Optimal Propagation Models for Path-loss Prediction in a Mountainous Environment at 2100MHz

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***Abstract*— The necessity and importance of path-loss determination for the purpose of mobile network planning and optimization requires that an optimal model should be developed for each specific environment. This will ensure proper planning leading to satisfactory service delivery to each environment at all times. In this study, 3G (2100MHz) mobile propagation in a mountainous area is investigated in order to determine a suitable model for optimizing path-loss prediction in urban, suburban and rural environments. Five models (free space, COST-231, Hata, Egli and ECC-33) were analyzed and compared with field measurement data. Their Mean Absolute Percentage Error (MAPE) and closeness (Root Mean Square Error) to the measured data were determined and compared. ECC-33 over-predicts path-loss for all the environments. Free space prediction was found to be impracticable. The RMSE of each of Egli, Hata and COST-231 were used to modify the models, predict new path-loss values and compare with the measured path-loss. The new RMSE values showed that the optimized models improved path-loss predictability by 76.42%, 25.50% and 73.67% for the rural, suburban and urban areas of the mountainous environment respectively.**

***Keywords*— Path-loss, COST-231 model, 2100MHz, mountainous, RMSE**

I. INTRODUCTION

Radio frequency (RF) planning and management is a continuous exercise in order to ensure customer satisfaction of service delivery by Network providers in any particular propagation environment. The effects of RF signal reflection, diffraction and scattering due to path obstruction in the propagation environment result in signal power losses along the path from the transmitter antenna to the mobile receiver antenna [1]. Other factors responsible for path loss include environment type, terrain, vehicle penetration, refraction, absorption and free space propagation. The determination of the path loss (PL) is key to effective planning and re-planning for network optimization. Several models for PL prediction have been developed for the three major propagation environments (Urban, Suburban and Rural). The methods employed in arriving at the model could be statistical (stochastic), deterministic or empirical. Stochastic models are developed from series of random variables. Deterministic models, such as ray tracing, utilize physical laws of electromagnetic wave propagation while empirical models are developed strictly from factual measurements taken on the field. Most of the models popularly used in path loss prediction for mobile telecommunication networks are empirical models. Examples are Okumura model, Hata model, Egli model, COST-231 (Extended Hata) model, ECC33 model and Standard University Interim (SUI) model [2]. These models were developed from extensive field measurements taken in some specific locations [3]. Each of the models has its limitations such that it may not be applicable in every other environment without modification. The limitations could be in terms of frequency range, environment type, range of Base Transceiver (BTS) antenna height, Mobile receiver antenna height, Transmitter-Receiver distance and terrain type. Hence it is concluded that path loss models should be site-specific [4].

This study is aimed at evaluating the power losses experienced by transmitted signals from cellular network BTS within the mountainous environments in Okene in Kogi State of Nigeria. The choice of Okene as a case study stems from her peculiar irregular and hilly terrain and the poor state of cellular network signal reception in some parts of the area. The network selected for the investigation is 9mobile because they have better coverage in the selected environments. The power losses evaluation is from field strength measurement taken at various distances away from the base stations within the environments. With the measured signal strength, the path-loss in the various environments will be calculated and compared with the predictions of some existing path-loss models in order to develop suitable and more accurate path-loss models for path-loss prediction in the area. A suitable model can only be obtained when the data used for its development is from that location or site. However, existing models can be modified to suit the environment which is an objective of this research.

The rest of this paper is organized as follows: Section II discusses the problem that motivated this research. Various Path-loss Prediction models in use are discussed in Section III with a brief review of literature of some related works. Section IV describes the Investigated Area and the methodology employed to achieve the objectives of this work. Section V is the Analysis of Data collected in Section IV. In Section VI, the Results are analysed and used to carry out the modeling. The new models are then evaluated for performance analysis. Lastly, Section VII is the Conclusion.

