urban areas are as shown in Table 3.

Table 3. Root mean squared errors in suburban and urban areas

Pathloss models	Root mean squared errors (dB)	
	Suburban area	Urban area
Free Space	34.9108	39.6194
COST 231 Hata	9.9103	5.1343
SUI	57.3672	48.4570
Ericsson	7.0797	15.1728
ECC -33	8.6927	18.9087
COST 231 W/I	13.8730	5.2496

5.4 Best Model Selection

Measured pathloss at 3400 MHz in Ajah and Lagos-highland areas of Lagos State, Nigeria have been compared against predicted path loss. From Table 3, the minimum value of the RMSE observed is 5.1343dB in the urban area. This corresponds to the RMSE of the predicted pathloss for the COST-231-Hata model. The COST-231-Hata model, which satisfied the RMSE closest to zero, is taken as the best candidate for predicting the pathloss in the urban area.

Similarly, the minimum value of the RMSE as observed from Table 3 is 7.0797dB, for the suburban area. This corresponds to the RMSE of the pathloss predicted for the Ericsson model. Hence, the Ericsson model is the most suitable model for predicting the pathloss of measured data in the suburban area.

5.5 Modification of Selected Model for Urban Areas

The COST-231 Hata model has been selected as the best candidate for path loss prediction in the urban area. This is because it gives the best prediction (a value closest to zero) when compared with other contending models. However, there is a need to modify the model to improve its prediction accuracy. A modification of the COST 231 model can be achieved by adding the value of the corresponding RMSE to the model (Ajose and Imoize, 2013; Ogbeide and Edeko, 2013; Famoriji and Olasoji, 2013).

$$PL = 46.3 + 33.9.\log_{10} f - 13.82.\ \log_{10} h_b - 3.20[\log_{10}(11.75\ h_r)]^2 - 4.97 + [44.9 - 6.55.\ \log_{10} h_b].\ \log_{10} d + C_m \tag{8}$$

where,

$f_c = 3400\text{MHz}$; $h_b = 24\text{m}$

$h_r = 1.5\text{m}$; $C_m = 3$ dB for urban

$d =$ distance between transmitter and receiver in meters

Adding the value of RMSE to Eq. (8) results in Eq. (9) in terms of *d*.

$$PL = 46.3 + 33.9.\log_{10}(3400) - 13.82.\ \log_{10}(24) - 3.20[\log_{10}(11.75 * 1.5)]^2 - 4.97 + [44.9 - 6.55.\ \log_{10} 20].\log_{10} d + 3 + RMSE \tag{9}$$

Here, it should be noted that the modification is aimed at giving better performance to the model, when compared to the actual predicted pathloss, hence the sign of the RMSE is important. By applying Eq. (7) in Eq. (9), we have;

$$PL = 46.3 + 33.9.\log_{10}(3400) - 13.82.\ \log_{10}(24) - 3.20[\log_{10}(11.75 * 1.5)]^2 - 4.97 + [44.9 - 6.55.\ \log_{10} 20].\log_{10} d + 3 + (-5.1343) \tag{10}$$

$$PL = 145.929 + 36.38.\log_{10}(d) \tag{11}$$

where $d = 0.1, 0.15, 0.2 \ldots 1.0\ km$

Equation (11) shows a simplified and modified COST-231 Hata model for the selected urban area at 3400 MHz. The comparison of the measured pathloss, modified and predicted COST 231 Hata model is as shown in Figure 10.

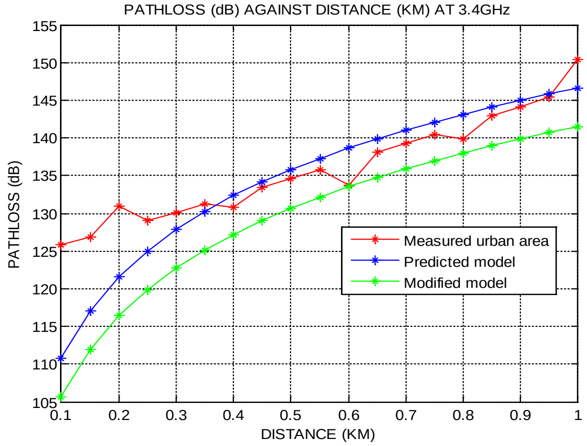

Figure 10. Comparison of measured pathloss, modified and predicted COST 231 Hata model for urban areas

