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ON THE STUDY OF EMPIRICAL PATH LOSS MODELS FOR ACCURATE PREDICTION OF TV SIGNAL FOR SECONDARY USERS

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Abstract—Demand for wireless communication technologies and systems keep increasing and has reached the peak where the capacity can only be achieved by improving spectrum utilization. The spectrum allocated to TV broadcast systems can be shared by wireless data services through exploiting spatial reuse opportunities (Spatial TV white space). Path loss models are used extensively in signal prediction, coverage optimization and interference analysis. Recently it is being used in estimating distances for safe operation of secondary users in TV white space. Peculiarities of these models give rise to high prediction errors when deployed in a different environment other than the one initially built for. It is however not very clear which model gives the best fit and what the penalties are for using the models outside the intended coverage area. In this paper, we assess the fitness of nine empirical widely used path loss models using five novel metrics to gauge their performance. In order to achieve this, field strength measurements were conducted in the VHF and UHF regions along six different routes that spanned through the urban, suburban and rural areas of Kwara State, Nigeria. A program was developed in VB 6.0 language to compute the path losses for the empirical models. The measurement results were converted to path losses and are compared with the model's prediction. The results show that no single model provides a good fit consistently. However, Hata and Davidson models provide good fitness along some selected routes with measured RMSE values of less than 10 dB. ITU-R P.1546-4, Walfisch Ikegami (WI),

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Egli, CCIR and FSPL perform woefully, with higher RMSE and SC-RMSE (Spread Corrected RMSE) values. Further analysis on the error spread as a function of distance along 60 km route revealed that Hata and Davidson models show symmetry up to about 30 km with slight divergence between 24 km and 30 km after which Davidson model gives lower prediction error along the route. The prediction errors for Davidson model distributes nearly symmetrically around the mean error of 2.15 dB. It is noteworthy that the Gaussian error distribution within the window of ± 5 dB dominates the frequency counts. However, the error counts for CCIR model closely follow normal distribution with a mean error of -6.37 dB but Hata, FSPL, Walfisch Ikegami and ITU-R P. 529-3 models do not follow normal distribution curve.

1. INTRODUCTION

Demand for wireless communication technologies and systems keeps increasing and has reached the peak where the capacity can only be achieved by improving spectrum utilization. Spectrum allocated to TV operators can potentially be shared by wireless data services, either at the times when the primary service is switched off or by exploiting spatial reuse opportunities. For a couple of years researchers have focused on how to evaluate/quantify TV white space. The TV white space can be temporal (i.e., times/periods the primary service is off) or spatial (i.e., where TV signals cannot be successfully received),technically when the reception level is less than -116 dBm for digital TV (DTV) and -94 dBm for analogue TV [1]. The temporal white spaces, have not been subjected to extensive research because the idea is that the DTV (digital television) will be operating for 24 hours daily. In order to recover the spatial TV white space, signal prediction techniques are required to make a decision whether the location is white space or not, and the decision is based on threshold (i.e., if the received signal level at the position is greater than a certain value as described in the IEEE 802.22 draft. The incumbent systems currently operating in the TV bands are analogue TV with sensitivity value of -94 dBm, digital TV with sensitivity of -116 dBm and wireless microphone with -107 dBm. In this regard, Federal Communications Commission (FCC) in the United States announced -114 dBm as the criteria of the empty spaces for TV white space [1]. The whole idea of these is to free more spectrums (white spaces) for secondary access so that low power, low-range wireless devices in a strictly localized manner (Keep-out distance) can utilize the white space without interfering with the TV transmission. Figure 1 shows the spatial deployment scenario

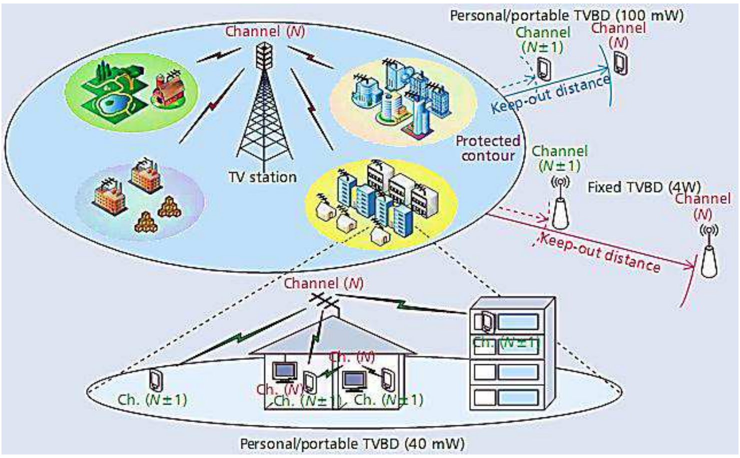


Figure 1. Deployment scenarios for co-channel and adjacent channel TV band devices in TV white space [2].

of TV band devices (TVBDs) also known as white space devices†, in TV white space (TVWS).

Figure 1 shows potential application scenario of primary user (TV broadcast service) and secondary user (TVBD) in TVWS. Several applications have been proposed to be deployed in TVWS as reported in [31] these include UMTS and LTE extension, Wi-Fi-2, Wimax and public safety and emergency networks. Public safety has been receiving attention globally due to global deserter; in this regard, [23] focused on deploying TETRA (terrestrial trunk radio access) in TVWS. TETRA systems is currently used by government agencies, emergency services, (police forces, fire departments, ambulance) for public safety networks, rail transportation staff for train radios, transport services and the military. Figure 2 shows typical deployment scenario of TETRA network in TVWS.

