

Measurement and Modeling of Penetration Loss in Glass Material at 4G and 5G Frequencies

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Abstract—This study presents measurements and modeling of penetration loss through single- and double-layer glass materials in the 1-4 GHz frequency band, relevant to Long-Term Evolution (LTE) and New Radio (NR) mobile networks. Experiments were conducted in an anechoic chamber using a software-defined radio (SDR) and a signal analyzer. We propose a new empirical penetration loss model based on least-squares fitting that accounts for the oscillatory sinusoidal behavior observed. The proposed model outperforms the 3GPP standard model, achieving a mean squared error (MSE) approximately five times lower.

Keywords—Measurements, Penetration Loss, Glass Material.

I. INTRODUCTION

The deployment of fifth-generation (5G) mobile networks marks a major milestone in the evolution of telecommunications, delivering higher data rates, lower latency, and enhanced support for Internet of Things (IoT) applications and massive connectivity [1].

Moreover, private 5G IoT connections are projected to grow rapidly, reaching a compound annual growth rate (CAGR) of 65.4% by 2030. Such links offer distinct advantages in terms of security and control, attracting sectors including healthcare and non-industrial facilities—such as buildings, ports, and stadiums [2]. In this context, there is an increasing need to ensure efficient and consistent coverage in indoor and outdoor-to-indoor (O2I) scenarios, where building materials can strongly influence radio propagation. Indeed, network performance critically depends on propagation conditions, which are substantially affected by physical barriers in the environment [3], [4].

The characterization of penetration loss has been the focus of numerous measurement campaigns across multiple frequency bands (FR1, FR2, and FR3) and material types (e.g., concrete, glass, and wood), e.g., [5]–[7]. These studies typically adopt the 3GPP standard for penetration-loss modeling [8], which uses a linear model with coefficients estimated by regression. Nonetheless, several works have reported oscillatory, approximately sinusoidal, frequency-dependent behavior. In addition, the 3GPP specification [8] provides penetration-loss models for various glass types such as single-pane,

laminated, and double-glazed that exhibit distinct attenuation characteristics, underscoring the need for more accurate modeling.

Understanding penetration loss through materials such as concrete [9], wood [10], and glass [11] is crucial for improving coverage predictions, optimizing network planning, and devising strategies to mitigate signal degradation e.g., [12] proposes a novel concrete structure to enhance electromagnetic-wave propagation. Therefore, penetration loss plays a central role in ensuring robust connectivity, particularly in indoor and O2I scenarios e.g., [13] analyzes different polarizations and incidence angles.

Therefore, this work models the penetration loss of 4G and 5G signals through single- and double-pane glass in the FR1 band, based on experimental measurements conducted in a controlled environment. Specifically, the main contributions of this paper are:

- Experimental characterization of penetration loss in the FR1 spectrum commonly used by 4G and 5G networks, for single- and double-pane glass. These measurements provide a robust basis for understanding and predicting penetration loss in contemporary cellular systems.
- A novel empirical penetration loss model fitted via least squares to a nonlinear formulation that incorporates a sinusoidal component capturing frequency-dependent effects introduced by glass. Unlike previous studies that rely exclusively on linear components, the proposed approach empirically accounts for the complex internal propagation effects experienced by signals as they propagate through the glass.

The remainder of this paper is organized as follows. Section II describes the measurement setup and procedures. Section III details the methodology and parameter estimation of the proposed penetration-loss model. Section IV presents comparative results among the studied models. Finally, Section V draws conclusions and outlines directions for future work.

II. MEASUREMENT

The measurement campaign is central to this work and provides the empirical dataset underpinning our analysis. It quantifies the received power (dBm) under line-of-sight (LOS) and non-line-of-sight (NLOS) conditions over the 1–4 GHz frequency range. This section describes the measurement setup and procedure in Sections II-A and II-B, respectively.

A. Measurement Setup

The measurement setup, depicted in Fig. 1, comprises a signal analyzer to measure the received power; a control

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PC running GNU Radio; a software-defined radio (SDR) to generate the continuous-wave (CW) signal; two wideband TC-93060 antennas [14] for transmission and reception; and an anechoic chamber to suppress multipath reflections and external interference. The device specifications are summarized in Table I.

