



# An improved path loss model for 5G wireless networks in an enclosed hallway

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Accepted: 16 January 2024 / Published online: 13 February 2024

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## Abstract

Given the disparity in signal transmission properties for both current bandwidths and millimeter wave radio frequencies, the present propagation models used for low frequency range up to few gigahertz are not suitable to be utilized for the path loss modelling techniques as well as modulation schemes for the high frequency ranges such as millimeter wave (mmWave) spectra. As a result, rigorous research on link analysis as well as path loss modeling are needed to create a broad and suitable transmission scheme with modeling variables that can handle a broad spectrum of mmWave frequency spectra. This paper proposes an improved path loss model for estimating the path loss in an indoor space wireless communication at 28 GHz and 38 GHz frequencies. The test results for the interior non-line-of-sight (NLOS) situations were collected every two meters over spacing of 24 m separating the transmitting and receiving antenna locations to make a comparison the well-known and improved large-scale generic path loss models. The results of the experimental studies obviously demonstrate that the improved propagation model works significantly better than the CI model, owing to its simple setup, precision, and accurate function. The results show that the presented improved model gives better performance. It is observed that the standard deviation of shadow fading can be significantly reduced in the NLOS scenario, implying greater accuracy in predicting the path loss in an indoor environment.

**Keywords** PATH loss model · Millimeter wave frequency · Propagation · Wireless communication

## 1 Introduction

In order to support the over 11 billion mobile linked devices brought about by the internet of things idea, the current development in the wireless communication system is necessitated by society's desire for information sharing and requires pervasive wireless connectivity. More mobile devices are connected to the internet than the current capacity can handle, so a larger network with greater encryption and vast size is required [1, 2]. The key barrier is bandwidth, which cannot keep up with the escalating rate of traffic demand [3–7], despite the fact that different radio waves can propagate in the 6GHz frequency ranges.

Due to the vast amount of available spectrum, which can support the demands of high data rate and massive capacity, millimeter wave (mmWave) communication is now the best technology for 5G deployment. The frequency range of mmWaves is 3–300 GHz, and their wavelength range is 1–100 mm. Due to the existence of unapproved bandwidths that are prepared for usage in next-generation networks and are particularly suitable for 5G networks, the World Radio Conference (WRC) has designate mmWave for fifth generation (5G) implementation. Despite these advantages, employing mmWaves has several disadvantages, such as a restricted beam width, high path loss (PL), and higher penetration loss. In particular, because it affects the path loss exponent (PLE) [8–12], this calls for a full understanding of the propagation path loss model (PLM) to be used for 5G deployment in mmWave propagation.

Before considering the full operating system in radio propagation, it is imperative to examine the propagation models because they are the fundamental part of wireless signal propagation. However, each system has unique

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characteristics that translate into various propagation processes; channel models that fit into these systems should be developed. This led to numerous wireless communication research initiatives over the past 50 years or so, yielding the five generations of wireless communication that are currently in use with a sixth generation on the horizon. The use of European Cooperation in Science and Technology (COST) and the Third Generation Partnership Project (3GPP) has been the primary method of propagation models from the first to the fifth generation. Studies show that radio system generations endure ten years. With a bandwidth of 40MHz and a singular focus on delivering calling services, they initially arrived in 1974. With a 200kHz bandwidth of frequency, the second generation (2G) of wireless communication was first established in the 1980s by the 3GPP with the intention of offering speech services identical to 1G with the additional capacity of data service, but at a relatively low capability. Even though it was initially restricted to the 3GPP spectrum, the International Mobile Telecommunications (IMT) started creating a channel model for the third generation (3G) in 2000. Along with enhanced voice services, multimedia application technology is also introduced. The COST model is consequently adopted, followed by the 3GPP model. The fourth generation, or 4G, debuted in 2010 with a 20 MHz capacity increase while retaining the 3GPP advanced format and working in MIMO mode [13, 14].

The top data rate for services in this generation is 150 megabits per second. The most recent rollout of 5G in early 2020 makes use of the IMT-2020/3GPP technology of channel models. The majority of nations worldwide are considering using the millimeter wave band to deliver 5G due to the available frequency bands, even if the majority of them still operate in the C band. Up to 20 Gbps of data rates could be offered by 5G [13–18].

The 5G data rate has been steadily increasing, requiring more network capacity and improved energy efficiency. The characterization and modeling of channels has been driven by the numerous requirements of the 5G network, such as security, traffic latency, reliability, and other major broadcast requirements in diverse applications for successful propagation. This has resulted in a notable improvement in channel performance. Path loss occurs when factors like reflection, refraction, diffraction scattering, and other atmospheric issues affect the signals along the way. In order to address this issue, an appropriate model for propagation that can measure performance based on propagation with respect to PL must be developed, especially for 5G. This will make it possible to create a solid system that takes antenna directions and arrays into account while also performing link budget analysis and signal strength prediction. Analysis of performance models in particular contexts cannot be done using statistical

