Measurement and Analysis of Penetration Loss for Building Materials in 5G mmWave Network

Helio R. O. Ferreira, Hugo A. O. da Cruz, Daniel da S. Souza, Iran M. Braga Jr., Janderson C. C. Meireles and Yuri H. S. Barbosa

Abstract— **This study explores how different materials affect signal transmission in 5G networks, specifically in the 28 GHz spectrum known as Frequency Range 2 (FR2). With an anechoic chamber, the research measures Reference Signal Received Power (RSRP), Signal to Noise Ratio (SNR), Throughput, and Block Error Ratio (BLER) with and without obstacles like wood, glass, and metal at various angles. The goal is to thoroughly understand how materials impact signal strength in 5G FR2 networks to improve propagation models. The study presents results on physical and network metrics based on the User Equipment (UE) angle, showing that the 5G FR2 network is resilient against dielectric, wood, and glass obstacles, but sensitive to conductive materials. This research helps design networks that can handle high throughput demands, identifies challenges in signal propagation, assesses penetration loss in building materials, and contributes to refining path loss models for better network performance.**

Keywords— **Measurement, Penetration Loss, mmWave, Throughput, Angles, 5G(FR2).**

I. Introduction

The arrival of Fifth-Generation (5G) wireless technology signals a significant turning point in the history of telecommunications and the beginning of an era of improved connectivity that has the potential to transform several societal facets completely. 5G is well-positioned to facilitate a diverse range of applications, including Ultra High Definition (UHD) video streaming, the Internet of Things (IoT), autonomous vehicles, and more, thanks to its assurance of unparalleled data speeds, decreased latency, and heightened dependability. This breakthrough, which is not only evolutionary but transformative as well, greatly aids technological innovation and socioeconomic development. It makes possible new services and applications that were not previously possible.

For the implementation of 5G technology, two distinct frequency ranges are considered: Frequency Range 1 (FR1), which spans sub-6 GHz frequencies, and Frequency Range 2 (FR2), which includes frequencies in the millimeter-wave (mmWave) band, typically above 24 GHz. FR1 is characterized by its ability to provide wide coverage and penetrate buildings effectively, making it suitable for general mobile connectivity and IoT applications [1]. In contrast, FR2 offers significantly higher data rates and capacity due to its use of higher frequencies, albeit at the expense of reduced penetration and increased susceptibility to attenuation. This characteristic presents a significant challenge for indoor 5G deployment, where walls and other building materials can severely attenuate or block the signal, impacting network performance.

The purpose of this research is to provide empirical data on the interaction between wireless signals and common building materials; this work contributes to the refinement of propagation models, which are essential for the planning and optimization of future 5G networks [2]. Accurate models enable network designers to predict signal behavior more effectively, ensuring that 5G services can deliver their intended performance even in challenging indoor environments.

Penetration loss has been studied for some works from the literature in FR1 [1], [3], and FR2 [4]–[8]. In general, the main point of these works is to determine the Penetration Loss caused by some types of common building materials (glass, wood, metal) in indoor environments, where this type of highest frequency is more appropriate. In turn, these materials have a different composition due to the process of manufacturing or primary material used, which ends up causing different losses for each material tested; for example, there is an expresses or composition of the wood in which the fiber disposition causes different penetration values [5]. However, these works ignore the receiver's angle in relation to the transmitter, analyzing only the distance between transmitter and receiver, and they also ignore performance metrics like throughput and BLER in their analysis.

Therefore, this study focuses on the penetration loss associated with different building materials (wood, glass, and metal) within the context of 5G mmWave networks. By utilizing an anechoic chamber to control environmental variables, we systematically evaluated the impact of these materials on signal strength and throughput at various angles of incidence. Such controlled experimentation is critical for quantifying the effects of material characteristics on 5G signal propagation and developing a comprehensive understanding of how indoor environments influence network performance.

The remainder of this paper is organized in the following form: Section II describes the measurement setup and procedures. Section III is described as measurements and calculations were performed to determine the Penetration Loss for each material tested. Section IV in which it demonstrates the computed values, conducting an analysis of the signal power, throughput in relation to the subjects and the angles of incidence. Finally, Section V presents the conclusions and perspective of future work.

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II. Measurement

For the development of the research, measurements were performed to evaluate how the wireless signal of the 5G mmWave networks is impacted by different types building material, specifically glass, wood, and metal. This section will describe the measurement procedure and setup in Sections II-A and II-B, respectively.