II. PROBLEM STATEMENT

It can be very frustrating in this era of advances in telecommunication technology, to constantly experience poor signal strength reception when it is needed most. This is the case in Okene area of Kogi State of Nigeria which is characterized by mountains in close proximity to one another. The high level of signal path-loss in this environment may not be unconnected with the terrain type in addition to the environmental effects of reflection, diffraction and scattering. The resultant effect is subscribers' dissatisfaction and network operators' losses. An accurate path-loss model will assist the network operators in proper planning which include sufficient capacity of transmission equipment and infrastructures for deployment, appropriate location of base stations, frequency assignments and network optimization. There is no known published literature that has modeled the path-loss for Okene area. However, authors in [13] carried out the modeling of power received in mountainous area in 2009 and included Okene as one of the case studies. The selected area in Okene did not represent the mountainous environment properly. This also is one reason why this study had to be undertaken. This is in addition to the fact that the environments have changed drastically from 2009 to 2020 and the path-loss must have changed too.

III. PATH LOSS PREDICTION MODELS

Path-loss models are mathematical equations used to predict or calculate the signal power loss in the transmitted signal at a distance from the BTS. Several empirical path-loss models have been discussed in literature. In [1], the Free Space Path-loss (PL_F) for Line of Sight (LOS) propagation is given as

$$PL_F(dB) = 32.44 + 20\log_{10}(f) + 20\log_{10}(d) \quad (1)$$

where f is the signal carrier frequency in MHz and d is the distance between the transmitter and the receiver in km. Okumura model was based on extensive measurement in urban areas for frequency range of 150MHz to 1920MHz, distance range of 1km to 100km and transmit antenna height of 30m to 1000m. Okumura model path-loss (PL_m) was expressed in [5] as:

$$PL_m(dB) = PL_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \quad (2)$$

where $A_{mu}(f,d)$ is the median attenuation relative to free space; $G(h_{te})$ and $G(h_{re})$ are the transmit and receive antenna height gain factors respectively; G_{AREA} which is gain due to type of environment and G_{AREA} are obtainable from Okumura graph.

$$G(h_{te}) = 20\log(\mathrm{h_B}/200), \quad 1000\mathrm{m} > \mathrm{h_B} > 30\mathrm{m}; \quad (2a)$$

$$G(h_{re}) = 10\log(\mathrm{h_M}/3), \quad \mathrm{h_M} \leq 3\mathrm{m} \quad (2b)$$

$$G(h_{re}) = 20\log(\mathrm{h_M}/3), \quad 10\mathrm{m} > \mathrm{h_M} > 3\mathrm{m} \quad (2c)$$

Hata Model, based on Okumura data, presents a standard empirical formula that simplifies path-loss calculation instead of the graph. It is given in [2][16] as

$$P_L(\mathrm{dB}) = 69.55 + 26.16\log f - 13.82\log h_t - a(h_r) + (44.9 - 6.55\log h_t)\log d \quad (3)$$

where $a(h_r)$ is a correction factor for effective mobile antenna height given by

$$a(h_r) = (1.1\log f_c - 0.7)h_r) - (1.56\log f_c - 0.8)\mathrm{dB} \quad (3a)$$

for medium sized city.

For a large city,

$$a(h_r) = 8.29(\log 1.54\, h_r)^2 - 1.1\ \mathrm{dB} \quad (f_c \leq 300\ \mathrm{MHz}) \quad (3b)$$

$$a(h_r) = 3.2(\log 1.75\, h_r)^2 - 4.97\ \mathrm{dB} \quad (f_c \geq 300\mathrm{MHz}) \quad (3c)$$

In [6], COST-231 model was explained to be an extension of Hata model to a frequency of 2GHz, and is given by:

$$P_L\ (\mathrm{dB}) = 46.3 + 33.9\log f_c - 13.28\log (h_t) - a(h_r) \; (44.9 - 6.55\log h_t)\log d + C_M \quad (4)$$

$$\text{Where } C_M = \begin{cases} 0\mathrm{dB} & \text{for medium sized city and suburban areas} \\ 3\mathrm{dB} & \text{for metropolitan centers} \end{cases} \quad (4a)$$