models that need universality of application. It is necessary to construct an accurate model that tends to fit propagation PL parameters in many applications, whether indoor or outdoor situations, because 5G satisfies the desire for huge data consumption in the mmWave band [19]. The importance of PL in mmWave channel transmission cannot be overemphasized in terms of implementation, design, assessment, as well as planning. It establishes the network coverage area, interference ratios, and data speeds. High-fidelity models are therefore necessary since the focal reference affects the wireless network's propagation channel's main performance [20]. Various academics have proposed and supported numerous path loss models (PLMs), including quantitative and evidence based models based on linear regression quantification. Both indoor and outdoor contexts can be used to quantify PL, but the results are different. Interior route loss models will consider a number of factors, such as the furniture in the indoor office or corridor, indoor designs, construction materials, any smart devices present, and human mobility in the surrounding area, among others. The parameters of the received signal are affected by multipath fading, reflection, scattering, shadowing, PL due to distance, refraction, as well as penetration [20–22].

In an indoor setting, mobile communication signals encounter obstructions on their passage from the transmitter (Tx) to the receiver (Rx), which increases the PL of the signal [23]. The height disparity between the Tx and Rx is another factor that affects path loss. These two potential 5G options; 28 and 38 GHz are the two frequency ranges that this study examined. Barriers frequently have a greater impact on or attenuate high-frequency signal transmissions. Radio waves travel differently indoors depending on the distance between the walls, the materials used for the passage as well as other irregular objects that are placed along the hallway [24].

To the extent that we are aware, there is a limited study in the precise modeling and characterization of single frequency PLMs that take the antenna height difference of the Tx as well as Rx into account at 28 and 38 GHz frequency bands in the SHF band (FB). This work aims to close the gap by developing an improved model that allows for easier design and performance evaluation for NLOS situations using measured data collected in normal indoor passageway surroundings at 28, as well as 38 GHz. The vertical to vertical (V-V) as well as the vertical to horizontal (V-H) polarizations of the antenna were adopted for the measurement of the data. Furthermore, the model outperforms the conventional CI and FI models, as explained in Sect. 4.

This study proposes to improve the Close-In (CI) PL prediction models. Comprehensive modeling and characterization are essential components of a general model. The

research was conducted in an indoor corridor setting on the 5th floor of the building of the Department of Electrical, Electronics, and Computer Engineering (EECE) at the University of KwaZulu-Natal (UKZN) in Durban, South Africa. To gain a good comparison of the existing and new large scale PLMs, a measurement process was done for the scenario in the NLOS for two different antenna polarizations. The two antenna polarizations adopted were V-V and V-H polarizations. To create a general model in the mm Wave frequency ranges, extensive research and modeling are needed. This study examines channel estimation and path loss modeling in the 28 as well as 38 GHz FBs. In the previous study, extensive measurement analysis of indoor corridor propagation at V-V as well as V-H antenna polarizations were made for the 28, and 38GHz FBs [2]. However, a novel improved PLM is proposed in this work. Nonetheless, in order to accurately evaluate the established and proposed large-scale PLMs, the process of data gathering by measurement was done for the NLOS, and the results of the propagation parameters were compared. Propagation modeling and channel characterization were investigated using existing and proposed single-frequency path loss models, as well as directional path loss models. The need to simply reduce the standard deviation and path loss parameters of these models while maintaining their simplicity motivates this work. This has led to the improvement of the accuracy of the PLMs and also reduces the standard deviation of the shadow fading of these standard path loss models without adding parameters that will complicate the path loss model equations.

The contribution of this research can be summed up as follows: the shadow fading (SF) of these typical PLMs can be improved and the standard deviation (SD) can be reduced without complicating the equations, to improve the accuracy and PLE, as shown in Sect. 4, the improved model is straightforward and more accurate at predicting PL. Another point of importance of this study is that this improvement is simple and highly efficient since almost all the communication methods for indoor environments are NLOS. Moreover, it can be seen from the research that our proposed model provides more sensitivity to the antenna polarization and capture more accurately the wireless propagation characteristics caused by the mismatching of the Tx and Rx antenna polarizations. The rest of the study is organized as follows: Sect. 2 encompasses related works, whilst Sect. 3 contains measurement campaign details and large scale PLMs. Section 4 presents the results and discussions, while the conclusion is given in Sect. 5.

## 2 Related works

Traditional methods for PL forecast characterization are essentially stochastic, deterministic as well as empirical in nature. Site-specific and requiring appropriate knowledge of the propagation environments are requirements for deterministic route loss prediction models. These models, like the ray-tracing models, are frequently connected to 3-D map propagations. These deterministic models also have significant computing cost since they repeat calculations when the environment changes. The Hata model as well as the COST 231 model is two examples of empirical PLMs that are based on measurements and observations. Although these models are simpler to use, they take more time to implement because they call for comprehensive measurement processes in certain settings and network scenarios. Additionally, these models offer poorer prediction accuracy than deterministic models [24–27].