A. Measurement Setup

The measurement setup can be divided into two parts: the external part of Software Defined Radio (SDR) modules and the inner part (propagation: anechoic chamber). Since the emulated scenario is a 5G non-standalone (NSA) network, the external setup consists of two SDR modules, one to generate 4G signals and the other to generate 5G signals. The 5G module can generate only baseband signals. Thus, up-converter modules were employed to obtain FR2 signals. It is also necessary to use a PC control equipped with Rapid Test Designer (RTD) software to manage the and emulate the 5G NSA communication. Finally, the control of the angular variation of the UE within the anechoic chamber is done by a drive module controlled by the PC control.

The internal setup consists of an anechoic chamber with dimensions: width = 1240mm x height = 1050mm x length 900mm. The chamber is internally equipped with electromagnetic wave absorbing material to avoid wall reflections; one antenna, TC-93060A, is used to transmit 4G signals, and two horizontal and vertical polarization antennas were used to transmit 5G mmWave signals, where the comprised operation band is 22.65-45.1 GHz and, to emulate the receiver, it was used a Samsung high-end Device with support for 4G and 5G mmWave bands. The specifications of the UE are described in Table I. The overview of the measurement setup is shown in Figure 1 and Figure 2 presents a picture of inside the chamber.

TABLE I
UE Specifications

Components	Mobile UE specifications
Chipset	Snapdragon 8 Gen 1
Modem-RF	Snapdragon™ X65 5G
+Operating System	One UI 4.1, based on Android 12

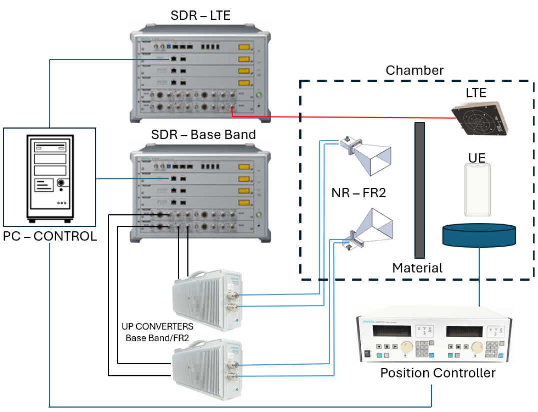

Fig. 1. Overview of the measurement setup.

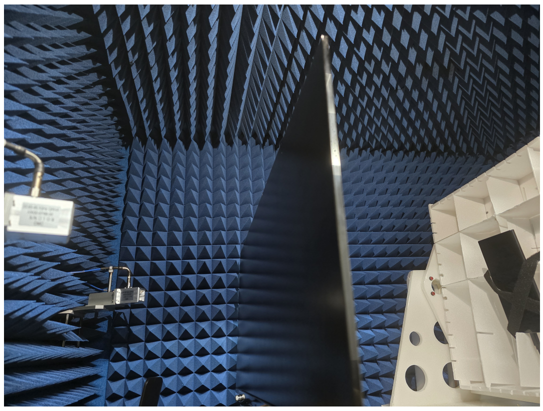

Fig. 2. Picture of inside the anechoic chamber.

B. Measurement Procedure

The methodology applied in the development of measurements is constituted in the use of the device, which varies the angles of 0º, 30º, 60º, 90º, 120º, 150º, and 180º compared to the horn antennas positioned in front of it. Material samples were placed perpendicular to the line of propagation between the antennas, 20 cm from the transmit antennas and 40 cm from the receiver, as we can see in Figure 3. In this measurement campaign, metrics from the physical layer such as RSRP (dBm) and SNR (dB) were collected as well as the throughput (Mbps) and BLER (%) of medium access control (MAC) layer. Each measurement at a certain angle has a duration of 20 seconds, and the results are the average of three different measurements.

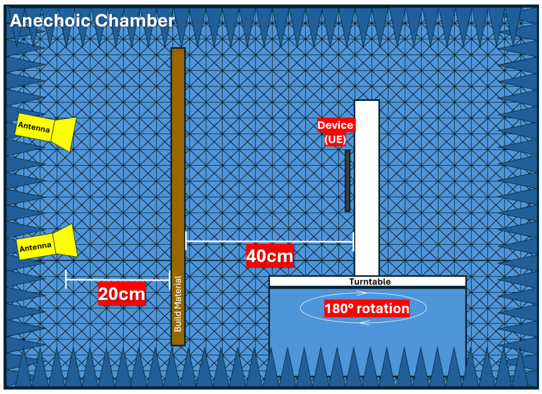

Fig. 3. Measurement procedure setup test.