Egli path-loss model is given by [7]:

$$PL_{egli} = G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 \quad (5)$$

and simplified in [8] as:

$$P_{Legli}\ (\mathrm{dB}) = 76.3 - 20\log_{10} h_t + 10\log_{10} h_r + 40\log d + 20\log f_c \quad (6)$$

According to [9], the Electronic Communication Committee (ECC-33) path-loss model was an extrapolation of the Okumura model for frequencies higher than 3GHz up to 3.5GHz. It is given by:

$$P_L = A_{fs} + A_{bm} - G_t - G_r \quad (7)$$

Where A_{fs}: Free space attenuation (dB):

$$= 92.4 + 20\log(d) + 20\log(f) \quad (7a)$$

A_{bm}: Basic median path loss (dB):

$$= 20.41 + 9.83\log(d) + 7.894\log(f) + 9.56[\log(f)]^2 \quad (7b)$$

$$G_t{:} = \log(h_t)\{13.958 + 5.8[\log(d)]^2\} \quad (7c)$$

For medium cities,

$$G_r{:}= [42.57+13.7\log(f)][\log(h_r) - 0.585] \quad (7d)$$

For large city $\quad G_r{:} = 0.759h_r - 1.862 \quad (7e)$

In addition to the popular models generally in use, several researchers and authors have completed works on PL modeling in various parts of the world with reasonably good results. While investigating and modeling power received at 1800MHz in a mountainous terrain in 2008, authors in [4] obtained a path loss exponent of 3.58 indicating poor GSM signal reception in the mountainous environments of Igarra in Edo State and Ajaokuta and Okene in Kogi State. The authors in [10] developed an optimized model for four GSM environments in Lagos State based on COST-231 as reference model. The optimized model returned an RMSE of 6dB which was less than the reference COST-231 indicating a better path loss prediction for the investigated area. In [11], the authors compared measured path loss values for 3G UMTS (2100) in GRA, Benin City, Nigeria, with Lee, COST-231, Okumura-Hata and Egli models to determine their suitability for the environment. The study areas are characterized by high buildings with trees sandwiched in-between them. The result showed that the duo of Okumura-Hata and COST-231 Hata performed well in the area because they are independent of receiver antenna heights. In [12], the Mean Square Error (MSE) approach was used to analyze the field measurement data collected within urban GRA Phase II and sub-urban Aggrey Road areas of Port Harcourt City, Nigeria. The path loss exponent and standard deviations obtained were 3.57 and 2.98dB respectively for the urban area and 19.6 and 13.2dB for the sub-urban area. When compared with existing path loss models, it was observed that Okumura-Hata model gave better performance in urban environment while COST 231 performed better in rural environment. The study conducted by authors of [9] in urban Al-Habebea and rural Al-Hindea districts of Baghdad, Iraq, showed Hata model and Ericcson model giving small deviation from real measurements in urban environment and Hata model gave better prediction in the rural area. Authors in [13] used Okumura-Hata, COST231 -Hata and Egli to predict RF propagation in Idanre town hilly environment, Akure, Nigeria in the UHF frequency. The analysis shows COST231-Hata gave the lowest mean path-loss error of 2.39dB and was therefore considered the more suitable model for the environment.

IV. INVESTIGATED AREAS

The mountainous area chosen for this investigation is Okene which is located on Latitude 7.551220 ($07^0$33'N) and Longitude 6.235890 ($06^0$14'E) with altitude ranging from 384m to 496m above sea level. Okene is a local Government Area in Kogi State, Nigeria, with a headquarter bearing the same name. It has an area of 328km^2. It is an area with several mountains situated close to one another. It does not have many high rise buildings. The major source of RF signal degradation is the mountainous terrain [4]. The three selected locations for investigation are Okene town (urban, 7° 32' 44" N, 6° 15' 14" E), Okengwe (suburban, 7° 32' 56" N, 6° 11' 30" E) and Agasa/Upogoro (rural, 7° 32' 01" N, 6° 14' 05" E). Figure 1 shows the nature of the terrain of the area.