Channel modeling characterization for an enclosed surrounding at FBs of 4.5, 28, and 38 GHz is presented in the work of [28]. For 28 GHz as well as 38 GHz FBs, a novel PLM is proposed. Measurements for the interior LOS as well as NLOS situations were taken at every meter over range of 23 m between the TX and RX antenna positions in order to compare the conventional PLMs with a new large-scale generic PLMs. Conventional and suggested PLMs for single-frequency, multi-frequency, directional as well as Omni-directional PLMs, were used to examine the results. The outcome shows that the proposed PLM, which has only one variable and is physically centered to the Tx power, can model the large-scale PL over distance more accurately than the well-known models. Also the absence of physical basis for the transmission signal, have more issues (involve additional parameters), and lack expectation when describing parameter values. The PLE values for the LOS scenario at the frequencies of 28, 38, and GHz were, respectively, 0.92, 0.90, and 1.07 for the V-V, V-H, and V-Omni antenna polarizations and 2.30, 2.24, and 2.40 for the same polarizations.

Al-Saman et al. carried out another examination of models in an interior environment for mmWave in terms of PL in 2021. Different PLMs, which include the CI PLM, the 3GPP and WINNER FI PLM, were presented and analyzed for the interior channels at different mmWave FBs. The PLM determines the rate of signal degradation along the propagation path for both LOS and NLOS channels at a specified distance [29]. Further researches on the traditional CI as well as the FI PLMs was adopted for both interior and outdoor airport environments as a result of additional mmWave propagation research on a 73 GHz measurement campaign at Boise State University and the airport [30]. The study shows that although the PLEs of the

CI and the free-space model ( $= 2$ ) are substantially similar, however, the FI PLM offers a superior match to the measured data. These data also show how distinctly different the inside airport environment is from other indoor settings due to its roomy and open layout. Additional mmWave propagation study by [31] presents measurement studies at the 30, 140, and 300 GHz FBs in the interior LOS surroundings. The performance of the single-frequency CI, CIF, and ABG PLMs was tested at these FBs. The results show that all four PLMs perform equally, but the PLM with the fewest parameters would be the best choice for simplicity. PL as well as small-scale fading on the corridor were looked into in [32, 33] utilizing antennas operating at 30 GHz. The improved model produced the exact PLE as the FI PLM while requiring less mathematical complexity [33]. In their latest work, Oladimeji et al. 2023, [34] both the CI and FI PLMs receive a remarkable improvement. The key findings demonstrate that the upgraded PLMs outperform the conventional CI and FI PLMs for the LOS as well as NLOS network situations. Also the stability and sensitivity of the suggested models are also noticeably better than those of the conventional models in both network scenarios. The need of acceptable common PLMs, like the FI, CI, as well as the ABG model, has recently increased due to the requirement to construct wireless channels using PLMs [34].

The goal of modeling channel models is to predict the signal propagation between the transmitter and the receiver. The methods should be reproducible as well as cost-effective. Channel modelling is responsible for accurate system deployment and air-radio interface design [35]. The carrier frequency and environmental impacts, the 2D or 3D distance between transmitter and receiver, and the bandwidth are all information contained in the typical wireless channel models. Creating a flexible and accurate intrinsic physical system in the high-frequency region of 0.5–100 GHz is the difficult obstacle in favor of channel models in 5G, where various researchers have published their research in [36–38]. The beneficial effect of characterizing path loss in terms of both LOS and NLOS motivated mobile industry players to investigate it more thoroughly. The purpose is to develop a statistical prediction technique that investigates the probability of LOS between the user and the base station, as well as the case of NLOS, which occurs when there are obstacles between the user and the base station. In terms of performance, LOS outperforms NLOS because it provides more reliability in millimeter wave connectivity.

Diffraction losses, on the other hand, are more common in high-frequency waves than in 6 GHz sub-waves [39]–[40], and NLOS also documented higher fading ratios in terms of shadowing variance and path loss exponent (PLE) [41]. The TX-RX 2-D separation distance is the basic

function of LOS probability modeling. Frequency is ignored in this model because it is mostly dependent on a specific scenario or the geometric context of the medium [42]. For example, in 5G channel model [36], it can be determined whether or not the path connecting sender and receiver has been obstructed or not by identifying the sender and receiver on a map.

### 3 PL Measurement and PLMs

Details about the setting for the measurement as well as the propagation PLMs are provided in this section.

