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# Effective 60 GHz Signal Propagation in Complex Indoor Settings

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## Abstract

This study addresses the challenges and solutions associated with the deployment of 60 GHz frequency bands for indoor wireless communication. The 60 GHz band offers significant advantages such as high data rates and large bandwidth, essential for applications like high-definition video streaming, virtual reality, and next-generation wireless networks. However, the propagation characteristics at this frequency present unique challenges, including high attenuation, limited range, and significant sensitivity to obstacles and environmental factors. This abstract explores recent advancements in overcoming these challenges, focusing on innovative techniques such as beamforming, adaptive antenna arrays, and smart reflective surfaces to enhance signal coverage and reliability. Additionally, the paper discusses the impact of different indoor materials, furniture, and human movement on signal propagation. Simulation results and experimental data from various complex indoor environments are analyzed to provide insights into optimal deployment strategies. The study concludes that while 60 GHz propagation in indoor settings is inherently complex, leveraging advanced signal processing techniques and strategic placement of access points can significantly improve performance, paving the way for robust and efficient indoor wireless communication systems at higher frequencies.

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## 1. Introduction

The insatiable demand for higher data rates and capacity has fueled the exploration of the millimeter-wave spectrum, with the 60 GHz band emerging as a prime candidate for future indoor wireless communications. This frequency range offers abundant bandwidth, enabling multi-gigabit data transmission, a promising solution to the spectrum scarcity below 6 GHz.The 60 GHz band, in particular, holds immense potential for high-capacity indoor applications, such as 60 GHz wireless bridges. However, to fully harness its capabilities, a comprehensive understanding of indoor propagation characteristics and channel modeling at this frequency is crucial. This article delves into the propagation mechanisms, large-scale path loss models, and channel models tailored for complex indoor scenarios involving 60 GHz signals [1]-[4].

## 2. Propagation Characteristics in Indoor Environments at 60 GHz

### 2.1 Free-Space Propagation

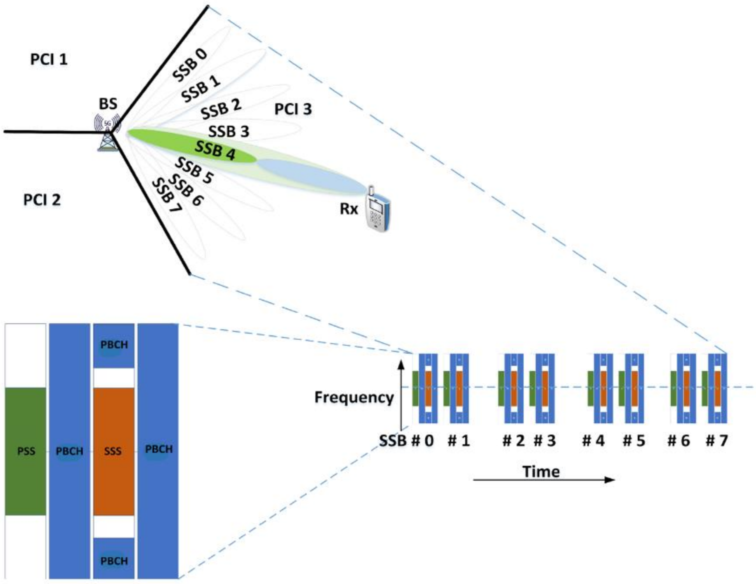


**Fig. 1: Data-Driven Analysis of Outdoor-to-Indoor Propagation for 5G**

Free space is considered to be a completely unobstructed region, meaning that there are no obstacles or surfaces interacting with the electromagnetic wave propagating between the transmit and receive antennas as in Fig. 1. Equation 1 and Equation 2 show that, for a fixed separation distance and a fixed antenna gain at the transmitter and receiver, the free-space path loss (FSPL) is proportional to the square of the carrier frequency. This implies a high FSPL at the millimeter-wave frequency band when compared to the sub-6 GHz band.Although the high FSPL can limit the range of links operating in millimeter-waves, the severe attenuation at the 60 GHz band can be beneficial in indoor environments, since frequencies can be reused between neighboring rooms. This approach allows for simultaneous transmissions in a given building [5]-[6].

