Indoor Material Transmission Measurements between 2 GHz and 170 GHz for 6G Wireless Communication Systems

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Abstract—The sixth-generation wireless communication research activities were launched worldwide. A tendency of some researchers to use the sub-terahertz frequency band for 6G is noticed. This frequency band is selected as a candidate for 6G due to its remarkable wide unused frequency bandwidth. In this paper, typical indoor environment material transmission measurements from 2 GHz to 170 GHz are presented. These measurements aim to further understand and compare wave-material interaction for above and below 100 GHz frequencies by providing a continuous measurement up to 170 GHz of 16 different materials (e.g. glass, plasterboard, concrete, and wooden materials). The measurement system is based on a vector network analyzer, with frequency extension modules for frequencies above 50 GHz.

Index Terms—Measurements, 6G, Sub-THz, propagation, wave-material interaction.

I. INTRODUCTION

Starting a few decades ago, mobile communication systems showed significant development that transformed human society and the life of billions of people. With its evolution decade after decade, the year 2010 witnesses the launch of 4G commercial services. In 2020, the world marked the rollout of 5G mobile communication targeting frequencies up to 71 GHz [1]. In the meantime, 6G wireless communication research activities rolled off worldwide. In Europe, many research projects, such as the European 6G flagship Hexa-X project [2], were launched to investigate 6G requirements, use cases, and key enabling technologies and hardware.

Nowadays, among all 6G research, THz communication, which refers to communications utilizing frequencies from 300 GHz to 3 THz [3], is envisioned as one of the key enablers of future wireless communication technologies [4] [5]. Some researchers tend to use the term sub-THz or upper mmW for frequencies 100 - 300 GHz [6]. The sub-THz band is seen as a promising band for 6G wireless communication systems [5] due to the wide unused available bandwidth, and the low atmospheric absorptions and rain attenuation compared to above 300 GHz frequencies.

Considering indoor environments, 6G use cases target the use of high throughput access points utilizing sub-THz frequencies [7]. On below 100 GHz frequencies, several papers reported studies, measurements, and analyses of the propagation channel and wave interaction with materials that could be found in an indoor environment. The International Telecommunication Union recommendation (ITU-R) P.2040 [8] specified the characteristics of building materials and structures affecting radio wave propagation up to 100 GHz. In [9], penetration loss measurements and analysis of different glazing structures from single to quadruple glazed units with and without low emissivity coating were investigated in the frequency band 4 GHz - 95GHZ. In [10], measurements of both transmission and reflection coefficients were performed at 5.8 GHz and 62.4 GHz to characterize the electromagnetic properties of typical building materials. Reflection and scattering measurements at 60 GHz of several painted and unpainted common building materials were analyzed in [11].

Whereas, few documents dealing with indoor material measurements for above 100 GHz frequencies are found in the literature. Transmission measurements of typical building materials up to 330 GHz with a special focus on glass window elements were performed and analyzed in [12]. In [13], measurements of the frequency-dependent refractive index and absorption coefficient of a variety of common building and plastic materials were investigated between 100 GHz and 1 THz. Reference [14] described the penetration loss measurement at 300 GHz of several building materials for building entry loss estimation. Finally, frequency dependency of building shadowing and scattering effect measurements from a rough building surface up to 150 GHz were reported in [15].

However, to the best of our knowledge, no paper in the literature reported a continuous transmission measurement of indoor building materials from a few GHz up to the sub-THz band. Therefore, this paper aims to provide continuous transmission measurements of some building materials of an indoor environment (such as glass, wood, plasterboard, plastic, concrete and ceramic) from a few GHz up to 170 GHz. The obtained results will give an insight to researchers of the propagation channel behavior and wave-material interaction above 100 GHz compared to below 100 GHz frequencies, and allow a comprehensive study and analysis of the sub-THz band up to 170 GHz for 6G wireless communication applications.