#### 3.1 Measurement campaign and environment

This section explains measurement campaigns carried out as a wireless communication channel between both the Tx and Rx in a typical indoor passageway setting. The equipment utilized for the measurement, was used at the EECE Departmental building in UKZN Durban, South Africa. The channel sounder was cautiously calibrated prior to the start of the measurements to ensure accurate data collection. Furthermore, we affirmed that there were no interfering signals in the corridor. The wireless propagation channel, as previously stated, is an enclosed interior corridor. This corridor measures 30 m in length, 1.4 m in width, and 2.63 m in height. This corridor, as it typically exists, is made primarily of bricks and dry concrete, with wooden doors to entrance offices on one side and a staircase and elevator on the other. The Rohde and Schwarz SMB 100A Signal Generator was used as a transmitter, and the Rohde and Schwarz FSIQ 40 Signal Analyzer was used as receiver, in the channel sounder used for the measurements as shown in Fig. 1. Coaxial cables connected both to broadband horn antennas. Images of the transmitter and receiver units used in measurement campaigns are shown in Figs. 2, 3, 4, and 5. The parameter setup as well as equipment set-up are shown in Table 1. During the campaign, the transmitting horn antenna was positioned at one end of the passage, while the receiving horn antenna shifted away from the transmitter in 2 m increments up to the opposite end. When both antennas were not aligned toward each other, the received wireless signals at each transmitter–receiver separation distance (non-line of sight transmission). The center frequency bands used for continuous wave signal transmission between two broadband horn antennas adopted in both the sending and receiving ends, with horn antenna heights of 1.6 m at the transmitter horn antenna and 2.3 m at the receiver horn antenna stand, were 28 and 38 GHz. At the transmitter end only the vertical–vertical polarization was used, while the receiving end used both the vertical–vertical and vertical-horizontal



