Performance Study of Empirical Path Loss Models at 11 GHz in an Irregular Environment for Wireless Communications

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ABSTRACT

In this paper, we report the performance study of two of the most widely used empirical models, 3GPP and CI models at 11 GHz in an irregular environment for future communication networks. Large-scale fading simulation has been carried out under the line-of-sight (LoS) and non-line-of-sight (NLoS) scenarios. An RF planning software package, Path Loss 5 (PL5) was used to carry out the simulation to reveal the expected receiver power, path loss, and terrain profile for the environment under consideration. From the simulated report, the simulated values were fitted with the path loss models. With the path loss exponent of 3.1, the results of the models' comparisons revealed that the CI model overestimated the path loss throughout its path in both LoS and NLoS scenarios with an MAE of 16.32 dB and 19.21 dB. The 3GPP model shows its best performance in LoS scenario but within a short distance ($< \mathbf{400\,m}$) in NLoS scenario with an MAE of 9.14 dB and 11.09 dB respectively. The simulations suggest that the 3GPP model is better for path loss prediction in an environment under consideration at mm-Wave frequency.

Keywords: *Empirical Path Loss, 5G/6G Network, mm-Wave, Irregular Environment, Wireless Communication.*

1 INTRODUCTION

Path loss modeling has gained significant notice as one of the important elements for the ideal planning and configuration of base stations because of the unstable channel characteristics of millimeter waves (Wang & Lee, 2021). An accurate and efficient method for path loss modeling for millimeter wave communications is crucial for the general adoption of a fifth-generation (5G) mobile communication system (Chen *et al.*, 2021).

Path loss prediction methods are useful tools that network optimization engineers can use to deploy base stations, choose the location for base station setup, choose the transmitting and receiving antennas, choose the operating frequency, and conduct feasibility studies on interference.

Nigeria has chosen millimeter waves (mm-Waves) in the 3.4–3.8 GHz frequency band for fifth generation (5G) communications with unique usage situations.

Fifth-generation mobile communication systems are expanding the utilization of high-frequency bands at 6 GHz and above, and it is expected that sixth-generation mobile communication systems will utilize even higher frequency bands, like the THz band (6G) (Sasaki *et al.*, 2021) (ITU, 2020).

The millimeter wave channel in this Fifth Generation (5G) communication network has many difficulties, among which is path loss (Maccartney et al., 2015).

To develop path loss models, a combination of computer methods and approximations based on empirical measurements from channel-sounding experiments is used.

For estimating wireless signal coverage in specific environments, several models have been developed. However, sometimes these models fall short of the desired level of performance in terms of accuracy because they do not properly consider the peculiar nature of the environment.

Based on scenarios for LoS and NLoS in open, unreliable urban environments, this study offers a statistical evaluation of mm-wave propagation candidate for 5G systems at 11 GHz. Figure 1 and Figure 2 show these two scenarios.

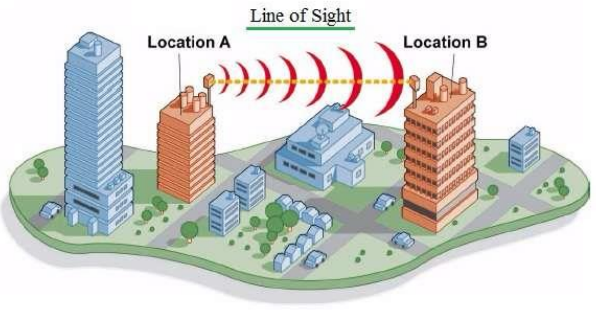


Fig. 1: Line-of-Sight channel (World, 2012)

Irregular urban environment refers to an environment characterized by the combination human structures less and more than 45 meters in height, a dense grid of roads, virgin lands, and densely populated.

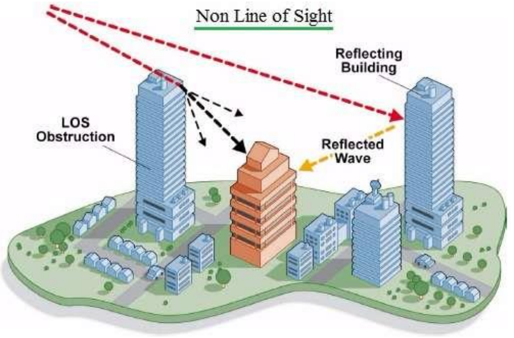


Fig. 2: Non-Line-of-Sight scenario (World, 2012)

The frequency band under evaluation was chosen because it provides an appropriate trade-off between undesirable channel characteristics like path loss, rain fading, and the atmospheric absorption effect.