5.6 Modification of Selected Model for Suburban Areas

The Ericsson model gives the best prediction in relation to the measured path loss in the suburban area, with an RMSE of 7.0797dB. The modification to the Ericsson model can be achieved by adding the value of the corresponding RMSE (± 7.0797dB). The Ericsson model is given (Ibhaze et al., 2017) as shown in Eq. (12).

$$PL = a_0 + a_1.\log_{10}(d) + a_2.\log_{10}(h_b) + a_3.\log_{10}(h_b)\ \log_{10}(d) - 3.2(\log_{10}(11.75h_r))^2\ ) + g(f) \tag{12}$$

$$PL = 36.2 + 30 * \log_{10}(d) + 12 * \log_{10}(20) + 0.1 * \log_{10}(20)\ \log_{10}(d) - 3.2 * (\log_{10}(11.75 * 1.5))^2) + 44.49 * \log_{10} 3400 - 4.78 * (\log_{10} 3400)^2 + RMSE \tag{13}$$

Applying Eq. (7) in Eq. (13), gives;

$$PL = 36.2 + 30 * \log_{10}(d) + 12 * \log_{10}(20) + 0.1 * \log_{10}(20)\ \log_{10}(d) - 3.2 * (\log_{10}(11.75 * 1.5))^2) + 44.49 * \log_{10} 3400 - 4.78 * (\log_{10} 3400)^2 + (-7.0797) \tag{14}$$

$$PL = 137.2683 + 30.33.\log_{10}(d) \tag{15}$$

where, $d = 0.1, 0.15, 0.2 \ldots 1.0\ km$

The results showing a comparison of the measured pathloss, predicted and modified Ericsson model is as shown in Figure 11.

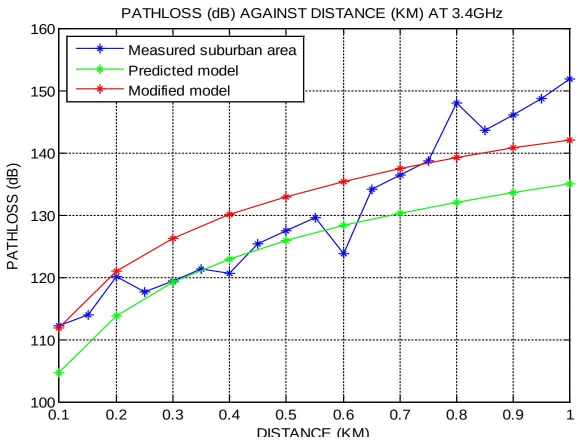

Figure 11. Comparison of the measured pathloss, modified and predicted Ericsson model for suburban areas

5.7 Development of Best Curve for Measured Pathloss

The least square regression method is generally adopted to fit a straight line or a curve to a set of data points (Hoffman and Frankel, 2001; Hamming, 2012; Stroud, and Booth, 2013). A second order polynomial of the form $y = a + bx + cx^2$ has been chosen to fit the measured path loss data. Generally for a j^{th} order polynomial of the form of Eq. (16) (Stroud and Booth, 2013);

$$f(x) = a_j x^j + a_{j-1} x^{j-1} + a_{j-2} x^{j-2} + \ldots + a_0 \tag{16}$$

Polynomial equations of the best fit are given as;

$$a_0 N + a_1\sum x_i + \ \ldots. + a_j\sum x_i^{\ j} \ = \sum x_i\, f(x)_i \tag{17}$$

$$a_0\sum x_i + a_1\sum x_i^{2} + \ldots. + a_j\sum x_i^{\ j+1} = \sum x_i^{2} f(x)_i \tag{18}$$

$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots$$

$$a_0\sum x_i^{\ j} + a_j\sum x_i^{\ j+1} + \ldots. + a_1\sum x_i^{2j} = \sum x_i^{\ j} f(x)_i \tag{19}$$

where

N = number of data points

i = position of each of the data points

j = order of the polynomial

Equations (17) – (19) can be written in matrix form as shown in Eq. (20).

