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Transmission and reflection loss measurements for indoor environments at 26 to 40 GHz and 55 to 65 GHz frequency bands

Monika Drozdowska, Sławomir J. Ambroziak, Krzysztof K. Cwalina, Piotr Rajchowski, and Narcis Cardona

***Abstract*—This paper presents an empirical investigation of the propagation characteristics of common indoor materials, focusing on transmission and reflection losses in two frequency ranges: 26–40 GHz (Ka-band) and 55–65 GHz (V-band). As the development of 5G and future 6G networks moves towards millimetre-wave frequencies, understanding the interaction between radio waves and elements of the office environment, such as furniture and structural components, becomes essential for reliable system deployment. The results indicate that while transmission loss increases significantly at higher measured frequencies, the mean reflection loss remains relatively stable across both investigated bands. However, the instantaneous reflection characteristics exhibit significant fluctuations, particularly at lower measured frequencies. The paper identifies materials with dominant blocking or reflecting properties, providing a set of empirical parameters for indoor channel modelling. These findings are instrumental for engineers designing high-capacity indoor wireless networks and precision localisation systems, offering a quantitative basis for link budget calculations in complex indoor scenarios.**

***Keywords*—Millimeter-wave (mm-Wave) measurements; Transmission and reflection loss; Material properties; Indoor propagation modeling; 5G/6G wireless communication**

I. Introduction

WIRELESS communication systems are evolving rapidly, with millimetre-wave (mmWave) frequencies playing an important role in next-generation networks. Indoor environments such as offices, classrooms and auditoriums vary significantly in materials, layouts and furniture, which affects the propagation of radio waves. Understanding how commonly used indoor materials affect signal propagation in terms of transmission and reflection is essential to optimise network planning and deployment.

Millimetre-wave bands, particularly at 27 GHz, 40 GHz, and 60 GHz, are interesting due to their allocation in 5G Frequency Range 2 (FR2) and standards such as IEEE 802.11ad/ay [1], [2]. However, the high-frequency nature makes the signals vulnerable to increased path loss, penetration loss, and reflection effects. To assess material-dependent propagation characteristics, which are essential for realistic coverage planning, interference management, and beamforming strategy design in indoor environments, this study investigates transmission loss (TL) and reflection loss (RL) across two frequency bands: Band 1 (Ka-band: 26–40 GHz) and Band 2 (part of the V-band: 55–65 GHz).

Previous studies found in the literature explored TL and RL in outdoor-to-indoor (O2I) and indoor-to-indoor (I2I) scenarios, providing insights into the attenuation properties of building materials [3]–[11]. As shown in Table I, the existing studies either lack consistent frequency band coverage across publications or focus on a limited number of materials. A comprehensive characterisation of a diverse set of materials in comparable indoor environments and frequencies remains limited. Therefore, it is not possible to fairly compare the impact of different materials on a propagation environment. To address this research gap, this study presents the largest reported set of transmission and reflection measurements (to date) for indoor materials at FR2 frequencies, conducted under uniform measurement conditions using a custom movable stand.

It is important to mention that building materials are not standardised in the same way across different countries; thus, if the measured material is not described in detail, it is not possible to align it perfectly with materials used in different environments in different countries.

If there is sufficient knowledge about the measured material and the measurements are performed in a sufficiently wide frequency band, their electromagnetic properties can be obtained. The guidelines for calculating materials' conductivity and permittivity, along with example values for some materials, can be found in the ITU-R P.2040 recommendation [12]. Accordingly, the TL and RL of a given material are expected to vary with frequency. The phenomena may be theoretically explained by the frequency dependence of the complex permittivity. As frequency increases from Band 1 to Band 2, the real part of the dielectric constant decreases (reducing RL), while the conductivity and loss tangent increase (increasing TL). Combined, these effects result in higher TL and lower RL in Band 2 compared to Band 1.

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M. Drozdowska and N. Cardona are with iTEAM Research Institute, Universitat Politècnica de València, València, Spain (e-mail: mdrozdo, ncardona@iteam.upv.es).

S. J. Ambroziak, K. K. Cwalina, and P. Rajchowski are with Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, Gdańsk, Poland (e-mail: slawomir.ambroziak,kkcwalina, piorajch@pg.edu.pl).

TABLE I
COMPARISON OF RELATED WORK ON MATERIAL CHARACTERISATION IN MMWAVE BANDS

Ref.	Scenario	# Materials	Measured	Frequency Bands (GHz)	Remarks
[3]	I2I	8	TL, RL	60	Internal office structures
[4]	I2I	2	RL	60	Wall and floor of mine gallery
[5]	I2I	6	TL, RL	28, 39	Materials samples
[6]	I2I	4 + clutter	TL	2.5, 60	Internal structures including indoor clutter
[7]	I2I	3	TL	27, 38	Flooring across buildings
[8]	O2I	several	TL	3, 10, 17, 60	Building partitions
[9]	I2I, O2I	10	TL	26–40 (Band 1)	Materials samples
[10], [11]	I2I	17	TL, RL	2–170	Materials samples
This Work	I2I	**22**	**TL, RL**	**26–40 (Band 1)** **55–65 (Band 2)**	Internal structures and furniture

In [13], the guideline provided in [12] was applied to measurements reported in [10], [11], and the authors proposed the extension of the ITU-R P.2040 model at frequencies above 100 GHz.