In general, propagation path loss typically increases with distance and frequency (Rouphael, 2009). Equation 1 illustrates this.

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

Where d is the separation between the transmitter and receiver, n is the path loss exponent, which varies from 2 for propagation in open space to 6 for propagation through obstructions in buildings, P_l is the average propagation path loss, $d,$ and λ is the free space wavelength, which is determined by the relationship between the carrier frequency in Hz and the speed of light in meters per seconds (Maccartney & Rappaport, 2017; Rouphael, 2009).

Equation 1 can be reduced to equation 2, as;

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

Where f is the frequency of operation in MHz and d_0 is the distance in km between the transmitter and the receiver.

The primary factor in the design of wireless networks is path loss, which quantifies the energy lost when a wave travels between a transmitter and a receiver. Since the wavelength in the mm-Wave band is on the order of a millimeter, interacting with the surroundings becomes difficult.

Many propagation mechanisms contribute to multipath propagation in the mm-Wave spectrum, but their importance is different from that in frequency bands below 6 GHz.

Path loss is presented as given in equation 3.

$$Path\ loss, P_l\ in\ dB = EIRP - R_p \quad (3)$$

Where, R_p is the received power in dBm and $EIRP$ is the Effective Isotropic Radiated Power, which is given in equation 4, as;

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

P_T stands for “transmitting power” in dBm, “transmitter antenna gain” (G_T), “receiver antenna gain” (G_r), and C_l, K_l, A_l, A_{fl} represents the connector loss, cable loss, antenna loss, and antenna filter loss, respectively.

This paper aim to perform the comparative study of two widely used 5G empirical methods to predict path loss in an irregular environment for wireless communications. Therefore, the main contributions of the paper are summarized as follows;

1. To predict path loss in an outdoor irregular urban environment, we compared the applicability of 3GPP 38.901 and Close-In (CI) free space reference distance 5G empirical models.
2. Focusing on the analysis of the propagation of frequency band that is a candidate for 6G systems, considering the possible outcomes with more information.
3. We evaluated the validity of these models in the context of performance indicators.

The rest of the paper is structured as follows. Section II reports the recent developments on use of 5G empirical models for path loss prediction in different scenarios.

Section III reports on the simulation setup for the path loss analysis at 11 GHz. Section IV presents the selected 5G current cellular empirical models for the path loss investigation.

In section V reports on the obtained results and discussion from the simulation, and the comparative analysis for the selected models.

Finally, section VI provides concluding remarks.

2 RECENT DEVELOPMENT

Numerous works have been carried out to select the best path loss model for 5G communications. For instance, in an indoor setting, (Elmezughi *et al*., 2021) demonstrated measurements of propagation at three frequencies of 14, 18, and 22 GHz. Additionally, the ability to forecast path loss was compared between the FI model and the CI model (Oladimeji et al., 2022; Sun et al., 2016). The LoS performance study (Elmezughi et al., 2021) revealed that both CI and FI models operate very similarly at all frequencies and fit the actual measured data (Elmezughi *et al*., 2021).

In (Daho *et al*., 2021), Path loss models at the 28 GHz 5G system were thoroughly examined for the outdoor environment in a tropical climate. Two high-directional horn antennas with a 1.5-meter height and a half-power beam width (HPBW) of 39 degrees at the Rx side were used in this experiment. The Tx transmitter was positioned 5 meters above the surface of the earth. The impact of return and mismatch losses within the system may be affected by the impedance matching method used between the feed line and the horn antennas, which was not examined. Co-polarization decays rapidly in a Line-of-Sight (LoS) situation, according to the results.

For the analysis of mmWaves and sub-tetra hertz propagation for outdoor Urban Microcells, (Bedda-Zekri & Ajgou, 2022) took into account a number of possible situations. The findings of their research showed that the 60, 100, and 120 GHz channels are more sensitive to the effects of changing environmental circumstances than the 38 and 73 GHz channels. Although, there was no physical measurement campaign on those channels.

In (Juan-Llacer *et al.*, 2022), wideband measurements carried out in the middle of a street was used to model a path loss in the frequency bands of 1.8, 3.5, and 28 GHz. The environment was static and there was no wind during the measurement session. The outcome shows that after a certain distance between the transmitter and recipient, the 1.8 GHz and 3.5 GHz bands, multiple-scattering effects from trees must be taken into account.

