Abstract—In this paper, the reflection characteristics of the house flooring construction materials at MilliMeter-Wave (MMW) frequencies are studied. Since this investigation is performed for North American housing, the 57-64 GHz frequency band is considered. In this study, three common flooring materials: hardwood, vinyl and carpet (cut- and loop-pile) are chosen. The reflection characteristics of the aforementioned materials are also measured when the supporting materials, i.e. plywood and underpad, exist. A Continues Wave (CW) transmit-receive measurement setup with measuring possibility of entire range of 57-64 GHz is employed. The reflection coefficient for all available incident angle and transmission loss for face-to-face antenna direction are measured for the chosen flooring materials. The relative permittivity associated to these materials based on the Fresnel’s reflection formula are found. Moreover, the results reveal the frequency dependence of the flooring materials within 57-64 GHz.

Index Terms—Communication channels, multipath channels, MilliMeter-Wave (MMW), reflection coefficient.

I. INTRODUCTION

Recently, there has been an increasing interest in providing broadband communications in the 57-64 GHz unlicensed band for Wireless Local Area Networks (WLANs). A wide available spectrum, e.g. 57-64 GHz for North American services, surrounding the 60 GHz operating frequency has the ability to support high-rate broadband wireless systems such as voice, data, and full-motion real-time video for home entertainment applications [1]. Due to special propagation properties at this frequency range such as high absorption loss, there is an improved frequency reuse compared to the lower frequencies. However, multipath effects still exist for indoor applications and they must be precisely characterized for diversity transmission purposes. Hence, the characterization and modeling of radio propagation channel of MilliMeter-Waves (MMWs) is an essential step in the design of these future systems [2].

There are several published studies of the 60 GHz propagation for indoor channels. Different aspects of the 60 GHz propagation channel were investigated in these measurement based campaigns [2]-[8]. Basically, all these results help to improve the channel models designed for the simulation of radio systems at these frequencies. Modeling approaches can be categorized as deterministic, semi-deterministic, and empirical modeling. However, deterministic modeling such as ray-tracing method has shown very close results to the measurement ones for high frequency, e.g. MMW applications. In this type of modeling, the electromagnetic characteristics of the propagation environment must be perfectly defined. In other words, we need to find the propagation properties of the materials used in the indoor structure. The transmission and reflection are two dominant phenomena which are usually being considered in this regard. Since these models are mainly developed based on the empirical approach, extensive measurement campaigns with large amounts of data in different environments are required.

To the best of authors’ knowledge, only a few papers were published on the transmission and reflection coefficient measurements at 60 GHz. Langen et al. [9] conducted one of the earliest studies of the reflection and transmission characteristics of the building materials at MMW frequencies on the basis of power measurements. The authors in [10] estimated the complex permittivity from the data reported in [9]. The results reported in [10] are currently being used in one of the most well-known ray-tracing softwares, namely, the Radiowave Propagation Simulator (RPS) [11]. In another measurement campaign [12], the reflection and transmission coefficients of the interior parts in an office environment at 57.5 GHz were reported. Hashimoto et al. [13] obtained the complex permittivity of the radome materials for automotive radar applications. However, there is no measured data reported for home construction materials particularly for North American houses. Moreover, all the above research studies were only performed at single frequency within MMW frequency band, while the channel can be highly frequency selective due to the frequency dependence of the channel construction materials. Frequency selectivity is an important issue in broadband communication systems, and it may remarkably damage the signal integrity. One common way to characterize channel frequency selectivity is to study the frequency dependence of the channel components. Thanks to the special propagation properties at MMW frequency band, for which free space propagation and reflection are the dominant propagation factors, this characterization becomes feasible.

The objective of this paper is to study the reflection coefficient of the house flooring materials at 60 GHz frequency band. The material samples are chosen from those typically used in an North American style house and therefore we consider 57-64 GHz frequency band which is defined for North American services. Three common flooring materials: hardwood, vinyl and carpet (cut- and loop-pile) are chosen for this study. However, the reflection characteristics of the
The reflection coefficient and transmission loss for face-to-face antenna direction are measured for all the flooring materials. Furthermore, the relative permittivity is estimated for different materials based on the Fresnel’s reflection formula for all the frequencies within 57-64 GHz band in order to demonstrate the frequency selectivity of the reflection coefficient for the flooring materials.