This work expands on prior research by measuring and analysing TL and RL for 22 different materials, referred to as materials under test (MUT), commonly used in offices and conference rooms. The objective is to identify their frequency-dependent properties and understand implications for mmWave network deployment. All identified MUTs are part of the built indoor environment, i.e., university facilities; thus, some MUTs are not movable. Therefore, the movable measurement stand was built to ensure the same conditions for all of the MUTs. Since the focus was on the differences in TL and RL due to frequency, the measurement stand was predestined only for working with a normal incidence angle for TL and a 30° incidence and reflection angle for RL. However, the study on the angular dependency should be continued. Obtaining TL and RL from the measurements and through the reference method is the first step of the performed analysis. Further, the studies are performed on each MUT separately and on groups of MUTs belonging to the same class.

The key contribution of this work is a consistent measurement campaign for TL and RL of 22 common indoor materials in relevant frequency bands for modern wireless systems.

The paper is structured as follows: Section II covers materials under test and methodology of the measurements and data processing, Section III presents results and discussion, and Section IV concludes the study.

II. METHODOLOGY

This section outlines the study's methodology. It begins with a summary of the MUTs, followed by a description of the measurement equipment. The setup of the measurement stand is then detailed. Finally, the reference method used to calculate TL and RL is explained.

A. MATERIALS UNDER TEST SELECTION

Measurements were conducted in three rooms at the Gdańsk University of Technology: a large auditorium, a large classroom, and a small seminar room. These environments, previously studied in [14], contain various structural elements and furniture commonly found in indoor workspaces.

A total of 22 MUTs were tested and put into five classes: *wood*, *glass*, *walls*, *chairs*, and *other materials*. Additionally, as the reference signal, the Free Space System Loss (FSSL) was measured. Some materials were only tested for RL due to measurement constraints. To ensure consistency, all materials were photographed, and their thickness was noted when applicable. The complete list, along with thickness parameters, is provided in Table II.

TABLE II
MATERIALS UNDER TEST DESCRIPTION

#ID	Name	Class	Thickness [cm]	Parameters
1	Concrete	Wall	32	RL
2	Wood door	Wood	4	RL, TL
3	Drywall	Wall	49	RL
4	Projector Screen	Other	N/A	RL
5	Whiteboard (on the wall)	Other	N/A	RL
6	Pinewood	Wood	0.9	RL, TL
7	Upholstered chair	Chair	3.6	RL, TL
8	Drywall	Wall	14.5	RL, TL
9	Room divider	Other	10.5	RL, TL
10	I2I Glass	Glass	N/A	RL, TL
11	Upholstered Chair	Chair	4.5	RL, TL
12	Ceiling panel	Other	2	RL, TL
13	Chipboard Desk	Wood	2.5	RL, TL
14	Whiteboard (standalone)	Other	N/A	RL, TL
15	Whiteboard (standalone)	Other	N/A	RL
16	I2I Glass	Glass	N/A	RL, TL
17	Chipboard Table	Wood	2.5	RL, TL
18	Double-Paned Window	Glass	N/A	RL, TL
19	Window with a blinder	Glass	N/A	RL, TL
20	Chipboard Wardrobe	Wood	1.8	RL, TL
21	Upholstered chair	Chair	3.5	RL, TL
22	Concrete	Wall	N/A	RL

B. MEASUREMENT SETUP

Measurements were performed using a Keysight N5227B Microwave Network Analyzer (MNA), capable of operating between 10 MHz and 67 GHz [15]. The testbed consisted of a double-ridged horn antenna (DRH67) for both transmission (Tx) and reception (Rx) [16]. The testbed diagram is shown in Fig. 1.

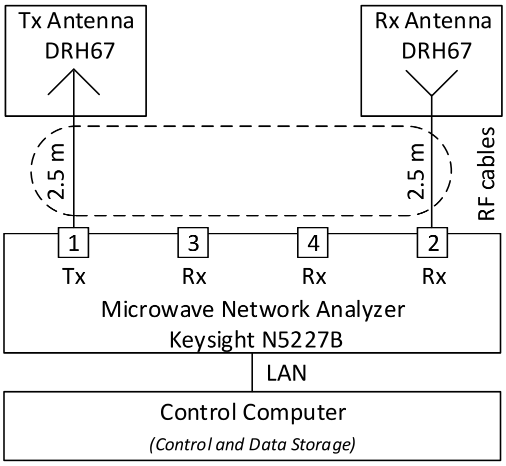

Fig. 1. Block diagram of measurement stand.

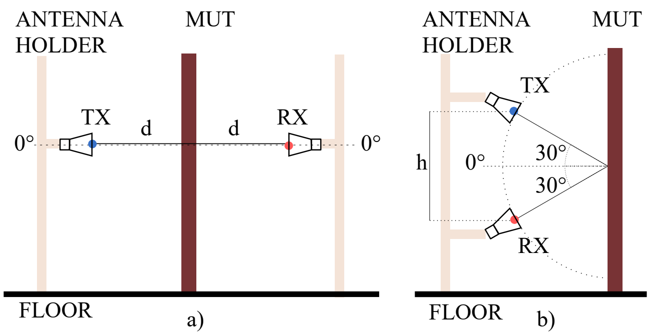

Fig. 2. Measurements setups: a) TL, b) RL.

For TL measurements, the Tx and Rx antennas were placed at a height of 1 m with 0.3 m separation and MUT between them, ensuring direct signal alignment (Fig. 2a). RL measurements were conducted with both antennas on the same side of the MUT, separated by 0.3 m in height and tilted at a 30° angle to minimise coupling effects and avoid direct transmission (Fig. 2b).

Before the measurements, the MNA was calibrated in order to properly compensate the delays and attenuation in the cable tracks. Thus, the recorded CIRs represent the relative attenuation between the power at the Tx antenna port and the output power at the Rx antenna port, i.e. the system loss (SL) [17]. Thirty channel impulse responses (CIR) were recorded for each material to provide steady measurements. The collected data were processed using a reference method, which is explained in Section II. II-C. Table III summarises all of the measurement parameters.

