2023 2nd International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS) | 979-8-3503-5883-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICMEAS58693.2023.10379225

Performance Analysis of Path Loss Models for Wireless Communications at 3.5 GHz and 23 GHz in a Regular Urban Environment

Farouq E. Shaibu
Department of Telecommunication
Federal University of Technology
Minna, Nigeria
farouqebira@gmail.com

Elizabeth N. Onwuka
Department of Telecommunication
Federal University of Technology
Minna, Nigeria
onwukaliz@futminna.edu.ng

Nathaniel Salawu
Department of Telecommunication
Federal University of Technology
Minna, Nigeria
salawunathaniel@gmail.com

Stephen S. Oyewobi
Department of Telecommunication
Federal University of Technology
Minna, Nigeria
oyewobistephen@gmail.com

Abstract— **Accurate channel models are required to evaluate the performance of mobile communication systems and optimize coverage for existing and future wireless networks. To improve two of the most widely used empirical path loss models; 3GPP and CI, this paper considered the elevation angle from the receiver to the transmitter to evaluate 5G coverage in real scenarios of a regular urban environment at 3.5 GHz. Measurement campaigns were carried out to evaluate the chosen models' accuracy in the 3.5 GHz environment, while simulation experiments for the environment under consideration at the 23 GHz channel were carried out using an RF planning software tool, Path Loss 5 (PL5). The assessment criteria of Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and Root Mean Square Error (RMSE) were used to test the outcomes of the changes to the path loss prediction models. With a path loss exponent of 3.1, the model comparison showed that, at a 3.5 GHz channel, the enhanced 3GPP and CI models outperformed the conventional models in both scenarios. The 3GPP outperformed admirably on the 23 GHz channel with an MAE of 5.41 dB and 7.32 dB in both scenarios (LoS and NLoS), while the CI model underestimates the path loss. This indicates that the improved models are highly suitable for use in an outdoor regular urban environment.**

Keywords—Path loss, RF propagation, 5G, Millimeter wave.

I. INTRODUCTION

In recent years, academia and industry have become more interested in research on fifth-generation (5G) wireless networks, which aim to solve numerous unprecedented technical requirements and challenges. To fulfill the 5G requirements, it may be possible to increase the spectrum and energy efficiency of the fourth-generation (4G) network, which is predominantly congested between 600 MHz and 3 GHz [1].

Meanwhile, the communication network has a lot of challenges along its millimeter wave channel, among which is path loss [2].

To create fitting path loss models, a combination of computer methods and approximations based on empirical measurements from channel-sounding tests is used. As indicated in equation 1, the propagation path loss often increases as frequency and/ or distance [3]:

$$P_l = 10\log_{10}\left(\frac{16\pi^2 d^n}{\lambda^2}\right) \tag{1}$$

Where P_l represents the path loss, d is the path length between the Rx and Tx, n is the PLE (path loss exponent), and λ is the free space wavelength in meter [3]:

Equation 1 can be reduced to equation 2, as;

$$P_L(f, d_0) = 32.5 + 20n\log_{10}(d_0) + 20\log_{10}(f) \tag{2}$$

Where d_0 is the path length between the reference point and the receiver in km, and f is the frequency in MHz.

The key factor in the design of wireless networks is path loss, which quantifies the energy lost while a wave travels between a transmitter and a receiver [4].

Path loss is also computed as given in equation 3.

$$Path\ loss, P_l\ in\ dB = EIRP - R_p \tag{3}$$

Where, R_p is the receiver power in dBm and $EIRP$ is the Effective Isotropic Radiated Power, which is given as;

$$EIRP = P_T + G_T + G_R - C_l - K_l - A_l - A_{fl} \tag{4}$$

P_T stands for the transmitting power in dBm, G_T for the transmitting antenna gain, G_R for the receiving antenna gain, and C_l, K_l, A_l, A_{fl} for the respective connector, feeder cable, antenna, and antenna filter losses.

The paper aims to investigate the application of the two widely used 5G empirical models to predict path loss in an outdoor regular urban environment. Therefore, the major contributions of the paper in direct contrast to related papers reviewed are summarized as follows;

1. We compared the applicability of the CI model against the 3GPP 38.901 5G empirical model for the prediction of path loss in a clustered regular urban environment at 3.5 GHz and 23 GHz.
2. We improved the applicability of these models by introducing a new parameter i.e. angle of inclination in our formulation.

