D-Band Channel Measurements and Characterization for Indoor Applications

Seunghwan Kim, Student Member, IEEE, Wasif Tanveer Khan, Member, IEEE, Alenka Zajić, Senior Member, IEEE, and John Papapolymerou, Fellow, IEEE

Abstract—This paper presents measurements and characterization of D-band indoor channels. The measurements are performed in line-of-sight (LoS), obstructed-LoS (OLoS), and reflected non-LoS (RNLoS) environments. For OLoS scenario, cylindrical objects of different materials are used as an obstruction. For RNLoS, different surfaces are used as reflectors. From the large set of LoS and OLoS measured data, the parameters for single-slope path loss model with shadowing are devised. Furthermore, the analysis of multipath propagation is performed. The results show that strong multiple reflections from the transmitter and receiver electronics are present both in LoS and OLoS environments. Additionally, the results show that glass and ceramic objects in the propagation path produce surface-diffracted rays which clock-wise and counter clock-wise superposition leads to frequency-dependent path loss. Finally, the results show that the RNLoS measured path loss with aluminum plate as a reflector is very similar to free-space path loss when the angle of incidence and the angle of reflection are equal.

Index Terms—Channel measurements, channel modeling, D-band channels, indoor channels.

I. INTRODUCTION

ULTRA-WIDEBAND wireless communication systems are expected to help satisfy the ever-growing need for smaller devices that can offer higher speed wireless communications anywhere and anytime. In the past years, it has become obvious that wireless data rates exceeding 10 Gbps will be required in several years from now [1]. To achieve this goal, several frequency bands have been explored. For example, propagation characteristics of 60 GHz with an unregulated bandwidth of 7 GHz have been presented in [2]–[10] and references therein. Similarly, propagation characteristics of 300 GHz with an unregulated bandwidth of 47 GHz have been presented in [11]–[25] and references therein. While 60-GHz communications have limited bandwidth, 300 GHz communications are limited in range.

As an alternative, the 60 GHz of spectrum from 110 to 170 GHz (D-band) offers a promising approach to provide sufficient bandwidth and range required for ultra-fast and ultra-wideband data transmissions [26]. This frequency band is ideally suited for short- and medium-range communications. This large bandwidth paired with higher speed wireless links has potential applications in precision positioning and velocity sensors [27], passive millimeter-wave cameras [28] and can open the door to a large number of novel applications such as ultra-high-speed pico-cellular links, wireless short-range communications, and on-body communication for health monitoring systems. Note that this frequency band is currently unregulated for wireless communications, and is typically used for atmospheric applications.

To enable wireless communications in D-band, it is imperative to understand propagation mechanisms that govern communication at these frequencies. While D-band has been extensively used for microwave atmospheric sounding (e.g., [29]), to the best of our knowledge, no indoor D-band channel characterization based on measurements has been reported in the open literature. Although channel characterization at 120 GHz for an indoor office scenario has been reported in [30], the work only presents ray-tracing simulation results without channel measurements. While atmospheric absorption is the main focus of microwave atmospheric sounding, this loss plays minor role in indoor propagation. Reflections, diffraction, and scattering are more prevalent propagation mechanisms in indoor D-band channels.

As the first step toward characterizing D-band channel, we have performed line-of-sight (LoS), obstructed-LoS (OLoS), and reflected non-LoS (RNLoS) measurements at 140 with 60 GHz of bandwidth between the transmitter (T_x) and the receiver (R_x). The contributions of this paper are as follows.

1) Devised parameters for the single-slope path loss model with shadowing for LoS and OLoS environments. The results show that the path loss exponent is around 1.9 for LoS environment and the variations due to shadowing are negligible. Furthermore, the results show that the path loss exponent for plastic cup OLoS path is the closest to the LoS path loss exponent and that glass and ceramic OLoS path loss exponents increase to 3. Additionally, we find that glass and ceramics objects in the propagation path cause multiple strong reflections leading to higher frequency-dependent path loss. Finally, we observe that the RNLoS path loss with aluminum plate as a reflector is very similar to free-space path loss when the angle of incidence and reflection are equal. This indicates that communication is possible in RNLoS scenarios.
2) Analyzed the rms delay spread $\tau_{\text{rms}}$, the mean excess delay $\tau_m$, and the coherence bandwidth for LoS, OLoS, and RNLoS environments. In LoS environment, the mean values of $\tau_{\text{rms}}$ and $\tau_m$ are 12.84 and 16.95 ps, respectively. The mean excess delay increases in the presence of obstructions, with the smallest increase in the presence of plastic cup and the largest increase in the presence of ceramic mug. There is almost no increase in the mean excess delay in RNLoS environment for aluminum plate as a reflector and the equal angles of incidence and reflection.