II. MEASUREMENT SYSTEM AND PROCEDURE

The measurement system available at Orange Labs is a Vector Network Analyser (VNA) based system. For the measurement campaigns illustrated in this paper, two VNAs were used to continuously cover the frequency band 2 GHz -
TABLE I. Measurement equipment for different frequency band selection

| Frequency band  | VNA                  | Frequency extenders | Waveguide - Connector standard | Antenna                      | Gain   |
|-----------------|----------------------|--------------------|-------------------------------|------------------------------|--------|
| 2 GHz - 12 GHz  | Rohde & Schwarz ZVA-40 | No                 | SMA                           | Dual ridge horns SH800       | 6 - 15 dBi |
| 12 GHz - 30 GHz |                       | Coolant PNA-67     | WR15                          | Flann Microwave horns 23240-25 | 25 dBi |
| 30 GHz - 50 GHz | Keysight PNA-67      | No                 | SMA                           | Dual ridge horns SH2000       | 6 - 15 dBi |
| 50 GHz - 75 GHz | Rohde & Schwarz ZVA-40 | V15VNA2            | WR15                          | Flann Microwave horns 25240-20 | 20 dBi |
| 75 GHz - 110 GHz| Keysight PNA-67      | No                 | WR10                          | Flann Microwave horns 27240-20 | 20 dBi |
| 110 GHz - 170 GHz| VDI E8257DV06        | No                 | WR6.5                         | Millitech horns SGH-06       | 25 dBi |

170 GHz. As the measured frequency band is significantly wide. The measurements were done in sub-bands with adaptable equipment for each band. The Rohde & Schwarz ZVA 40 four ports VNA was used to measure frequencies from 2 GHz to 30 GHz and from 50 GHz to 170GHz, whereas the Keysight PNA 67 two ports network analyzer was used to measure the frequency band gap 30 - 50 GHz. Above 50 GHz, frequency extenders were used to cover the frequency bands: 50 GHz - 75 GHz (Waveguide Rectangular 15 (WR15) ), 75 GHz - 110 GHz (WR10), and 110 GHz - 170 GHz (WR6.5).

VNA maximal power was set between -5 dBm and 10 dBm depending on the frequency band, and intermediate frequency (IF) bandwidth to 1 kHz. Table I resumes all appropriate equipment used for each frequency band. The frequency extenders were connected to the ZVA 40 VNA, where Tx extenders are connected to the source and Rx extenders to the meas of ports 1 and 2, whereas the local oscillator (LO) signal of both extenders was driven by the source of ports 3 and 4.

The available measurement system allows transmission and reflection coefficient measurements of different materials under test (MUT) at normal incidence for the frequency range 2 - 170 GHz. Fig.1 shows a general schematic of the measurement setup that includes: VNA, antennas, and frequency extenders. In this paper, we will focus on transmission measurements only. All the measurements were done in a complex indoor space. The holding system for antennas and frequency extenders is illustrated in Fig.2. It consists of two pillars with fixation support at the height of 1.62m. The first pillar is set to a linear mechanical rail so that it can move along a horizontal axis (x-axis), and its equipment holder height is fixed. The second equipment holder is set to move on a 2-dimensional plane y-z. The distance between the two measurement equipment is adjusted by the horizontal movement, and the 2-D positioner configures the face-to-face alignment. After the alignment of antennas, the distance between the two antennas is set to 1m.

A specific material sample holder was fabricated to hold the materials under test at normal incidence and at a fixed position during the whole measurement process. The material sample holder of dimensions 1.50 m x 1.50 m with a square hole of 50 cm x 50 cm sculpted in its center to allow material samples to fit inside, illustrated in Fig.3, is placed in the middle between the two antennas. The absorbing side faces the transmit antenna. This support allows to hold the different kinds of materials with different weights and thicknesses and mainly to minimize the diffractions around the material sample edges and to eliminate other undesired reflected or diffracted components near the direct trajectory of the wave (at a relative distance of 80 cm or relative delay of 2.67 ns with respect to the direct path).

Materials that could build an indoor environment, such as glass, wood, concrete, and plasterboard, were investigated. Table II illustrates the set of available material samples of dimensions 50cm x 50cm and their thickness.
The measurements were performed based on free space (FS) measurement method. For each frequency sub-band, the measurement process consisted of three steps. First, the measurement setup was adjusted, the VNA was configured, and antennas with frequency extenders above 50 GHz were set on the equipment holder. Second, an FS transmission measurement \( S_{FS} \) that is considered as a reference measurement for all transmission measurements was carried out. Third, the material holder was placed between the two antennas, and the materials were measured. The raw material measurement refers to \( S_{Meas} \). Once done, the system is reconfigured for a higher frequency band with the dedicated antennas and frequency extender modules. Then, the same process is applied.