3 SIMULATION PROCEDURE

To study the empirical models at 11 GHz mmWave in an irregular Urban environment, an OpenStreeMap was used to import a 3D map of the considered environment into an RF planning tool software for simulating the propagation modelling.

Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) scenarios were used to categorize the surroundings (Landolsi et al., 2019), as shown in Figure 2.

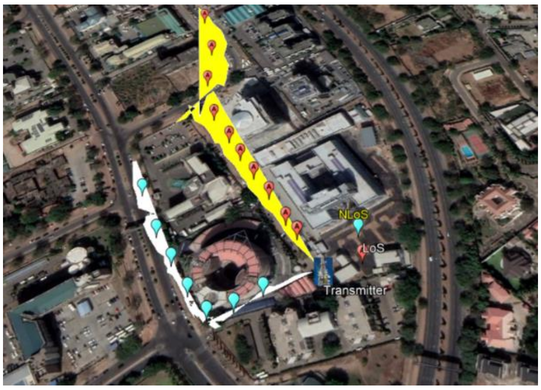


Figure 3: Simulation environment with a LOS and NLOS scena

Using the simulation parameters in Table 1, the RF planning tool software, (PL5) was used to simulate the propagation modelling to generate path loss, terrain data (path profile) and link design.

Figure 3 depicts the basic organization of the path loss program in the PL5.

For every location, the position of the Transmitter (Tx) was fixed, and simulations were performed with the Receiver (Rx) at different distances (moved along the line ranging from a reference distance of 1 m, and then from 50 m to 500 m with a spacing of 50 m.

From the simulated data, we generated CI and 3GPP models.

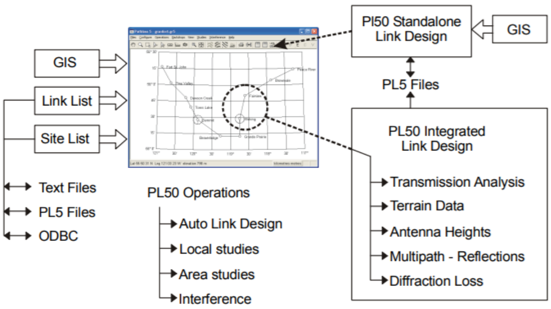


Fig. 4: Basic organization of the path loss program

TABLE 1: Simulation parameters

Parameter	Value
Frequency	$11\ GHz$
Transmitter height	$10\ m$
Transmitter 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	$463\ m\ ASL$

The illustration of the measurement campaign is shown in figure 4.

4 EMPIRICAL CHANNEL MODEL

Numerous empirical models have been created for the measured environment, but when used in other measurement environments and experimental setups, they are found to be ineffective.

A. 3GPP TR 38.901 Model

i. Equation 5 presents the path loss model in urban macro and its corresponding description, as shown in equations 6 and 7. Equations 8 and 9 present the path loss for model description in non-line-of-sight (NLoS) scenario.

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

$$PL_1 = 28.0 + 22\log_{10}(d_{3D}) + 20\log_{10}(f_c) \tag{6}$$

$$PL_2 = 28.0 + 40\log_{10}(d_{3D}) + 20\log_{10}(f_c) - 9\log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2) \qquad (7)$$

ii. For NLOS scenario.

$$PL_{UMa-NLOS} = max(PL_{UMa-LOS}, PL'_{UMa-NLOS})\ for\ 10m \le d_{2D} \le 5km \qquad (8)$$

$$PL'_{UMa-NLOS} = 13.54 + 39.08\log_{10}(d_{3D}) + 20\log_{10}(f_c) - 0.6(h_{UT} - 1.5) \qquad (9)$$

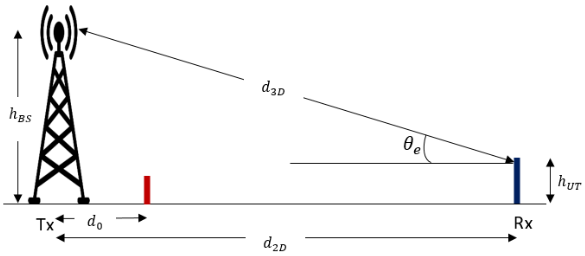


Fig. 5: Definition of d_{2D} and d_{3D} for outdoor UT_S

The above equations hold for shadow fading std, $\sigma_{SF}\ [dB] = 6$; applicability range, antenna height default values of $1.5m \le h_{UT} \le 22.5m;\ and\ h_{BS} = 25m$.