Individual examples of TL and RL measurement setups are presented in Fig. 3. For TL measurements, the #9 room divider and #12 ceiling panel are shown in Fig. 3(a) and (b). Fig. 3(c) and (d) present RL measurement configuration for #18 window and #16 I2I glass.

TABLE III
SUMMARY OF THE MEASUREMENT PARAMETERS.

Measurement type		CIR
Polarisation		VV
Tx power (port 1)		0 dBm
Center frequency	Band 1	26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 GHz
	Band 2	55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65 GHz
Bandwidth		400 MHz
IF Bandwidth		100 kHz
Tx pulse time		4.89 ns
CIR duration (max. delay)		20 ns
No. of samples per CIR		4001
No. of CIRs averaged per one PDP		30
Window function		Kaiser-Bessel ($\beta = 6$)
Average triggering time		201 ms

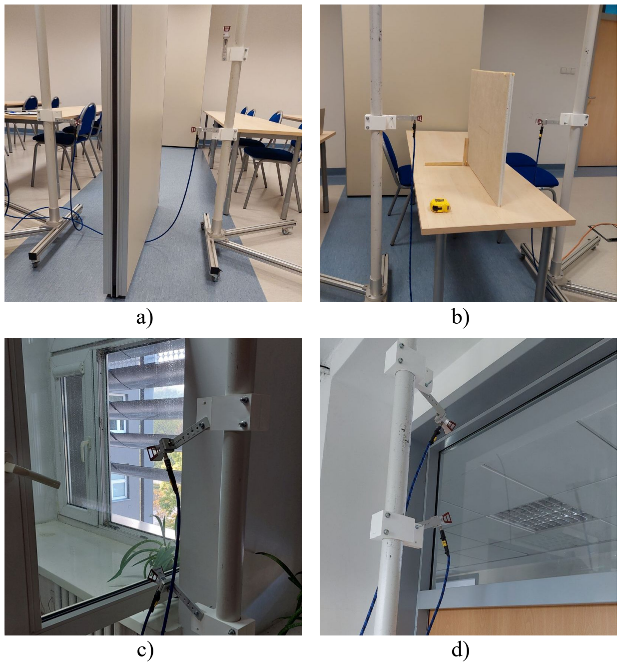

Fig. 3. Photos of measurements setups: a) #9 room divider - TL, b) #12 ceiling panel - TL, c) #18 window - RL, d) #16 I2I glass - RL.

C. DATA PROCESSING

The TL and RL values were derived using the reference method. This method is typically used to obtain the TL value. However, when dealing with reflections, some researchers also use the reference method [5], [18], and some calculate the reflection coefficient [3], [4]. The reference method is based on the subtraction of the reference system loss (RSL) signal measured without the material in between the antennas from the SL received from the measurement with the considered MUT. The method is given by equations 1 for TL and 2 for RL:

$$TL\ [\mathrm{dB}] = SL_{MUTsetup_{a)}}(f)\ [\mathrm{dB}] - RSL(f)\ [\mathrm{dB}], \quad (1)$$

$$RL\ [\mathrm{dB}] = SL_{MUTsetup_{b)}}(f)\ [\mathrm{dB}] - RSL(f)\ [\mathrm{dB}], \quad (2)$$

where $SL_{MUT}(f)$ represents the measured system loss with the MUT measured in setups a) and b), as shown in Fig. 2, and $RSL(f)$ is the reference system loss without any obstruction. The frequency-dependent characteristics of each material were analysed using statistical metrics, including mean (μ) and standard deviation (σ).

Since both the reference signal and signal with MUT are obtained for identical antennas under the same setup, the results are independent of antenna gain, transmitted power, half-power beamwidth (HPBW), and Tx-Rx distance [18]. RL and TL correspond only to the radio signal carrier frequency.

The analysis methodology to obtain TL and RL for all MUTs was identical. For better clarity, it will be explained in one example. Consider the concrete wall (#1 Concrete) for which the RL was measured. For each of the 26 center frequencies (Table III), 30 CIRs were recorded, 780 in total. CIRs were averaged to obtain one power delay profile (PDP) per frequency. The observation time was short, so we can identify a first-arriving single-bounce-reflection component. Note that for some MUTs for RL measurements, a second reflection from objects behind the MUT may be observed. To obtain RL for the concrete wall, the measured RSL value has to be subtracted from the SL of MUT for the same frequency. Data obtained from this processing is used to present frequency-dependent characteristics of MUT.

TABLE IV
STATISTICAL PARAMETERS OF MUTS.

	TL [dB]				RL [dB]			
	Band 1		Band 2		Band 1		Band 2	
MUT	μ_{TL}	σ_{TL}	μ_{TL}	σ_{TL}	μ_{RL}	σ_{RL}	μ_{RL}	σ_{RL}
Class: Wood								
#2	13.2	3.7	15.3	3.4	12.4	2.4	13.5	1.8
#6	3.5	0.4	5.8	0.4	15.5	3.7	26.4	6.4
#13	7.1	1.0	12.2	1.0	13.3	1.6	12.7	0.6
#17	6.2	0.6	11.3	0.7	13.5	2.2	13.6	1.1
#20	5.8	1.3	12.3	1.0	12.8	2.2	12.2	0.6
Class: Chair								
#7	6.0	1.2	9.0	0.6	17.3	2.9	23.6	3.4
#11	5.7	0.8	10.0	0.7	15.8	4.4	16.9	3.1
#21	3.2	0.9	3.9	0.3	19.4	9.1	23.5	9.1
Class: Glass								
#10	2.8	1.3	3.6	1.0	8.3	5.4	8.2	4.0
#16	3.4	1.7	3.8	1.2	8.4	5.3	8.8	3.8
#18	32.0	2.9	33.9	2.2	2.6	1.5	2.6	0.9
#19	31.6	3.3	34.2	3.2	3.0	1.7	3.3	1.5
Class: Wall								
#1	-	-	-	-	11.7	2.0	12.8	1.8
#3	-	-	-	-	10.0	4.5	14.1	6.8
#8	4.6	1.8	8.9	1.9	16.4	11.2	12.2	3.8
#22	-	-	-	-	9.1	1.5	9.8	0.7
Class: Other								
#4	-	-	-	-	13.3	4.8	9.7	2.0
#5	-	-	-	-	1.9	0.4	3.4	1.7
#9	12.4	2.7	25.4	1.4	10.8	3.4	10.5	0.9
#12	0.3	0.1	1.1	0.1	19.4	3.7	15.3	0.6
#14	44.1	4.2	43.4	1.8	1.4	0.5	1.1	0.2
#15	-	-	-	-	0.9	0.5	0.8	0.2

