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Performance Analysis of Millimeter-Wave Propagation Characteristics for Various Channel Models in the Indoor Environment

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Abstract: Due to the recent surge in the proliferation of smart wireless devices that feature higher data speeds, there has been a rise in demand for faster indoor data communication services. Moreover, there is a sharp increase in the amount of mobile data being generated worldwide, and much of this data comes from residential wireless applications like high-definition TV, device-to-device communication, and high data rate indoor networks (i.e., local and cellular). These technologies need large capacity, high data rate indoor wireless networks with huge bandwidth. Consequently, a greater interest exists in implementing an effective and trustworthy indoor propagation model for next-generation wireless systems operating in the massively bandwidth-rich millimeter wave (mm-wave) frequency range. The analysis of mm-wave propagation characteristics in an indoor environment using the ray tracing approach is proposed in this paper. Propagation modeling for 60 GHz bands is included. The aspects of wideband propagation characteristics such as angular spread, path loss, delay spread, and power delay profile are modeled in this paper. The position of transceivers, antenna effect, and attenuation, in the hallways, and stairwells will all be considered while determining the propagation parameters. This includes wave propagation characteristics like absorption, reflection, and diffraction by building structures and furniture. The specifications for propagation characteristics are included in the article for developing indoor local and cellular networks. In this paper, the IRT model has been tested at 60 GHz for potential mobile communication and is identified as the best method for predicting signal attenuation caused by objects, barriers, or humans within buildings in internal millimeter wave transmission.

Introduction

The management of Future wireless communications networks will need a lot of bandwidth since the mobile data requirement is growing substantially on a global scale, with indoor wireless applications (IoT devices) accounting for the bulk of this data. Due to the growing number of connected devices, IoT devices, indoor wireless networks with high capacity and massive data rates must be developed, demanding a lot of bandwidth. Fortunately, millimeter wave frequencies offer a wider bandwidth (Hou et al., 2023; Kumar et al., 2023; Vengurlekar and Saxena, 2024). However, walls, ceilings, furniture, and people significantly contribute to the propagation loss (due to the mm-waves reflection, diffraction, scattering, and absorption). Specifically, complicated indoor generates severe multipath that presents significant path loss and propagation delay. Therefore, millimeter propagation in interior contexts has to be investigated to design and optimize future 5G and beyond wireless networks, ubiquitous coverage and dependable communications (Ali et al., 2021; Chaudhari and Dinesh, 2023). Humans, furniture, and building

*Corresponding Author: ritesh.pratap@haramaya.edu.et materials' absorption and reflection attributes are greatly influenced by propagation, material qualities, antenna beam width, building element geometries, and transceiver placement. In contrast to lower frequencies, obstacles may significantly affect propagation at mm-wave frequencies (Dangi et al., 2021). Given their short range of a few hundred meters, base stations that operate on mm-wave frequencies are usually placed in proximity to the ground. These results provide a significant problem for the development of wireless communications of the future generation (B5G). B5G wireless communication designers will thus need far more precise data to plan their networks. To guarantee dependable B5G accessibility and capacity, it is essential to comprehend the likely rates, timings, and durations of propagations.

Channel modelling has to take into account the needs of B5G systems, which include mobility and spatial consistency, diffuse vs specular dispersion, massive antenna arrays, and mm-wave frequency. Precise models assist the system designer in evaluating the anticipated coverage inside structures or regions, guaranteeing system performance when approximations approach actual values (Aragon-Zavala and A. A., 2017). When modelling radio wave propagation in a particular channel, estimating the propagation route loss as a function of frequency, distance, and propagation scenario is crucial. For stationary or mobile wireless communications, there are several categories for propagation models. The configuration attained when there is a straight line free of impediments between the communication devices (Tx-Rx) is known as the line-of-sight (LOS) condition and it is significant. The absence of an apparent line of sight between the communication devices (Tx-Rx) is known as the non-line-of-sight (NLOS) scenario (Ebrahimizadeh et al., 2024). Due to an obstruction (such as a wall, furniture, etc) casting a shadow, the transmitter is unable to view the receiver and vice versa. Based on the IEEE 802.11ad standard, commercially accessible technologies are already operating in the 60 GHz unlicensed frequency region for indoor usage. However, mm-wave technologies are still in their infancy regarding ultrahigh-capacity mobile communication. Though the first findings and experiments are encouraging, many significant obstacles must be surmounted before the technology's integration into B5G communication protocols and, eventually, its commercial implementation (Al-Saman et al., 2021).

In this study, the situations where both terminals are located within a building will be deemed indoor scenarios (Ahumada et al., 2024; Al-jzari et al., 2024; Possenti et al., 2023). As a case study for the present paper, the second floor of a multi-storied building is considered. The anticipated results quantify the size of the upcoming wireless (B5G) issues and take into account the advantages of the 5G modelling software. The task entails analysing the mm-wave wideband properties concerning propagation delay, path loss, power delay profile, and angle spread for both NLOS and LOS transceiver systems operating in indoor environments to replicate the indoor cellular mm-wave environment at 60 GHz to assess the transceiver's mobility.

Wireless communication networks, operating at mm-wave frequencies ranging from 30GHz to 100GHz, will be developed to provide rapid data transfer in indoor local and narrow coverage cellular networks. Nonetheless, the propagation properties of millimetre waves vary substantially from sub-6 GHz waves (Samad et al., 2023). The following are the main variations: Firstly since mm-waves have a lower wavelength and are thus more susceptible to obstruction, they have a significant loss in penetration through many typical interior materials including glass and concrete. Network implementation requires thorough propagation modelling using software techniques like ray tracing tools and/or empirical methodologies.