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The rest of the paper is presented as follows. Section II reports the recent developments in the use of 5G empirical models for path loss prediction in different scenarios. Section III presents the measurement campaign description and the selected 5G current cellular empirical models for the path loss investigation. Section IV presents the model validation. Section V reports on the simulation setup for the path loss analysis at 23 GHz. Section VI reports on the obtained results and discussions from the measurement campaign, simulation, and comparative analysis for the selected models. Finally, section VII provides concluding remarks.

The 3.5 GHz frequency band was considered because it is representative of the frequency band that is currently being used for the mid-band 5G deployment in Nigeria and to have live 5G coverage for the measurement. The selection of 23 GHz for path loss modeling simulations is driven by its relevance in wireless communication systems, as it provides a good tradeoff for path loss.

Regular urban in this paper typically have a well-planned layout and infrastructure, with streets and modern buildings arranged in an organized pattern, and without any virgin land.

This paper is limited to the performance analysis of two widely used current 5G empirical models to predict path loss at 3.5 GHz and 23 GHz in a regular urban environment in distinct scenarios.

II. LITERATURE REVIEW

Quite several works have been carried out in the effort to determine the best path loss model for 5G communications, for example, empirical path loss models at 3.5 GHz for indoor scenarios were discussed in [5] for 5G communication. Extensive measuring campaigns across comparable buildings will be necessary to obtain representative models.

Grey model-based path loss prediction for 5G mm-Wave was presented in [6]. The 5G empirical models that were selected are 5GCM, 3GPP, METIS, and mm-MAGIC [6, 7]. However, the error analysis was only limited to Mean Absolute Error (MAE), in which the suggested LoS models offer the prediction with the lowest MAE.

In [8], propagation measurements at three frequencies of 14, 18, and 22 GHz were presented [9, 10]. According to the LoS performance investigation, CI and FI models [8] perform similarly and fit the measured data [8].

To look into five possible path loss scenarios, the authors of [11] built a model of a 5G communication testbed at 28 GHz. However, the modification of free space path loss was only based on the shadow factor. They found that for the scenarios they were considering, the FI model outperformed the CI model with the lowest value of RMSE.

Saba *et al* [12] reported conducting a thorough measurement experiment at 26 GHz during the summer in two rural areas of southern Finland. To choose a better prediction path loss model [13], three different prediction models; the ABG, CI, and 3GPP rural macro (RMa) models were analyzed based on distinct scenarios of LoS, OLoS, and NLoS. According to the data gathered, the mean path loss increased from 4 dB to 6 dB for every 20 m increase in antenna height.

In [14], path loss models were extensively investigated for a 28 GHz 5G system in a tropical outdoor environment. The impedance matching technique between the feed line and the horn antennas was not investigated, which might influence the effect of return and mismatch losses within the system. The result revealed that co-polarization decays rapidly in the LoS scenario.

To evaluate mm-Waves and sub-tetra hertz propagation, the authors in [15] took into account several possible scenarios for outdoor Urban Microcell (UMi), whereas wideband measurements were carried out in [16] to model a path loss in the frequency bands of 1.8, 3.5, and 28 GHz. According to the findings, it is necessary to take into account the multiple-scattering contributions from trees [16] in the 1.8 GHz and 3.5 GHz bands once a certain amount of distance has passed between the transmitter and receiver.

The previous works, however, did not take into factor how these models behave when the elevation angle from the receiver to transmitter is taken into consideration and when used in a typical outdoor regular environment. Therefore, this study tries to close this gap by presenting the performance of the well-known 3GPP and CI models in terms of angle of elevation. Diversification of measurement campaigns in different scenarios is recommended for further fine-tuning of the improved empirical models.

III. MEASUREMENT CAMPAIGN DESCRIPTION

To investigate the path loss modeling at 3.5 GHz and 23 GHz mm-Wave in a regular Urban scenario, a measurement campaign with stationary Tx and directional Rx on the rooftop of a moving vehicle was conducted for the 3.5 GHz, in the Federal Capital Territory of Nigeria, using a handheld spectrum analyzer (N9344C) and a directional antenna (HE200), shown in Figure 1.

Figure 1: Measurement campaign setup

Figure 2 illustrates how the measured path loss was divided into distinct scenarios of LoS and NLoS inside a typical regular urban environment at various locations.