Fig. 1 Measurement setup

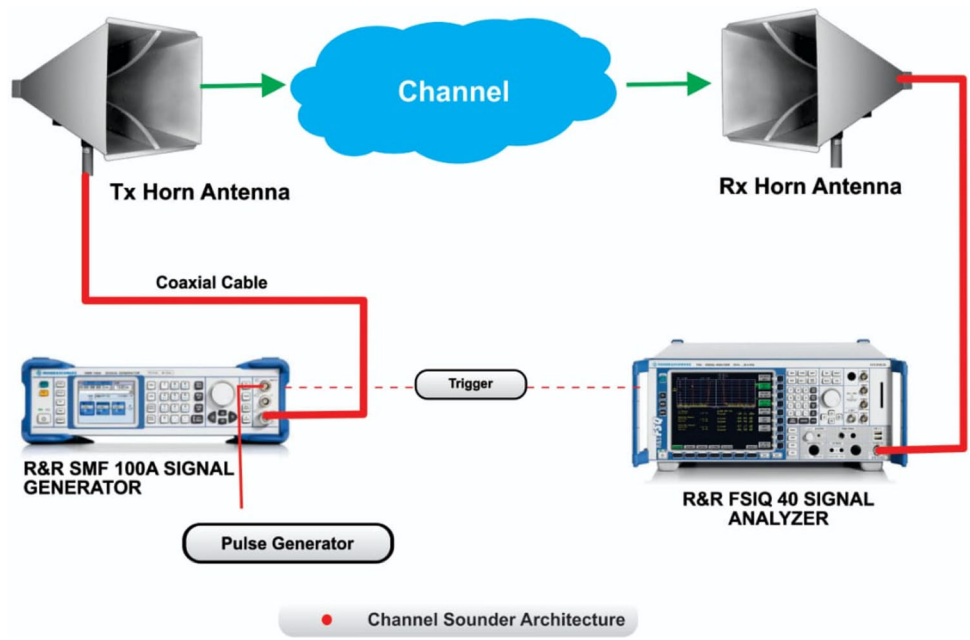


Fig. 2 The interior passage

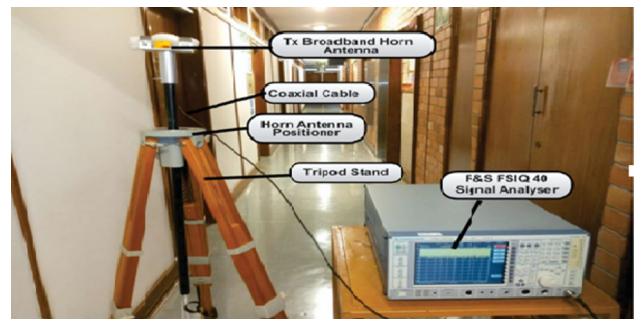


Fig. 4 Setup for Receiver

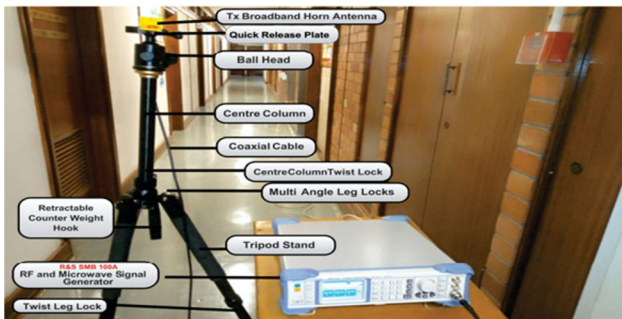


Fig. 3 Setup for Transmitter



Fig. 5 The Tx and Rx configuration in the indoor passage

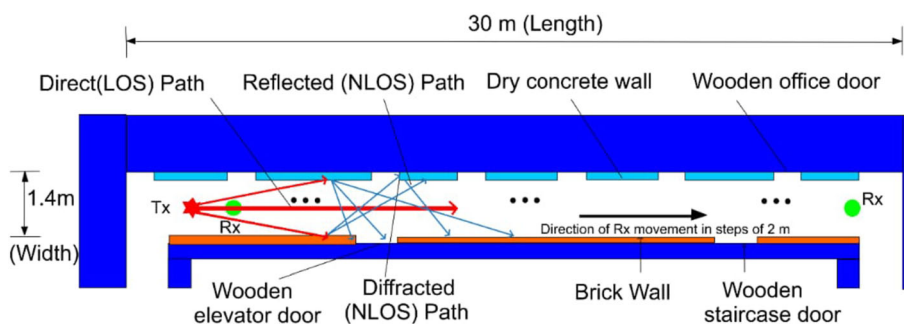
polarizations. The receiving horn antenna was placed 24 m away from the transmitter by starting at one end of the hallway and shifting away from it by 2 m at a time. There are a minimum of 13 transmitter–receiver separation lengths with a 1 m reference distance ( $d_o = 1m$ ). Authors have conducted previous research works using the same case study but with the application of the standard path loss

models. To further improve the prediction of path loss model, authors proposed this PLM in other to reduce the shadow fading and the standard deviation which are the major factors that determine the accuracy of predictability in path loss analysis. Figures 2 and 6 show a comprehensive view of the floor plan and the interior passage. Thus, the path loss was calculated using Eq. (1) [2]:

**Table 1** Equipment set-up parameters’ description

Measuring equipment parameters	Equipment configuration	Unit
Centre FBs	28, 38	GHz
Transmission bandwidth	100	MHz
Transmission signal	CW	
Tx and Rx HAs	Broadband HA	
Power of Tx HA	10	dBm
Height of Tx HA	1.6	m
Height of Rx HA	2.3	m
Gain of Tx and Rx HA at 28 GHz	15	dBi
Gain of Tx and Rx HA at 38 GHz	17	dBi
Polarizations of Tx and Rx HA	V/ H	
Dimension of HA (L x W x H)	71 × 32 × 28.6	mm <sup>3</sup>
Weight of HA	0.08	Kg

**Fig. 6** A floor plan for the indoor passage



$$P_L = P_t - P_r + G_t + G_r \tag{1}$$

where Tx power =  $P_t$ , Rx power =  $P_r$ , the gain of Tx antenna =  $G_t$  and the gain of Rx antenna  $G_r$ .

### 3.2 Path Loss in mmWave propagation

PL is a process that happens when a Tx’s signal weakens in the transmission channel due to the distance traveled and the propagation channel’s properties. Additionally, it describes the attenuation that occurs during propagation from the Tx to the Rx. Since the broadcast power level is higher, it resulted in the lower received power. The PL is often expressed in decibels (dB) [29]. When used in wireless propagation, PL is dependent on a logarithm factor since the relationship between Tx and Rx distance and PL is not linear. Nevertheless, in LOS conditions, signal degradation over distance matched the square power law in signal propagation and free space path loss (FSPL) signal attenuation equation [2, 43].

### 3.3 Large scale PL prediction model

Radio propagation in physical surroundings affects how well wireless communication systems operate because

fading of the radio waves occurs frequently. Any wirelessly propagated signal from the transmitting antenna(s) of a communication system is subject to degradation over distances as well as FBs, which are considered as fading (it may either be on a large scale or small scale). The air conditions and nearby physical objects also induce signal losses, which results in multipath transmission since the Rx antenna (or antennas) primarily picks up the signal through reflections, diffractions, and scattering mechanisms [24, 34, 44]. Signal power fluctuation and increased signal power uncertainty are also caused by these multipath effects [34, 45]. PL impacts on the communication signal at the Rx end can be widely reflected by the use of models for propagation path loss. It’s a valuable method to determine how much a signal will diminish and decay as it advances from Tx to Rx, taking propagation distance and other factors into account. Some PLMs specify the profile of the topographical to make signal analysis simpler, while others merely use the frequency of the carrier frequency as well as the distance to accomplish their objectives [46–50].

### 3.3.1 CI PL prediction model

This PLM’s fundamental principle is grounded in the point of anchor as well as the reliance on the frequency in empty space. FSPL a model variable that also rely on the frequency ( $f$  in GHz) of the transmitting signal. Both the distance (in meters) between the Tx and Rx as well as the reference distance ( $d_o$ ) are essential. The sole parameter in the CI model that needs to be worked out in dB is PLE ( $n$ ) [11, 38]. The expression for the CI PLM can be seen in Eq. (2) as follows (computed by [2]):

$$P_L^{CI}(d)[dB] = FSPL(f, d_o)[dB] + 10.n. \log\left(\frac{d}{d_o}\right) + X_{\sigma SF}^{CI} \tag{2}$$

For  $d \geq d_o$ , where  $d_o = 1m$

Where  $X_{\sigma SF}^{CI}$  is a zero mean Gaussian random variable that has standard deviation  $\sigma$  in dB

$$FSPL(f, d_o)[dB] = 10 \log_{10}\left(\frac{4\pi d_o}{\lambda}\right)^2 \tag{3}$$

To calculate the CI PLM, PLE  $n$  is obtained by adopting the MMSE method which commiserates with the recorded measurements.

$$FSPL(f, d_o)[dB] = 10 \log_{10}\left(\frac{4\pi f d_o}{c}\right)^2 \tag{4}$$

$$FSPL(f, 1m)[dB] = 10 \log_{10}\left(\frac{4\pi f}{c}\right)^2 \tag{5}$$

where  $c$  represents the speed of light.