1.1. Predicting TV Coverage Using Path Loss Models

Today, propagation models are used extensively in coverage planning and optimization and signal prediction, and is found very useful for interference analysis. Path loss models are applied in cellular environments, fixed wireless access systems and TV broadcast systems. They are to be used here for the prediction of TV coverage. The

† White space device is an FCC-certified wireless device that can be used in the RF spectrum below 700 MHz. The devices are divided into two categories: fixed and personal/portable.

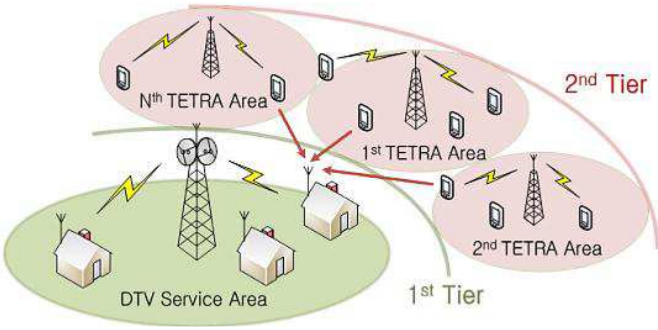


Figure 2. TETRA system deployments in TV white space [23].

success and peaceful coexistence between the primary users and the secondary users (white space devices) depend on the propagation characteristics of the channel. Received signal prediction models would play an important role in the coverage optimization and maybe efficiently used based on FCC's rule to predict locations for safe operation for secondary users. The existing path-loss models have been classified into theoretical and empirical models. The theoretical models predict transmission losses by mathematical analysis of the path geometry of the terrain between the transmitter and the receiver and the refractivity of the troposphere [3]. Empirical models add environmental-dependent loss variables to the free-space loss to compute the net path loss in the corresponding environment. These models require measurements and so considered more accurate in view of its environmental compatibility. Path loss models will help in the design of transmission strategy such as the transmit power and frequency. These models can differ in their properties with locations due to different terrain environment.

Most existing TVWS studies employ the use of propagation curves such as the ITU Radio communications Sector (ITU-R) P.1546-2, Egli, Okumura and Hata models for predicting the TV coverage. These models are built based on measurements conducted in regions that are different from Nigeria; suitability in terms of usage may therefore vary due to environmental factors and terrain profile. In addition, peculiarities of these models gives rise to high prediction errors when deployed in a different environment other than the one initially built for. These errors may consequently affect secondary operations. This raises the question of whether to adopt or modify the existing prediction models or to build a new model that will minimize the errors and protect the primary users from excessive interference from secondary users. Interference is not the only case; the error could also have effect on the amount of white space recovery and could have significant impacts on the deployment of secondary networks. For instance Camp et al. [4] show that wireless mesh network planned with a given path loss model can massively under or over provision as a results of small change in model parameters. This is a big issue as over-provision would add cost during roll out phase while under provision would affect the QoS of the network. Anang et al. [12] show that cellular systems information capacity changes due to propagation loss and system parameters, including the path loss exponent. It was concluded that decrease in path loss exponent causes severe interference. It is however not very clear, which models give the best fit and what the penalties are for using the models outside the intended area. Therefore, it is necessary to have accurate assessment of the propagation models in order to modify a model or choose a better model to achieve high accuracy thereby minimizing errors and thus, increasing flexibility in local spectrum usage.

In this paper, we assess the fitness of nine widely used empirical path loss models using five novel metrics to gauge their performance. The focus in this paper is the efficacy of these models at predicting path loss values for safe operation of secondary users in the chosen environment. In order to achieve these, field strength measurements were conducted in the VHF and UHF frequencies along six different routes that spanned through the urban, suburban and rural areas. A program was developed in VB 6.0 language to compute the path loss for the empirical models. The measurement results were converted to path losses and are compared with the model's prediction. The chosen models are Hata [5], COST 231 [6], Walfisch [7] and Ikegami [8], Egli [9], ITU-R P.529-3 [10], ITU-R P.1546-4 [11], CCIR [13], Davidson [14] and FSPL [15]. This paper is organised as follows Section: Section 1 provides introduction; Section 2 presents the related work; method of data collection is presented in Section 3; Section 4 provides the metrics used; Section 5 presents the results and, finally, Section 6 concludes the paper.