B. Close-In (CI) Free Space Reference Distance Model

Equation 10 illustrates how we applied the CI free space reference distance model (Sun et al., 2016), for a single frequency.

$$P_L^{CI}(f,d)[dB] = P_L(f,d_0) + 10n\log\left(\frac{d}{d_0}\right) + W_\sigma^{CI} \qquad (10)$$

$P_L(f,d_0)$ is the free space path loss in dB at a T-R separation distance of 1m at the carrier frequency (ZEKRI & AJGOU, 2019), where f, n is the path loss exponent, d_0 is the initial separating path, and W_σ^{CI} is a zero-mean Gaussian-distributed random variable, and $\sigma\ dB$ is the standard deviation (shadowing impact).

The prediction result of the considered empirical models were compared with the simulated results to validate their performances, using performance indicators; Mean Absolute Percentage Error (MAPE), Mean Error (ME), and Root Mean Square Error (RMSE), as presented from equation 11 to 13.

$$MAE = \left| \frac{1}{N_{test}} \sum_{i=1}^{N_{test}} \left| PL_i^{sim} - PL_i^{pred} \right| \right| \qquad (11)$$

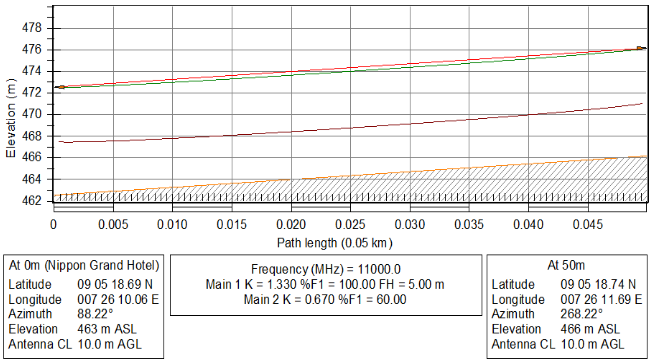
$$MAPE = \frac{1}{N_{test}} \sum_{i=1}^{N_{test}} \left| \frac{PL_i^{sim} - PL_i^{pred}}{PL_i^{sim}} \right| \times 100 \qquad (12)$$

$$RMSE = \sqrt{ME} = \sqrt{\frac{1}{N_{test}} \sum_{i=1}^{N_{test}} \left(PL_i^{sim} - PL_i^{pred}\right)^2} \qquad (13)$$

Where PL_i^{sim} represents the simulated path loss value.
PL_i^{pred} represents the predicted path loss values.
N_{test} is the total number of tested samples.
i is the index of the simulated sample.

5 RESULTS AND DISCUSSION

The simulation report for the 11 GHz propagation modelling presents the path profile and terrain data, as shown from Figure 6 to Figure 15. The considered distances ranged from 1 m to 500 m with a step of 50 m.

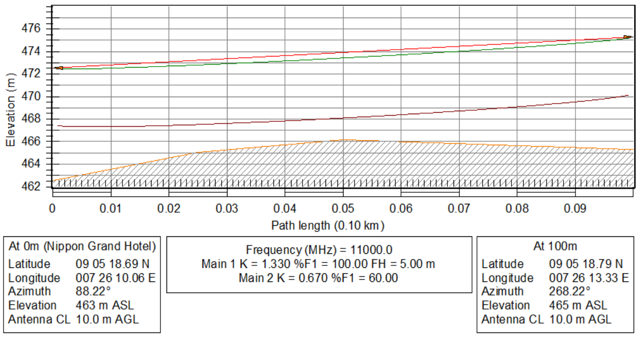


At 0m (Nippon Grand Hotel)
Latitude 09 05 18.69 N
Longitude 007 26 10.06 E
Azimuth 88.22°
Elevation 463 m ASL
Antenna CL 10.0 m AGL

Frequency (MHz) = 11000.0
Main 1 K = 1.330 %F1 = 100.00 FH = 5.00 m
Main 2 K = 0.670 %F1 = 60.00

At 50m
Latitude 09 05 18.74 N
Longitude 007 26 11.69 E
Azimuth 268.22°
Elevation 466 m ASL
Antenna CL 10.0 m AGL