### 3.3.2 Improved CI PL Prediction Model

The improved model offers simplified design and performance evaluation. The parameters of barriers inside the measuring environment were not taken into account by the existing single slope PLMs. However, the proposed model takes into account the Close-in height and obstruction factors. The PL value is proportional to the separation  $d$ , which are the coefficient in both LOS as well NLOS situations. Although the proposed PLM is quite comparable to the CI PLM, it is evaluated at data PL sites at the reference distance  $d_o = 1m$ .

The proposed improved Close-In (CI)-based PLM in decibel (dB), is expressed as:

$$PL^{CI-HO}(f, d, h) = PL(f, d_o) + 10n \log_{10}(d) + 10k_{CI} \log_{10}(h)^2 + X_{\sigma}^{CI-HO} \tag{6}$$

where.

$PL(f, d_o) = 20 \log_{10}(4\pi f d_o / c)$  is the FSPL,  $f$  is the carrier frequency which is assumed to be 28 GHz or 38

GHz in this study,  $d_o$  is the reference distance which is taken to be 1 m,  $n$  is the PLE of the environment,  $d$  is the distance between Tx and Rx,  $h(= h_{R_x} - h_{T_x})$  is the difference in Tx height  $h_{T_x}$  and Rx height  $h_{R_x}$ . It is assumed that  $h_{R_x}$  is larger than  $h_{T_x}$ ,  $k_{CI}$  is the second PLE variable for CI, (as a result, the path loss exponent concept has two variables  $n$  and  $k_{CI}$ )  $X_{\sigma}^{CI-HO}$  is shadow fading for CI which is presumed to be zero mean Gaussian distributed random samples with standard deviation  $\sigma$ . In terms of changing antenna heights as reported in the works of [43] and [51], the MSE curves show that the CI model parameters are sensitive (although the degree of sensitivity is more in FI model). Comparing when both antennas are the same height, the PLE improved performance resulting from altering the Tx antenna height value is greater. In addition, adjusting the antenna altitude alters the incidence angle of the transmitted signals on obstructions near the receiving antenna. Furthermore, in the work of [20], with difference in Tx and Rx height during the experiment in the same surroundings used for this investigation, stronger constructive interferences as well as better wave guiding influence in the corridor were observed. Therefore, this approach will pave the way for optimized PL prediction models that take the altitude of the Tx and Rx antennas into consideration. As a result, greater accuracy is provided in predicting PL for design process as well as link budget estimations.

The two parameters in Eq. (6) to be determined are  $n$  and  $k_{CI}$ . Assuming  $A = PL^{CI-HO}(f, d, h) - PL(f, d_o)$ ,  $B = 10 \log_{10}(h)^2$ , and  $D = 10 \log_{10}(d)$ , then Eq. (2) can be expressed in terms of the shadow fading as:

$$X_{\sigma}^{CI-HO} = A - k_{CI}B - nD \tag{7}$$

The standard deviation of  $X_{\sigma}^{CI-HO}$  can be obtained using minimum mean squared error (MMSE) as:

$$\sigma^{CI-HO} = \sqrt{\frac{\sum (X_{\sigma}^{CI-HO})^2}{N}} \tag{8}$$

The representation of PL sample numbers is denoted by  $N$ . To minimize the error in  $\sigma^{CI-HO}$ , the partial derivative of  $\sum (X_{\sigma}^{CI-HO})^2$  is taken with respect to  $n$  and  $k_{CI}$  and set the derivatives to zero as follows:

$$\frac{\partial \sum (A - k_{CI}B - nD)^2}{\partial n} = 0 \tag{9}$$

$$\frac{\partial \sum (A - k_{CI}B - nD)^2}{\partial k_{CI}} = 0 \tag{10}$$

Equations (9) and (10) are simplified into the following:

$$\sum B^2 k_{CI} + \sum (BD)n = \sum (AB) \tag{11}$$

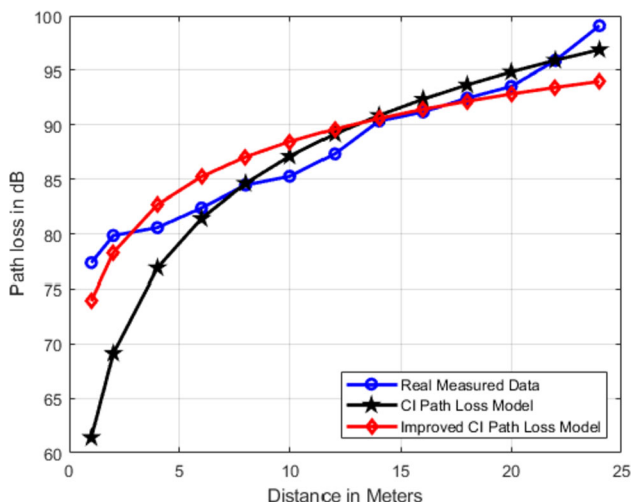


Fig. 7 Proposed Improved-CI PL against distance for 28 GHz NLOS at V-V polarization