Future wireless communication problems stem from the lack of an all-encompassing indoor mm-wave propagation model that takes into consideration the human body effect, mobility impact, and other interior effects for mm-wave wireless communications employing intelligent ray tracing. The mm-wave propagation characterization requires wideband propagation properties, namely delay spreads, which are needed to reduce inter-symbol interference (ISI) and are desirable in transceiver development. This research uses ray-based simulation to simulate propagation, which is desirable for developing indoor mm-wave wireless networks (Yun et al., 2023).

The ray tracing approach allows for the incorporation of complicated antenna designs and directivity since it makes it possible to represent complex interior settings that are appropriate for all kinds of wireless transceivers in the future (Samad et al., 2023; Schott et al., 2023; Topal et al., 2023; Zulkefly et al., 2024). When compared to empirical procedures, it is adaptable and replaces measuring efforts with simulations (more likely repeatability, less work, cheaper costs). Deterministic processes may be tested and analysed with less material consumption and can assess the cross-correlation wideband properties and cumulative distribution function (also known as co-existence studies) across various radio systems. Furthermore, it is more precise and allows us to get a wealth of information on route loss, delay spread, power delay profile, and angle spread at each point inside the network's coverage region. There is a strong possibility that the mm-wave frequencies will provide significant capacity for both bandwidth and spatial multiplexing. Significant research has been done on millimetre propagation at 60 GHz frequency. However, important features like highly determined angular characteristics and NLOS propagation loss are yet unknown.

As a result, it makes indoor local and narrow coverage cellular network planning precise and reliable. Future mm-wave wireless propagation predictions are important for base station coverage regions, frequency assignments, interference analysis, handover optimization, and power level changes. They also help in determining the appropriate electric field strength (Moraitis and Nikita, 2024; Schott et al., 2023). To utilize the information in this article on wireless radio propagation and maybe enhance their services going forward, the IRT prognosis model for interior propagation environments is provided and examined.

Related Works

Creating a reliable communications network requires accurate signal propagation modelling. Since mm-waves are directional, have extremely high propagation losses, and are susceptible to human and object interference, smaller cell sizes are recommended to improve the spectrum utilization of communication systems. According to Hossain et al. (2018), backhaul linkages, tiny cells, and interior settings are the primary locations for mm-wave applications.

According to Hossain et al. (2018) and Ren et al. (2020), a well-crafted wireless channel model accurately replicates the wireless channel's normal behaviour and provides an understanding of the most pertinent radio wave propagation processes. A mm-wave propagation model may be created in two different ways. According to Itu-r ed. (2023), these modelling methodologies are deterministic (mostly ray tracing) and empirical (measurement-based statistics).

Ju et al. (2021) performed comprehensive radio propagation investigations at 28 and 140 GHz in an interior office setting, which served as the basis for this paper's indoor 3D spatial probabilistic channel simulation for mm-waves and sub-THz frequencies. More than 15,000 observed power delay profiles were used to generate directional and omnidirectional route loss models as well as channel data, including the amount of time groupings, delays, and clustered powers. For both LOS and NLOS settings at 28 and 140 GHz, the obtained channel characteristics demonstrate that the number of temporal groupings approaches a Poisson distribution while the overall length of sub-paths inside every cluster reflects an integrated exponential distribution. By following the mathematical principles, this study suggests a single indoor probabilistic channel structure for mm-wave as well as sub-Terahertz frequencies.

Al-Saman et al. (2021) used the important potential bands for fifth-generation mm-wave communication, 26 GHz and 38 GHz, are used in this study. Both an interior hallway and a stairway, whose mm-wave channel has been studied previously, are used for measurements. Steerable directional horn antennas are employed as the receiver and omnidirectional antennas are used as the transmitter in these experiments. For both LOS and NLOS scenarios, the directional and omnidirectional path loss coefficients, shading factors, cross-polarization bias ratios, and RMS delay spreads are analyzed in both co-polarization and cross-polarization scenarios, and these characteristics are analyzed and compared for various frequencies.

Sun et al. (2018) describes the mm-wave propagation characteristics are studied by simulating the interior setting of a lab using the SBR/IM (shooting and Bounding Ray tracing/Image) approach. To determine the associated power received and RMS latency of various scenarios, the simulation results are analysed. It also computes the received power at various separations between transmitters and receivers. After the data is analysed, all of the outcomes may provide a theoretical foundation for determining the transmitter's position in actual indoor laboratory settings.

Abdulwahid et al. (2019) define the characteristics of 5G and beyond (B5G) wireless communication systems—which are currently being developed for usage in mm-wave frequency bands—are summarized. This article describes the channel modelling efforts of several worldwide organizations for both licensed and unlicensed applications, and it presents early findings and essential principles of 5G networks. We examine the 0.5-100 GHz range of propagation characteristics and channel models modelled by different standardization organizations for mm-wave propagation, including line-of-sight (LOS) probability, large-scale route loss, and structural piercing loss.

Wang et al. (2017), an effective wall loss model—a modified indoor route loss prediction model—is introduced. Real-time measurements and simulation data are used to compare the updated model with existing indoor route loss prediction methods. To validate the findings, several antenna polarisations and operational frequencies are taken into account. During the simulation phase, the effective wall loss model surpasses the other models by a factor of two, surpassing the dual-slope model, leaving it in second place. The experimental findings were noted to support these observations. The one-slope and linear attenuation models behave similarly; the parameters of both models rely on the antenna polarization and the operating frequency.