Fig. 6: Path profile for 11 GHz at 50 m



At 0m (Nippon Grand Hotel)
Latitude 09 05 18.69 N
Longitude 007 26 10.06 E
Azimuth 88.22°
Elevation 463 m ASL
Antenna CL 10.0 m AGL

Frequency (MHz) = 11000.0
Main 1 K = 1.330 %F1 = 100.00 FH = 5.00 m
Main 2 K = 0.670 %F1 = 60.00

At 100m
Latitude 09 05 18.79 N
Longitude 007 26 13.33 E
Azimuth 268.22°
Elevation 465 m ASL
Antenna CL 10.0 m AGL

Fig. 7: Path profile for 11 GHz at 100 m

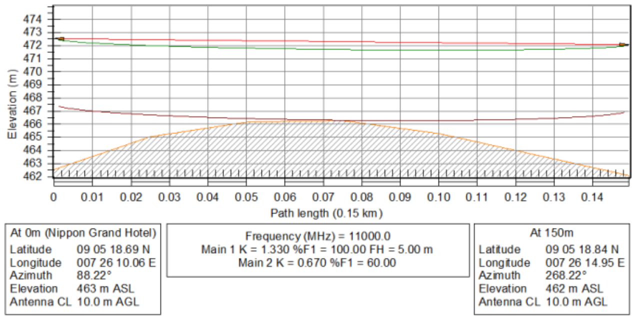


Fig. 8: Path profile for 11 GHz at 150 m

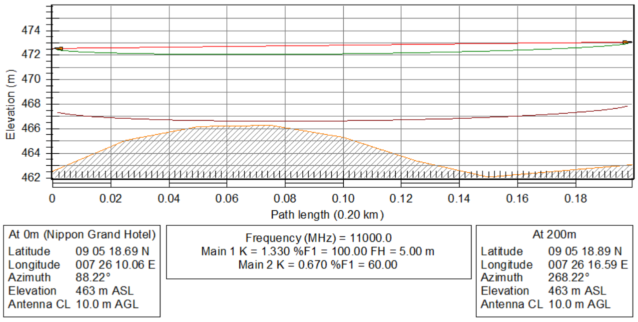


Fig. 9: Path profile for 11 GHz at 200 m

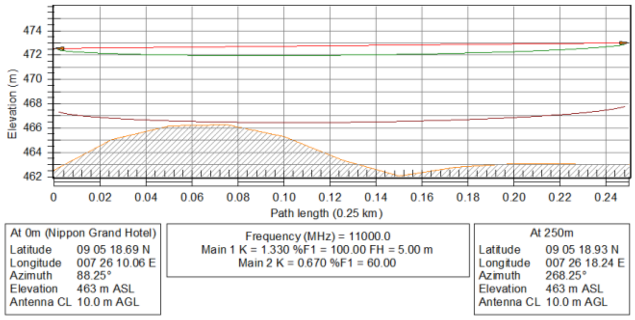


Fig. 10: Path profile for 11 GHz at 250 m

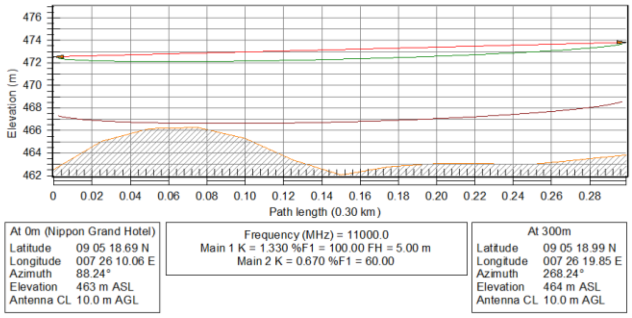


Fig. 11: Path profile for 11 GHz at 300 m

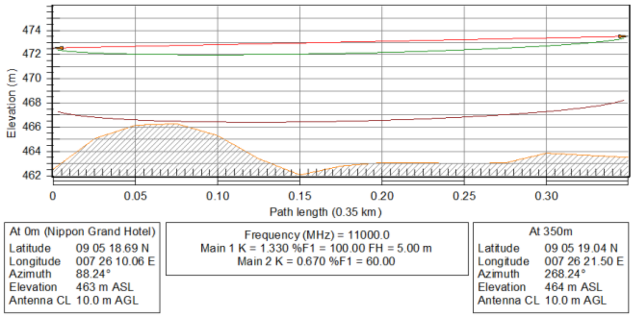


Fig. 12: Path profile for 11 GHz at 350 m

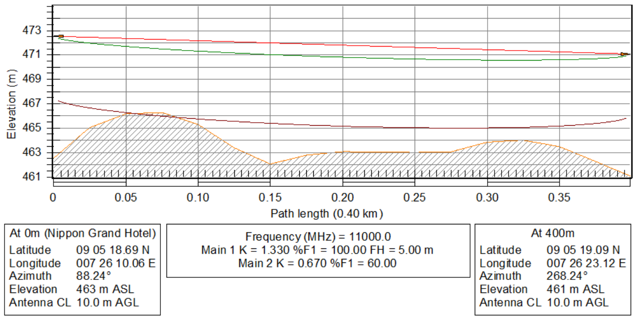