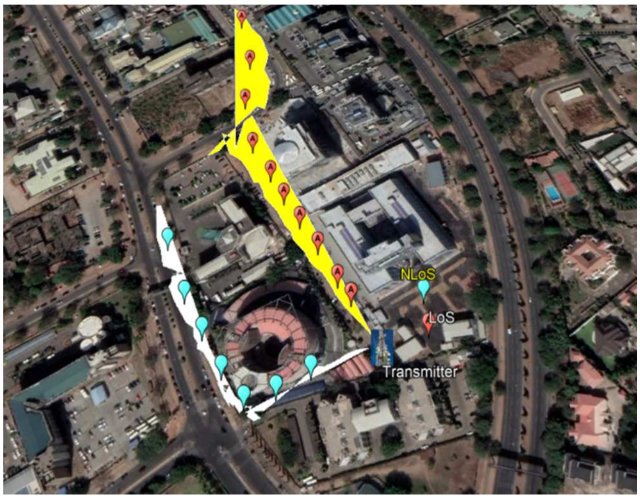

Figure 2: Simulation and measurement environment with a LOS and NLOS scenario

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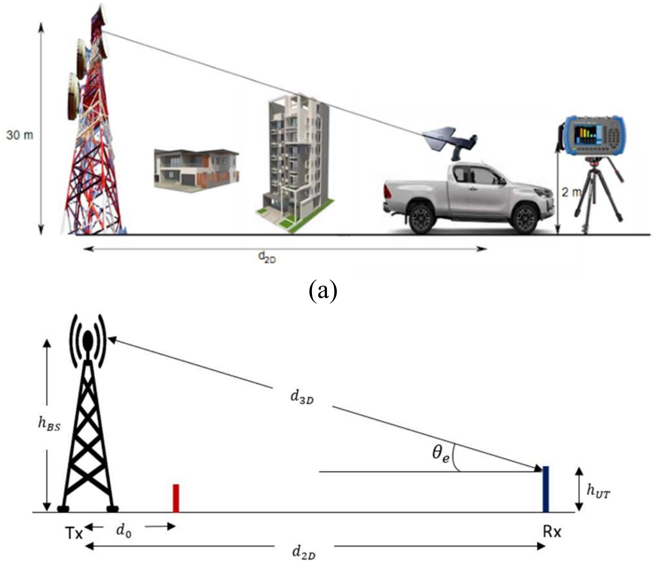
For every location, the position of the Tx is fixed, and measurements were performed with the Rx at different distances (moved along the line (yellow and white lines) depicted in Figure 2. By combining the measurements from all locations, we get PL data for distances ranging from a reference distance of 1 m, and then from 50 m to 500 m with a spacing of 50 m.

From the data, we generated the CI and 3GPP models with and without the angle of elevation.

The illustration of the measurement campaign is shown in Figure 3(a), whereas Figure 3(b) as well as equations 5 and 6 show the relationship between d_{2D}, d_{3D}, and θ_e.



(a)

(b)

Figure 3 (a): Illustration of the measurement campaign (b) Definition of d_{2D} and d_{3D} for outdoor UT_S

$$d_{3D} = \sqrt{(d_{2D})^2 + (h_{BS} - h_{UT})^2} \tag{5}$$

$$Angle\ of\ Elevation, \theta_e = tan^{-}\left(\frac{h_{BS}-h_{UT}}{d_{2D}}\right) \tag{6}$$

A. 3GPP TR 38.901 Model

i. For Urban Macro and Line-of-Sight (LoS) scenarios.

$$PL_{UMa-LOS} = \begin{cases} PL_1 & 10m \leq d_{2D} \leq d'_{BP} \\ PL_2 & d'_{BP} \leq d_{2D} \leq 5km \end{cases} \tag{7}$$

$$PL_1 = 28.0 + 22\log_{10}(d_{3D}) + 20\log_{10}(f_c) \tag{8}$$

$$\begin{aligned} PL_2 = 28.0 &+ 40\log_{10}(d_{3D}) \\ &+ 20\log_{10}(f_c) \\ &- 9\log_{10}((d'_{BP})^2 \\ &+ (h_{BS} - h_{UT})^2) \end{aligned} \tag{9}$$

Considering the angle of elevation from the receiver to the point of transmitting antenna, as demonstrated in Figure 4(b).

$$\begin{aligned} PL^{3GPP}{}_{im} = 28 &+ 22\log_{10}(d) + 20\log_{10}(f_c) \\ &- \theta_e \end{aligned} \tag{10}$$

ii. For NLOS scenario.

$$\begin{aligned} PL_{UMa-NLOS} = max(&PL_{UMa-LOS}, \\ &PL'_{UMa-NLOS})\ for\ 10m \leq d_{2D} \\ &\leq 5km \end{aligned} \tag{11}$$

$$\begin{aligned} PL'_{UMa-NLOS} = 13.54 &\\ &+ 39.08\log_{10}(d_{3D}) \\ &+ 20\log_{10}(f_c) \\ &- 0.6(h_{UT} - 1.5) \end{aligned} \tag{12}$$

The above equations hold for shadow fading standard deviation of $6\ dB$; applicability range and antenna height default values of $1.5m \leq h_{UT} \leq 22.5m; and\ h_{BS} = 25m$ [17].