III. RESULTS AND DISCUSSION

A. *MATERIALS' CHARACTERISTICS*

Characteristics of measured materials are presented in Figs. 4, 5, 7, 8, and 9. The dotted lines indicate values for RL, while the solid lines indicate values for TL. Table IV summarises mean values (μ) and standard deviations (σ) of TL and RL obtained in Band 1 and 2 for all MUTs. Additionally, the normalised values of the μ_{TL} for MUTs with measured thickness are shown in Table V.

The general tendency for MUTs presented in this work is that in the case of TL, μ_{TL} increases in Band 2; meanwhile, the σ_{TL} does not change significantly. However, in the case of RL, μ_{RL} does not change significantly, but σ_{RL} is higher in Band 1. In this subsection, a short summary is presented for each MUTs' class.

TABLE V
NORMALISED TL [DB/CM].

	wood				
#ID	#2	#6	#13	#17	#20
Band 1	3.3	3.9	2.8	2.5	3.2
Band 2	3.8	6.4	4.9	4.5	6.8

	chairs			wall	others	
#ID	#7	#11	#21	#8	#9	#12
Band 1	1.7	1.3	0.9	0.3	1.2	0.2
Band 2	2.5	2.2	1.1	0.6	2.4	0.5

1) WOOD CLASS: Fig. 4 presents losses obtained for wooden MUTs. In Band 1, except for the #2 wood door, the TL is lower than the RL. For Band 2, except for the #6 pinewood piece, the values of TL and RL overlap within 10 and 20 dB. Obtained values follow trends reported in the literature [5], [9], [18].

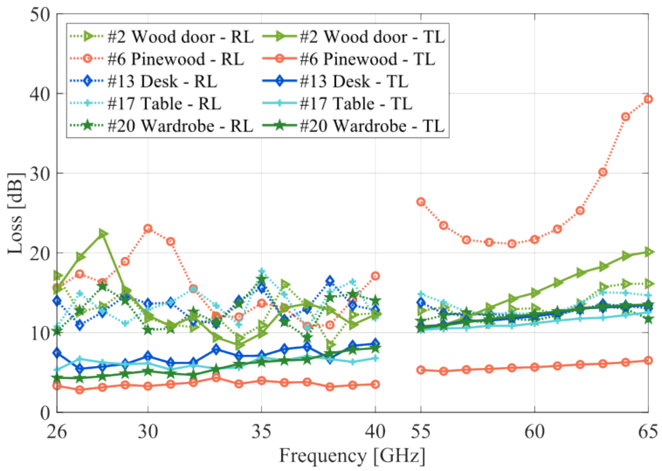

Fig. 4. Wood class materials characteristics: TL and RL.

The TL value is higher for thicker pieces of wood and increases with frequency. The lowest TL in Band 2 was obtained for #6 pinewood piece, the thinnest of all measured MUTs in the wood class. However, its normalised TL given in dB/cm was not the lowest. As given in Table V, the lowest value was obtained for #2 wood door.

2) CHAIR CLASS: The most significant difference between all measured chairs is their components. MUT #7 consists of #6 pinewood and a textile, MUT #11 is assumed to be built from a textile and unknown components hidden inside, and MUT called #21 combines plastic and textile.

In Fig. 5, TL is below 10 dB for most cases. The smallest values of normalised TL, as shown in Table V, were obtained for #21 (with plastic) and the largest for #7 (with wood). For all measured frequencies, the RL exceed 10 dB. Therefore, the TL is lower than the RL in both measured bands.

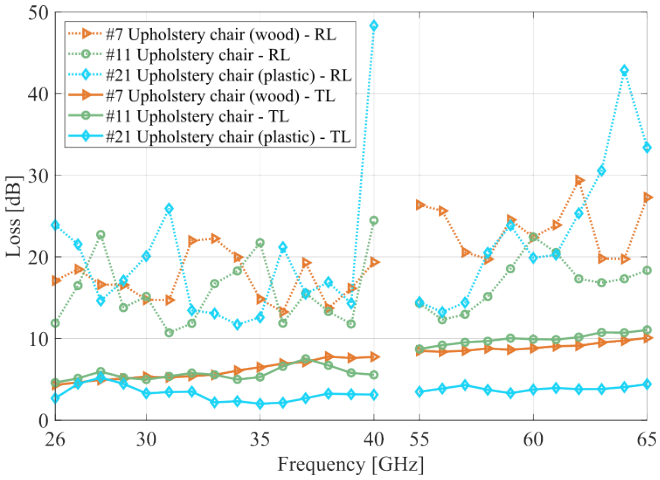

Fig. 5. Chair class materials characteristics: TL and RL.