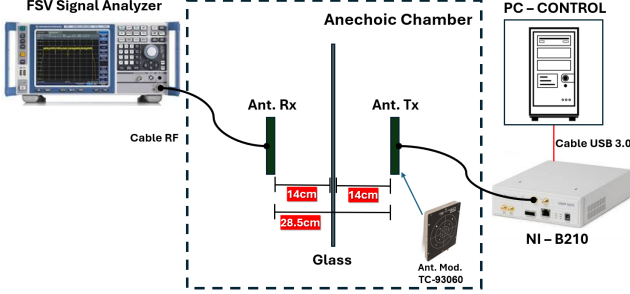


Fig. 1. Measurement setup.

TABLE I
EQUIPMENTS

Name	Model	Manufacturer	FR(MHz)
Antennas	TC-93060A	TESCOM	700 to 7500
Signal Analyser	FSV	R&S	0.07 to 7000
USRP	B-210	Ettus	70 to 6000
Anechoic Chamber	MA8171A	ANRITSU	0.8 to 3800

Furthermore, Fig. 2 shows the measured antenna radiation pattern. The plots depict azimuth and elevation cuts at 1 GHz and 3 GHz, respectively, evidencing the antenna's directional behavior.

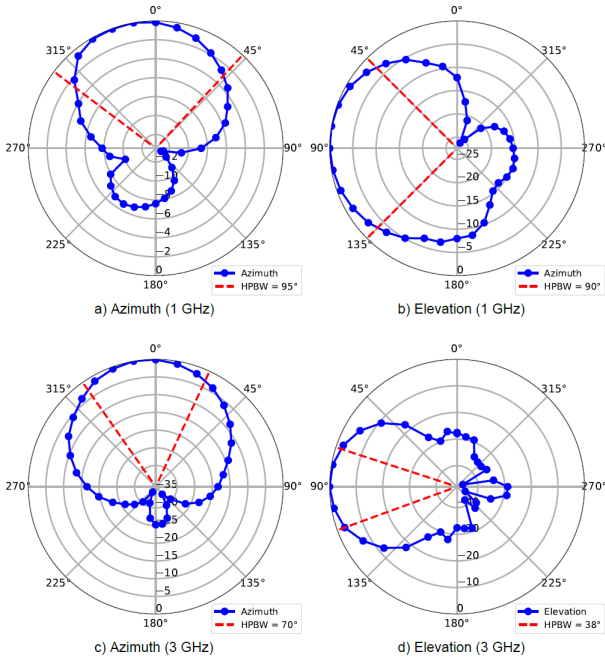


Fig. 2. TC-93060A Antenna Radiation Pattern, Azimuth and Elevation Planes.

The separation distance between the transmitting and receiving antennas was set at 28 cm due to the internal dimensional limitations of the anechoic chamber. Considering

the broadband spiral geometry of the TC-93060A antenna, the measurement setup was established to investigate the electromagnetic field radiated by the antenna's active region the part responsible for the dominant, frequency-dependent radiation mechanism [15].

B. Measurement Procedure

First, we generate a CW signal using GNU Radio and the USRP B210, and set the USRP B210 output power to 0 dBm. Next, the transmit and receive antennas are positioned at a fixed separation and connected to the USRP B210 and the signal analyzer, respectively. We first record the received power under line-of-sight (LOS) conditions. Then, the glass sample under test is placed midway between the transmitter and receiver, creating an obstructed path in which the signal must penetrate the material; we then record the received power under non-line-of-sight (NLOS) conditions. The glass penetration loss at frequency f , $L(f)$, is computed as the difference between the LOS and NLOS received power levels:

$$L(f) = P_{\text{LOS}}(f) - P_{\text{NLOS}}(f) \quad [\text{dB}], \quad (1)$$

where $P_{\text{LOS}}(f)$ and $P_{\text{NLOS}}(f)$ denote the received power under LOS and NLOS at frequency f , respectively. Thus, $L(f)$ represents the attenuation introduced by the material at frequency f . The procedure is repeated over the 1–4 GHz band with a frequency resolution of 50 MHz, resulting in a total of 80 samples.

III. METHODOLOGY

In this paper, we investigate the penetration loss, focusing on signal attenuation through glass. Specifically, we consider 1 and 2-layer systems, which are crucial to understanding signal intensity reduction in obstructed environments such as buildings or vehicles. The methodology involved measuring penetration loss, collecting data for analysis, referencing a standard model, and developing a more accurate model by incorporating linear and sinusoidal components to better fit the observed data and employing the nonlinear least squares method with the Levenberg-Marquardt algorithm.