2. RELATED WORK

There are lots of published research that worked on analyzing the efficacy of path loss models. In such cases, the authors often collect measurement data in an environment of interest and make an assessment of whether the models fit in. [16] and [17] provide practical lower bounds on the prediction accuracy of path loss models. In the works 30 propagation models that had been published in the last 70 years were considered. A large scale measurement was conducted in the diverse set of rural and urban environments. In the end, it was concluded that no single path loss model was able to predict path loss consistently. In [18], a comparative assessment of five models was presented with respect to the data collected in the urban and suburban environments at 910 MHz. However, the paper does not provide a conclusion about which model gives the best results. [32] provides a comparative analysis using four empirical models for WCDMA and GSM systems based on drive test data collected from Kano city and Abuja city, which are all urban areas in Nigeria. In all of the measurements taken, it was found that COST 231 and Hata give fairer results for Kano and Abuja environment. The work is considered as an extension of the one presented in [3] where COST 231 was found more suitable for use in the GSM 1800 band for Kano environment. [28] provides a comparison of empirical propagation path loss models for fixed wireless access systems based on measurement conducted in Cambridge, UK. It was found that, among the contenders, the ECC-33 model, the Stanford University Interim (SUI) model, and the COST-231 model show the most promise and that the SUI model shows quite a large mean path loss prediction error. [19] presents similar results to that in [28]. Also [20] conducted a mobile propagation path loss studies at VHF/UHF bands in Southern India. In the work, field strength was measured at 200, 400 and 450 MHz and their result shows that Hata's prediction method gave better agreement in all cases. This work is similar to that presented by [21]. Achtzeh et al. [22] analysed the accuracy of three widely used path loss models in predicting TV signal strength using data carried out in a medium-sized central European city. In the work, spatial statistics based technique was employed for estimating the coverage. Also in [23], three empirical path loss models, i.e., ITU-R P.1546-3, Hata and ETRI (Electronic Telecommunication Research Institute) models were used to calculate propagation distances for safe operation of TETRA system on DTV white space. In [33] ITU-R model is used to address spectrum sharing issues between IMT-advanced, fixed wireless systems (FWS) and TV broadcast service. In the work, the path loss model was used to investigate inter system interference between Wimax, FWS and mutual coexistence between them.

The amount of white space that would be free for the TVBD in accordance with the regulatory guidance on interference has been a subject of extensive studies. The amount of white space has been acquired in several places across the globe, for the United States Harrison et al. [24] and for central Europe by Van de Beek et al. [25]. Very few studies exist for outside the United States, such as [26], which attempts to quantify TVWS capacity in the United Kingdom in a limited area, and [27] for southern Europe using ITU-R model. Of recent, [2] presented experimental and simulation results for the use of TVBD in TVWS. In the work, keep-out distance which is the minimum separation distance of TVBD from the DTV protected contour was obtained using the Okumura, ITU-R 1546, FCC and measurements of UHF signals in Korea. The schematic of the deployment scenario is shown in Figure 1. So far, there has not been any published report from Africa indicating such studies. U.S and related studies cannot be directly extrapolated to Nigeria case due to differences in deployment scenario, activities of the primary users, regulatory aspects and terrain profile. The work presented in this paper is the first of its kind in Nigeria that carries out an extensive analysis of large number of propagation models using large amount of data set produced from real-time measurements.

3. MEASUREMENT CAMPAIGN

This section provides the steps followed during data collection and it gives the description of the equipment used. The propagation measurements were conducted in Ilorin (Long 4°36′25″E, Lat

Table 1. Description of measurement routes.

S/N	Route	Description	No. Points	Route (km)	STD DEVIATION PL (dB)
1	ASADAM	Suburban area. It has regular building structure with dual carriage way.	12,712	10	10.33
2	UNILORIN	Urban area. It has very complex terrain; some areas are very high whereas, some parts are very low. Within the University, heavy trees cover the road. Along the route, the road is very narrow with averagely two-storey buildings.	24,310	7	6.71
3	GAMBARI	Dense urban area. It is historical area with very old buildings around. It is very busy commercial area.	26,634	11	11.87
4	MURTALA	Urban area. It has regular building structure with arrange of three-storey buildings with dual carriage road.	12,004	8	13.95
5	OLD JEBBA	Urban area. It has regular building structure with arrange of two-storey buildings with teo-lane road	18,418	13	13.93
6	BODE-Sa'adu	Route spans from the urban to rural areas. It has regular building structure with average of two-storey buildings within the city, then outside the city hotspots villages at an average distance of 15 km interval.	18,0274	60	15.28

8°25′55″N) and its environs within Kwara State, Nigeria. Ilorin is a large city characterized by a complex terrain due to the presence of hills and valleys within the metropolis. Outside the metropolis, the routes are covered with thick vegetation. The altitude within the transmitter's coordinates is 403.7 m; this can be as low as 150 m when travelling within and outside the metropolis. (see Figure 10 for path profile for Bode-Sa'adu route) Six routes were covered during the measurement campaign. The routes are Olorunshogo via ASADAM, University of Ilorin (UNILORIN) via Pipeline, GAMBARI via Agaka, MURTALA Mohd way, Old Jebba Road and BODE-Sa'adu.

Table 1 shows details of the measurement routes. Figure 3 shows the screens hot of the measurement routes and Figure 4(b) shows an aerial view of Ilorin metropolis and outside Ilorin. NTA Ilorin and Kwara TV transmitters were utilized. NTA transmits on channel 5 at 203.25 MHz while Kwara TV transmits on channel 35 at 583.25 MHz. While the transmission is taking place, a dedicated Agilent spectrum analyser was placed inside a vehicle and driven at an average speed of 40 km/h along these routes. Details of the transmitter and the analyser can be found in Table 2. Field strength was measured continuously and stored in an external drive for subsequent analysis. Total route length and number of points were 109 km and 286,870 respectively.