A. Materials and Methodology

Measurement campaign was carried out in the three areas of Okene town (urban), Okengwe (suburban) and Agasa/Upogoro (non-urban). RF signal analyzers (Netmonster, Network Cell Info Lite and Cellmapper) were installed in an Itel P33 plus smart phone to measure and indicate the received signal power (RSSI), serving cell id, transmit frequency and other network information. The installed GPS tools software reads the location data (latitude, longitude and altitude) of measurement points and cell tower locations. Measurements were taken at about 50m interval along test routes. The network used in the investigation is 9mobile NG. The RSSI readings were taken five times within a period of about ten minutes and the average reading was computed.

Fig. 1. A landscape view of Okengwe in Okene, Kogi State Nigeria (Taken: 7th July, 2019)

B. Transmitter-Receiver distance calculation

The separation d between the mobile receiver and the fixed BTS at each measurement position was calculated from the recorded GPS data of each position and the serving cell using the Haversine equation given by [9]:

$$d = 2r\sin^{-1}\left(\sqrt{\sin^2\left(\frac{\varnothing_2-\varnothing_1}{2}\right)+\cos(\varnothing_1)\cos(\varnothing_2)\sin^2\left(\frac{\varphi_2-\varphi_1}{2}\right)}\right) \quad (6)$$

where r is the radius of earth (= 6371km), $\varnothing_1$, $\varnothing_2$ are latitudes of the two points and φ_1, φ_2 are longitudes of the two points respectively.

V. DATA ANALYSIS

In the analysis of the collected data, 3G UMTS 2100MHz frequency, 43dB BTS power, Transmit antenna height of 30m and receive antenna height of 1.5m were used.

A. Measured Path-loss

The measured Path-loss (PL_m) at any measurement point is given by the equation [14]:

$$PL_m(\text{dB}) = EIRP_t\,(\text{dB}_\text{m}) - P_r\,(\text{dB}_\text{m}) \quad (7)$$

where $EIRP_t$ is the effective isotropic radiated power of the BTS and P_r is the received signal power.

B. Calculated Path Loss using selected reference models

The free space path-loss was calculated using equation (1). Hata model path-loss was computed using equations (3) and (3a-c). COST-231 path-loss was calculated using equation (4). Egli model path-loss was compiled using equation (6). ECC-33 path-loss was computed using equations (7) and (7a-e). These five models were selected because they have the flexibility of adaptation to various terrain and frequency of propagation and have been used in various previous studies [13][15][16].

C. Statistical Analysis of Calculated Path-loss

The percentage predictability of the reference models were determined by their Mean Absolute Percentage Error (MAPE) given by [6]:

$$MAPE = 100\%\left(\sum_{i=1}^{k}\left(\frac{|PL_m(d)-PL_r(d)|}{PL_m(d)}\right)\right)/k \quad (9)$$

The root mean square deviation (RMSD or RMSE) shows the closeness of the calculated or predicted path-loss to the measured path-loss, and is given by [10][21]:

$$RMSE = \sqrt{\sum_{i=1}^{k}\frac{[PL_m(d)-PL_r(d)]^2}{k}} \quad (10)$$

where $PL_m(d)$ = measured path loss (dB), $PL_r(d)$ = calculated path loss (dB) and k = number of measured data points.

VI. RESULTs ANALYSIS

The variation of Received Signal Strength Indicator (RSSI) in decibels, with distance are shown in figures 3 to 5. The irregular shape of the graph is mainly a result of shadowing effect of hills and mountains in the environment.