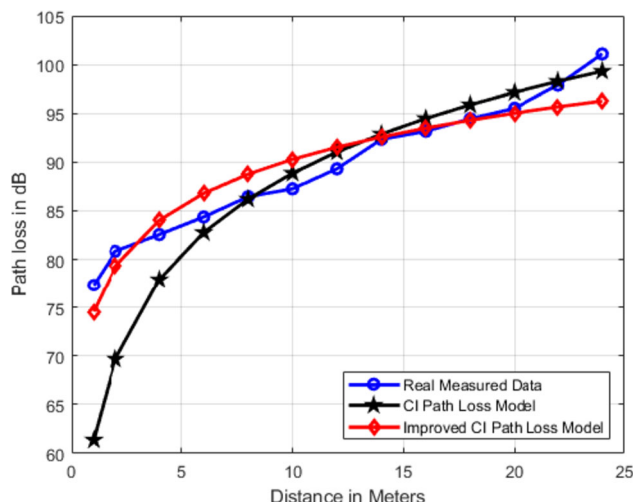


Fig. 8 Proposed Improved-CI PL against distance for 28 GHz NLOS at V-H polarization

$$\sum(BD)k_{CI} + \sum D^2n = \sum(AD) \tag{12}$$

Equations (11) and (12) in matrix form gives:

$$\begin{bmatrix} \sum B^2 & \sum(BD) \\ \sum(BD) & \sum D^2 \end{bmatrix} \begin{bmatrix} k_{CI} \\ n \end{bmatrix} = \begin{bmatrix} \sum(AB) \\ \sum(AD) \end{bmatrix} \tag{13}$$

Therefore, the CI\_HO parameters can be determined in closed form as:

$$\begin{bmatrix} k_{CI} \\ n \end{bmatrix} = \begin{bmatrix} \sum B^2 & \sum(BD) \\ \sum(BD) & \sum D^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum(AB) \\ \sum(AD) \end{bmatrix} \tag{14}$$

### 4 Results and discussion

This part discusses the improved model’s performance results in the NLOS scenario. Figures 7, 8, 9, and 10 depict the PL versus distance for the proposed improved-CI model at 28 GHz and 38 GHz for V-V as well as V-H antenna polarizations. These figures present the measured path loss for CI model as well as for the proposed PLM for the two frequencies and antenna polarizations in the NLOS scenario. There was clear evidence that both models appropriately match the measured path loss, despite the significant superiority of performance in the curves of the proposed improved CI PLM. The parameters in Table 2 shows that the SFSD when using the proposed improved CI PLM has better values at 28 GHz (V-V), 28 GHz (V-H), 38 GHz (V-V), and 38 GHz (V-H) antenna polarizations, which were: 6.7717 dB, 9.173 dB, 0.3959 dB, and 1.2852 dB, respectively.

The increased values of SFSD at 28 GHz were previously explained in [2]. When our proposed improved PLM was used, the PLE, which is a major factor used in

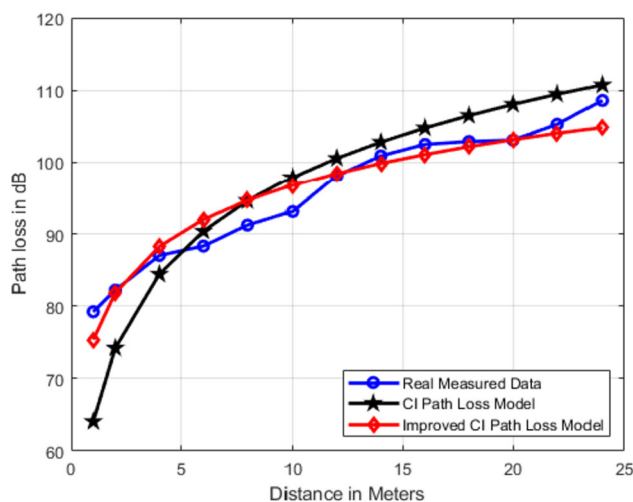
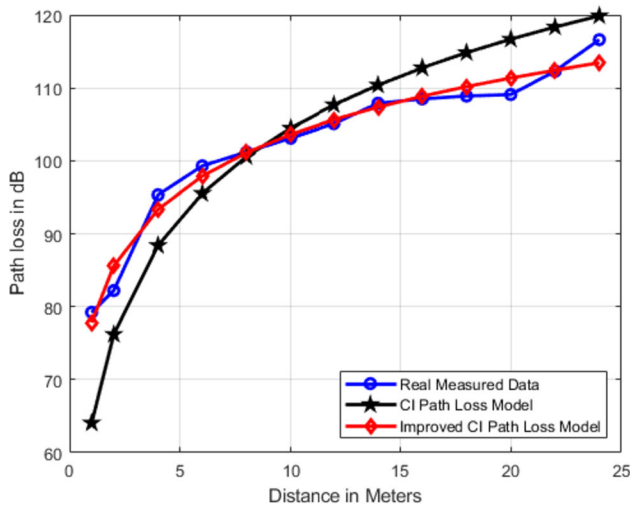