## 2.2 Propagation Mechanisms

Indoor propagation models at 60 GHz must consider several characteristics, such as reflection properties of different surfaces, diffraction, blockage, and scattering. These characteristics substantially impact communications on millimeter-waves. Due to the short wavelengths, ranging from 1 to 10 mm, the millimeter-wave signals propagation mechanisms are drastically different from those of sub-6 GHz and, therefore, must be analyzed and studied in order to properly model and evaluate wireless communications systems operating in these frequencies.Reflected, diffracted, and scattered waves from nearby objects result in the multipath fading effect, which influences the performance of indoor wireless communication systems as given in the Fig. 2. Reflection is the dominating factor in the channel delay profile at 60 GHz. Considering a perfectly smooth surface, the reflection would lead to a single wavefront. However, according to experimental investigations, each reflected path actually consists of a number of wavefronts propagating in different directions.

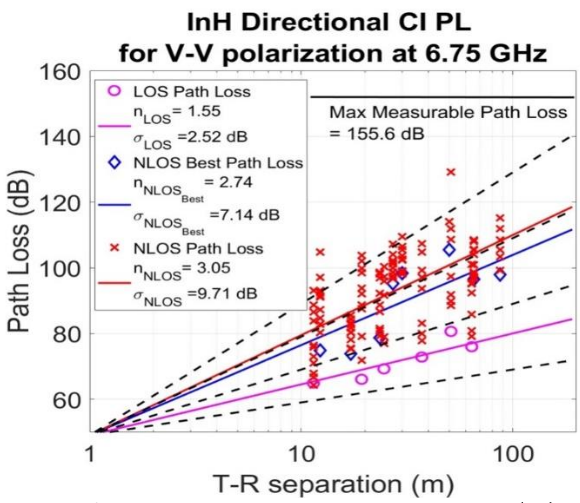


**Fig. 2: Propagation measurements and channel models**

Transmissions at 60 GHz in indoor environments are highly vulnerable to human blockage due to the small wavelength and the use of narrow beams. Thus, a person crossing the link causes its temporary blockage, which can last as long as the person stands between the transmit and receive antennas.Therefore, it is necessary to characterize and categorize the human blockage at 60 GHz links based on human activity and evaluate its effect on the systems' quality of service (QoS) [7]-[9].

### 2.3 Material Penetration

The physical characteristics of the materials present in an indoor environment, e.g., building materials, furniture, partitions, and openings (windows, doors, etc.), also play an important role in indoor signal propagation at 60 GHz mainly because these characteristics impact the signal penetration loss.

## 3. Large-Scale Path Loss Models

The free-space propagation model does not apply in situations where the number of obstacles, diffraction, and reflection points are high. In these environments, the propagation mechanisms and obstructions cause a variation in the received power level even when the transmitter and receiver are stationary. This phenomenon is known as shadowing. Large-scale propagation models aim to predict the signal local mean power level in a given location as described in the Fig. 3. This section describes the basic types of large-scale path loss models: the CI free space reference distance path loss model; the CIF model, which is the CI model with a frequency-weighted PLE; and the ABG model [10]-[14].

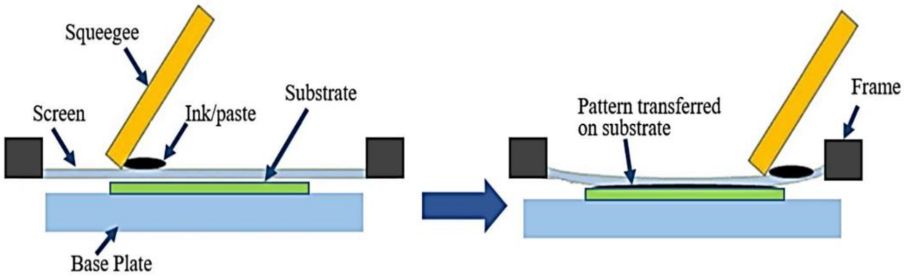


**Fig. 3: 60-GHz Ultra-Thin and Flexible Metasurface**

### 3.1 CI Model

The CI path loss model uses a CI reference distance based on the FSPL and accounts for the frequency dependency of the path loss. In this model, the path loss in dB is given by (Sun et al., 2016b) :