The results show that there is no significant difference between cut- and loop-pile carpets in terms of MMW signal reflection. Supporting the carpets with a plywood layer increases the reflectivity of a house floor; however, the reflection coefficient is reduced when an underpad material is placed between the carpet and plywood layers. A vinyl floor represents a very reflective floor construction material where its reflection coefficient is highly frequency-dependent when compared with the other flooring materials. Moreover, a plywood supporting layer can reduce the frequency dependence of vinyl while enhancing this factor for the carpet flooring.

The rest of the paper is organized as follows. Section II presents the reflection model for a single layer material. The measurement setup is described in Section III. Section IV summarizes the measurement results. We provide the relative permittivity results estimated for all materials at different frequencies in Section V. Finally, Section VI states the conclusions.

II. REFLECTION MODEL

The reflection coefficients of the sample materials are measured for specular reflection scenario, i.e. where the angle of incidence equals the angle of reflection (see Fig. 1). In this case, the reflection coefficient for a single layer sample can be represented as [14]

$$\Gamma = \frac{1 - e^{-j2\delta}}{1 - e^{-j2\delta} \Gamma', \text{ for } i \in \{\perp, \parallel\}}$$  \hspace{1cm} (1)

where $\delta = \frac{2\pi d}{\lambda} \sqrt{\epsilon_r - \sin^2 \theta}$, $\lambda$ is the wavelength in free space, $d$ is the thickness of the sample plate, $\epsilon_r$ is the relative permittivity of the sample plate, and $\theta$ is the angle of incidence. Moreover, $\Gamma'_\perp$ and $\Gamma'_\parallel$ denote the Fresnel’s reflection coefficients for the interface between air and a dielectric material when the electric field is perpendicular and parallel to the plane of incidence, respectively. We define the plane of incidence as the plane including the wave propagation direction and the normal to the sample surface. The $\Gamma'_\perp$ and $\Gamma'_\parallel$ coefficients are given by [14]

$$\Gamma'_\perp = \frac{\cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}}$$  \hspace{1cm} (2)

and

$$\Gamma'_\parallel = \frac{\epsilon_r \cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\epsilon_r \cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}}$$  \hspace{1cm} (3)

III. MEASUREMENT SETUP

The configuration of the experimental system is shown in Fig. 1. The CW wave produced by Agilent E8257D PSG Signal Generator [15] is directly sent to a standard gain, measured 23.5 dB at 60 GHz, pyramidal V-band horn antenna [16]. The signal generator can provide a tested maximum 10 dBm unclipped waveform at its output port. To send the signal to the horn antenna we use a 4-feet low loss, i.e. about 10 dB loss in total at 60 GHz, flex 1.85 mm coaxial cable [17]. The horn antenna is connected to the cable via a QWA-15 V-band adapter [16]. The insertion loss of this adapter is...
about 1.5 dB at 60 GHz. The wave reflected from the sample is down-converted by Agilent 11970V Waveguide Harmonic Mixer [15] and observed by Agilent E4448A PSA Spectrum Analyzer [15]. The mixer Local Oscillator (LO) input is driven by the spectrum analyzer. Fig. 2 shows the actual setup used for the measurement.

To avoid receiving a dominant direct wave by the receiving antenna from the transmitting antenna when the incident angle is large, and the mutual coupling effect between the transmitting and receiving antennas when the incident angle is small, the incident angle is restricted between 10° and 65° with 5° resolution. The transmitting-receiving horn antennas are put on two arms such that the transmitted wave reflects at the center of the sample plate.

The measurement setup is set for the perpendicular polarization, i.e. where the electric field is perpendicular to the plane of incidence, as shown in Fig. 2. The distance between the horn antenna and sample, and the sample size are chosen based on the horn antenna specifications. The horn antennas used for transmitting and receiving have an aperture size of 37.8 × 29.2 mm², and a measured 3 dB beam-width 11.3°−11.8° for 57-64 GHz. For this reason, we chose a 60 cm antenna-sample distance based on the antenna aperture size in order to have a plane wave at the sample surface. Moreover, the measurement samples size was set to 40 × 34 cm² based on the 3 dB beam-width. To combat any possible multipath received by the receiving antenna, we used LF-77 electromagnetic absorbers [18] of size 24 × 24 × 2.25 in³.