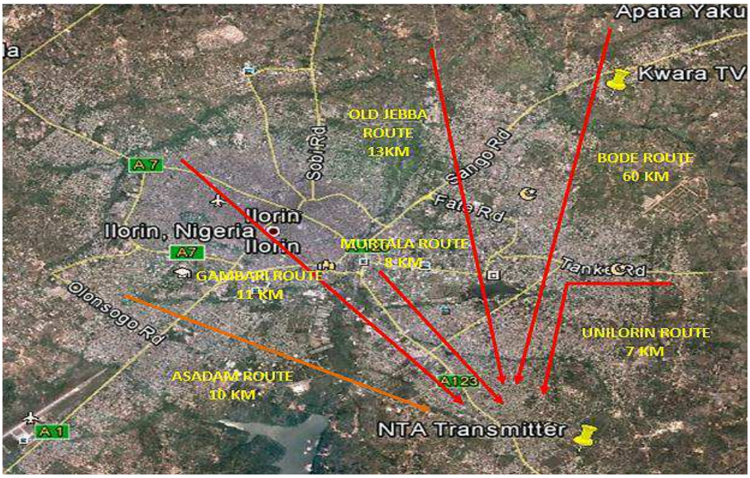


Figure 3. Measurement routes in Ilorin.

(a) (b)

Figure 4. (a) Mountain and vegetation cover outside Ilorin (BODE-Sa'adu route). (b) Aerial view of Ilorin metropolis.

4. PERFORMANCE METRICS

The performance of the models is analysed using five metrics; Prediction error, root mean square error (RMSE), spread-corrected root mean square error (SC-RMSE), normalized error probability density function and rank correlation. The Prediction error, ε, is the difference between the measured path loss (P_i) at distance i, and model's predicted path loss ($p_{m,i}$) and is evaluated using Equation (1).

$$\varepsilon_i = P_i - p_{m,i} \tag{1}$$

Other sub metrics are the maximum and mean prediction error of sample (n_j)

$$\text{MaxError} = \max_i(\varepsilon_i) \tag{2}$$

$$\text{MeanError} = \frac{1}{n_j}\sum_i^j \varepsilon_i \tag{3}$$

RMSE also known as Root Average Squared Predication Error (RASPE) and it is the most apparent metric for analysing error of predictive models. We compute the prediction error values using Equation (1) for each model as a function of distance from the transmitter. The overall RMSE for a given model m, for a given data

Table 2. Measurement equipment and configuration.

Spectrum Analyzer N9342C Agilent, 100 Hz–7 GHz	
Displayed average noise level (DANL)	−164 dBm/Hz
Preamplifier	20 dB
Resolution bandwidth (RBW)	10 kHz
Center frequency (NTA) Center frequency (KWARA TV)	203.25 MHz 583.25 MHz
Impedance	50 Ohms
Receiver Antenna: Diamond RH799 RH 795	
Frequency range	70 MHz–1 GHz
Form	Omni directional
Height	1.5 m
Gain	2.51 dBi
NTA Ilorin Transmitter	
Power	2.4 kW
Frequency	203.25 MHz
Antenna height above the ground	185 m
Cable Type	RFS HEL FEX 512
Impedance	50 Ohms
Coordinates	4°36′25″E, 8°25′55″N

set n is defined as;

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\varepsilon_{m,i}\right|^2} \tag{4}$$

A RMSE value closer to 0 indicates a better fit. However, the acceptable RMSE for a model is about 6–7 dB for urban areas [30] and 10–15 dB for suburban and rural areas [29]. Another important metric is the SC-RMSE, which helps to extract the impact of dispersion from the overall error. This has the effect of reducing the error associated with a noisy link. Computing SC-RMSE is similar to that of RMSE; the only difference is that the error is obtained by subtracting the standard deviation from the absolute value of the error.

$$\varepsilon'_{m,i} = \left|\varepsilon_{m,i}\right| - \sigma_i \tag{5}$$

$$\mathrm{SC-RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\varepsilon'_{m,i}\right|^2} \tag{6}$$

The fourth metric is error distribution, i.e., the probability density function of a Gaussian (Normal) random variable. Firstly, the model has to follow normal distribution curve. Secondly, the error counts from 0 to ± 10 dB should dominate the frequency counts since 0–10 dB RMSE is the chosen performance criteria in this work.

The fifth metric is the Spearman's rank correlation coefficient (ρ). Which is a nonparametric measure of statistical dependence between the measured and predicted path losses across the links. It assesses how well the relationship between two variables can be described using a monotonic function. A perfect Spearman correlation of $+1$ or -1 occurs when each of the variables is a perfect monotone function of the other.

$$\rho = \frac{\sum_i \left(P_i - \overline{P_i}\right)\left(P_{m,i} - \overline{P_{m,i}}\right)}{\sqrt{\sum_i \left(P_i - \overline{P_{m,i}}\right)^2 \sum_i \left(P_i - \overline{P_{m,i}}\right)^2}} \tag{7}$$

where, $\overline{P_i}$ and $\overline{P_{m,i}}$ are the mean measured path loss at distance i, and mean model's predicted path loss respectively.

5. RESULTS AND DISCUSSION

Figures 5 through 9 provide the graphical depictions of measured and prediction path losses along the five predefined routes. Figure 5 shows the comparison of the measured path loss with the predicted path loss as a function of distance for ASADAM route. Within the first 2 km along the route, CCIR model agrees with the measured path loss; thereafter, CCIR over estimates the path loss. Walfisch Ikegami, ITU-R P.1546-4 and Egli models underestimate the path loss throughout the range of interest. ITU-R P.529-3, Hata, Davidson and COST 231 model give better results. For the overall route, COST 231 model provides the best result with RMSE value of 0.4 dB which is a fantastic result. ITU-R P.529-3 and Davidson models are actually derivatives of Hata and the results are, thus, expected to be the same for distance of less than 20 km. Hata model turns out to give RMSE value of 10.7 dB and SC-RMSE value of about 4 dB. However, ITU-R P.1546-4, Walfisch, Ikegami, Egli, CCIR and FSPL perform woefully with higher RMSE and SC-RMSE values. The corresponding error statistics in terms of the RMSE and SC-RMSE are shown in Table 3.