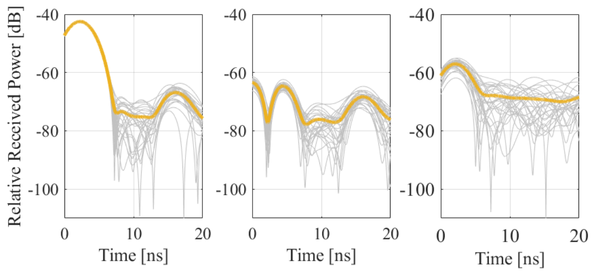

Fig. 6. PDP of #21 upholstered chair for RL setup a) 39 GHz, b) 40 GHz, and c) 65 GHz.

The RL for #21 exceeds 30 dB for 40 GHz, and above 62 GHz. There are two reasons for that: 1) in the case of the 40 GHz presented in Fig. 6b), destructive multipath propagation influence occurred. It may be compared to PDP obtained in 39 GHz in Fig. 6a), where the maximum relative received power is observed at 2.25 ns. 2) For frequencies above 62 GHz, the received power was very low, close to the noise floor level, as presented in Fig. 6c) for 65 GHz. For other frequencies, results obtained for all chairs rarely exceed 25 dB loss.

3) GLASS CLASS: The most unexpected and diverse results were obtained for glass measurements. Characteristics are presented in Fig. 7. Two measured MUTs were the I2I 1-layer glass walls between the room and the corridor (#10 and #16), and two were the O2I 2-layer glass window with and without a thin textile blinder (#18, #19).

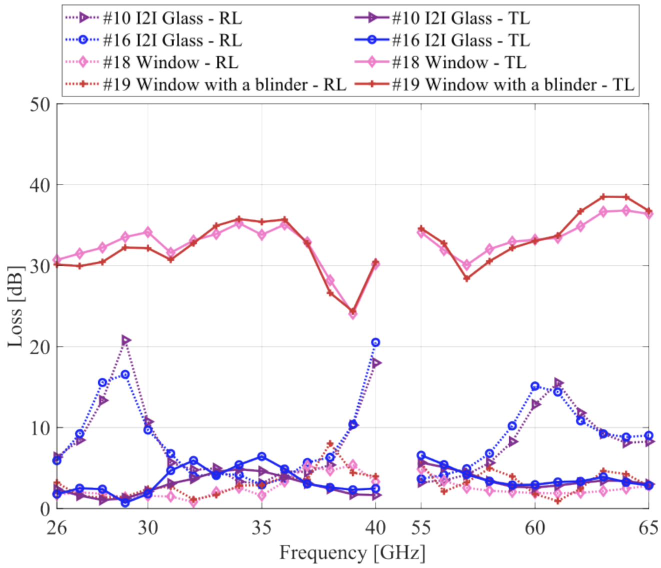

Fig. 7. Glass class materials characteristics: TL and RL.

For the #18 and #19 I2O window, the TL for most frequencies obtains values between 30 and 40 dB. Differences between the two of them are introduced by the blinder and are minor, as summarised in Table IV. Meanwhile, TL values for I2I glass walls (#10, #16) do not exceed 7 dB. This difference is significant and requires further investigation. The question is whether this difference is caused by the Single-Glazing/Double-Glazing glass structure or the type of glass used indoors and outdoors. In [8], similar differences in TL are observed for double-layered glass with and without silver coating. Besides that, TL values for #10 and #16 agree with that reported in [5], [6] for 1-layer glass. Interesting research on penetration loss through glassy windows is presented in [19]; however, for lower frequencies.

The RL characteristics of the I2I and O2I glass are also very different. The distinguishable maximum values for I2I glass (#10, #16) are observed at 29 GHz, 40 GHz, and around 60 GHz. For the O2I window (#18, #19), RL is below 8 dB for all frequencies, having a mean value more than 5 dB lower than I2I glass. Therefore, #18 and #19 are highly reflective independently of the used frequency in Band 1 and Band 2; meanwhile, #10 and #16 have the frequency-dependent characteristic. Values for RL obtained through the measurements agree with those reported in [5], [18].

4) WALL CLASS: Walls characteristics are presented in Fig. 8. TL is measured only for the #8 drywall walls (2 layers of drywall and an air gap between). It was not possible to measure TL for #3 drywall due to the length of the cables used. An attempt was made to measure TL for concrete walls, but no signal was received. High TL for concrete is reported in [9]. However, RL was measured for all walls.

The TL of the #8 drywall has to be discussed in both measured frequency ranges. It can be observed that TL increases for Band 2; thus, for higher frequencies. However, it has to be noted that TL values are actually decreasing in Band 1. Results for #8 drywall agree with values reported in [6]. Normalised TL for #8 drywall is given in Table V,

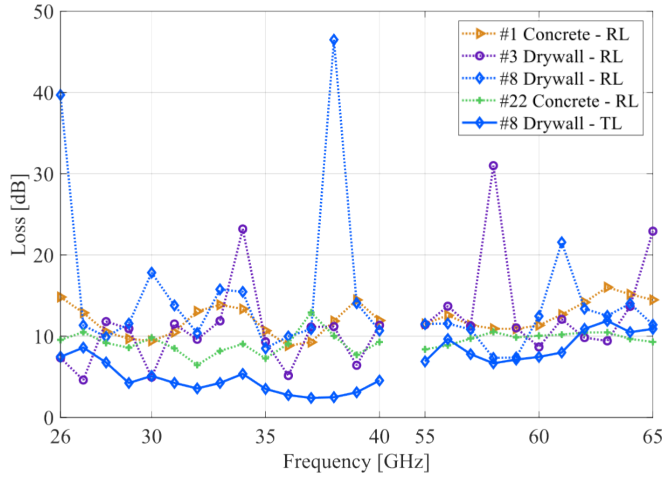

Fig. 8. Wall class materials characteristics: TL and RL.

and is very low compared to values obtained for other MUTs, probably due to its non-homogenous structure.