This article presents an overview of propagation modelling for ray tracing, with a focus on future directions and applications. In particular, prospective applications like real-time ray tracing and the expansion of ray-based propagation modelling to diffuse scattering, multidimensional channel characterization, and multiple-input multiple-output (MIMO) capacity evaluations are considered frontiers.

Previous proposals for local multipoint distribution systems (LMDS), intelligent transport systems (ITS), personal communication networks (PCN), and wireless local area networks (WLANs) have all been made for the mm-wave spectrum (Lee et al., 2022). In addition, it has been used in military applications, long-distance point-to-point communications, and satellite communications. At the moment, certain cellular companies transmit data between fixed locations, such as two base stations, using mm-wave frequencies. It is a completely different strategy to use them to link mobile terminals to the base station. The quantity of bandwidth in mm-wave bands, which includes frequencies higher than 6 GHz, or the 28 GHz band, is beneficial for the implementation of B5G or 6G wireless communication.

The building materials, height, and frequency all affect the building penetration loss, according to measurements. For frequencies between 900 MHz and 2 GHz, the usual bottom floor building penetration loss is between 8 and 20 dB (Rudd et al., 2014). Another important factor influencing penetration loss in a structure is the kind and quantity of windows. Furthermore, according to (Rappaport et al., 2015), lead-lined glass has an attenuation ranging from 3 to 30 dB, whereas plate glass attenuates around 6 dB.

The study was conducted in an indoor office environment spanning many levels (Majed et al., 2018). A multiple gradient model with a greater value of 2 was used in the investigation over a radius of up to 10 m. Additionally, Saleh and Valenzuela examined indoor multipath propagation. A 10-ns probing pulse at 1.5 GHz was used in the investigation, which was carried out at 2 m heights using V-V polarization antennas for the receiver and transmitter.

According to Aslam et al. (2017), the results showed that the propagation path loss for 1.3 GHz and 4 GHz was equivalent and that the cross-polarization discrimination for LOS channels was higher than that of NLOS or blocked channels. After that, it was reported that how crucial it is to use a 1 m reference radius when aiming for considerable indoor path loss models. An open-space reference radius of one metre was observed to have PLE values of 1.7 and 3.1 for LOS and NLOS at the 5 GHz bands in a home structure (Wang et al., 2016). Furthermore, PLE values of 2.4 and 2.6, respectively, were found in an examination of indoor workplaces utilizing soft dividers at 900 MHz and 1900 MHz, and a 1 m free-space reference distance that constitutes typical 'd'. The radio waves in mm-wave systems are often more attenuated than in systems operating at lower frequencies, which is a significant distinction. Systems operating at mm-wave frequencies have more shadowing from blocking objects, a higher penetration loss, and a bigger free space path loss (assuming constant-gain antennas).

Consequently, mm-wave systems may achieve a reduced achievable communication range, despite the existence of long-range point-to-point mm-wave networks. For instance, short-range, high-data-rate WLAN and device-to-device communications are intended to use the 60 GHz spectrum. The compact form factor of the antennas is another intriguing feature of mm-wave systems. Since the wavelength and antenna size are connected, it is possible to pack many antenna components into a compact space or even incorporate them onto a chip. An appealing method for generic mm-wave channel modelling is a hybrid or stochastic approach. The following succinctly describes the primary causes of this situation:

a) Provide support for modelling wideband channels;

b) Take into account the antenna correlation as well as small- and large-scale fading effects.

c) Can generate a propagation channel model that works with any array arrangement and any number of antenna components.

d) Create a model of the channel's directional characteristics, which is essential for beam formation and shadowing analysis of human bodies.

e) Allow for the simple addition of geometrical human body shadowing models to the model framework.

Materials and Methods

A multi-story building's interior scenario with a randomly selected level is considered to perform a simulation to

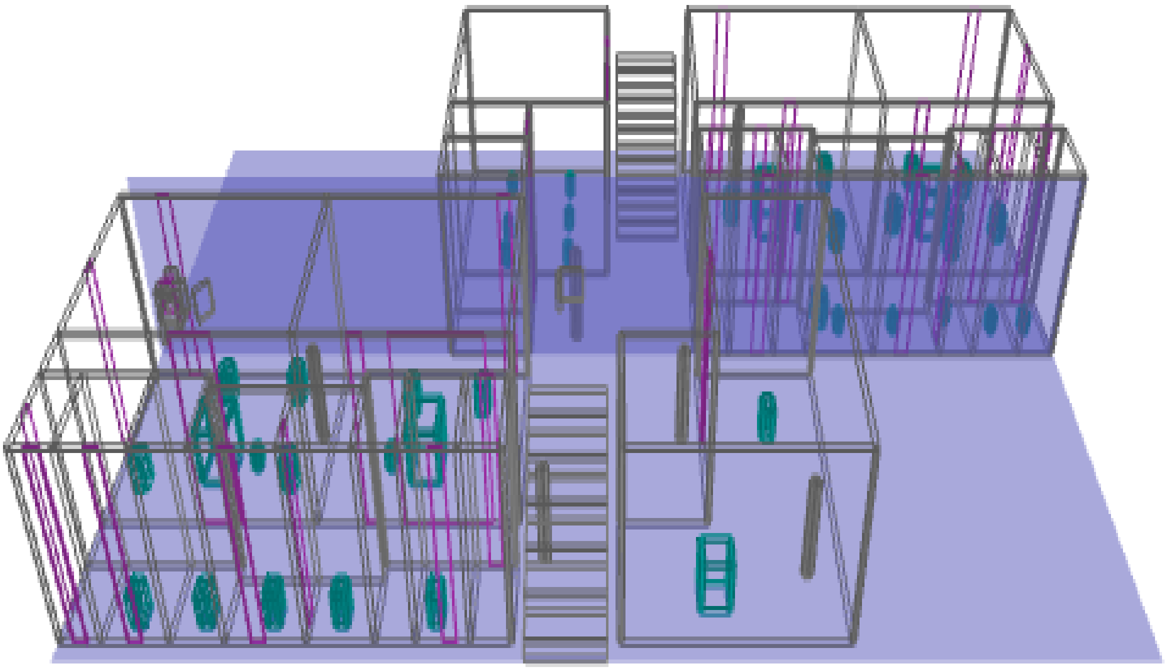

Figure 1. A 3D indoor building floor has been drawn on WallMan with indoor materials.