### III. POST PROCESSING METHOD

This section shows the applied data post-processing method to obtain the intrinsic material response in terms of transmission coefficients for the frequency range 2 GHz - 170 GHz. Sixteen different materials were measured and their raw transmission data were collected in addition to the FS measurement. The post-processing was performed in three steps. The first step is to eliminate all possible undesired components from the complex environment, such as reflections, diffractions, or scatters of the transmitted wave that were not blocked by the material holder absorbers while keeping the useful components from the material response. For this purpose, a Time-Domain Gating (TDG) technique is used [16]. The Time Domain Impulse Response of reference and material measurements are computed from the raw \( S_{21} \) measurements and time-gated as illustrated in Fig.4 that shows a TDG window applied to plexiglass on the frequency band 30 GHz - 50 GHz. The TDG window size considers the dimensions of the material samples to preserve material response and all possible internal reflections. It also considers the dimensions of the material holder to reject all complex environment components. For these reasons, a window size of 3 ns centered around the peak corresponding to the direct path is selected. We denote by \( S_{21}^{Meas} \) and \( S_{FS}^{Meas} \) the frequency domain responses of time-gated IR of free space and material measurements, respectively.

The second step is to normalize material measurements with respect to the reference measurement. This step removes the effect of free space path loss, cables, antennas, and frequency extenders losses from the raw measurements. The normalized measurement \( S_{Meas}^{MUT} \) corresponding to the pure material responses is computed from equation 1.

\[
S_{Meas}^{MUT}(f) = \frac{S_{Meas}^{Meas} - S_{FS}^{Meas}}{S_{FS}^{Meas}}
\]

In the last step, a second TDG is applied to the Inverse Fourier Transform of \( S_{Meas}^{MUT} \). It aims to conserve a specific part of the normalized IR as the direct path component or the internal multi-reflections from the material. In the framework of this paper, no selection is applied, and the second TDG was only used to improve noise reduction and undesired rejection while conserving the response of all material components. For this purpose, a window size of 2 ns is selected. Fig.5 illustrates an example of this process applied to plexiglass on the frequency range 30-50 GHz.

This process is applied to the six sub-bands listed in Table I. Finally, results from sub-bands analysis are joined together to form continuous material transmission coefficients response for the frequency band 2 - 170 GHz. The obtained results are presented in the next section.

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**TABLE II.** Measured material samples and their thickness

| Material                        | Thickness |
|---------------------------------|-----------|
| Laminated Glass                 | 8 mm      |
| Blurred Glass                   | 3 mm      |
| Plexiglass                      | 19 mm     |
| Composite fiber panel           | 14 mm     |
| Plywood                         | 22 mm     |
| Laminated Wood                  | 22 mm     |
| Medium density fibreboard (MDF) | 22 mm     |
| Plasterboard BA13               | 13 mm     |
| Plasterboard BA18               | 18 mm     |
| Plasterboard Duotech19          | 19 mm     |
| Mortar (Cement+sand)            | 22 mm     |
| Glass wool                      | 19 mm     |
| Polystyrene                     | 19 mm     |
| Floor vinyl tile                | 4 mm      |
| Floor ceramic tile              | 8 mm      |
| Office carpet                   | 4 mm      |

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![Fig. 4: Raw Impulse Response of plexiglass transmission coefficient for the frequency band 30 GHz - 50 GHz.](image)
of internal reflections will be considered in future studies. When the periodical oscillations were observed. The analysis internal reflections. The results are in agreement with [9] Also, periodic oscillations are observed. It might be due to natural mineral glass attenuates more than organic glass. An average attenuation of 8 dB at 100 GHz. It is remarked that presents the highest attenuations in this collection with an thickness. The laminated glass panel of 8 mm thickness above 100 GHz even though the fiber panel has smaller frequency band. This is due to their homogeneity. The composite fiber attenuations are at an equivalent level with the plexiglass for below 100 GHz frequencies. However, they are relatively more important when the frequency increases above 100 GHz even though the fiber panel has smaller thickness. The laminated glass panel of 8 mm thickness presents the highest attenuations in this collection with an average attenuation of 8 dB at 100 GHz. It is remarked that natural mineral glass attenuates more than organic glass. Also, periodic oscillations are observed. It might be due to internal reflections. The results are in agreement with [9] when the periodical oscillations were observed. The analysis of internal reflections will be considered in future studies.