3) Analyzed the power delay profiles (PDPs) for LoS, OLoS, and RNLoS environments. We can observe that the strong reflections from the $T_x$ and $R_x$ electronics are present both in LoS and OLoS environments. Additionally, OLoS channels with obstructions of cylindrical shape, such as a glass beaker, a plastic cup, or a ceramic mug, also experience the diffraction at the convex surface of the cylindrical obstruction. The creeping waves, or the surface-diffracted rays that travel around the cylinder in clock-wise and counter clock-wise directions superimpose leading to frequency dependent path loss.

The remainder of this paper is organized as follows. Section II describes the measurement equipment, antennas used in the measurements, and the measurement setup. Section III presents the path loss, shadowing, and multipath propagation analysis of LoS measured data. Section IV presents the path loss, shadowing, and multipath propagation analysis of OLoS measured data, while Section V presents the path loss and multipath propagation analysis of RNLoS measured data. Finally, Section VI provides some concluding remarks.

II. MEASUREMENT SETUP

A. Equipment

The block diagram of the D-band measurement setup is shown in Fig. 1. The Agilent E8361C vector network analyzer is used for all measurements. The E8361C has a frequency range up to 67 GHz; therefore, the N5260A (millimeter-wave controller) and OML V06VNA2 (millimeter-wave test head modules) are used to extend the range to the D-band (110–170 GHz). The N5260A millimeter-wave controller provides radio frequency (RF) and local oscillator (LO) signals to the millimeter-wave test head modules and returns the down-converted reference and test IF signals to the VNA for process and display. The OML V06VNA2 frequency extension module has an LO multiplication factor of 10, which up-converts the input LO frequency from 11 to 17 GHz, supplied by the millimeter-wave controller, to the D-band (110–170 GHz).

The full available bandwidth of 60 GHz is used in all measurements, which provides the spatial and temporal resolution of 5 mm or 0.0167 ns. Due to input power restrictions of the mixers, a test signal with a power of 0 dBm is used, providing a dynamic range of approximately 90 dB for the chosen intermediate frequency filter bandwidth of $\Delta f_{IF} = 100$ Hz. The number of sweep points is set to 801, and the maximum excess delay is 13 ns. All measurement parameters are summarized in Table I.

B. Antenna Characteristics

The antenna used in the measurement is a pyramidal horn with gain that varies from 22 to 28 dBi from 110 to 170 GHz, respectively. Both $T_x$ and $R_x$ antennas are vertically polarized and have theoretical half-power beamwidth (HPBW) of 12° and 13.5° in E- and H-plane, respectively, at 110 GHz. The E- and H-plane beamwidths also decrease to 9° and 12°, respectively, toward higher frequencies. Furthermore, antennas have sidelobes that are at least 25 dB below the main beam and all possible reflectors on the sides of the channel have been covered with absorbers as shown in Fig. 3, to ensure that any paths resulting from the sidelobes are suppressed. The measured $S_{11}$ and the frequency-dependent gain of the horn antenna are presented in Fig. 2. Note that the return loss shown here includes the reflections at the interfaces between cable and test head, as well as test head and the antenna due to mismatches between them. Nevertheless, we can observe that the $S_{11}$ is below $-25$ dB across the entire bandwidth. In further analysis, antennas are considered to be part of the channel impulse response, which is typically the case in wireless communication applications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Measurement points</td>
<td>$N$</td>
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</tr>
<tr>
<td>Intermediate frequency bandwidth</td>
<td>$\Delta f_{IF}$</td>
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</tr>
<tr>
<td>Average noise floor</td>
<td>$P_N$</td>
<td>$-85$ dBm</td>
</tr>
<tr>
<td>Input signal power</td>
<td>$P_m$</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Start frequency</td>
<td>$f_{\text{start}}$</td>
<td>110 GHz</td>
</tr>
<tr>
<td>Stop frequency</td>
<td>$f_{\text{stop}}$</td>
<td>170 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$B$</td>
<td>60 GHz</td>
</tr>
<tr>
<td>Time domain resolution</td>
<td>$\Delta t$</td>
<td>0.0167 ns</td>
</tr>
<tr>
<td>Maximum excess delay</td>
<td>$\tau_m$</td>
<td>13 ns</td>
</tr>
</tbody>
</table>
C. Measurement Scenarios

In this measurement campaign, three different scenarios have been considered: LoS scenario shown in Fig. 3(a), OLoS scenario shown in Fig. 3(b), and RNLoS scenario shown in Fig. 3(c).