Fig. 13: Path profile for 11 GHz at 400 m

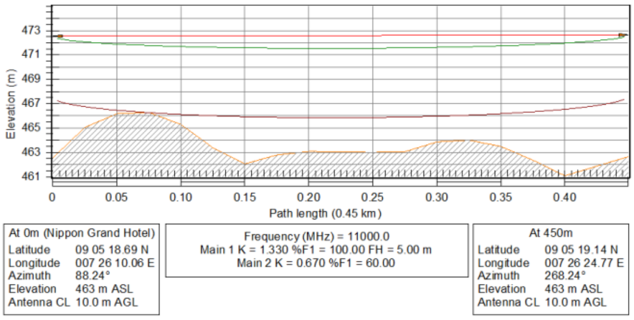


Fig. 14: Path profile for 11 GHz at 450 m

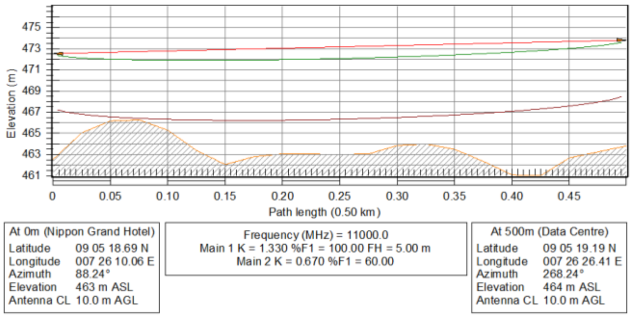


Fig. 15: Path profile for 11 GHz at 500 m

The model comparison carried out in Line-of-Sight (LoS) scenario shows that the CI model overestimated the path loss throughout the range of interest, while the 3GPP model performed excellently, especially to the point of 350 m, as shown in Figure 16.

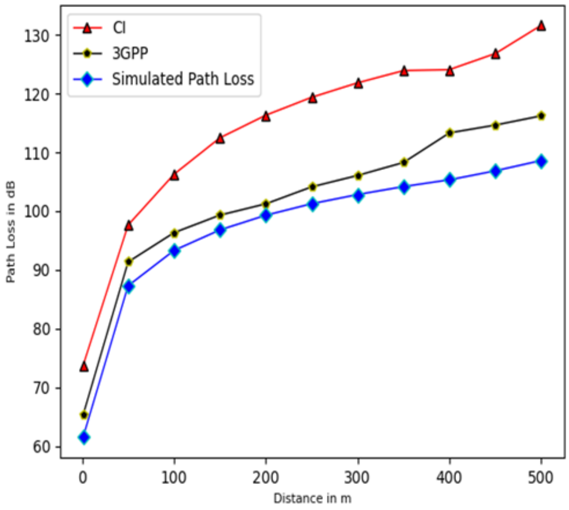


Figure 16: Comparison of models in LoS scenario

On the condition of Non-Line-of-Sight (NLoS), its clearly shown in Figure 17, that the 3GPP model tends to fit with the simulated path loss within a short distance ($< 400\ m$), and then overestimated the path loss.

Meanwhile, the CI model also overestimated the simulated path loss throughout its path, but not as much as in the case of Line-of-Sight (LOS) condition.