Different RL characteristics may be observed for concrete walls (#1 and #22) and drywall walls (#3 and #8). The most distinguishable difference is the values of standard deviations: below 2 dB for concrete, and above 4.5 dB in Band 1 and 3.7 dB in Band 2 for drywalls. Therefore, RL characteristics are more frequency dependent for drywall than for concrete. RL for concrete was reported in [18]. Measured RL values for 28 GHz are in agreement with the reference. However, RL at 60 GHz reported in the literature is much higher (35 dB) compared to 10 dB and 11.3 dB obtained through the measurements.

5) OTHER CLASS: Fig. 9 presents characteristics of the rest of the materials: whiteboards, ceiling panel, and room divider.

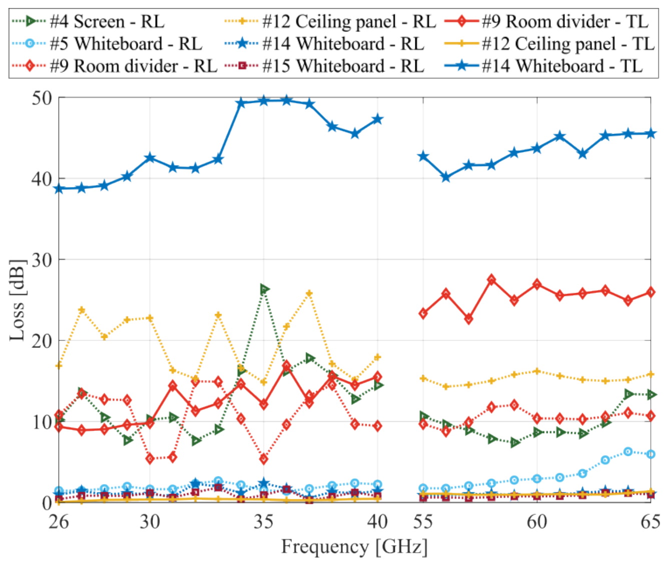

Fig. 9. Other class materials characteristics: TL and RL.

In general, RL for all measured whiteboards is very low. The difference between the #5 whiteboard and the two others (#14 and #15) is that #5 is mounted on the wall, whereas the two others are standalone, without any additional layer behind. The TL was measured only for #14 whiteboard. For all frequencies, TL exceeds 38 dB and almost reaches 50 dB. However, values obtained for frequencies above 33 GHz correspond to the value of the noise floor since no signal was received.

The exact opposite characteristic was obtained for the #12 ceiling panels made of mineral wool. The mean TL is very low; however, the μ_{RL} is higher: 19.4 dB in Band 1 compared to 15.3 dB in Band 2. This MUT is characterised by the lowest normalised TL reported in Table V.

The last MUT presented in Fig. 9 was a #9 room divider made of two metallic layers on the outside and foam inside. The $\mu_{TL,\#9}$ increases significantly between Band 1 and Band 2, whereas the $\sigma_{TL,\#9}$ decreases. Normalised TL reported in Table V is lower than for wooden structures, but it is important to remember that this MUT is not homogeneous.

The difference between the mean values of RL in both Bands is 0.3 dB. However, the standard deviation in Band 2 is smaller. The comparison of the obtained values leads to the conclusion that the MUT #9 introduces similar TL and RL in Band 1, but in Band 2, higher attenuation is introduced due to transmission than reflection.

B. *PROPERTIES COMPARISON*

Having the collection of TL and RL results for 22 MUTs, it is possible to define which are more reflective or transparent than others and how strong their dependency on the frequency is. Such knowledge may help to decide how to deploy antennas to optimise coverage using the properties of materials in the given room or which materials should be used when additional blockage or reflection is needed in the environment (in the case when it is possible to introduce or remove some objects). Thus, it is not about defining which materials are the best, taking into account radio signal propagation, but rather how to use them, knowing their properties. To make a comparison, the mean values of TL and RL for each material in each of the two measured bands are shown in Fig. 10. Each MUT is represented by a dot of the same colour as in the previous figures.

Dotted horizontal lines in Fig. 10 represent contractual values to differentiate MUTs with lower- and higher-transparency/reflectivity properties. The values were chosen by the visual observation of the graphs, and they are not general - they correspond to the MUTs measured in this study. Due to the different spread of mean values obtained for TL and RL, different values were applied for their comparison: 2 dB, 8 dB, and 20 dB were used for transmission properties, and 5 dB, 15 dB, and 20 dB for reflective properties. Note that for TL no MUT has values between 15.5 dB and 25 dB, and for RL there are no materials with values reported between 3.5 dB and 8 dB.

For most MUTs, the mean values of TL and RL lie within the same limits in Band 1 and Band 2. Thus, they introduce a similar level of loss at all measured frequencies. The observed changes between Band 1 and Band 2 are more frequent for TL than RL. The largest difference between μ_{TL} in Band 1 and Band 2 is observed for MUT (#9): TL changes from 8-20 dB

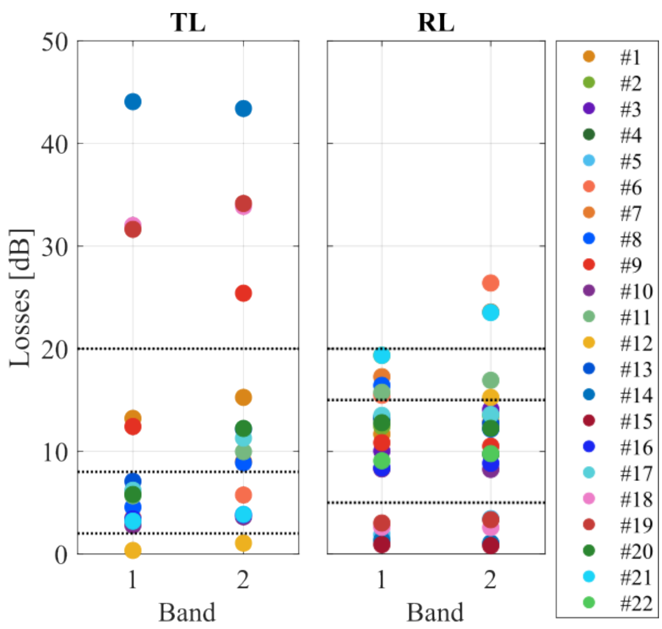

Fig. 10. Grouping of reflective and transmissive materials.