Considering the short-range of D-band applications, the T_x–R_x separation distance d shown in Fig. 1, has been varied from 35.56 (14″) to 86.36 cm (34″) in 5.08 cm (2″) increments, giving a total of 11 different distances for LoS scenario. Furthermore, to mitigate the reflections from the ground and the metallic transceiver cases, the T_x and R_x test heads have been placed on top of a supporting plastic container, and all possible reflecting surfaces, including the ground, the equipment rack cabinet, and the front faces of the test heads, have been covered with absorbers as shown in Fig. 3(a). For OLoS scenario, obstructions of circular cylinder shape, i.e., cups, have been used as typical objects present on desk tops. To study the impact of different materials on propagation in D-band, three different types of material, i.e., glass, plastic (polystyrene), and ceramic have been considered. The same 11 T_x–R_x separations as in LoS scenario have been used for OLoS scenario. Each obstruction is placed such that the cylinder’s center coincides with the midpoint of the separation distance, and its top edge is 3.5 cm above the LoS path. Furthermore, to investigate the effect of obstruction height on path loss, we have varied the positions of the top rim of the cylinders, or h in Fig. 1, from 14.3 to 21.9 cm. The obstruction height has been varied by having different number of styrofoam pads (which have been tested to cause minimal reflections at the frequencies of interest) underneath the cylinder obstruction, as shown in Fig. 1. Note that the centers of the horn antennas are located 20.6 cm above the table. Finally, in RNLoS scenario, we use reflection as the main mechanism of wave propagation. Two types of reflecting surfaces, aluminum plate and fiberboard, having different reflectivity and surface roughness, have been used. Furthermore, by varying the angular position of the R_x, while keeping the T_x position fixed, the range of R_x angular offsets at which the R_x can detect the reflected signal is studied. For RNLoS, the LoS separation distance was fixed to 76.2 cm.

III. Characterization of D-Band LoS Channel

A. LoS Path Loss and Shadowing

In this paper, we refer to mean path loss as the transmit power multiplied by the transmit and receive antenna gains divided by the mean received power, i.e.,

$$PL = \frac{P_t \cdot G_t \cdot G_r}{P_r} = \left(\frac{4\pi d}{\lambda}\right)^2 \cdot (1)$$

The mean path loss is obtained by averaging a swept continuous wave over time and frequency, i.e.,

$$PL(d) = \frac{1}{MN} \sum_{i=1}^{N} \sum_{j=1}^{M} |H(f_i, t_j, d)|^2 \quad (2)$$

where $H(f_i, t_j, d)$ is the measured complex frequency response data matrix, $N$ is the number of observed frequencies, $M$ is the number of frequency-response snapshots over time, and $d$ is the distance in meters.

Fig. 4 compares the measured path loss with the theoretical path loss calculated using (1). We plot only 5 out of 11 separation distances to avoid clutter. We can observe that the measured path loss curves very closely follow the theoretical lines. The oscillations observed in the path loss curves have been found to be a result of multiple reflections between the front faces of the T_x and R_x test heads. Although they were covered with a layer of absorbing material, as shown in Fig. 3(a), it was apparently not thick enough to completely mitigate the reflections. This resulted in the constructive and destructive interference between the direct and reflected rays, which led to the oscillation in the measured S_21.

Fig. 5 shows the scatter plot of the mean path loss as a function of transmitter–receiver (T–R) separation on a desktop for an LoS environment. We can observe that the variation between different frequency-response snapshots over time is minimal. This is because there are no temporal or spatial variations nor additional clutter in the channel that would cause significant variations in the measured path loss. Note that this finding is significantly different from typical indoor measurements, where path loss significantly varies around the mean value. This finding leads us to conclude that the number of frequency-response snapshots over time does not have to be large and we have found that ten measurements are sufficient to capture all temporal variations in the signal.

Path loss over distance can be modeled by the path loss exponent model [31], i.e.,

$$PL(d) = 10\gamma \log_{10} \left(\frac{d}{d_0}\right) + PL(d_0) + X_\sigma \quad (3)$$

where $PL(d)$ is the average path loss in dB at the distance $d$, $PL(d_0)$ is the free-space path loss at the reference distance $d_0$, $\gamma$ is the path loss exponent that characterizes how fast the path loss increases with the increase in the separation between the T_x and the R_x, and $X_\sigma$ represents shadow fading that can be modeled as a zero-mean Gaussian distributed random variable (in dB) with standard deviation $\sigma$. Single slope path loss model
is a statistical method used to estimate the path-loss slope and the variation from the mean path loss. This is an important tool when designing communication systems. More advanced statistical models can be devised from the measurements if the single slope model does not produce adequate fit, which is not the case in our paper. Alternative approach is a deterministic approach (e.g., ray-tracing [22] and diffraction modeling [23]), which is expected to produce more repeatable results; however, it depends on the detailed and accurate description of all objects in the propagation space.