III. Methodology

This section explains the test case, which was submitted for data collection, the treatment applied to the data, and the method used to calculate penetration loss.

A. Test case scenario

The measured data is obtained and evaluated through laboratory experiments. For this, a test case was developed using the aforementioned setup, capable of emulating an NSA network. The setup parameters are presented in Table II. Also, the measured 5G data rates are obtained directly from the Anritsu RTD software. Finally, note that the 4G cell is explicitly used for the control plane, i.e., to transmit signaling messages between the UE and the network.

TABLE II
NETWORK CELL PARAMETERS

Parameter	Value (FR2)
Frequency Band	LTE: Band 2; NR: Band 261
Subcarrier spacing (SCS)	120KHz
MIMO configuration	MIMO 2x2
Bandwidth (BW)	LTE: 5MHz, NR: 100 MHz
Modulation Scheme	256-QAM

B. Data Treatment

The logs collected in each measurement were processed using the QCAT tool, a Qualcomm solution for analyzing UE log metrics [9]. In the processing of the UE log, data from Throughput, BLER, SNR, and RSRP was sought. With the files of the filtered logs, the next step was to extract the metrics and relate them to the given time of the capture. From this, samples were collected at an interval of 5 seconds for each angle to determine the exact location of the metric, given an angle in relation to time. Finally, the average of the metrics was taken for the measurements of each material.

C. Electromagnetic Properties of Materials

The attenuation of electromagnetic signals is determined by several material properties, including electrical permittivity (ε), magnetic permeability (μ) and electrical conductivity (σ). Electrical conductivity, in particular, plays a crucial role in the energy dissipation of signals for different materials such as glass, wood, and metal exposed in Table III [10], [11].

TABLE III
ELECTROMAGNETIC PROPERTIES OF MATERIALS

Material	**Thickness (mm)**	ε_r	μ_r	$\sigma(\Omega.m)^{-1}$
Air	-	1.0006	1	-
Wood	9	1.5 to 2.1	1	0.3 to 3.72
Glass	5	4.7 to 6.15	1	0.51 to 1.68
Metal	1	-	5500	11.2^6

1) Electric conductivity (σ): Metals such as copper, aluminum, and iron have high electrical conductivity. Thus, when an electromagnetic signal inced on a metal, induced currents (i.e., Foucault's currents) are generated, dissipating the signal's energy in the form of heat, which causes high penetration loss. The penetration depth (δ), or skin depth, is defined in (1):

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}, \quad (1)$$

where ω is the angular frequency of the signal. The high conductivity of metals means that the penetration depth is very small, resulting in rapid signal attenuation.

2) Magnetic Permeability (μ): This propriety also significantly influences signal attenuation. Ferromagnetic metals, such as iron, have high magnetic permeability, which increases interaction with the magnetic fields of electromagnetic signals, resulting in greater losses. In contrast, materials such as glass and wood have magnetic permeability close to that of a vacuum (μ_0), contributing less to signal attenuation.

3) Electrical Permittivity (ε): It affects how the electric fields of electromagnetic signals interact with the material. Although glass and wood have different permittivity than air, the resulting attenuation is generally lower compared to that caused by the high conductivity of metals.

D. Penetration Loss Calculation

After having the measured and treated data, we can use it to determine the Penetration Loss, described in (2), empirically through a simple subtraction calculation between the signal power values obtained in the reference measurement in Line-of-Sight (LOS), in relation to obstruction of the specific materials measured in Non-Line-of-Sight (NLoS) [4].

$$L(dB) = REF_{LOS}(dB) - Material_{NLoS}(dB) \quad (2)$$

Therefore, this value calculated $L(dB)$ demonstrates how attenuate the signal is due to the material to which it was exposed.

IV. RESULTS

In this section, will be presented data values measured in a 5G network emulation for 28 GHZ frequency (FR2) for metrics such as: RSRP, SNR, Throughput, and BLER in relation to the angles (0° to 180º) of signal incidence and Penetration Loss values for each type of material building in different distance will be presents.