(strongly blocking) to above 20 dB (very strongly blocking the signal). It is noted in Table VI. For six more MUTs, the mean value changes from 2-8 dB to 8-20 dB. However, for RL only four MUTs change their properties. For #10 the mean value of RL is lower in Band 2 (almost not noticeably). For #6, #7, and #21 the μ_{RL} is visibly higher in Band 2.

TABLE VI
DIFFERENCE IN μ_{TL} BETWEEN BANDS.

$\mu_{TL,B2} - \mu_{TL,B1}$	MUT #ID
< 1 dB	I2I glass (#10, #16), ceiling panel (#12), upholstery chair with plastic (#21)
$1 - 3$ dB	wood door (#2), pinewood piece (#6), chair made of pinewood and textile (#7), window with and without a blinder (#18, #19)
$4 - 6.5$ dB	drywall (#8), upholstery chair (#11), desk (#13), table (#17), wardrobe (#20)
12 dB	room divider (#9)

The mean TL for all MUTs (except #14 whiteboard) increased in Band 2. It has to be noted, however, that in the case of #14, the TL in Band 2 is less than 1 dB lower than in Band 1, and the values obtained above 33 GHz exceeds the dynamic range of the measurements because no signal was received.

Each material is characterised by the different increase in the mean TL value in Band 2. The changes are summarised in Table VI. The smallest changes, below 1 dB, are observed for I2I glass (#10, #16), ceiling panel (#12), and upholstered chair with plastic (#21). The largest difference, 12 dB, was observed for the room divider (#19).

For RL, for half of the MUTs, the mean value is higher in Band 1 and for the other half, in Band 2. Therefore, values given in Table VII show absolute differences.

TABLE VII
DIFFERENCE IN μ_{RL} BETWEEN BANDS.

$\lvert\mu_{RL,B2} - \mu_{RL,B1}\rvert$	MUT #ID
< 1dB	glass (#10, #16, #18, #19), desk, table, and wardrobe made of chipboard (#13, #17, #20), room divider (#9), standalone whiteboards (#14, #15), concrete wall (#22)
$1 - 4.3$ dB	wood door (#2), chairs (#11, #21), walls (#1, #3, #8), screen (#4), whiteboard (#5), ceiling panel (#12)
> 6 dB	pinewood piece (#6), chair made of pinewood and textile (#7)

IV. CONCLUSIONS

This study examines the transmission loss (TL) and reflection loss (RL) of various materials commonly used in indoor environments, specifically within the 26–40 GHz (Band 1) and 55–65 GHz (Band 2) frequency ranges. A total of 22 materials were tested and categorised into five classes: walls, wood, glass, chairs, and other objects. The results highlight key differences in how materials interact with signals at these frequencies, with important implications for wireless communication design, particularly for 5G networks.

It is confirmed that TL generally increases at higher frequencies. Results obtained in Band 2 showed greater attenuation than in Band 1, with the room divider experiencing the largest increase of 12 dB between the two bands. In contrast, materials such as I2I glass, ceiling panels, and plastic-upholstered chairs showed slight variation in TL, remaining within 1 dB across both bands. Thicker wood samples tended to exhibit higher TL values, especially in Band 2, aligning with previous research. Nevertheless, drywall showed moderate TL, which increased at higher frequencies, confirming the trend observed in other layered materials.

The study also revealed distinct patterns in RL, which behaved differently from TL. Some materials reflected more in Band 1, whereas others had higher RL in Band 2. Glass samples, in particular, showed varying characteristics: single-layer I2I glass had low TL but fluctuating RL. In contrast, Double-Paned O2I glass windows exhibited consistently high TL with stable RL across both bands. It is important to note that these results were obtained for incidence and reflection angles of 30°; thus, other setups should be further studied.

Other materials showed contrasting behaviours. Whiteboards had high TL but low RL, whereas ceiling panels exhibited the opposite—low TL but high RL. Interestingly, RL values varied more in Band 1 than Band 2, possibly due to material composition and surface geometry affecting signal reflections at lower mmWave frequencies.

Performed analysis emphasise the need to consider material properties when designing indoor mmWave networks. The increased TL at higher frequencies suggests that environments with dense structures or multiple partitions may require additional repeater nodes or intelligent reflecting surfaces to maintain reliable connectivity. Similarly, the variations in RL highlight the importance of adaptive beamforming and strategic placement of access points, particularly in non-line-of-sight (NLOS) conditions.

Further research should explore how RL and TL change based on different angles of incidence, as this could provide a clearer picture of signal behaviour across various materials. full-angle reflection measurements would be a valuable direction for future research to support accurate ray-tracing modeling. Studying multi-layer materials, such as reinforced glass or metal-coated surfaces, would help refine models for real-world applications. Additionally, examining environmental factors like humidity and temperature could offer insights into their effects on signal propagation. Finally, testing these findings in an actual mmWave network setup will be crucial for evaluating their practical impact on wireless system performance.