$$\begin{bmatrix} n & \sum x_i & \ldots.. & \sum x_i^{\ j} \\ \sum x_i & \sum x_i^{\ 2} & \ldots.. & \sum x_i^{\ j+1} \\ \vdots & \vdots & \vdots & \vdots \\ \sum x_i^{\ j} & \sum x_i^{\ j+1} & \ldots.. & \sum x_i^{\ 2j} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_j \end{bmatrix} = \begin{bmatrix} \sum x_i f(x)_i \\ \sum x_i^{\ 2} f(x)_i \\ \vdots \\ \sum x_i^{\ j} f(x)_i \end{bmatrix} \tag{20}$$

In terms of the path loss of measured data $PL_{measured}$ and the distance between the transmitting and the receiving antennas, Eq. (20) can be re-written as in Eq. (21);

$$\begin{bmatrix} n & \sum d_i & \ldots.. & \sum d_i^{\ j} \\ \sum d_i & \sum d_i^{\ 2} & \ldots.. & \sum d_i^{\ j+1} \\ \vdots & \vdots & \vdots & \vdots \\ \sum d_i^{\ j} & \sum d_i^{\ j+1} & \ldots.. & \sum d_i^{\ 2j} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_j \end{bmatrix} = \begin{bmatrix} \sum d_i PL_{measured,i} \\ \sum d_i^{\ 2} PL_{measured,i} \\ \vdots \\ \sum d_i^{\ j} PL_{measured,i} \end{bmatrix} \tag{21}$$

A resultant second order polynomial in terms of the fitted values for the measured path loss PL_{fitted} and the distance d is of the form of Eq. (22);

$$PL_{\ fitted} = a + b * d + c * d^2 \tag{22}$$

Comparing Eq. (16) to Eq. (22), a_0 = a, a_1 = b, a_2 = c. The least square regression data for measured path loss in the suburban and urban areas are as shown in Table 4, and Eq. (23) follows directly from Eq. (21) and Table 4.

Table 4. Least square regression data for measured path loss in suburban and urban areas

Parameters	Suburban Area	Urban Area
d	10.45	10.45
$d^{\ 2}$	7.1725	7.1725
D^3	5.1524	5.1524
$d^{\ 4}$	4.5169	4.5169
$PL_{measured}$	2478.8	2582.6
$d \ * PL_{measured}$	1425.6	1453.7
$d^{\ 2} * PL_{measured}$	1006.1	1012.8

$$\begin{bmatrix} 19 & 10.45 & 7.1725 \\ 10.45 & 7.1725 & 5.1524 \\ 7.1725 & 5.1524 & 4.5169 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 2582.6 \\ 1453.7 \\ 1012.8 \end{bmatrix} \tag{23}$$

As shown in Eq. (23), the constants a, b and c are solved using a third order determinant method in MATLAB (Hoffman and Frankel, 2001). The results are highlighted as shown in Eq. (24);

$$a = 126.2429,\ b = 8.0496,\ c = 13.9272 \tag{24}$$

Now, we substitute the values in Eq. (24) into Eq. (22), resulting in the curve that best fit the measured data in the urban area as shown in Eq. (25);

$$PL_{\ fitted} = 126.2429 + 8.0496d + 13.9272d^2 \tag{25}$$

Similarly, we derive a suitable equation for the suburban area, following the same approach for the urban area. From Table 4, and applying Eq. (21), the values of a, b and c are computed for the suburban area by solving Eq. (26);

$$\begin{bmatrix} 23 & 10.45 & 7.1725 \\ 10.45 & 7.1725 & 5.1524 \\ 7.1725 & 5.1524 & 4.5169 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 2478.8 \\ 1425.6 \\ 1006.1 \end{bmatrix} \tag{26}$$

Similar to Eq. (24), the values of a, b, and c are as shown in Eq. (27);

$$a = 111.1971,\ b = 20.5984,\ c = 21.0234 \tag{27}$$

The equation of the curve that best fit the measured path loss in the suburban area is given in Eq. (28).

$$PL_{\ fitted} = 111.1971 + 20.5984d + 21.0234d^2 \tag{28}$$

The comparison of the fitted data for the urban and suburban areas is as shown in Figures 12 and 13, respectively. The results depicted in Fig. 12 and Fig. 13 show that the least square (LS) curve fitting, approximately fits the measured data points with smaller error bound.