$PL(d)=FSPL(d0)+10n\log10(d/d0)+X\sigma$

### 3.2 CIF Model

The CIF model is derived from the CI model and is also suitable for multi-frequency modeling. The path loss for the CI model is given in dB by (Eq. 4) when *d*0 = 1 m (Sun et al., 2016b) :

$PL(f,d)=20\log10(4\pi d0/\lambda)+10n\log10(d/d0)+X\sigma$

### 3.3 ABG Model

Assuming distance *d* in meters and frequency *f* in GHz, the path loss for the ABG model is given by (Sun et al., 2016b) :

$PL(f,d)= \beta +10\alpha\log10(d)+\gamma\log10(f)+X\sigma$

## 4. Channel Models for Indoor Scenarios

The channel models defined in 3GPP TR 38.901 (3GPP, 2019)are generally applicable over the frequency range between 0.5-100 GHz and include several scenarios of interest.

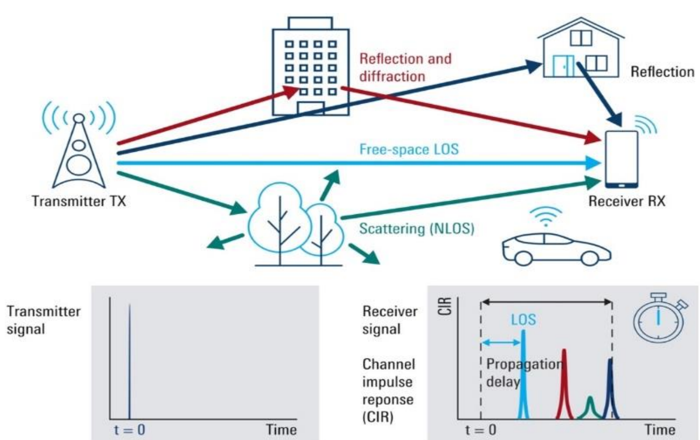


**Fig. 4: Experiments bring hope for 6G above 100 GHz**

### 4.1 3GPP TR 38.901

The InH office scenarios are valid for distances up to 150 m and are typically comprised of open cubicle areas, walled offices, open areas, and corridors as given in the above Fig. 4. In addition, the base stations (BSs) are mounted at a height of 2-3 m, either on the ceilings or walls. The path loss models are presented for both LOS and NLOS conditions and employ 3-D Tx-Rx separation distance *d*3D that accounts for the BS height (*h*BS) and user equipment (UE) height (*h*UE).

### 4.2 5GCM

The studies presented in the 5GCM white paper (5GCM, 2016)are an extension of the existing 3GPP models and support 5G operation across frequency bands up to 100 GHz. The indoor scenarios described in this paper include open and closed offices, corridors within offices, and shopping malls. The typical office environment is comprised of cubicle areas, walled offices, open areas, and corridors, where the partition walls are composed of different materials. For the office environment, the APs are mounted at a height of 2-3 m either on ceilings or walls as described in Fig. 5. The shopping malls are generally 2-5 stories high and often include an open area. In the shopping mall environment, the APs are mounted at a height of approximately 3 m on the walls or ceilings of the corridors and shops.