CI Model

We adopted the conventional CI model, which is presented in Equation 13, as well as its improved version in Equation 14.

$$\begin{aligned} P_L^{CI}(f,d)[dB] = P_L(f,d_0)|_{1m} &\\ &+ 10n\log\left(\frac{d}{d_0}\right) + W_\sigma^{CI} \end{aligned} \tag{13}$$

$$\begin{aligned} PL^{CI}{}_{im} = &f(d,\theta_{ei}) \\ &= 27.05 + 31\log_{10}(d) - \theta_e \end{aligned} \tag{14}$$

Where $PL^{CI}{}_{im}$ is the improved path loss model in dB [8], $P_L(f,d_0)$ is the path loss in free space [18], as shown in equation 2, at a T-R separation distance of 1m at the carrier frequency [18], f, n is the path loss exponent, d_0 is the initial separating path, of 1m, θ_e is the angle of elevation from the receiver to the transmitting antenna, and W_σ^{CI} represents the zero-mean Gaussian distribution with an std, $\sigma, in\ dB$.

IV. MODEL VALIDATION

The prediction results of the considered models were compared with the measured and simulated results to validate their performances, using performance indicators; MAE, MAPE, and the RMSE.

$$MAE = \left|\frac{1}{N_{test}}\sum_{i=1}^{N_{test}}\left|PL_i^{sim} - PL_i^{pred}\right|\right| \tag{15}$$

$$MAPE = \frac{1}{N_{test}}\sum_{i=1}^{N_{test}}\left|\frac{PL_i^{sim} - PL_i^{pred}}{PL_i^{sim}}\right| \times 100 \tag{16}$$

$$\begin{aligned} RMSE &= \sqrt{MAE} \\ &= \sqrt{\frac{1}{N_{test}}\sum_{i=1}^{N_{test}}\left(PL_i^{sim} - PL_i^{pred}\right)^2} \end{aligned} \tag{17}$$

Where PL_i^{sim} is the simulated path loss value.

PL_i^{pred} represents the predicted path loss values.

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N_{test} is the tested total number of samples.

i is the index of the measured sample.

V. SIMULATION SETUP

An RF planning tool software, (PL5) was used to simulate the propagation modeling in a regular urban environment at 23 GHz to generate path loss, terrain data (path profile), and link design. Figure 4 shows the basic organization of the path loss program in PL5.

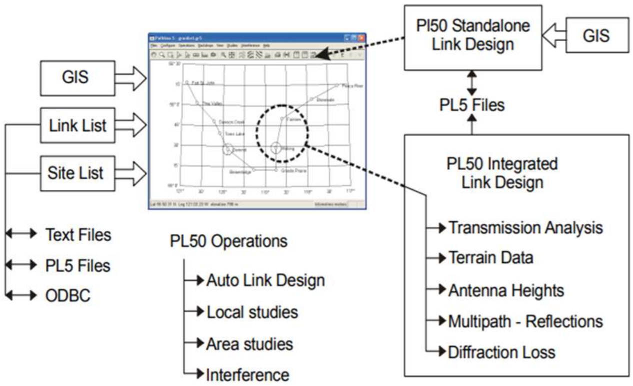

Figure 4: Basic organization of the path loss program

For validation, the same regular environment and its path were used for the measurement campaign and simulation analysis, importing the coordinate into the PL5 software tool.

The path loss determined from the simulated report using the parameters in Table 1 is shown in Table 3.

Table 1: Propagation simulation configuration

Parameter	Value
Frequency	23 GHz
Tx height	30 m
Tx Polarization	Vertical
Tx antenna type	Horn antenna
Tx antenna gain	35 dBi
EIRP	35.30 dBm
Connector loss	1 dB
True azimuth	88.22^0
Elevation	463 $m\ ASL$

VI. RESULTS AND DISCUSSIONS

The findings and discussions from a performance investigation of path loss models at 3.5 GHz and 23 GHz in a typical regular urban environment for wireless communication are presented in this section.