Fig. 9 Proposed Improved-CI PL against distance for 38 GHz NLOS at V-V polarization

characterization of large scale impacts of the propagation channel, improved substantially. Although it is understandably higher than in LOS, it should be noted that higher frequencies suffer from numerous propagation effects, particularly in NLOS where the Tx is not aligned with the Rx during wireless signal transmission. The following are the PLE improvement values when the improved PLM was used: 28 GHz (V-V) = 1.69, V-H = 1.74, 38 GHz (V-V) = 0.4351, and V-H = 0.3036. The values of  $k_{CI}$  rise as the antenna polarization shifts from V-V to V-H at both FBs.

Figure 7 shows that the improvement in path loss recorded in the improved PLM occurs from distances greater than 12m, despite the fact that there is similarity in the V-H polarization as shown in Fig. 8, but the level of improvement is still better in Fig. 7. However, when





**Fig. 10** Proposed Improved-CI PL against distance for 38 GHz NLOS at V-H polarization

looking at figs. 9 and 10, the range of distance for improvement begins at less than 10m. Even though the Figs. 7, 8, 9 and 10 indicate that the predicted path loss using the proposed improved-CI model matches the measured path loss adequately. The higher path loss is understandable given that both (Figs. 9 and 10) operate at higher frequencies than Figs. 7 and 8. Apart from this, the performance of the improved CI PLM shown in Figs. 7, 8, 9 and 10 in which both the CI and the improved CI PLM matches the measured PL effective has a significant improvement to the CI PLM. Also, looking at the SFSD at the two frequencies, the betterment of the results was obvious in that the proposed CI model minimizes the SFSD in the two FBs. Ultimately, the proposed improved CI model has been demonstrated to be best suited for indoor environments due to its exactness, ease, and excellent frequency response achievement because of its close-in free-space point of reference, considering that evaluated PL in interior spaces has very little reliance on frequency after

the initial meter of free-space transmission (encapsulated in the FSPL term).

### 5 Conclusion

An improved version of the CI PLM has been presented and explored thoroughly in this study. The model’s accuracy was validated by using the CI PLM and the outcomes to match the measured values. In a typical indoor corridor scenario, data was gathered in two FBs, 28 and 38 GHz. Antenna polarization was divided into two categories: vertical to vertical and vertical to horizontal for the NLOS connectivity situation. Our proposed improved PLM outperforms the mentioned model when compared to the conventional CI PLM. The PLMs in this work are physically anchored to a reference distance in the open space of 1m for NLOS situations. The free space reference distance of 1 m has been established in the CI path loss model because it enhances stability and streamlines the model. The main achievement of this work is that the proposed improved CI PLM performs better the current standard CI PLM in a number of ways, including predicting PL with the least potential value of the PLE, reducing the SF’s standard deviation for the NLOS conditions, and offer superior sensitivity as well as consistency of the PLM’s parameters with antenna polarization variations. In an indoor setting, the models show that a strong communication link can be created at the frequency bands of 28GHz and 38GHz while accurately indicating path loss with regard to distance and other environmental factors. The proposed model has the advantage of offering a broad form of model for PL prediction in mmWave propagation in addition to taking height difference into account. The precision of the model that the planning engineers will use to build wireless systems and determine the link budget has not much increased. Finally, this work demonstrates that the suggested models are trustworthy and accurate for estimating the path loss at mmWave frequencies in enclosed indoor situations.

**Table 2** A comparison of the parameters of the Improved-CI & CI PLMs in NLOS

Frequency		28 GHz		38 GHz	
		V-V	V-H	V-V	V-H
CI PLM	PLE ( <i>n</i> )	2.8815	3.3303	2.8207	3.4682
	$\sigma_{min}^{CI}$ [dB]	8.1287	10.4790	1.6822	3.0257
Proposed Improved model	PLE ( <i>n</i> )	1.1850	1.5879	2.3856	3.1646
	$k_{CI}$	8.1178	9.4686	2.1631	2.3922
	$\sigma_{min}^{CI}$ [dB]	1.357	1.306	1.2863	1.7405

**Author contributions** Conceptualization, TO; Methodology, TO, PK and ME; Formal Analysis, TO and ME; Measurements, TO; Writing—Original Draft Preparation, TO; Writing, Review and Editing, PK; Supervision, PK; Project Administration, PK. All authors have read and agreed to the published version of the manuscript.

**Funding** The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

**Data availability** Not applicable.

## Declarations

**Conflict interest** The authors have no relevant financial or non-financial interests to disclose.

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