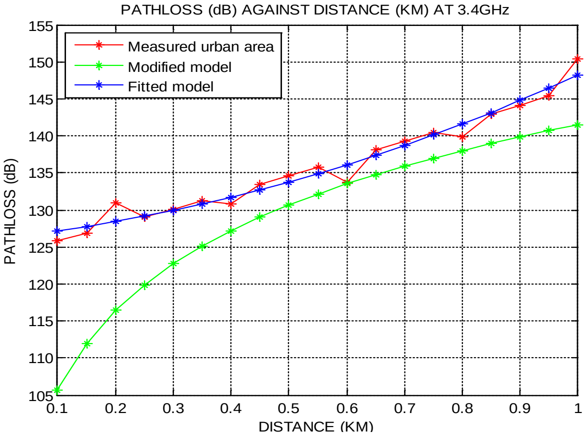

Figure 12. Comparison of measured pathloss, modified and fitted models for urban areas

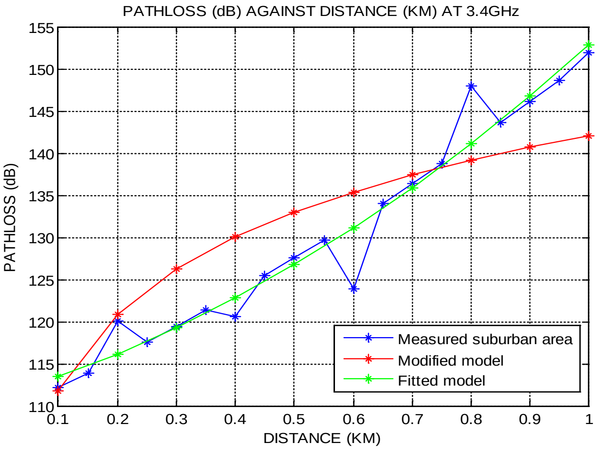

Figure 13. Comparison of measured pathloss, modified and fitted models for suburban areas

5.8 Validation of Models

In order to test the validity of the developed models for applicability in related environments, the RMSE analysis have been used to determine the error ratio based on the developed COST 231 Hata and the Ericsson models for urban and suburban areas, respectively. Applying Eq. (7), the results of the RMSE values are given as 6.20dB and 5.90dB for urban and suburban areas, respectively.

The developed models are found suitable for the investigated areas. This is because the RMSEs between the fitted, measured and predicted path loss values fall reasonably in the acceptable range of up to 6dB (Wu and Yuan, 1998; Ajose and Imoize, 2013; Ogbeide and Edeko, 2013; Famoriji and Olasoji, 2013, Popoola et al., 2018). However, the excess pathloss of 0.20dB observed for the urban area may be due to other dynamic factors such as high-density vehicular movements.

6. Conclusion

Path loss of propagation measurements taken from four eNodeBs of a 4G LTE network in the suburban and urban areas of Ajah and Lagos highlands in Lagos State, Nigeria, have been compared against well-known empirical models. Results revealed that the COST-231 Hata model outperformed other contending models in the urban area with an RMSE value of 5.13dB, and the Ericsson model showed the best performance in the tested suburban area, with an RMSE value of 7.08dB.

These models were selected and developed for the urban and suburban areas, respectively. The development was necessary to further reduce the RMSEs for improved path loss prediction in the areas. The developed models showed improved RMSEs values within the acceptable range of up to 6dB. Overall, the results compare favourably with related works reported for similar areas, and future work will focus on providing correction factors to ease the applicability of the models to other environments.

References:

Abhayawardhana, V. S., Wassell, I. J., Crosby, D., Sellars, M. P., and Brown, M. G. (2005), “Comparison of empirical propagation path loss models for fixed wireless access systems”, *Proceedings of the IEEE 61st Vehicular Technology Conference*, VTC 2005-Spring, Stockholm, Sweden, Vol. 1, May, pp. 73-77.

Ajose, S. O., and Imoize, A. L. (2013), “Propagation measurements and modelling at 1800 MHz in Lagos Nigeria”, *International Journal of Wireless and Mobile Computing*, Vol.6, No.2, pp.165-174.

Athanasiadou, G. E. (2009), “Fixed wireless access propagation modelling and measurements”, *Proceedings of the IEEE 69th Vehicular Technology Conference*, VTC Spring 2009, Barcelona, Spain, April, pp. 1-5.

Aragon-Zavala, A. (2008), *Antennas and Propagation for Wireless Communication Systems*, John Wiley and Sons.