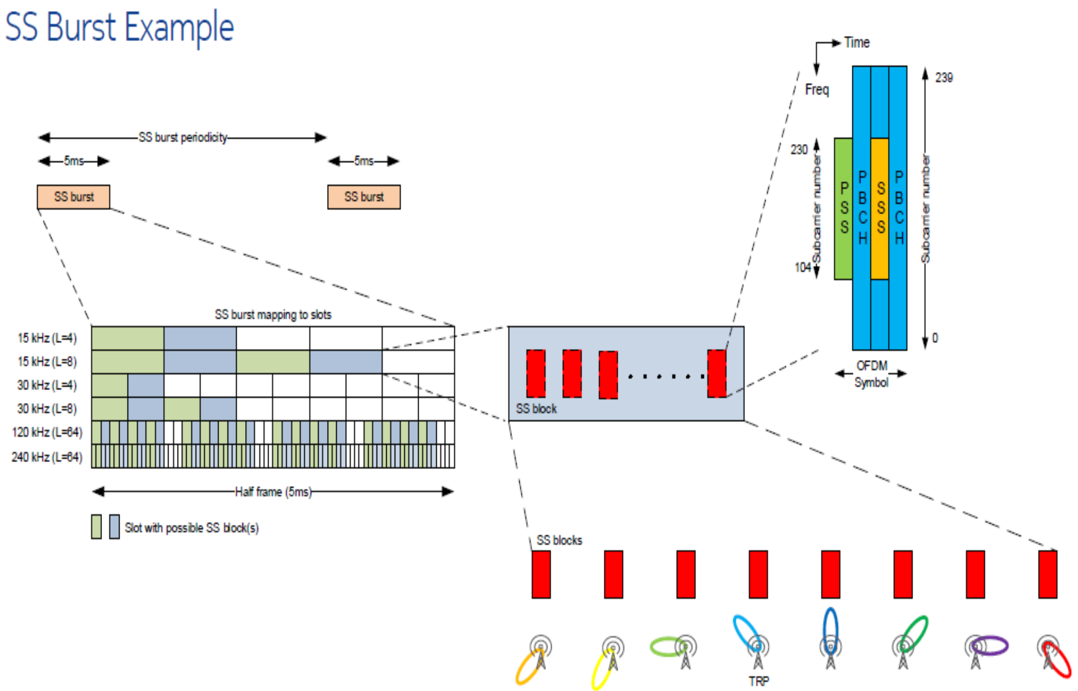


**Fig. 5: SS Burst Example for mmwave**

### 4.3 mmMAGIC

The main objective of the mmMAGIC project (mmMagic, 2017)is to develop advanced channel models for the frequency range of 6-100 GHz. For that purpose, various channel measurements have been conducted for a variety of InH scenarios at multiple frequencies, including 60 GHz. The InH scenarios comprise traditional enclosed offices, semi-closed offices (cubicle areas), and open offices. In this case, the BSs are mounted at a height of 1-5 m and can be placed at the ceilings or on the walls. In addition, channel models were developed for indoor airport scenarios, specifically the gate and the check-in areas, where the BSs should be installed near the ceiling at 4-9 m high [15]-[17].

### 4.4 METIS

The channel model investigation in the METIS project comprises the analysis of propagation measurements, extensive literature reviews, and simulations. The purpose of this research is to ensure the availability and applicability of relevant propagation models over the frequency range of 6-86 GHz. In this context, the channel model presented in the METIS white paper (METIS, 2015)is similar in form to the ABG model and was adopted for short-range 60 GHz links in shopping mall scenarios.