assess millimeter wave propagation characteristics. With a partition wall separating the outside and inner rooms of varying proportions, the area measures thirty meters in length and eight and a half meters in breadth. It is evident in Figure 1 that the space is equipped with tables, seats, and persons. Along with the linked objects, the utilized values are compiled in Table 1.

The Altair Feko WinProp software is used for parameter analysis and editing. This article uses the ProMan module for analysis and simulation. One transmitter that is situated on a building corner is taken into consideration when evaluating indoor small-cell situations. Calculating received power, latency, and route loss as well as investigating the whole behaviour of the propagation channel at 60 GHz are done using the Ray Tracing method, which is based on an IRT technique.

Choosing the item that the beam will strike is a fundamental stage in every ray-tracing technique. These items may be floor plans or architectural structures, and they can be visualized as groups of triangles that together form the structure's surface. The next step is to determine which triangle a ray will strike when it is fired at a source point and in a certain direction. Testing the ray's intersection with every triangle is a straightforward approach. Finding the triangle proximal to the origin point is important since a ray might pass through many triangles. Consequently, to identify the appropriate triangle that the ray has penetrated, the distance between the intersection point and the ray origin is computed and saved whenever a triangle is crossed by the ray. This one is the triangle closest to the ray origin. Rays that strike a triangle will either reflect or transmit back.

Table 1. The material properties of an indoor database are used (Rudd et al., 2014).

Material class	No of samples	Thickness (cm)	Operating frequency (GHz)	Conductivity (σ)	Permittivity (ε_r)
Concrete (floor)	1	30	60	0.8966	5.310
Brick wall	15	10	60	0.038	3.75
Wood (doors)	21	5	60	0.37326	1.97
Glass (windows)	26	0.5	60	0.5674	6.27
Furniture (tables and chairs)	32	10	60	0.37832	1.99
Metals	12	2	60	10^7	1
Human body	18	30	60	0.0116	0.7076

This method of tracking novel rays will continue till a certain condition is satisfied. We must fire a lot of rays to locate the rays from Tx to Rx. This straightforward approach has a relatively long total ray-tracing time, which limits its use for indoor propagation modelling and simulation (Lubke et al., 2021).

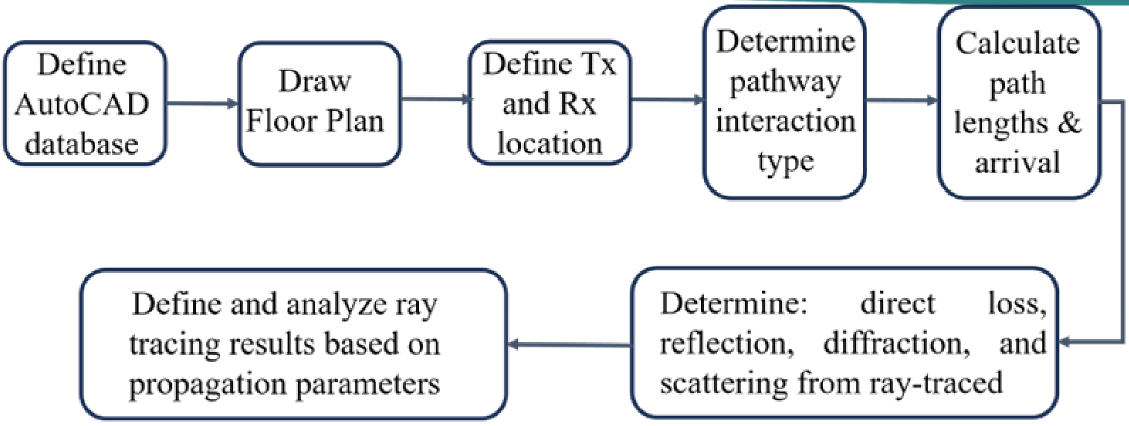

Figure 2. Propagation characteristics simulation method using WinProp tool.

(a) Indoor Intelligent Ray Tracing

In comparison to empirical models, the indoor IRT approach expedites ray optical models and decreases calculation time. This approach ignores the drawbacks of the two-ray optical models while combining their benefits. It is predicated on only one building database reprocessing. Ray optical models need a lot of time since every potential ray has to be identified. The building database was reprocessed only once, which served as the foundation for the model. Every building's wall has been separated into tiles, and every wedge has been divided into segments. Prepossessing is where the visibility relations are calculated since they are not reliant on the transmitter position and relate to all tiles, segments, and input points in the database.