Fig. 4 represents the compiled values of the collected metrics for the measurement at 20 cm, considering a fixed modulation of 256 QAM, in which we can observe the impact of building materials by angles. Using the LoS measurement as a reference, we can see that materials such as wood and glass did not have a significant impact on network metrics (throughput and BLER) for all measured angles, while physical metrics (RSRP and SNR) suffer a slight impact at angles of 0, 30, 60º degrees that do not affect network metrics, making it possible to maintain a high transfer rate, around 1 Gbps. These differences may be related to the diagram of the antennas integrated into the UE and may be less directive for the angles observed. Metal material, on the other hand, has a major impact on physical metrics, which cause significant losses in network metrics at various angles. Indeed, as we can see, the RSRP and SNR values are at most -94.01 dBm and 17.46 dB, respectively. Moreover, because we are using a fixed modulation, at some angles, 100

A. Penetration Loss

The penetration loss can be calculated according to the methodology described in section D, obtained through measurements in controlled environments. Considering the measurements in this work, Table IV presents the average power

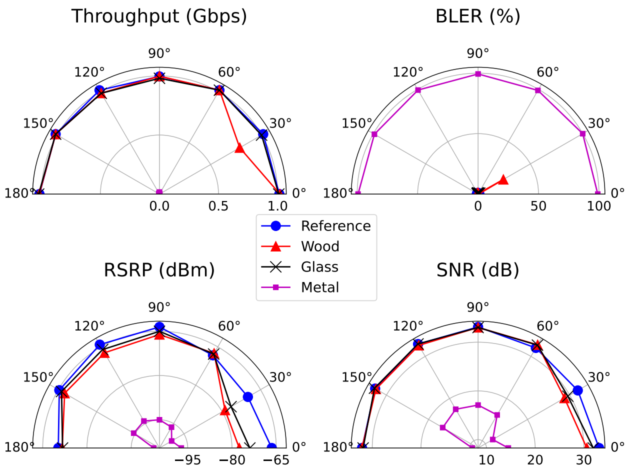

Fig. 4. Results for 20 cm distance.

loss imposed by the construction materials for each angle measured, added beam-forming adaptation effects for the Tx and Rx antennas. In general, the loss of electromagnetic signal penetration is significantly greater in metal (conductive material) due to its high electrical conductivity, which results in large induced currents and greater signal reflection due to the skin effect. On the other hand, materials such as glass and wood (dielectric materials) cause less attenuation when passed through by the signal at a frequency of 28 GHz. These results have important implications for the design and implementation of systems that rely on the propagation of electromagnetic signals through different materials.

TABLE IV

28 GHz Penetration Loss (dB)

Tx-Distance	Angle	Penetration Loss (dB) at 28 GHz		
		Wood	Glass	Metal
20 cm	**0º**	11.01	7.43	30.66
	30º	8.95	6.60	29.85
	60º	0.78	0.48	28.12
	90º	2.57	1.49	31.47
	120º	3.19	1.93	29.90
	150º	2.09	0.88	29.13
	180º	1.34	1.44	32.34

It is possible to observe that the propagation loss values in the materials vary according to the angle of the UE. This is because the antenna irradiation diagram in the UE gains more in one direction (90°, 120°, and 150°) than in others (0º, 30°, 60°, and 180°), as observed in the measurements.

V. Conclusions

This work presents a set of relevant measurements and analyses regarding building metrics penetration loss due to angles for 5G mmWave networks in the N261 band (28 GHz). To this end, a set of near-field measurements is carried out employing an anechoic chamber for nullifying external and internal influences. The methodology consists of carrying out a reference measurement and comparing it with measurements obstructed by construction materials to calculate the penetration loss, in addition to evaluating the impact of physical metrics (RSRP and SNR) in relation to network metrics (throughput and BLER), where it was shown that the metal having the highest penetration loss when compared to glass and wood. Measured values can be fed into indoor path loss models to improve prediction accuracy, as well as to help with future indoor 5G mmWave network planning. For future work, we intend to emulate scenarios with link adaptation and vary the number of carrier components to better explore the relationship between RSRP and throughput. It is also suggested that we measure the radiation diagram of the set of antennas arranged in the UE to better understand the losses per angle. A new approach can be also taken to understand how the diffraction effect is affecting the RSRP.

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