Figure 6 depicts the result of UNILORIN route. The path loss obtained using the empirical model resembles that presented in Figure 5. For all the measurement routes studied, ITU-R P.529-3, Hata and Davidson models give the best results followed by COST 231 model, except for MURTALA route in Figure 8 where CCIR model performs better with RMSE of 7.9 dB. Refer to Tables 3 and 4 for

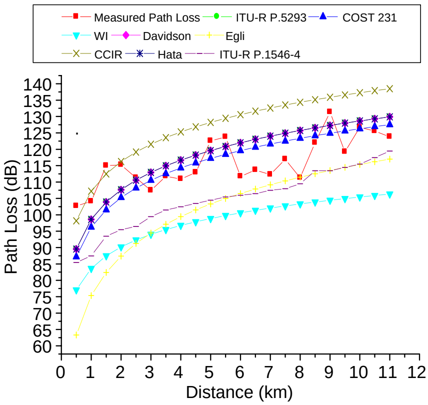


Figure 5. Comparison of empirical models with measured path loss for ASADAM route.

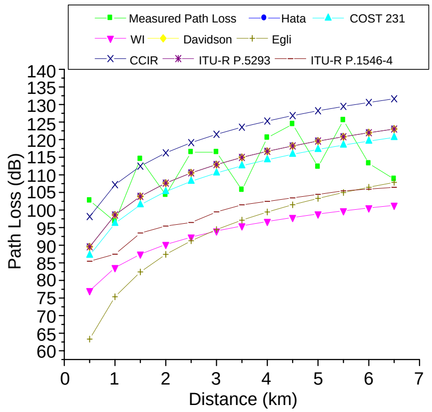


Figure 6. Comparison of empirical models with measured path loss for UNILORIN route.

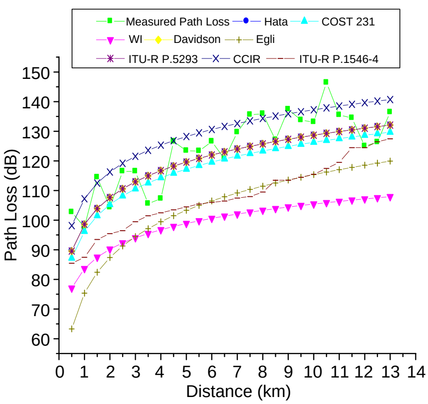


Figure 7. Comparison of empirical models with measured path loss for OLD JEBBA route.

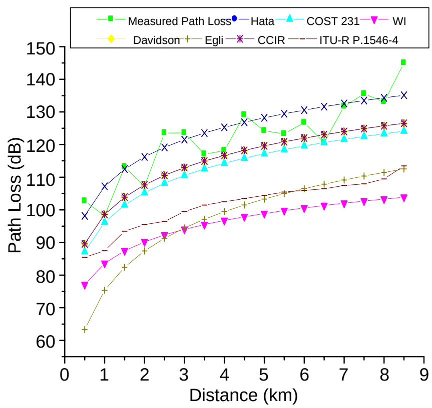


Figure 8. Comparison of empirical models with measured path loss for MURTALA route.

statistical RMSE and SC-RMSE values for all the models across all the measurement routes. Along ASADAM, UNILORIN and GAMBARI, COST 231, Hata, ITU-R P.529-3 and Davidson models give better fits. But, for MURTALA and OLD JEBBA routes, all the models perform badly except for CCIR with RMSE of about 7.9 dB along OLD JEBBA route. The reason for the high values of errors along MURTALA route is attributed to the fact that the route is the busiest in the city. There were present of scatters, moving vehicle and girder. Also the route

Table 3. Root mean square error for six measurement routes.

ROUTES	Hata (dB)	COST 231 (dB)	WI (dB)	ITU-R P.529-3 (dB)	EGLI (dB)
ASADAM	10.786	0.404	84.807	10.786	67.613
UNILORIN	0.866	9.468	68.297	0.866	68.431
GAMBARI	3.893	15.084	99.487	3.893	82.293
MURTALA	27.493	37.330	108.092	27.493	100.551
OLD JEBBA	18.972	29.266	106.906	18.972	91.090
BODE-Sa'adu	50.117	68.598	253.326	56.954	124.907
ROUTES	CCIR (dB)	DAVID SON (dB)	ITU-R P.1546-4 (dB)	FSPL (dB)	-
ASADAM	51.132	10.786	52.440	113.918	-
UNILORIN	30.147	0.866	17.643	89.355	-
GAMBARI	36.452	3.893	24.310	128.598	-
MURTALA	7.971	27.493	43.716	132.933	-
OLD JEBBA	18.139	18.972	37.132	133.684	-
BODE-Sa'adu	16.510	14.408	33.344	311.294	-

has building structure with average of three-storey buildings with dual carriage road.