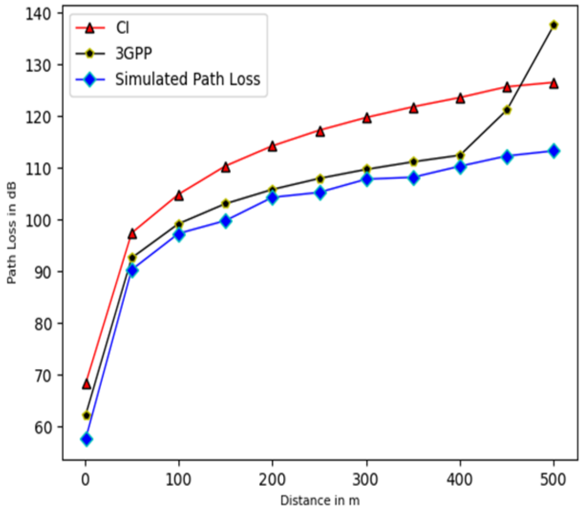


Fig. 17: Comparison of models in NLoS scenario

TABLE 2: Simulated result on Line-of-Sight (LoS) scenario

S/N	Path Length (m)	Elevation (m)	Rain Attenuation (dB)	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	53.05	42.28	-19.84	61.53	73.73	65.31
02	50	466.17	50.31	72.39	-23.69	87.29	97.62	91.34
03	100	465.30	44.30	27.56	-29.70	93.30	106.26	96.32
04	150	462.08	40.81	3.08	-33.19	96.79	112.46	99.31
05	200	463.07	38.30	2.61	-35.70	99.29	116.31	101.23
06	250	463.00	36.34	1.82	-37.66	101.25	119.36	104.12
07	300	463.82	34.79	4.27	-39.21	102.81	121.82	106.06
08	350	463.50	33.43	2.74	-40.57	104.17	123.90	108.27
09	400	461.08	32.28	3.68	-41.72	105.32	124.07	113.31
10	450	462.54	31.24	42.28	-42.84	106.85	126.81	114.63
11	500	466.17	30.33	72.39	-43.67	108.61	131.62	116.21

TABLE 3: Simulated result on Non-Line-of-Sight (NLoS) scenario

S/N	Path Length (m)	Elevation (m)	Rain Attenuation (dB)	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	53.05	32.56	-21.89	57.61	68.34	62.24
02	50	463.21	51.56	45.54	-25.74	90.34	97.45	92.62
03	100	465.48	46.21	2.65	-31.75	97.35	104.93	99.24
04	150	463.37	42.58	2.06	-35.24	99.84	110.41	103.11
05	200	462.44	40.31	19.43	-37.75	104.34	114.29	105.86
06	250	463.21	38.91	3.32	-39.71	105.30	117.31	108.00
07	300	463.40	36.07	2.56	-41.26	107.86	119.77	109.74
08	350	463.14	35.37	1.69	-42.62	108.22	121.85	111.21
09	400	468.32	34.12	9.59	-43.77	110.37	123.65	112.49
10	450	468.73	32.54	3.44	-44.81	112.35	125.73	121.24
11	500	468.05	29.32	3.51	-45.72	113.33	126.57	137.62

TABLE 4: Performance indicator

Models	Condition	MAE (dB)	MAPE (%)	RMSE (dB)
3GPP	LOS	9.14	21.76	2.92
	NLOS	11.09	16.32	4.13
CI	LOS	16.32	13.29	5.55
	NLOS	19.21	12.16	7.04

On the simulated report in Table 2 for the 11 GHz channel prediction, it can be deduced that the CI model overestimated the prediction, while the 3GPP performed excellently on the prediction of path loss within this channel.

ACKNOWLEDGEMENTS

We give thanks to the 9Mobile Communication Limited for providing the licensed RF planning software tool for this work.

CONCLUSION

In this paper, we report 11 GHz channel simulation in an irregular environment in the central city of Abuja, Nigeria. The simulations are done in Line-of-Sigh (LoS) and Non-Line-of-Sight (NLoS) scenarios. The aim of this study is to have a better understanding of the suitability of 11 GHz 5G systems for mm-Wave deployment.

We evaluate the fit of two of the most widely used empirical models to the simulated data. In this analysis, the 3GPP model gives better prediction in LoS condition against the NLoS with MAE 9.14 dB and 11.09 dB. In both scenarios, the CI model overestimated the path loss, with MAE values of 16.32 dB and 19.21 dB, respectively. The models indicate that the CI model is superior for predicting path loss in the environment being studied at mmWave frequency. In future work, we plan to concentrate on an extensive physical measurement campaign for evaluating the map-based machine learning models, as other environments still need to be addressed.

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