The house flooring samples considered in this study are classified into four main groups: cut-pile carpets, loop-pile carpets, hardwood, and vinyl. Each group gains with/without supporting materials: plywood and underpad, as they are being used in North-American constructions. Fig. 3 shows these four groups.

IV. MEASUREMENT RESULTS

A. Transmission Loss

For the measurement of the transmission coefficient, the transmitter and receiver face each other at 1.2 m distance and the sample is placed midway between them. The transmission coefficient is obtained by comparing the received power measured with and without a sample. The undesired diffraction and reflection were carefully suppressed by using the radio absorbers. Table I shows the results for different samples and configurations: No Plywood (NP), With Plywood (WP), and With Underpad and Plywood (WUP). As expected, the carpet samples show the lowest transmission loss and the hardwood configurations have the largest loss among the samples regardless of the thickness which is surely an important factor in this loss. Moreover, the results show that the underpad layer as a supporting material does not have a significant impact on the transmission loss while the plywood layer does.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>Configuration</th>
<th>Thickness (mm)</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>carpet I (cut-pile)</td>
<td>NP</td>
<td>12</td>
<td>0.9</td>
</tr>
<tr>
<td>carpet I (cut-pile)</td>
<td>WP</td>
<td>23.6</td>
<td>4.7</td>
</tr>
<tr>
<td>carpet I (cut-pile)</td>
<td>WUP</td>
<td>31.8</td>
<td>6</td>
</tr>
<tr>
<td>carpet II (loop-pile)</td>
<td>NP</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>carpet II (loop-pile)</td>
<td>WP</td>
<td>21.6</td>
<td>3.9</td>
</tr>
<tr>
<td>carpet II (loop-pile)</td>
<td>WUP</td>
<td>29.8</td>
<td>4.6</td>
</tr>
<tr>
<td>hardwood</td>
<td>NP</td>
<td>18</td>
<td>9.1</td>
</tr>
<tr>
<td>hardwood</td>
<td>WP</td>
<td>29.6</td>
<td>18.3</td>
</tr>
<tr>
<td>vinyl</td>
<td>NP</td>
<td>2.6</td>
<td>1.8</td>
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<tr>
<td>vinyl</td>
<td>WP</td>
<td>14.2</td>
<td>7.8</td>
</tr>
</tbody>
</table>
B. Reflection Coefficient

The absolute value of the reflection coefficient is calculated by comparing the received power at different frequencies (57-64 GHz) for reflection from a sample plate with that of an aluminum plate (whose absolute value of the reflection coefficient is considered to be 1). Fig. 4 reveals the measured reflection coefficient for carpet I (cut-pile) with different configurations at 60 GHz. Moreover, the reflection coefficient (1) is sketched at the same plot based on an estimated relative permittivity (see Table II). To plot the reflection coefficient for all configurations, we use the single layer formula (1). However, a more accurate modeling could be done by using the multi-layer reflection coefficient formulation [12] which has higher mathematical complexity. Therefore, it would make deterministic channel modeling more complex and time consuming.

As Fig. 4 shows, the cut-pile type carpets do not reveal a good reflection which is mostly due to the low transmission loss shown in Table I. As expected, when they are supported with a plywood layer the reflection from this type of house flooring material becomes noticeable. However, an interesting observation from this figure is, adding an underpad layer to the carpet-plywood configuration (as shown in Fig. 3) makes the reflection to become worse which is due to the scattering. Adding materials increases the transmission loss.

We observe the same results for the second group, i.e. loop-pile carpets, for different configurations used in this group (see Fig. 5). However, comparing the results in Fig. 4 and Fig. 5 reveals that loop-pile carpets represent more reflectivity than the cut-pile ones, though a higher transmission loss is reported for loop-pile carpets as shown in Table I. This result demonstrates a higher scattering factor for the low density carpets such as the cut-pile ones, than reflecting factor.