Figure 9 provides the graphical depiction of measured and prediction path losses for Bode-Sa'adu route, up to 20 km, ITU-R P.529-3, Hata and Davidson models give the same RMSE values, after which Davidson model provides better results over Hata. The recoded RMSE values for Hata and Davidson are 50 dB and 14.4 dB respectively. This result obviously favors Davison model for the fact that six correction factors were included into Hata model.This extended the range from 20 km to 300 km. Figure 4(a) shows mountain and vegetation cover just about 10 km from the city the terrain profile for this route is shown in Figure 10.

Along this route, there were high prediction errors for most of the models, because of the complex nature of the terrain. At the transmitter's location, 400 m altitude was recorded; this can be as low as 275 m just 5 km away from the transmitter and 150 m at a

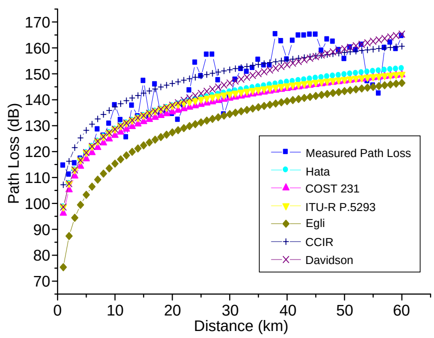


Figure 9. Comparison of empirical models with measured path loss for Bode-Sa'adu route.

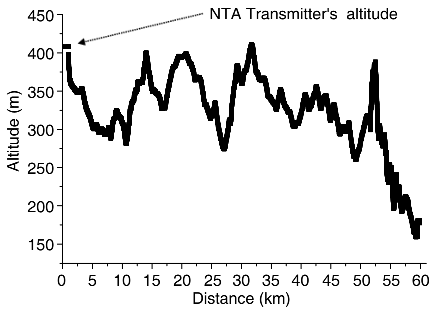


Figure 10. Path profile of Bode-Sa'adu route.

Table 4. Spread corrected root mean square error (SC-RMSE).

ROUTES	HATA (dB)	COST 231 (dB)	WI (dB)	ITU-R P.529-3 (dB)	EGLI (dB)
ASADAM	3.920	6.774	49.629	3.920	32.512
UNILRIN	4.968	4.018	37.650	4.968	37.784
GAMBAR	16.616	14.534	56.429	16.612	39.235
MURTALA	20.435	12.146	58.615	20.435	51.073
OLD JEBBA	25.344	19.149	52.585	25.344	36.770
BODE-Sa'ad	55.158	43.467	137.13	48.221	9.479

ROUTES	CCIR (dB)	DAVID SON (dB)	ITU-R P.1546-4 (dB)	FSPL (dB)	-
ASADAM	18.947	3.920	17.261	78.740	-
UNILRIN	3.132	4.968	13.393	58.708	-
GAMBAR	0.804	16.616	24.061	85.540	-
MURTALA	28.962	20.435	20.420	83.456	-
OLD JEBBA	28.284	25.344	17.877	79.363	-
BODE-Sa'ad	68.965	72.884	21.947	195.104	-

distance 60 km from the transmitter. This would obviously affect the signal reception and thus; contribute to the error. In addition, except for ITU-R P.529-3, ITU-R P.1546-4, CCIR and Davidson models, the validity of the transmission distance for other models is less than 20 km. Prediction error is expected to be higher when used to predict path loss for distances greater than 20 km. Furthermore, we studied the prediction and spread corrected errors as a function of distance for Hata and Davidson models for Bode-Sa'adu route. Figures 11 and 12 show the results.

In Figures 11 and 12, it is worth noting that Hata and Davidson prediction models show symmetry up to about 30 km with slight divergence between 24 km and 30 km window for both metrics, after which Hata model under predicts the path loss. Davidson model gives the best result along this route. This indicates that, for wider range path loss prediction, Davidson model would perform better than the widely used Hata model. Interestingly, the error spreading for both models follows the terrain profile (See Figures 10 & 11).

Figure 13 depicts the distribution histograms of the predication error for the eight empirical models considered along the BODE-Sa'adu route. The solid line indicates the probability density function (PDF) of a Gaussian (Normal) random variable. In this scenario, Davidson and CCIR models show similar shapes of their PDFs. The error were normalized to fit in to the Gaussian normal distribution.

In Figure 13(a), the prediction errors are nearly distributed symmetrically around the mean error of 2.15 dB. It can be observed that the error distribution within the ±5 dB window dominates the frequency counts. This indicates good fitness of the model in terms of predicting path loss in the region. However for CCIR model, which is the second that performs better along this route the prediction error

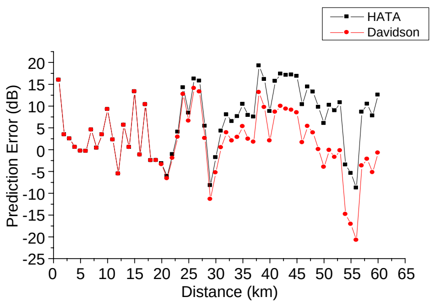


Figure 11. Prediction error along BODE-Sa'adu route.