Considering the performance of the well-known 3GPP and CI models in terms of angle of elevation in the 3.5 GHz channel, these models provide reliable path loss models in the two distinct scenarios of LoS and NLoS [19].

Following the successful performance study of the models at 3.5 GHz and 23 GHz in a regular urban environment for wireless communication, figure 5 represents the model comparison investigated on the 3.5 GHz channel prediction in a regular urban scenario, while Figure 6 represents the model comparison for the 23 GHz channel.

In figure 5, it is clearly shown that the conventional 3GPP model overestimated the path loss throughout the range of interest, with an MAE of 19.41 dB for LoS and 18.65 dB for NLoS scenarios, as shown in Table 4. The conventional CI model also overestimated the path loss, but not as much as in the 3GPP model, with an MAE of 13.09 dB for LoS and 11.23 dB for NLoS scenarios.

Meanwhile, the improved 3GPP and CI models display better performance from the beginning of the channel until they decide to overestimate the path loss.

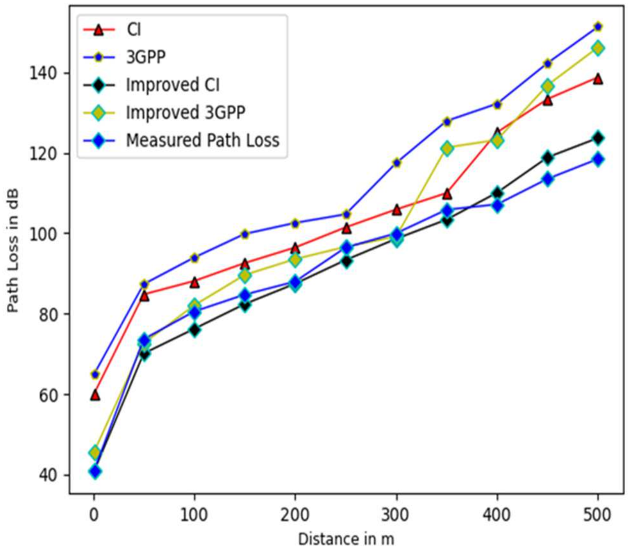

Figure 5: Model comparison for the 3.5 GHz

The improved 3GPP model tends to converge with the measured path loss, especially within a short distance of <300 m with an MAE of 16.52 dB and 13.22 dB in the scenarios of LoS and NLoS, while the improved CI model performed excellently throughout the distance under consideration with MAE of 10.65 dB and 9.32 dB in LoS and NLoS scenarios.

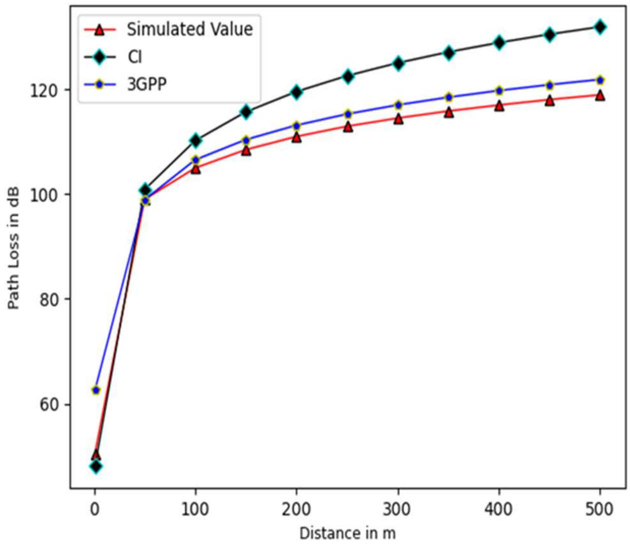

Figure 6: Model comparison for the 23 GHz channel

On the simulated report in Table 2 for the 23 GHz channel prediction, the 3GPP and CI models overestimated the path loss, but much more in the CI model, as shown in Figure 6.

The 3GPP performed admirably on the prediction of path loss within this channel, with an MAE of 7.32 dB in LoS and 5.41 dB in NLoS scenarios.

The CI model, on the other hand, performed excellently within a distance of 50 m and then uniformly overestimated the path loss across the channel with an MAE of 17.71 dB in LoS and NLoS scenarios.