Bola, G. S., and Saini, G. S. (2013), “Path loss measurement and estimation using different empirical models for WiMAX in urban area”, *International Journal of Scientific and Engineering Research*, Vol.4, No.5, pp.1421-1428.

Chebil, J., Lawas, A. K., and Islam, M. D. (2013), “Comparison between measured and predicted path loss for mobile communication in Malaysia”, *World Applied Sciences Journal 21 (Mathematical Applications in Engineering)*, pp. 123-128.

Chebil, J., Lwas, A. K., Islam, M. R., and Zyoud, A. H. (2011), “Comparison of empirical propagation path loss models for mobile communications in the suburban area of Kuala Lumpur”, *Proceedings of the IEEE 2011 4th International Conference on Mechatronics (ICOM)*, Kuala Lumpur, Malaysia, May, pp. 1-5.

Dahlman, E., Parkvall, S., and Skold, J. (2013), *4G: LTE/LTE-Advanced for Mobile Broadband*, Academic Press.

Dimou, K., Wang, M., Yang, Y., Kazmi, M., Larmo, A., Pettersson, J. and Timner, Y. (2009), “Handover within 3GPP LTE: design principles and performance”, *Proceedings of the IEEE 70th Vehicular Technology Conference* (VTC 2009-Fall), Anchorage, Alaska, USA, September, pp. 1-5.

ElNashar, A., El-Saidny, M. A., and Sherif, M. (2014), *Design, Deployment and Performance of 4G-LTE Networks: A Practical Approach*, John Wiley and Sons.

Famoriji, J. O., and Olasoji, Y. O. (2013), “UHF radio frequency propagation model for Akure metropolis”, *Research Journal of Engineering Sciences*, Vol. 2(5), May, pp.6-10.

Hamming, R. (2012), *Numerical Methods for Scientists and Engineers*, Courier Corporation.

Hoffman, J. D., and Frankel, S. (2001), *Numerical Methods for Engineers and Scientists*, CRC press.

Holma, H., and Toskala, A. (2007) (Eds.), *HSDPA/HSUPA for UMTS: High-speed Radio Access for Mobile Communications*, John Wiley and Sons.

Ibhaze, A. E., Ajose, S. O., Atayero, A. A., and Idachaba, F. E. (2016), “Developing smart cities through optimal wireless mobile network”, *Proceedings of the IEEE International Conference on Emerging Technologies and Innovative Business Practices for the Transformation of Societies (EmergiTech)*, Balaclava, Mauritius, August, pp. 118-123.

Ibhaze, A. E., Imoize, A. L., Ajose, S. O., John, S. N., Ndujiuba, C. U., and Idachaba, F. E. (2017), “An empirical propagation model for path loss prediction at 2100 MHz in a dense urban environment”, *Indian Journal of Science and Technology*, Vol.8, No.1, pp. 1-9.

Kale, S. S., and Jadhav, A. N. (2013), “Performance analysis of empirical propagation models for WiMAX in urban environment”, *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*, Vol.3, No.5, pp. 24-28.

Kamboj, V., Gupta, D. K., and Birla, N. I. (2011), “Comparison of path loss models for WiMAX in rural environment at 3.5 GHz”, *International Journal of Engineering Science and Technology (IJEST)*, Vol.3, No.2, pp.1432-1437.

Katev, P. D. (2012), “Propagation models for WiMAX at 3.5 GHz”, *Proceedings of the IEEE 9th International Conference – 2012 ELEKTRO*, Rajeck Teplice, Slovakia, May pp.61-65. DOI: 10.1109/ELEKTRO.2012.6225572

Khan, I., Eng, T. C., and Kamboh, S. A. (2012), “Performance analysis of various path loss models for wireless network in different environments”, *International Journal of Engineering and Advanced Technology (IJEAT)*, Vol. 2, No.1, October, pp. 161-165.

Korowajczuk, L. (2011), *LTE, WiMAX and WLAN Network Design, Optimisation and Performance Analysis*, John Wiley and Sons.

Milanovic, J., Rimac-Drlje, S., and Bejuk, K. (2007), “Comparison of propagation models accuracy for WiMAX on 3.5 GHz”, *Proceedings of the 14th IEEE International Conference on Electronics, Circuits and Systems, ICECS 2007*, Marrakech, Morocco, December, pp. 111-114.

Mishra, A. R. (2004), *Fundamentals of Cellular Network Planning and Optimisation: 2G/2.5 G/3G Evolution to 4G*, John Wiley and Sons.