References

[1] IEEE, "IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band," IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012), pp. 1–628, 2012. [Online]. Available: doi:10.1109/IEEESTD.2012.6392842

[2] ——, "IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks–Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhanced Throughput for Operation in License-exempt Bands above 45 GHz," IEEE Std 802.11ay-2021 (Amendment to IEEE Std 802.11-2020 as amendment by IEEE Std 802.11ax-2021), pp. 1–768, 2021. [Online]. Available: doi:10.1109/IEEESTD.2021.9502046

[3] K. Sato, T. Manabe, T. Ihara, H. Saito, S. Ito, T. Tanaka, K. Sugai, N. Ohmi, Y. Murakami, M. Shibayama *et al.*, "Measurements of reflection and transmission characteristics of interior structures of office building in the 60-GHz band," *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 12, pp. 1783–1792, 1997. [Online]. Available: doi:10.1109/8.650196

[4] S. A. M. Tariq, C. Despins, S. Affes, and C. Nerguizian, "Scattering effect based on measurements of reflection coefficients at 60 GHz in an underground mine gallery," in *2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*. IEEE, 2014, pp. 217–221. [Online]. Available: doi:10.1109/PIMRC.2014.7136163

[5] S. El Faitori and S. Salous, "Reflection and penetration loss wideband measurements of building materials at 28 GHz and 39 GHz," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*. IEEE, 2022, pp. 1–4. [Online]. Available: doi:10.23919/EuCAP53622.2022.9769651

[6] C. R. Anderson and T. S. Rappaport, "In-building wideband partition loss measurements at 2.5 and 60 GHz," *IEEE Transactions on Wireless Communications*, vol. 3, no. 3, pp. 922–928, 2004. [Online]. Available: doi:10.1109/TWC.2004.826328

[7] S. Kodra, M. Barbiroli, E. M. Vitucci, F. Fuschini, and V. Degli-Esposti, "Mm-wave building penetration losses: A measurement based critical analysis," *IEEE Open Journal of Antennas and Propagation*, vol. 5, pp. 535–544, 2024. [Online]. Available: doi:10.1109/OJAP.2024.3355817

[8] C. A. Diakhate, J.-M. Conrat, J.-C. Cousin, and A. Sibille, "Millimeter-wave outdoor-to-indoor channel measurements at 3, 10, 17 and 60 GHz," in *2017 11th European Conference on Antennas and Propagation (EuCAP)*. IEEE, 2017, pp. 1798–1802. [Online]. Available: doi:10.23919/EuCAP.2017.7928696

[9] C. E. O. Vargas, L. da Silva Mello, and R. C. Rodriguez, "Measurements of construction materials penetration losses at frequencies from 26.5 GHz to 40 GHz," in *2017 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM)*. IEEE, 2017, pp. 1–4. [Online]. Available: doi:10.1109/PACRIM.2017.8121917

[10] M. A. Aliouane, J.-M. Conrat, J.-C. Cousin, and X. Begaud, "Indoor material transmission measurements between 2 GHz and 170 GHz for 6g wireless communication systems," in *2022 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE, 2022, pp. 43–48. [Online]. Available: doi:10.23919/EuCAP53622.2022.9769465

[11] ——, "Material reflection measurements in centimeter and millimeter wave ranges for 6g wireless communications," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*. IEEE, 2022, pp. 1–5. [Online]. Available: doi:10.1109/EuCNC/6GSummit54941.2022.9815763

[12] ITU-R P.2040-3, "Effects of building materials and structures on radiowave propagation above about 100 MHz," 2023, accessed: 09.05.2025. [Online]. Available: https://www.itu.int/rec/R-REC-P.2040-3-202308-S/en

[13] J.-M. Conrat, M. A. Aliouane, J.-C. Cousin, and X. Begaud, "Material permittivity and conductivity estimation from 2 to 260 GHz and extension of the itu-r p. 2040 model at frequency above 100 GHz," in *2024 IEEE 35th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE, 2024, pp. 1–6. [Online]. Available: doi:10.1109/PIMRC59610.2024.10817451

[14] M. Drozdowska, S. J. Ambroziak, K. K. Cwalina, P. Rajchowski, and N. Cardona, "Channel impulse response measurements at mmwave band in office and conference rooms," in *2023 XXXV URSI General Assembly and Scientific Symposium (URSI GASS)*. IEEE, 2023, pp. 1–5. [Online]. Available: doi:10.23919/URSIGASS57860.2023.10265350

[15] Keysight, "Keysight PNA network analyzer N5227B 900 Hz to 67 GHz," 2022, accessed: 09.05.2025. [Online]. Available: https://www.keysight.com/us/en/assets/9018-04327/technical-specifications/9018-04327.pdf

[16] RF Spin, "Double ridged horn antenna; model DRH67," accessed: 09.05.2025. [Online]. Available: https://www.rfspin.com/product/drh67/

[17] ITU-R P.341-7, "The concept of transmission loss for radio links," Aug. 2019, accessed: 09.05.2025. [Online]. Available: https://www.itu.int/rec/R-REC-P.341-7-201908-I/en

[18] Y. Geng, V. Yajnanarayana, A. Behravan, E. Dahlman, and D. Shrestha, "Study of reflection-lass-based material identification from common building surfaces," in *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE, 2021, pp. 526–531. [Online]. Available: doi:10.1109/EuCNC/6GSummit51104.2021.9482524

[19] J. T. C. Seng, J. J. Tiang, S. Muhammad, and Y. C. Lo, "Investigation and enhancement of radio frequency signal losses of glassy window," *IEEE Access*, vol. 12, pp. 145 749–145 763, 2024. [Online]. Available: doi:10.1109/ACCESS.2024.3469631