Table 2: Measured and predicted results in a regular urban environment at 3.5 GHz

S/N	**Path Length (m)**	**Elevation (m)**	θ_e **(dB)**	**Received Signal (dBm)**	**Path Loss in Db**				
					Measured Value	**Predicted Value by the CI**	**Predicted Value by the 3GPP**	**Predicted Value by the** $\mathbf{CI_e}$	**Predicted Value by the** $\mathbf{3GPP_e}$
01	1	462.54	19.3	-25.56	34.01	57.05	61.89	37.75	42.59
02	50	466.17	14.7	-45.23	69.58	81.72	84.26	67.02	69.56
03	100	465.30	11.9	-46.01	76.46	85.05	90.88	73.15	78.98
04	150	462.08	10.2	-52.21	80.66	89.51	96.75	79.31	86.55
05	200	463.07	09.0	-53.46	83.91	93.38	99.50	84.38	90.50
06	250	463.00	08.1	-61.92	92.37	98.39	101.64	90.26	93.54
07	300	463.82	07.3	-64.46	95.91	102.84	103.38	95.54	96.08
08	350	463.50	06.6	-67.33	101.78	106.92	124.85	100.32	118.25
09	400	461.08	06.0	-75.57	106.12	122.02	126.13	116.02	120.13
10	450	462.65	05.5	-79.00	109.45	130.30	139.25	124.80	133.75
11	500	463.81	05.1	-81.42	111.87	135.72	148.26	130.62	143.16

Table. 3: Simulated and predicted results in the regular urban environment at 23 GHz

S/N	**Path Length (m)**	**Elevation (m)**	**EIRP (dBm)**	**Path Inclination (mr)**	**Received Signal (dBm)**	Path Loss in dB		
						Simulated Value	**Predicted Value by the CI**	**Predicted Value by the 3GPP**
01	1	462.54	35.30	72.39	-23.65	45.20	42.73	55.24
02	50	466.17	35.30	72.39	-25.10	93.69	95.57	92.62
03	100	465.30	36.30	27.56	-30.12	99.70	104.93	99.24
04	150	462.08	37.30	3.08	-32.62	103.19	110.41	103.11
05	200	463.07	38.30	2.61	-34.14	105.70	114.29	105.86
06	250	463.00	39.30	1.82	-35.11	107.66	117.31	108.00
07	300	463.82	40.30	4.27	-35.67	109.22	119.77	109.74
08	350	463.50	41.30	2.74	-36.04	110.57	121.85	111.21
09	400	461.08	42.30	3.68	-36.20	111.72	123.65	112.49
10	450	462.65	43.30	0.23	-36.24	112.76	125.25	113.61
11	500	463.81	44.30	2.54	-36.17	113.67	126.67	114.61

Table 4: Performance metrics for the selected models

Models	**Condition**	**3.5 GHz**			**23 GHz**		
		MAE (dB)	**MAPE (%)**	**RMSE (dB)**	**MAE (dB)**	**MAPE (%)**	**RMSE (dB)**
CI	LOS	13.09	17.53	3.62	17.71	8.18	4.21
	NLOS	11.23	14.35	3.35	14.02	7.62	3.74
3GPP	LOS	19.41	25.41	4.41	7.32	2.52	2.71
	NLOS	18.65	21.23	4.32	5.41	4.75	2.33
$\mathbf{CI_e}$	LOS	10.65	5.95	3.26	-	-	-
	NLOS	9.32	4.62	3.05	-	-	-
$\boldsymbol{3GPP_e}$	LOS	16.52	11.34	4.06	-	-	-
	NLOS	13.22	8.37	3.64	-	-	-

VII. CONCLUSION

In this study, empirical path loss models are presented for a typical outdoor regular urban environment at $3.5\ GHz$ and $23\ GHz$. The model parameters that are being presented were found using measurement data from a typical urban environment. The models presented have been enhanced while considering the elevation angle between the receiver point and the transmitting antenna. In the instance of the 3.5 GHz channel, the convergence of these improved models to the measured path loss has been compared to that of the traditional ones. The conventional 3GPP overestimated the path loss with an MAE of 19.41 dB for LoS and 18.65 dB for NLoS, whereas the CI model overestimated but not as much as in the 3GPP model. On short distances (under 300 m in LoS and 350 m in NLoS scenarios), the improved 3GPP and CI models outperformed the conventional 3GPP and CI models. The 3GPP model also outperformed the CI model on the 23 GHz channel with the lowest value of MAE. A comprehensive measuring campaign across similar terrain will be needed to obtain representative models.

The future scope of the study will use an ensemble supervised machine learning-based path loss model to improve a reliable empirical model at the mid-band frequency spectrum in similar regular urban environment.

ACKNOWLEDGMENT

We give thanks to the Nigerian Communication Commission (NCC) for providing equipment for the measurement campaigns.

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