Hardwood and vinyl materials are basically used with just plywood layer as a supporting material in house flooring constructions. A very good reflection is expected from this type of materials due to having a shiny surface with a very small roughness. The results shown in Figs. 6-7 confirm this good reflection. Comparing the results in Figs. 6-7 shows even a better reflection from vinyl than hardwood. As can be observed, adding a plywood supporting layer does not change the reflectivity of the hardwood and vinyl flooring materials significantly.

V. RELATIVE PERMITTIVITY ESTIMATION

To estimate the relative permittivity of the sample flooring materials, we use a nonlinear-least-squares method [13].

Fig. 5. Reflection coefficient for carpet II (loop-pile).

Fig. 6. Reflection coefficient for hardwood.

Fig. 7. Reflection coefficient for vinyl.
We repeat the measurement campaigns shown in Figs. 4-7, performed at 60 GHz, for all frequencies in 57-64 GHz band with 1 GHz step size. Table II shows the results for all the materials and configurations. As stated before, it is not possible to define/estimate one relative permittivity for multilayer configurations. In fact, for each homogeneous dielectric material one relative permittivity is estimated, using (1), from the measurement data that depends on the material type and thickness [12]. However, considering multi-layer materials in channel modeling makes the entire process too complex and time consuming. For the sake of simplicity, we consider that all house flooring materials and configurations, shown in Fig. 3, as the homogeneous single-layer dielectric material, and find one relative permittivity for each construction.

The values reported in this table come with some approximations which depend on the measurement setup and chosen materials. To find more accurate results, one solution is to measure the reflected and transmitted power for many samples of the same material with different thicknesses. We must not forget that even in this case we will have some errors coming from the limited measurement’s accuracy. However, keeping in mind that the main purpose of this study is the wave propagation modeling for the channel characterization applications, and that in most of these applications one does not have an exact knowledge of the materials but only knows the material type, this information appears to be enough.

The results in Table II show how reflective the flooring materials are. For both types carpets (cut- and loop-pile) a supporting plywood layer makes the configuration more reflective; however, when a softer floor equipped with an underpad layer is used the reflection becomes worse. Loop-pile carpets are more reflective than cut-pile ones at any case. In a hardwood flooring case, there is no significant difference in the reflection coefficient with or without using a supporting plywood material.

The relative permittivity results in Table II also show the frequency-selectivity of the flooring materials within 56-64 GHz band. According to the results shown in this table, a vinyl material represents the most and the carpet samples the least frequency dependence among the tested materials and configurations. Adding a plywood supporting layer to each of those aforementioned flooring materials, i.e. vinyl and carpet, respectively, reduces and increases the frequency dependence.

VI. CONCLUSION AND FUTURE WORK

The reflection characteristics of the house flooring construction materials for millimeter-wave propagation have been studied. We have considered 57-64 GHz frequency band and three common flooring materials: hardwood, vinyl and carpet (cut- and loop-pile). The reflection characteristics of the aforementioned materials have been measured when the supporting materials, i.e. plywood and underpad, exist. In order to investigate the frequency dependence of these characteristics, a continuous wave transmit-receive measurement setup with 57-64 GHz frequency range measurement capability has been employed. The reflection coefficient for all available incident angle and transmission loss for face-to-face antenna direction have been measured for the selected flooring materials. According to the measurement results, cut- and loop-pile carpets act the same and very weak in terms of millimeter-wave signal reflection. However, adding a plywood supporting layer significantly increases the reflectivity of a house floor, but this reflection becomes worse if we add an underpad material between the carpet and plywood layers. It has been observed that a vinyl floor is the most reflective floor construction material with a high frequency-dependent reflection coefficient when compared with the other flooring materials. The measurement results show that the frequency dependence of a vinyl floor decreases with a plywood supporting layer, but adding this layer can enhance the frequency dependence of the carpet flooring.

As it has been stated before, our results can be used not only for MMW system designers to optimally design a transceiver for this purpose, but also for channel modeling applications particularly for ray-tracing software users and developers. Moreover, house interior designers may use our results to optimize their house flooring architectures if they want to offer a “60 GHz based” house to the customers.

As future work, we plan to consider more factors such as polarization, material thickness, and more sampling frequencies in the reflection coefficient measurement for the house flooring materials. We will report some statistical distributions of each measured metric. Moreover, we plan to provide more results about the propagation coefficients in the MMW.
frequencies including reflection and transmission patterns for the aforementioned materials.

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