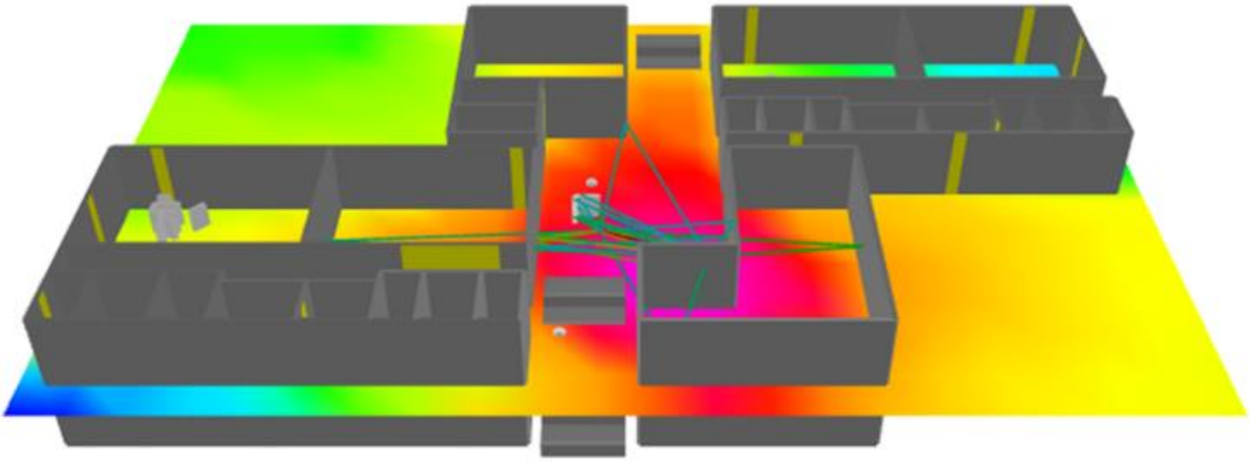

Figure 3. 3D view of indoor intelligent ray tracing of a building floor plan.

Structures are represented as three-dimensional cylinders in the environment, with values for conductivity (σ), permeability (μ0), and permittivity (ε). Every building is composed of convex polygons that depict its flat horizontal and vertical facades. A building's floor and roof are represented by its two horizontal sides alone. Vertical faces symbolize the building's outside walls. The related surfaces of every vertical face are used to determine the reflected fields. Structures are depicted using a three-dimensional coordinate system, where the building's height (h) is represented by the z coordinate and its placement on a horizontal plane by the x and y coordinates.

Results and Discussions

The signal that reaches the receiver might be a signal that has been delayed and overlaid after random directions of reflection, diffraction, or scattering. To validate the findings of the IRT simulations at 60GHz, simulations including future wireless propagation behaviours and multi-wall modelling have been conducted to evaluate the impact of reflection, diffraction, and scattering in this typical indoor setting. A comparison has been made between both LOS and NLOS components when time variances are included or excluded. With the interplay of electromagnetic waves in their propagating environment, IRT provides the optimal wireless channel dissemination at mm-wave frequencies, allowing for the precise prediction of propagation characteristics at these frequencies. In this scenario, the transmitter is stationary.

1) The received power

In the accompanying picture, the received power distribution is shown in an indoor simulation setting. To accurately represent the propagation characteristics of an

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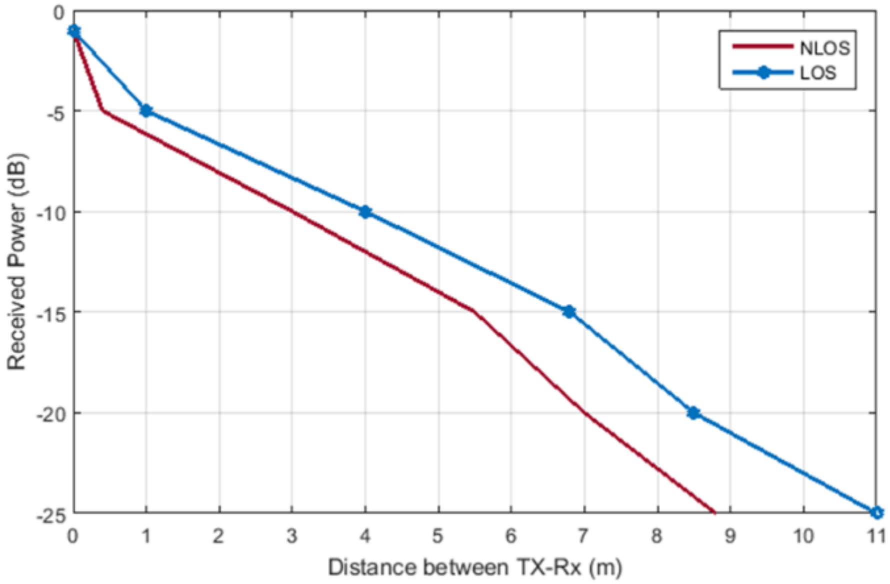

Figure 4. Plot predicted received power comparison with LOS and NLOS environment.

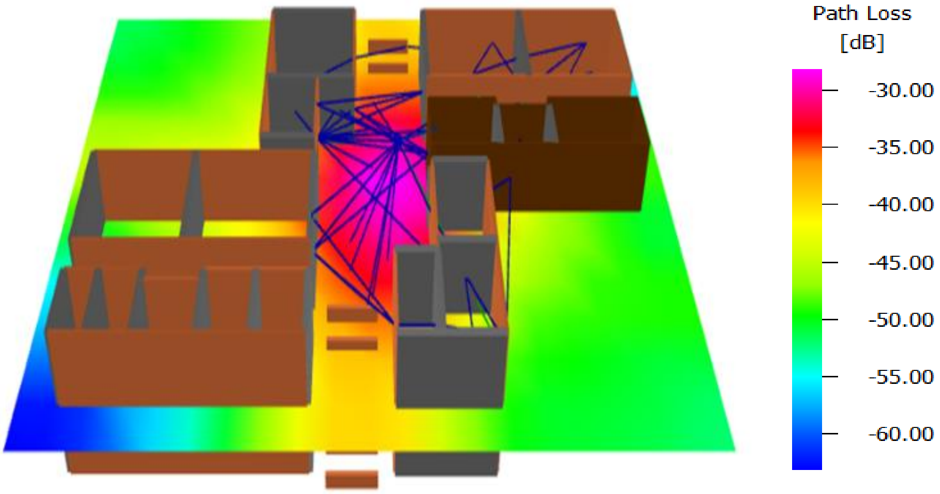

Figure 5. 3D view of building path loss in both LOS and NLOS.