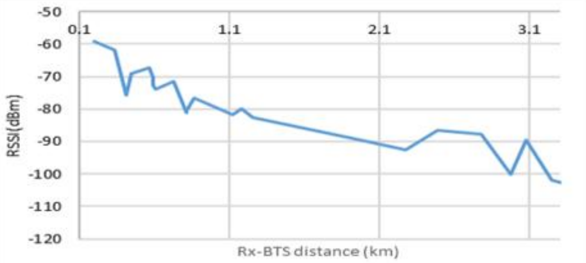

Figure 3. Received signal strength vs distance for rural environment

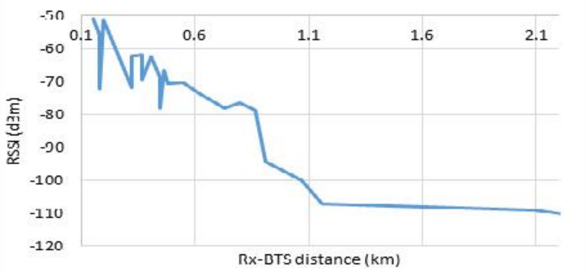

Figure 4. Received signal strength vs distance for suburban environment

Figure 5. Received signal strength vs distance for Urban environment

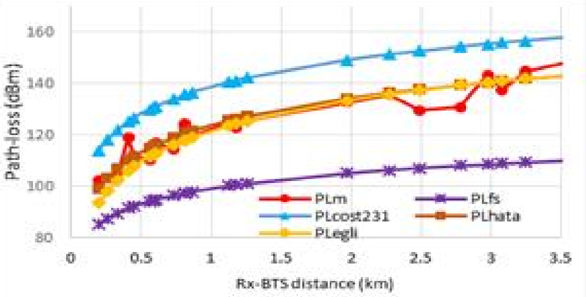

Figure 6. Measured and Calculated Pathloss for rural environment

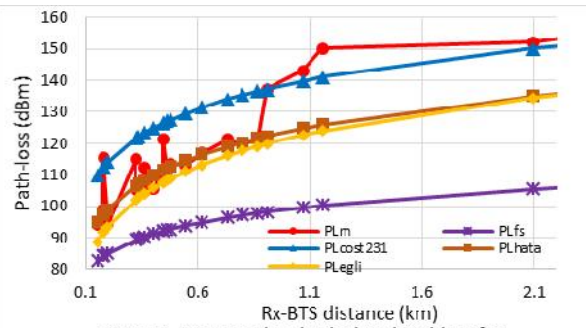

Figure 7. Measured and Calculated Pathloss for suburban environment

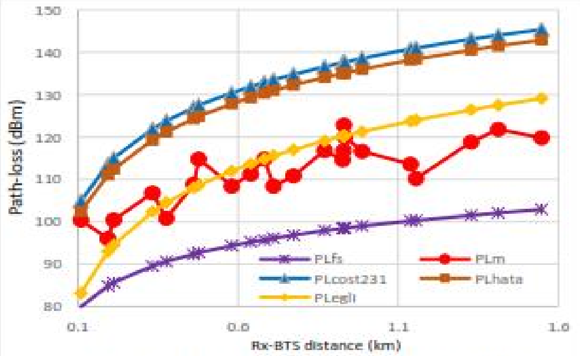

Figure 8. Measured and Calculated Pathloss for Urban environment

The MAPE and RMSE of the calculated Path-loss are shown in tables I, II and III for rural, suburban and urban environments respectively. The tables show that the ECC-33 model deviates from the measured path-loss by very wide margins of 172.97dB, 139.95dB and 154.18dB for rural, suburban and urban areas respectively. The Free Space model prediction is not realistic as it does not consider the other causes of path-loss [18][19]. Hence the two models were left out in the optimization process.