A. Materials and Methods

Two commercially available glass slides, each 5 mm thick, were used in the experiments. Two measurement setups were created: one utilizing a single slide and the other employing both slides. The two-layer setup involved bonding the glass slides together, ensuring any potential air gap between the interfaces was negligible. The measurements for these setups ranged from 5 mm (1-layer) to 10 mm (2-layers). Additionally, auxiliary items like fasteners, supports, and measurement systems were employed to ensure the accuracy of the measurements.

B. Data Collection and Analysis

The collected data is stored in structured databases for statistical and comparative analysis. A mathematical model relates the penetration loss in (dB) to the material, specifically glass, which has 1 or 2-layers. After data collection and analysis, it can be verified that the penetration loss in the glass as a function of frequency presents an oscillatory characteristic, as previously observed in [5]–[7]. However, this oscillatory characteristic was ignored in the previous model of penetration loss. Therefore, an innovative method to enhance the model of penetration losses in glass material can be developed by incorporating this sinusoidal characteristic.

C. Mathematical Modeling

Currently, standard penetration loss models are linear models as shown in [8]. As mentioned previously, penetration loss in glass has an oscillatory characteristic, which allows approaches using mathematical models with similar characteristics, such as the sinusoidal function. Therefore, in this section, we present a new model used to predict the loss in glass considering 1- and 2-layers.

To predict the penetration loss in the glass, we propose a new model as a function of frequency f following:

$$L_{\text{model}}(a, b, c, d, f) = \underbrace{a + b \cdot f}_{\text{Linear}} + \underbrace{c \cdot \sin(d \cdot f)}_{\text{Oscillatory}} \quad [\text{dB}]. \quad (2)$$

Note that in (2) we combine a linear trend with a sinusoidal oscillatory component in order to model systems with both steady-state (linear) and periodic (oscillatory) behavior. Moreover, the coefficients a and b of the equation represent the vertical shift and the slope of the linear component of the penetration loss, respectively. On the other hand, the coefficients c and d are related to oscillatory components, where c defines the maximum and minimum loss values and d adjusts the frequency of oscillation of the loss as a function of frequency, denoted by f in MHz. In summary, the model captures both steady state and periodic fluctuations, and each parameter controls different aspects of the system's behavior.

D. Optimization of Model Parameters

The nonlinear least squares method adjusted the proposed model to the measured data. This method aims to minimize the sum of the squared differences (residuals) between the measured and predicted data, which can be mathematically modeled as

$$\min_{a, b, c, d} \sum_{n=1}^N (L(f_n) - L_{\text{model}}(a, b, c, d, f_n))^2, \quad (3)$$

$$\text{s.t.} \quad a, b, c, d \in \mathbb{R}, \quad (4)$$

where:

- $L(f_n)$: is the measured penetration loss for frequency f_n ;
- $L_{\text{model}}(a, b, c, d, f_n)$: is the proposed model function given in (2) for frequency f_n
- N : is the total number of samples.

Note that the problem in (3) is nonlinear. However, we can obtain the optimal (a, b, c , and d) values that minimize the cost

function by employing the Levenberg-Marquardt algorithm, which is an effective method for solving nonlinear least squares problems [16].

IV. RESULTS

This section will present the results of the measurement and mathematical modeling carried out in this study. We compare the results with the 3GPP standard linear model for glass material presented in [8], named as “3GPP model”, and its adjusted version based on the measurement, denoted as “Adjusted 3GPP model”, i.e., it is a simpler version of the proposed model without the oscillatory component. Moreover, two glass measurement campaigns were carried out, one for 1-layer and the other for 2-layers, as presented below in Sections IV-A and IV-B.

A. Results for 1-Layer Glass

TABLE II
COEFFICIENTS FOR 1-LAYER GLASS

Models	Coefficients			
	a	b	c	d
3GPP Model	2	0.2	n/a	n/a
Adjusted 3GPP Model	1.6	0.38e-5	n/a	n/a
Proposed Model	1.22	0.41e-5	9.91	0.99

In Table II, we present the coefficients for 1-layer glass obtained from the measurement results. We also include the coefficients for the 3GPP standard linear model in [8]. Also, in Fig. 3, we can observe that the measurement results present oscillatory behavior about frequency, as previously observed in other works from the literature. Besides that, the penetration loss has an ascending linear trend with frequency for the 1-layer case.