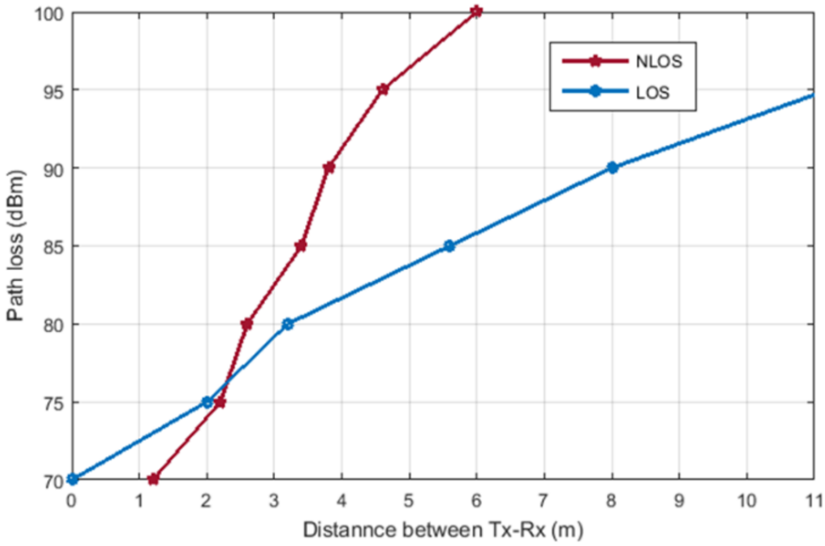

Figure 6. Predicted Path loss in NLOS and LOS at 60 GHZ with a given distance.

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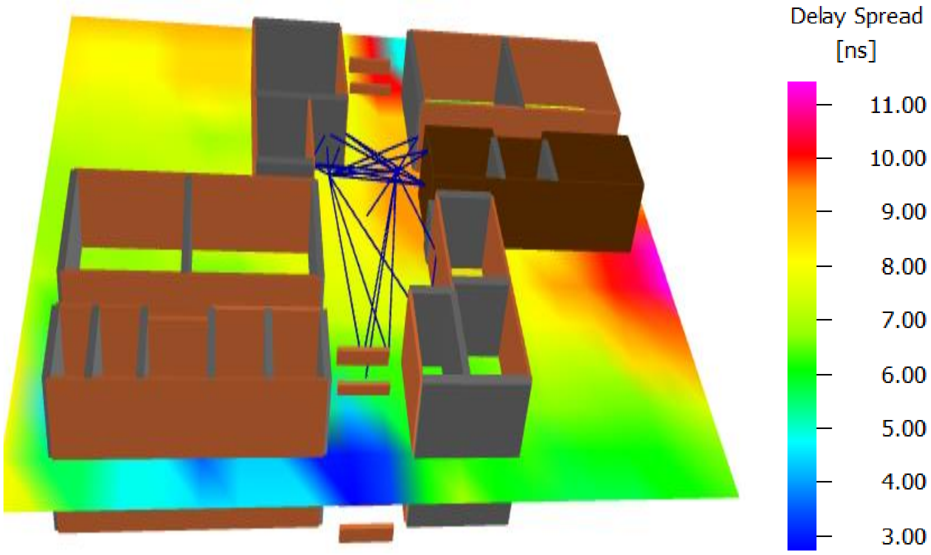

Figure 7. 3D view of building delay spread in both LOS and NLOS.

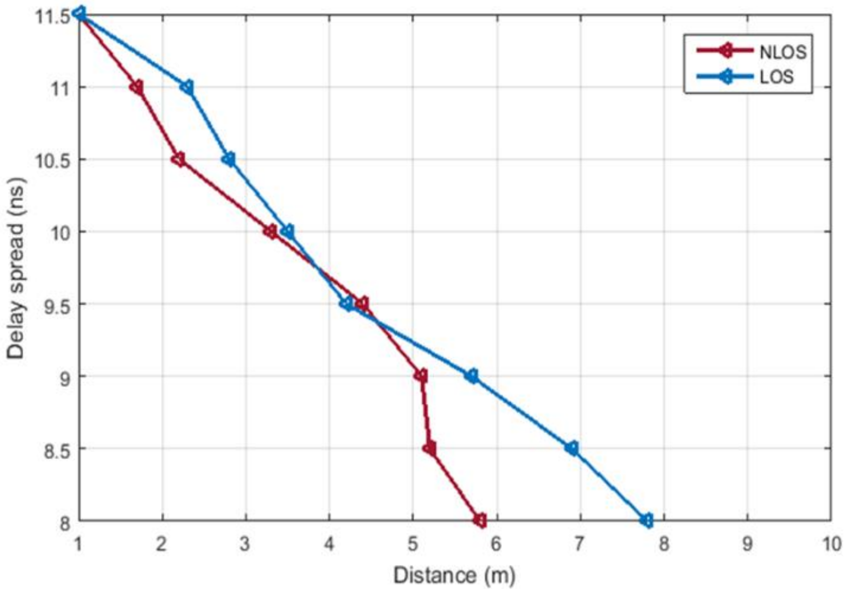

Figure 8. Delay spread comparison on Tx-Rx separation distance in LOS and NLOS.