Table I shows that the least RMSE of 3.38dB was obtained when the COST-231 model was modified by subtracting its original RMSE of 16.24 from the model equation [10]. The optimal path-loss model for the rural area is given by [20][21][22]:

$$P_L(\text{dB}) = 46.3 + 33.9\log f_c - 13.28\log(h_t) - a(h_r) + (44.9 - 6.55\log h_t)\log d + C_M \mathbf{- 16.24} \qquad (11)$$

TABLE I. STATISTICAL ANALYSIS OF PATH-LOSS MODELS FOR 3G MOBILE PROPAGATION FOR RURAL AREA

S/N	Model	Free Space	COST-231	Hata	Egli	ECC-33
1	MAPE	19.03%	13.04%	2.46%	3.15%	134.47 %
2	RMSE before modification	24.10dB	16.24dB	3.90dB	4.96dB	172.97 dB
3	RMSE after modification	-	3.83dB	5.27dB	5.84dB	-

TABLE II. STATISTICAL ANALYSIS OF PATH-LOSS MODELS FOR 3G MOBILE PROPAGATION FOR SUBURBAN AREA

S/N	Model	Free Space	COST-231	Hata	Egli	ECC-33
1	MAPE	19.81%	11.10%	4.82%	6.47%	115.72%
2	RMSE before modification	26.37dB	13.55dB	9.35dB	11.20 dB	139.95 dB
3	RMSE after modification	-	8.74dB	9.61dB	8.21dB	-

TABLE III. STATISTICAL ANALYSIS OF PATH-LOSS MODELS FOR 3G MOBILE PROPAGATION FOR URBAN AREA

S/N	Model	Free Space	COST-231	Hata	Egli	ECC-33
1	MAPE	14.79%	18.00%	15.70 %	4.97%	132.87%
2	RMSE before modification	17.03dB	20.89dB	18.42 dB	6.82dB	154.19dB
3	RMSE after modification	-	5.50dB	5.52dB	8.12dB	-

$$\boldsymbol{P_{Lopt} = 30.06 + 33.9\log f_c - 13.28\log(h_t) - a(h_r) + (44.9 - 6.55\log h_t)\log d + C_M} \quad (12)$$

The percentage improvement is calculated as:

%Improvement of $\boldsymbol{P_{Lopt}}$ = 100*(16.24-3.83)/16.24
= **76.42%**

From table II the Egli model modified by subtracting 11.20 from the model equation gives the lowest RMSE of 8.21dB to give us the optimal model for path-loss prediction in the suburban area.

$$P_{Legli}\,(\text{dB}) = 76.3 - 20\log h_t + 10\log h_r + 40\log d + 20\log f_c\ \mathbf{- 11.02} \quad (13)$$

$$\boldsymbol{P_{Lopt}(\text{dB}) = 65.28 - 20\log h_t + 10\log h_r + 40\log d + 20\log f_c} \quad (14)$$

The percentage improvement is calculated as:

%Improvement of $\boldsymbol{P_{Lopt}}$ = 100*(11.02-8.21)/11.02
= **25.50%**

Table III shows that the least RMSE of 5.50dB was obtained when the COST-231 model is modified by subtracting its original RMSE of 20.89 from the model equation. The optimal path-loss model for the urban area is given by:

$$P_L(\text{dB}) = 46.3 + 33.9\log f_c - 13.28\log(h_t) - a(h_r) + (44.9 - 6.55\log h_t)\log d + C_M\ \mathbf{- 20.89} \quad (15)$$

$$\boldsymbol{P_{Lopt} = 25.41 + 33.9\log f_c - 13.28\log(h_t) - a(h_r) + (44.9 - 6.55\log h_t)\log d + C_M} \quad (16)$$

The percentage improvement is calculated as:

%Improvement of $\boldsymbol{P_{Lopt}}$ = 100*(20.89-5.50)/20.89
= **73.67%**

The graphs of the path-loss predictions of the new set of optimized models are shown in figures 9, 10 and 11.