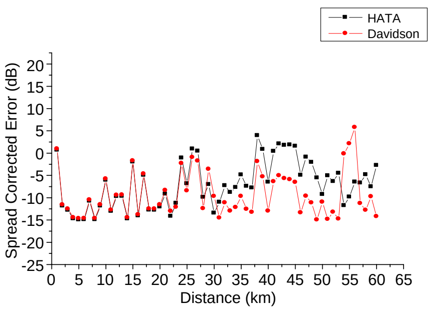
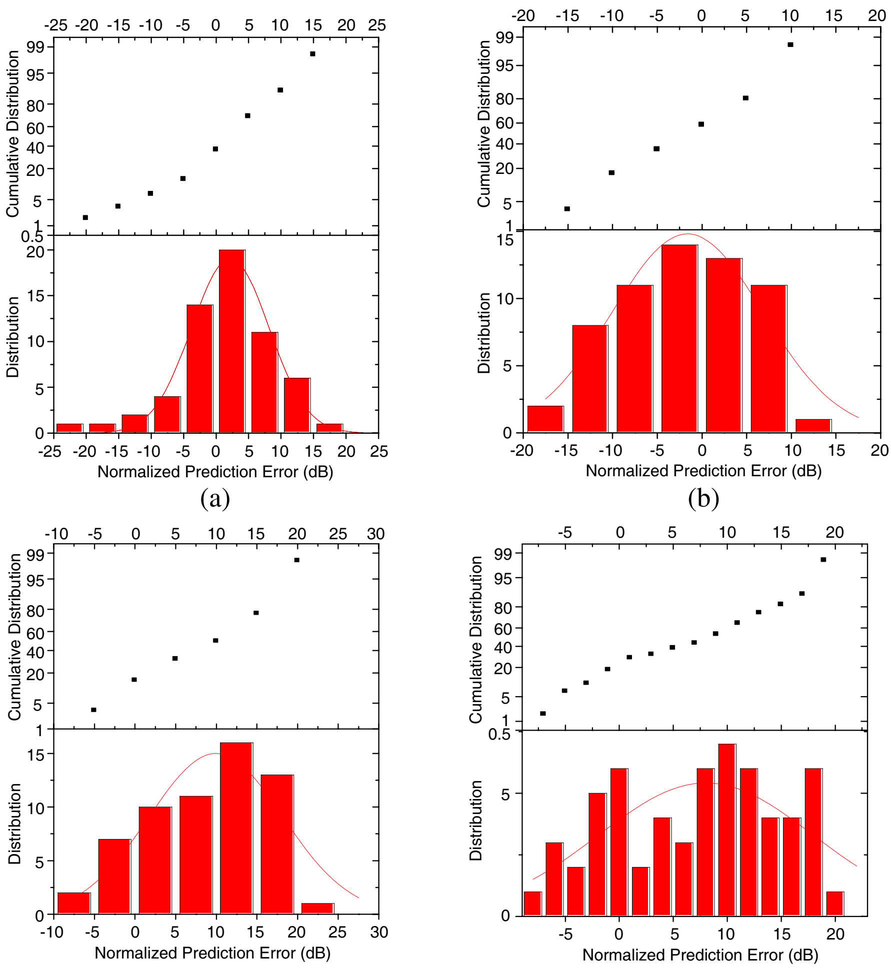
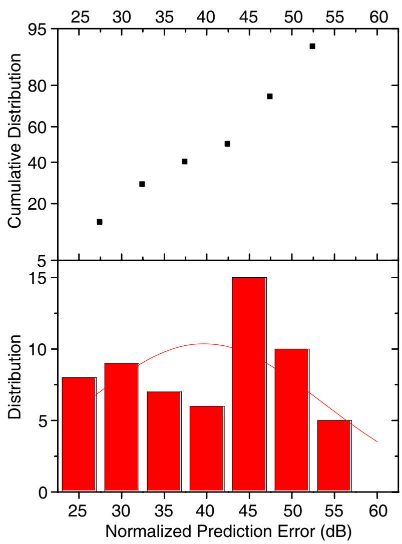


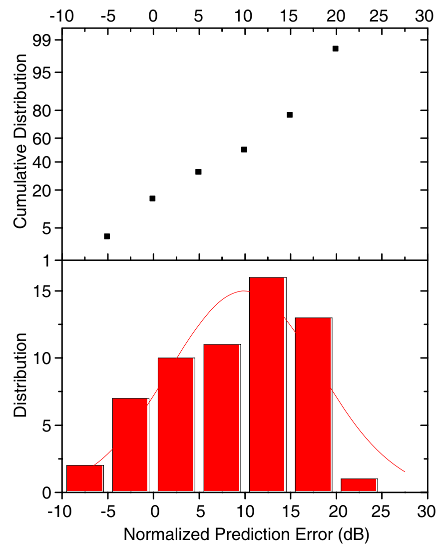
Figure 12. Spread corrected error along BODE-Sa'adu.

closely follows normal distribution with a mean error of $-6.37\,\mathrm{dB}$ as shown in Figure 13(b). From all indications, the model underestimates the path loss since the model is found to have negative skew. The error counts are quite high and spread along the distribution.Hata and ITU-R P.529-3 models do not follow the normal distribution curve, despite the fact that the mean errors were found to be $2.2\,\mathrm{dB}$ comparable with that of Davidson model that gives a better spread in the error distribution. Egli model gives fair distribution with mean error of $15\,\mathrm{dB}$ and slightly follows the normal curve as shown in Figure 13(h). FSPL and Walfisch-Ikegami models provide worst results under this