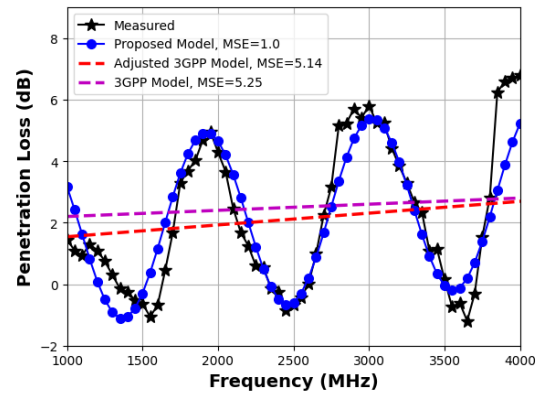


Fig. 3. Results for 1-layer.

Comparing the models, we can see a small difference between the 3GPP model and the Adjusted 3GPP model. Considering the mean square error (MSE) in relation to measured data, we have an MSE of 5.25 and 5.14 for the 3GPP model and the Adjusted 3GPP model, respectively. On the other hand, the proposed model presents an MSE of 1.0. This is an interesting result because it shows how accurate our model is compared to the standard models. The reason for

that is the sinusoidal component added to the model, which aims to better represent the variations in penetration loss with oscillatory characteristics as a function of frequency.

B. Results for 2-Layers Glass

For measurements considering 2-layers glass, the coefficients are as shown in Table III. Moreover, as we see in Fig. 4, the oscillatory behavior happens again about frequency. However, this time, we observe a descending linear trend. Note the negative value for the coefficient b in the Adjusted 3GPP model and the proposed model. This is a surprising result because it differs from that proposed in the 3GPP model. We believe this is potentially linked to refraction effects between the slides, but additional analysis is still required (e.g., by varying the incidence angle) and is left for future work. Finally, comparing the models, we find that the MSE for the 3GPP model and the Adjusted 3GPP model are 5.71 and 5.62, respectively, while the proposed model resulted in an MSE equal to 0.98.

TABLE III
COEFFICIENTS FOR 2-LAYER GLASS

Models	Coefficients			
	a	b	c	d
3GPP Model	2	0.2	n/a	n/a
Adjusted 3GPP Model	2.82	-4.67e-5	n/a	n/a
Proposed Model	3.83	-39e-5	3.11	0.99

Finally, making an overall analysis of Figs. 3 and 4, the proposed model demonstrated superior precision due to its ability to adapt to variations observed in measurements, achieving an MSE five times smaller when compared to the 3GPP standard model. Therefore, the proposed model is more appealing for planning indoor and/or outdoor-indoor networks.

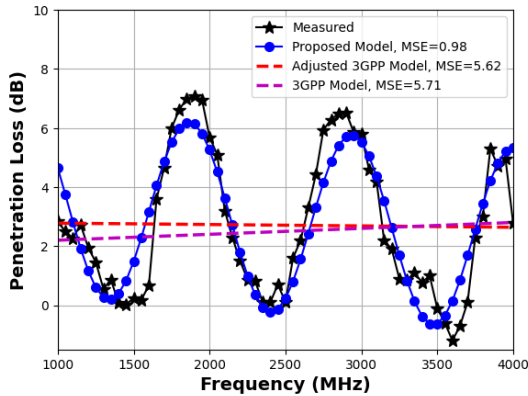


Fig. 4. Results to 2-layers.

The gains observed in the loss graphs in Figs. 3 and 4, where values fall below 0 dB indicate an actual increase in the signal. Instead, they show that the signal strength measured after passing through the glass was higher than expected under unobstructed line-of-sight conditions. This phenomenon is associated with complex wave propagation effects within the glass, such as waveguiding, lensing, constructive interference, and so forth. These phenomena could be further investigated in future studies.

V. CONCLUSIONS

The results presented in this study are of great importance when planning indoor and outdoor-indoor wireless networks, where most building partitions are made of glass. Penetration Loss measurements were carried out in these studies on glass considering 1 and 2-layers. Based on measurements, an adjustment model has been proposed to predict the loss of penetration using the technique of least squares.

Through this novel model, which captures the sinusoidal oscillatory behavior inherent in signal penetration, the proposed work sets itself apart from conventional methodologies that oversimplify these phenomena. Integrating a sinusoidal component into the model provides a more accurate representation of the intricate dynamics at play during signal transmission through glass materials, thereby advancing the field of wireless communication engineering. Furthermore, the obtained results hold substantial value for enhancing network planning tools and optimizing antenna placement strategies. Furthermore, they contribute to developing mitigation solutions to improve service quality in indoor and urban environments.

As a perspective for future works, we suggest extending the proposed model to other types of materials, such as wood and concrete, and considering more layers. Moreover, further research on how an oblique wave interacts with glass sheets could provide deeper insights into the observed phenomena when 2-layers are considered.

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