VII. CONCLUSION AND FURTHER RESEARCH

The main objective of this study is to develop an optimized path-loss model for a mountainous environment at 2100MHz 3G UMTS frequency. This has been successfully achieved. The results revealed that the COST-231-Hata model gives a better path-loss prediction in rural and urban environments, when optimized, than Hata, Egli and ECC-33 models, while the optimized Egli performed best for the suburban area. The optimized models for the urban, suburban and rural areas of the environment produced an improvement of 76.42%, 25.50% and 73.67% respectively with lower RMSE for the mountainous area than the reference models. The results clearly show the adverse effect of the mountainous terrain on signal path-loss which is responsible for the poor signal reception in many places.

While this research is considered successful, it should be noted that the environments are dynamic as a result of man-made and natural features changing. Path-loss pattern changes along with the changing environment. Therefore, it is recommended that the research should be repeated as soon as possible. This work employed signals and data from 9mobile network. But within the same spectrum, different frequency bands are allocated to different networks. This will have a slight effect on the path-loss model. It is therefore recommended that the research be carried out using data from the rest three networks –MTN, Globacom and Airtel in order to gain broader view of the path-loss behavior of the environment.

The network operators are advised to study the model and reconsider the location of their base stations. They should also mount repeater stations in places highly obstructed by hills and mountains for effective coverage.

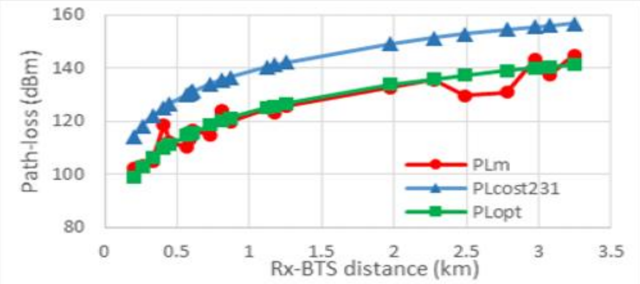

Figure 9: Optimized Path-loss model for Rural environment

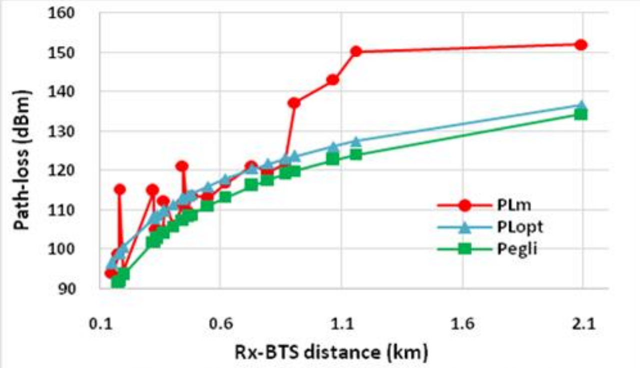

Figure 10. Optimized Pathloss for suburban environment

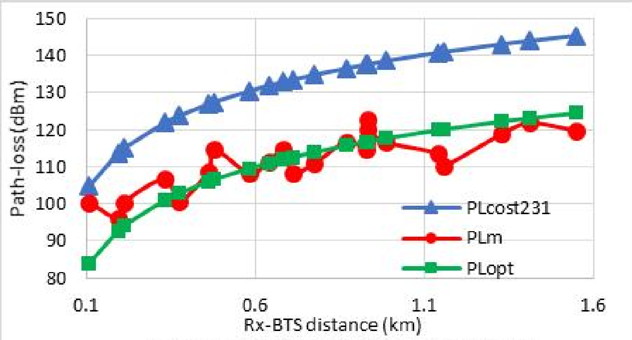

Figure 11. Optimized Pathloss for Urban environment

ACKNOWLEDGEMENT

The authors wish to appreciate the support and wonderful contributions of the Heads of Departments and Staff of the Departments of our Institutions of affiliation –Federal University of Technology, Minna and Kogi State Polytechnic, Lokoja. They made the research work a reality.

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