### 4.5 IEEE 802.11ad

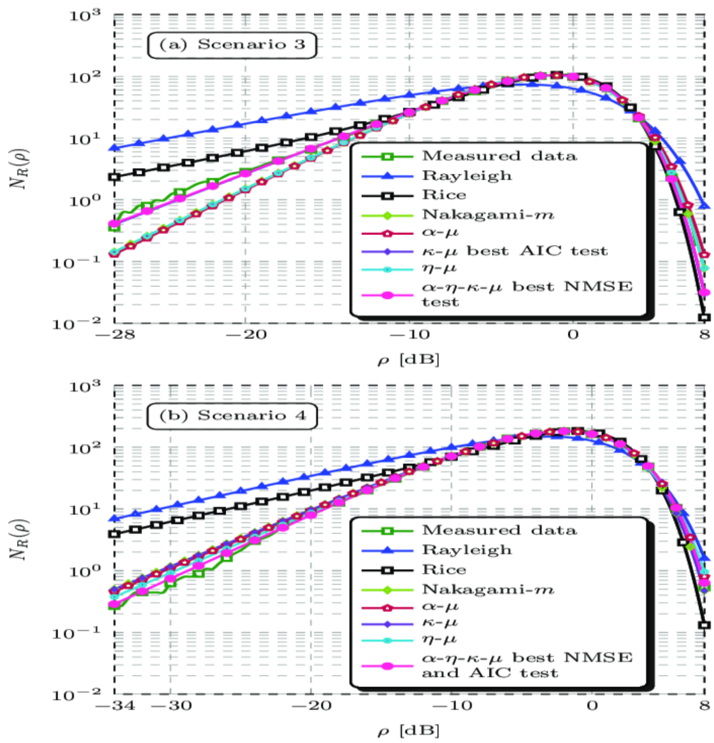


**Fig. 6: LCR s fitting approach for Scenarios**

The IEEE 802.11ad standard (Maltsev et al., 2010a)describes channel models for 60 GHz WLAN systems based on the results of experimental measurements in indoor environments. The InH office scenario is comprised of a cubicle environment, where the wireless AP is located on the ceiling. In both LOS and NLOS scenarios, the path loss model is similar to the CI model. However, no shadowing term is provided in the LOS condition, as the path loss for different antennas configurations match each other very closely and may be approximated by the same polynomial law as mentioned in Fig. 6. For the NLOS condition, the obtained channel model presents $\sigma$SF equals 1.5 dB. In both conditions, the 2-D distance $d$2D is employed [18].

## 5. Channel Models Comparison and Analysis for Indoor Scenarios

### 5.1 Channel Models Comparison

The channel models were compared considering the base station (BS) and the user equipment (UE) heights to be 2 and 1.5 m, respectively, for both indoor office and shopping mall scenarios, defined according to the information available in (5GCM, 2016; mmMagic, 2017; METIS, 2015; Maltsev et al., 2010a). For the indoor office scenario, the 2-D distance (d2D) ranges from 1 to 100 m, and the 3-D distance (d3D) was calculated based on the BS and UE heights. Another key observation is that, in this work, the models were compared based on the worst-case scenario. In other words, the model considered best suited for a particular scenario is the one that obtained the highest path loss. Consequently, it is possible to obtain a conservative prediction and an increased safety margin for a future project link budget [19].

For the line-of-sight (LOS) condition in the indoor office scenario, as shown in Figure 6, the mean path loss obtained with the IEEE 802.11ad standard is identical to the theoretical free-space path loss (FSPL), since the path loss exponent (PLE) is equal to two, and no shadowing term is provided. Moreover, the 3GPP and 5GCM channel models have the same parameters, yielding identical path loss values. On the other hand, the mmMAGIC model presents a more optimistic channel estimation compared to the other models. For instance, considering a Tx-Rx separation distance of 80 m, the free-space/IEEE 802.11ad and 3GPP/5GCM mean path losses are approximately 10 and 5 dB higher than the mmMAGIC path loss, respectively, since the mmMAGIC PLE (equivalent to α in the ABG model) is smaller than those presented by the other models. However, at shorter distances, the four models present very similar mean path loss values [20]-[22].

For the non-line-of-sight (NLOS) condition in the indoor office scenario, Figure 7 shows that the IEEE 802.11ad standard presents a very optimistic path loss estimation. The obtained mean path loss is only 8.6 dB higher than the theoretical FSPL at a Tx-Rx distance of 40 m. On the other hand, the other six models predict much higher path loss values, even at short distances, which is consistent with the NLOS environment. The 5GCM dual-slope (DS) CIF and ABG models present high mean path loss and are similar to the other models, although the breakpoint distances used are not visible in Figure 6, since they are very short, i.e., 7.8 and 6.9 m for the DS CIF model and DS ABG model, respectively.