IV. MEASUREMENT RESULTS AND ANALYSIS
In what follows, we present the transmission frequency responses of the measured materials. Results are grouped and presented in material collections. Each collection of materials has similar construction properties or similar utilities.

The considered glass collection includes a laminated glass panel composed of two pure mineral glass layers of 4 mm thickness with plastic film inserted in between and without metallic coating, blurred mineral glass, a plexiglass (organic glass) panel, and a composite fiber panel, with similar construction composition to plexiglass, made of 30% of a blend of plant fibers and 40% of polymers. Fig.6 illustrates the frequency response of the above-listed materials. It is noticed that the frequency response behavior of these materials is quasi similar along the whole measured frequency band. This is due to their homogeneity. The composite fiber attenuations are at an equivalent level with the plexiglass for below 100 GHz frequencies. However, they are relatively more important when the frequency increases above 100 GHz even though the fiber panel has smaller thickness. The laminated glass panel of 8 mm thickness presents the highest attenuations in this collection with an average attenuation of 8 dB at 100 GHz. It is remarked that natural mineral glass attenuates more than organic glass. Also, periodic oscillations are observed. It might be due to internal reflections. The results are in agreement with [9] when the periodical oscillations were observed. The analysis of internal reflections will be considered in future studies.

The measurement results of three different wooden panels (MDF, plywood, and laminated wood) of 22 mm thickness are shown in Fig.7. For above 100 GHz frequencies, the laminated wood exhibits significant attenuation compared to the other wooden boards where the transmission coefficient is less than -20 dB. Whereas the plywood and the MDF attenuations are comparable, they range between 12 dB and 28 dB. The composite fiber has a common utility in indoor environments as wooden materials. It allows frequencies higher than 100 GHz to penetrate without significant losses where it reaches 5 dB of average attenuation at 170 GHz. Therefore, it would be beneficial to use organic materials rather than wooden ones when considering low transmission losses at above 100 GHz frequencies for furnishing an indoor environment.

Regarding wall materials, four different plasterboard plates and a mortar board composed of cement and sand were measured. Fig.8 shows the obtained results, whereas Fig.9 presents the measurement results of ceiling tile insulation plates (glass wool and polystyrene) and floor tile panels (ceramic tile, vinyl tile, and office carpet). In general, and as expected, the transmission coefficients decrease with the frequency increase but not in a regular manner for all materials. Irregular oscillations are observed for plasterboard, wooden materials, and insulation plates due to their heterogeneous structure. Some attenuation gaps between the measured frequency bands are also observed. For example, the mortar presents a discontinuity at 50 GHz and the glass wool at 75 GHz. It might be explained by the material non-homogeneity as the material holder was repositioned for each sub-band measurements and the exact position was not maintained from one band measurement to another. In addition to that, materials were repositioned for each series of measurement and a non-intentional rotation of materials might happen from one measurement to another. These factors depict some of the encountered difficulties when performing the measurements. Also, for above 100 GHz, several frequency selectivities were noticed for mortar, ceramic tile, and laminated wood. No clear physical reasons were found to explain such a phenomenon. It is under investigation with the analysis of the reflection coefficients. Polystyrene presents lower penetration losses than glass wool, and both are considered efficient thermal insulators.
As the polystyrene allows the transmitted waves almost completely to penetrate with penetration losses around 0 dB for the whole measured band, it is useful to be chosen when considering low penetrations through walls or roofs. The plasterboard exhibits minor attenuations. For example, the BA13 attenuations are less than 6 dB even at 170 GHz. With the transparency of the glass wool, it would be useful to construct indoor walls with plasterboard and glass wool as thermal and sound insulator.

Fig. 8: Measurement results of plasterboard and concrete

Fig. 9: Measurement results of Insulation plates and floor tile panels

V. CONCLUSION

In this paper, we presented material transmission measurements in the frequency band 2 GHz - 170 GHz. Sixteen different material samples that could be found in an indoor environment were measured. The study focused on comparing material transmission coefficients continuously through the measured band. Results showed a change of behavior of some materials above 100 GHz.

In future work, reflection measurements will be analyzed to furthermore understand the wave-material interaction mainly above 100 GHz. The measurements that are illustrated in this paper were performed at a fixed position throughout the whole process. For the sake of investigating the impact of materials heterogeneity on wave-material interaction, material measurements with variation in y-z positions will also be considered in future studies.

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