Molisch, A. F. (2012), *Wireless Communications*, Vol.34, John Wiley and Sons.

Mollel, M. S., and Kisangiri, M. (2014), "Comparison of empirical propagation path loss models for mobile communication", *Computer Engineering and Intelligent Systems*, Vol.5, No.9, pp. 1-10.

Ogbeide, O. K., and Edeko, F. O. (2013), "Modification of the Hata empirical propagation model for application in VHF band in Edo State, Nigeria", *International Journal of Engineering Science Invention*, Vol.2, No.8, pp. 35-39.

Podder, P. K., Islam, F., Sarker, D. K., Hasan, M. G., and Kundu, D. (2012), "An analytical study for the performance analysis of propagation models in WiMAX", *International Journal of Computational Engineering Research*, Vol.2, pp.175-181.

Popoola, S. I., Adetiba, E., Atayero, A. A., Faruk, N., and Calafate, C. T. (2018), "Optimal model for path loss predictions using feed-forward neural networks", *Cogent Engineering*, Vol.5, No.1, 1444345. https://doi.org/10.1080/23311916.2018.1444345

Ramiro, J., and Hamied, K. (2011) (Eds), *Self-organising Networks (SON): Self-planning, Self-optimisation and Self-healing for GSM, UMTS and LTE*, John Wiley and Sons.

Rappaport, T. S. (1996), *Wireless Communications: Principles and Practice*, Vol. 2. Prentice Hall, New Jersey

Sesia, S., Baker, M., and Toufik, I. (2011), *LTE-the UMTS Long Term Evolution: From Theory to Practice*, John Wiley and Sons.

Shabbir, N., Sadiq, M. T., Kashif, H., and Ullah, R. (2011). "Comparison of radio propagation models for long-term evolution (LTE) network", *International Journal of Next-Generation Networks (IJNGN)*, vol.3, No.3, pp. 27-41.

Song, L., and Shen, J. (2010) (Eds.), *Evolved Cellular Network Planning and Optimisation for UMTS and LTE*, CRC Press.

Stroud, K. A., and Booth, D. J. (2013), *Engineering Mathematics*, Palgrave Macmillan.

Wu, J., and Yuan, D. (1998), "Propagation measurements and modeling in Jinan city", *Proceedings of the 9th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Boston, Massachusetts, USA, Vol. 3, September, pp. 1157-1160.

Authors' Biographical Notes:

Agbotiname Lucky Imoize *is a Lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria, and presently a Fulbright Visiting Research Scholar with the Wireless at Virginia Tech Labs, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Virginia USA. He received his BEng (Hons) in Electrical and Electronics Engineering from Ambrose Alli University, Ekpoma, Nigeria, in 2008, and MSc in Electrical and Electronics Engineering with specialisation in Communications Engineering from University of Lagos, Nigeria, in 2012. He was elected as a Corporate Member of the Nigerian Society of Engineers, and he is a registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN). His research interests are in the areas of propagation measurements, channel modeling and multi-channel communications.*

Augustus Ehiremen Ibhaze *is presently a Lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He holds an M.Sc in Electrical and Electronics Engineering from the University of Lagos (2012) and B.Eng (Hons) in Electrical Engineering from Ambrose Alli University, Ekpoma, Nigeria, in 2008. He holds a Professional Certification in Information Technology service management (ITILversion3), Netherlands. He was elected as a Corporate Member of the Nigerian Society of Engineers and he is a registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN).*

Peace Oluchukwu Nwosu *is presently a practicing Engineer in Lagos, Nigeria. She completed Masters of Science in Electrical and Electronics Engineering, with specialisation in Communications Engineering at the University of Lagos, Akoka, Lagos, in 2012. Her current research interest is in the area of wireless communications engineering.*

Simeon Olumide Ajose *is a Professor of Electronics and Computer Engineering in Lagos State University. He was the Dean of Engineering from 1998 to 2002. He holds a BSc (Hons) in Electrical Engineering from the University of Lagos, Nigeria (1971), MSc and PhD from the University of London King's College in 1974 and 1976, respectively. He became a Fellow of the Nigerian Society of Engineers (FNSE) in 1989 and was featured in the first issue of International Who's Who in Engineering. His research interests are in the areas of microwave networks, digital signal processing and communication technology.*

■