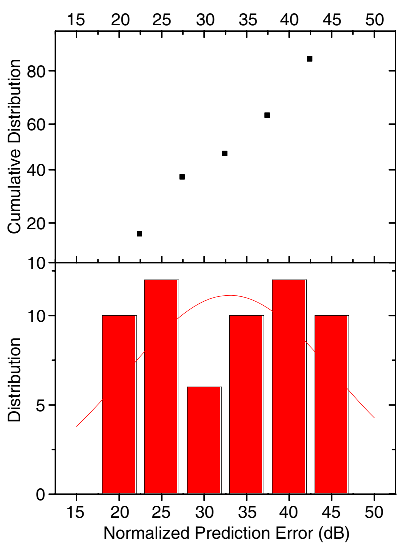




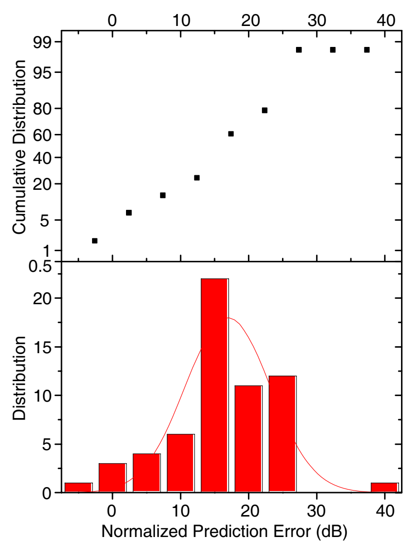
(e)



(f)



(g)



(h)

Figure 13. (a) Davidson model. (b) CCIR model. (c) Hata model. (d) ITU-R P. 529-3 model. (e) FSPL. (F) COST 231. (g) Walficsh-Ikegami. (h) EGLI.

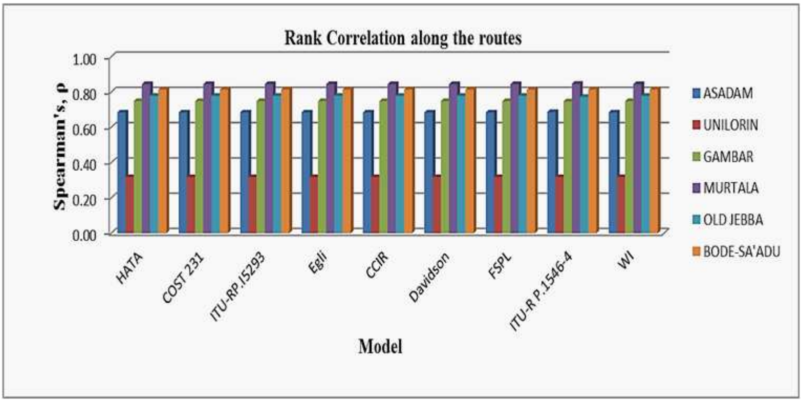


Figure 14. Spearman's correlation between measured and model's prediction.

metric; the least frequency counts was found to be 30 dB and 55 dB for WI and FSPL models respectively and the error spread do not follow the normal distribution curve.

Figure 14 gives the rank correlation coefficient between measured and model's prediction. In terms of this metric all the models perform better along all the routes except for UNILORIN where the correlation value is less than 0.5 at $p < 0.001$. The correlation coeeficient of 0.81 ($p < 0.001$) was calculated along BODE-Sa'adu route for HATA model this indicates very strong correlation. However, this metric does not provide consensus on which model performs best at rank ordering. Above all, the results show strong correlation between the measured and prediction path losses for all the routes.

6. CONCLUSIONS

In this paper, we have assessed the fitness of nine widely used empirical path loss models using five novel metrics to gauge their performance based on field strength measurements along six routes that spanned through the urban, suburban and rural areas of Kwara State, Nigeria. The performance criteria were based on prediction error, RMSE, SC-RMSE, normalized error probability density function and rank correlation. The results show that no single model provides a good fit consistently. The measure of fitness is when the RMSE value is 0–10 dB in the urban scenario and 10–15 dB in the rural scenario. However, Hata and Davidson models provide good fitness along some selected measurement routes with measured RMSE values of less than 10 dB.

ITU-R P.1546-4, Walfisch, Ikegami, Egli, CCIR and FSPL models perform woefully, with higher RMSE and SC-RMSE values. Further results on the error spread as a function of distance along a wider route revealed that Davidson model gives a better fit over Hata this is perhaps expected since Hata model is only valid for a maximum transmission distance of 20 km.

The novel feature of this study is that, the work provides detailed error analysis of the path loss models of which is the first of its kind in Nigeria to carry out an extensive analysis of large number of propagation models using large amount of data set produced from real time measurements. Other important contributions of this work are:

1. The provision of the error bounds for the models studied and introduction of a new matric, i.e., normalized error probability density function. Other metrics are commonly used when assessing models performance, but this new metric helped in studying the error distribution counts for each model across the link and aid towards judging which model fit into Gaussian normal distribution.
2. Error spread as a function of distance, to examine the impact of the terrain profile on error as a function of distance. This metric helps to demarcate the point of divergence between Hata and Davison models despite they had the same RMSE and SC-RMSE values for considerable distance, i.e., $d < 20$ km, and consequently, this gives an insight of their performance in terms of distance.
3. These bounds will provide guidelines for researchers and practising engineers in choosing appropriate path loss model(s) for coverage optimization and interference analysis for wireless devices operating in the TV band in our environment and also, to predict TV coverage and keep-out distances for potential secondary users operation in the TV white space.

However tuning of Davidson model is necessary to minimize the RMSE values within the acceptable ranges that would cover all the routes. Minimizing these errors would of course, have significant impact on the amount of white space recovery and thus increase flexibility in local spectrum usage and deployments of the secondary networks in the TVWS.

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