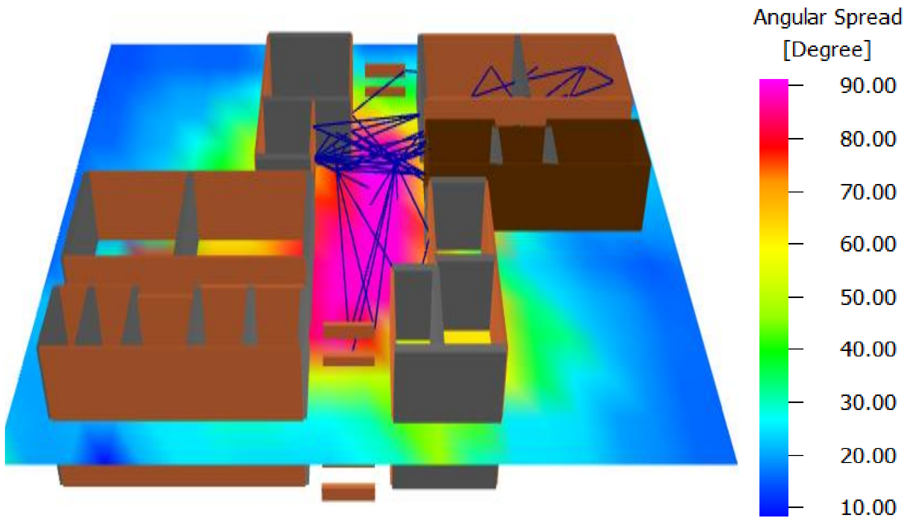

Figure 9. 3D view of building angular spread in both LOS and NLOS.

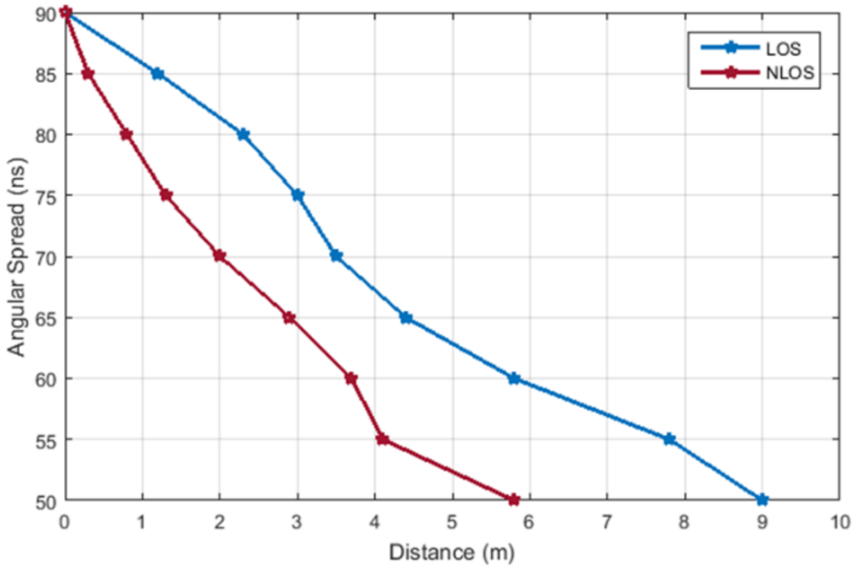

Figure 10. Angular spread on Tx-Rx separation distance in LOS and NLOS.