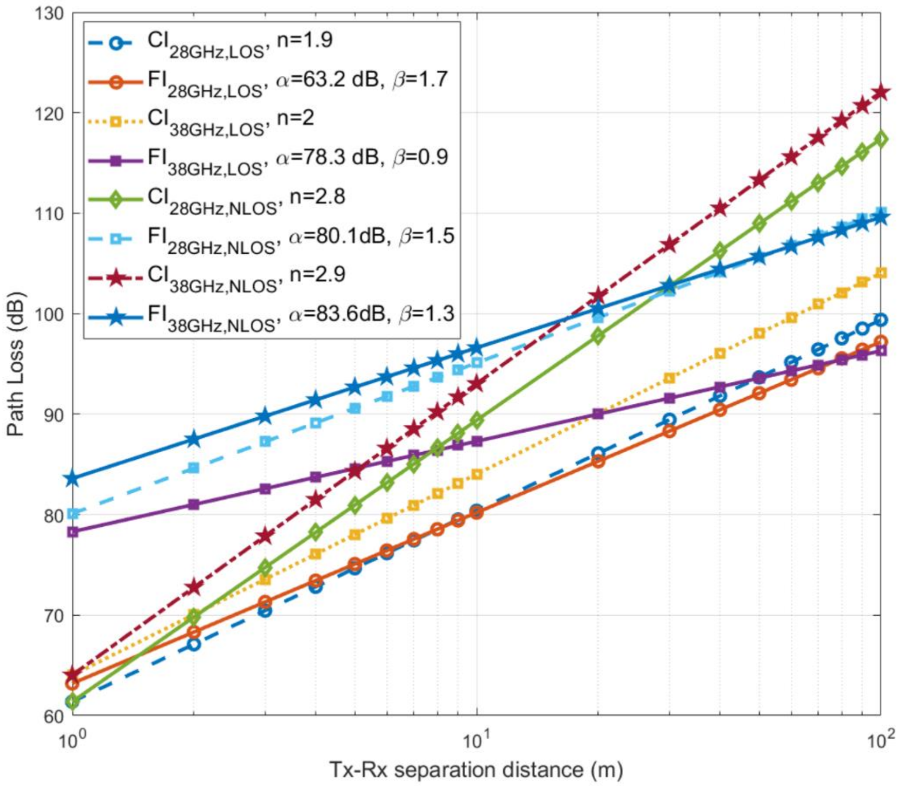


**Fig. 7: Survey of Millimeter-Wave Propagation Measurements**

It is not clear from the data available in (5GCM, 2016) that the DS models are consistent for indoor office scenarios, since the use of a breakpoint distance has not been reported in millimeter-wave measurement campaigns (Rappaport et al., 2017). In addition, the breakpoint distance measurements and calculations were not detailed in 5GCM (2016). However, for distances greater than the breakpoint, the CIF PLE parameter increases from 2.51 to 4.25, and the ABG α parameter increases from 1.7 to 4.17, which is consistent with the theoretical breakpoint definition (MacCartney and Rappaport, 2017). In this context, the 5GCM single-slope (SS) channel models are well suited for indoor office scenarios for both LOS and NLOS conditions, although the IEEE 802.11ad standard predicts higher mean path loss values for distances greater than 20 m in the LOS condition [23].

## 5.2 Channel Models and Measurement Campaign Comparison

The channel models' comparison for the LOS and NLOS indoor shopping mall scenarios is presented in Figures 8 and 9, respectively. It can be observed from Figure 8 that the METIS and the free-space model predict very similar path loss values. Moreover, the 5GCM path loss is approximately 3 dB lower than the path loss obtained with the METIS model at a Tx-Rx separation distance of 100 m. For the NLOS condition, depicted in Figure 9, the path loss predicted by the METIS model is practically constant and less than the FSPL for distances greater than 53 m, due to the very small B parameter. By contrast, the 5GCM DS CIF and ABG channel models predict much higher path losses, especially for distances higher than the respective breakpoint distances (i.e., 110 and 147 m), as shown in Figure 9. In this case, the CIF PLE increases from 2.43 to 8.36, and the ABG α increases from 2.9 to 11.47 for distances greater than the breakpoint. The comparison between the models and the measurement campaign is based on the mean-squared error (MSE), a widely used metric that depends on the average squared difference between the estimated values and the actual value, evaluated as (Yates and Goodman, 2014):

## Conclusion

The millimeter-wave spectrum, particularly the 60 GHz band, offers abundant bandwidth and multi-gigabit data transmission capabilities, making it a promising solution for future indoor wireless communications. This article provided a comprehensive overview of the propagation characteristics, large-scale path loss models, and channel models tailored for complex indoor scenarios involving 60 GHz signals. Understanding these propagation mechanisms and employing appropriate channel models are crucial steps in harnessing the full potential of the 60 GHz band for high-capacity indoor applications.The analysis and comparison of various channel models highlighted the importance of selecting the most suitable model for a given indoor scenario, considering factors such as line-of-sight conditions, building materials, and obstructions. By choosing a conservative model that predicts higher path losses, system designers can ensure a reliable link budget and increased safety margins for their 60 GHz indoor wireless systems. This comprehensive understanding paves the way for optimizing the deployment and performance of next-generation indoor wireless networks operating in the millimeter-wave spectrum.

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