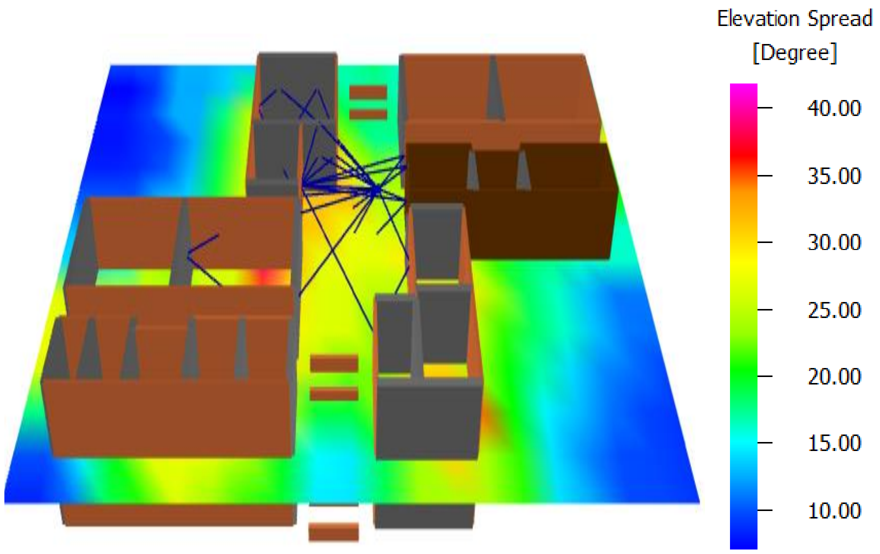

Figure 11. 3D view of building angular spread in both LOS and NLOS

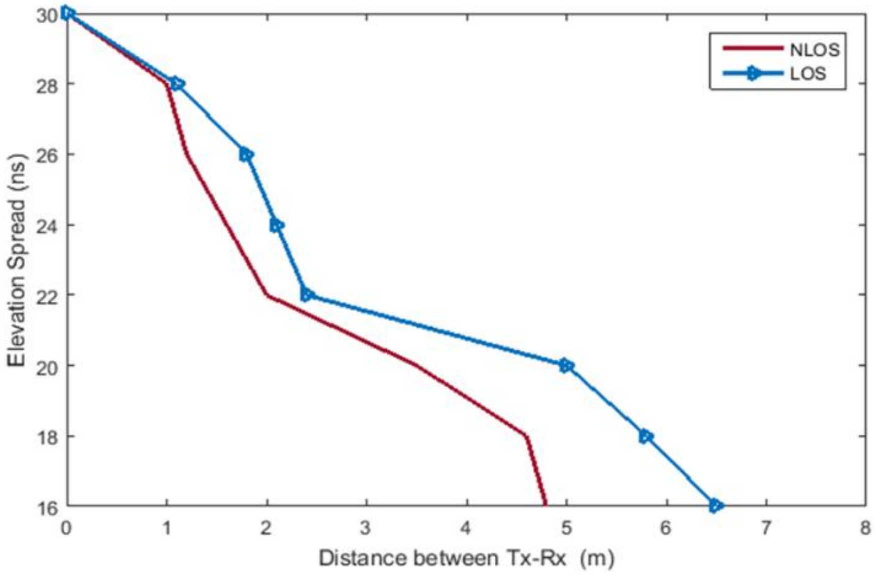

Figure 12. Elevation Spread on selected TX-Rx separation distance in NLOS.

indoor channel, the received power of Tx is adjusted in seven reflections, two transmissions, and three diffraction modes. This ensures that the ray tracing-based forecast is accurate. Results show that the received power is comparatively lower in the NLOS case than in the LOS position. This is because there aren't as many reflection routes that can go there. The received power is observed to grow when the receiver approaches the emitter and enters the LOS case.

The location where the direct beam from the transmitter may reach the receiver is where the greatest received power occurs. It is proposed that in interior contexts, the direct ray has a prominent influence. However rather than steadily rising, the distribution of transmitted power is fluctuating. This is because, in addition to a straight route, there are channels for reflection and diffraction. Additionally, in the case of NLOS, the received power abruptly decreases as the receiver goes to the right corner. The power decreases as the receiver gets further away and eventually reaches its lowest point.

2) Path Loss

The mm-wave path loss across the LOS and NLOS pathways at 60GHz is shown in Figure 6. The average 60 GHz path loss in a LOS environment is 75.60 dBm, whereas in an NLOS environment, it is 82.21 dBm. Because there is a direct route in the LOS environment that contributes more to the received power, the path loss in LOS is thus about 6.61dBm lower than that in NLOS. The graphic below illustrates how the separation between the transmitter and receiver affects the broader pattern of path loss. The path loss increases as the Tx-Rx separation distance increases. At certain distances between Tx and Rx, the rate of growth varies.

3) Delay spread

The receiver travels via many channels of propagation rays to reach the transmitter at millimetre frequency, and the duration of each path varies. Inter-symbol interference (ISI), which restricts the data rate, occurs when the delay time spread is greater than the symbol period. The primary cause of a delay spread is the buildings' reflections and diffractions surrounding the transmitter and receiver, as shown below in Figure 8. With increasing transmitter and receiver separation in the LOS situation, delay spread reduces. As a result, the rate in LOS differs from NLOS since there are fewer barriers in the path of the signal. The following diagram illustrates the relationship between delay spread and distance.

The greater the distance separating the receiver and the transmitter, the smaller the delay spread was at 60GHZ frequencies. The traveling durations of all arriving multi-path components are minimized at large separation distances, leading to a lower delay spread.

4) Angular Spread

The angular spread measures the propagation channel's multipath richness and angular dispersion. It explains the dispersion of power arrival in the channel due to multipath propagation.

Furthermore, angular spread results from a multipath constituent at an interval brought on by multiple waves that arrive at the point of reception from various arrival angles. In intelligent ray tracing, the propagation model should take into account the angular coordinates of the channel radiating at both the transmitter and receiver sides; in this study, only the reception sides are employed. Both the antenna gain and the propagation environment affect the path rays' angular spread characteristics. This section examines how the human body and interior construction materials affect angular spreads. Angular spread diminishes as a function of receiver distance at each location, as Figure 10 illustrates.

5) Elevation spread

The elevation angle is needed to get a precise transmitter correlation value. As the transmitter and receiver are further apart, the elevation spread gets less. Nevertheless, as frequency rises, the elevation spread does not alter.

Conclusion

Radio-design techniques were used to simulate indoor propagation models and anticipate coverage regions depending on the locations of transmitters and receivers. IRT techniques were used, which resulted in cheap computing cost simulations with excellent accuracy and computational time. Winprop software has parameterized the mm-wave propagation model for the utilized scenario and frequency bands. The 60GHz mm-wave frequency has been studied and examined for indoor wireless communication applications. Because multipath propagation has constructive effects in LOS, the IRT model under the LOS condition exhibits an incremental boost in the received signal while contrasted with the NLOS condition. The radio connection in non-LOS environments has shown a notable susceptibility to obstructions, including furniture. Due to obstacles, the parameters used for simulation in non-LOS circumstances indicate increased signal attenuation with distance. The IRT model indicates that multipath propagation has a small impact on LOS channel communications. However, surrounding objects and obstructions significantly impede NLOS transmissions.

The investigation carried out in this work has demonstrated that the IRT model in indoor mm-wave propagation is the most effective method to anticipate signal attenuation caused by barriers or humans within buildings. In this context, geometrical interpretations presented here have been used to validate additional investigation of propagation parameters.

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Conflict of Interest

The authors declare no conflict of interest.

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