To estimate the path loss model parameters $\gamma$ and $\sigma$ (dB) in (3), we have performed the least-squares linear regression fitting through the scatter of measured path loss points in decibels such that the root mean square (rms) deviation of path loss points about the regression line is minimized. The reference distance is $d_0 = 1$ m and the free-space path loss at the reference distance $d_0$ is $PL(d_0) = 75.19$ dB. The found path loss exponent is around 1.97 and the variations due to shadowing are around $\sigma = 0.12$ dB. To confirm that shadowing can be modeled as a zero-mean Gaussian distributed random variable, Fig. 6 compares the measured distribution of shadow fading with the Gaussian distribution. This shadowing is due to misalignment between the $T_x$ and $R_x$ antennas. While this may not be a conventional shadowing process, it is still a random process that causes variations of received power at a given distance.
### TABLE II

<table>
<thead>
<tr>
<th>d (cm)</th>
<th>Without absorbers</th>
<th>With absorbers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_m$ (ps)</td>
<td>$\tau_{rms}$ (ps)</td>
</tr>
<tr>
<td>35.56</td>
<td>17.18</td>
<td>32.12</td>
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<tr>
<td>55.88</td>
<td>17.08</td>
<td>30.50</td>
</tr>
<tr>
<td>76.2</td>
<td>17.04</td>
<td>31.28</td>
</tr>
</tbody>
</table>

**B. LoS Multipath Characterization**

Multipath propagation is the propagation mechanism manifested when the transmitted signal reaches the receive antenna along two or more paths. Such waves typically arrive at the $R_x$ from many different directions and with different delays, and combine vectorially at the $R_x$ antenna. Such channel impulse response can be characterized as [31]

$$h(t, \tau, d) = \sum_{k=1}^{L} a_k(t, d) \exp(j\theta_k(t, d))\delta(t - \tau_k)$$

where $L$ is the number of multipath components, $a_k$ represents the amplitude of the $k$th multipath component, $\theta_k$ is the associated phase, and $\tau_k$ is the excess delay of the $k$th path relative to the first arrival, and $\delta(\cdot)$ denotes the Dirac delta function.

An estimate of the channel impulse response is made by taking the inverse discrete Fourier transform (IDFT) of the measured frequency response. The impulse response is then normalized such that the area under the squared magnitude of the power-delay response is equal to one. We refer to a normalized squared magnitude of the impulse response as the multipath intensity profile (MIP) at the single point in space.

The noise floor of the MIP is set to 10 dB above the average $R_x$ noise floor. Part of the MIP characterization is based on rms delay spread $\tau_{rms}$, which is a measure of multipath spread within the channel. It is an important parameter for characterizing time dispersion or frequency selectivity. It is the square root of the second central moment of the MIP and is given by [31]

$$\tau_{rms} = \sqrt{\sum_{k=1}^{L} (\tau_k - \tau_m)^2|h(t, \tau_k, d)|^2}$$

where $\tau_m$ is the mean excess delay (the first moment of the MIP) and is defined as

$$\tau_m = \sum_{k=1}^{L} \tau_k \cdot |h(t, \tau_k, d)|^2.$$
increasing T–R separation as they travel further distances with more power spreading. In summary, the unwanted reflections from the transceiver electronics will have a profound impact on the channel, and attenuating these reflected signals below certain threshold could be an important issue when building the transceiver systems.

IV. CHARACTERIZATION OF D-BAND OLoS CHANNEL

A. OLoS Path Loss and Shadowing

The OLoS environment is created by placing a glass beaker, a plastic cup, and a ceramic mug in the midpoint of the separation distance, and its top edge is 3.5 cm above the LoS path. The measured path losses for these three scenarios and three different separation distances are presented in Fig. 9(a)–(c), respectively. The measured results are compared with the free-space theoretical path loss obtained using (1). The plots show that the measured path loss is much higher than the free-space path loss, which is an expected result since the OLoS has higher losses due to obstructions in LoS. Furthermore, we can observe that the plastic cup introduces the least amount of attenuation compared to free-space path loss and that the variation of path loss across frequencies is minimal. The glass beaker introduces higher attenuation and as the distance increases, the path loss variations as the function of frequency become more pronounced. Finally, the ceramic mug introduces the highest attenuation and the path loss variations as the function of frequency become dominant. We can observe that ceramic material introduces similar attenuation as a glass at lower frequencies, i.e., 110–130 GHz, but then the loss increases to over 100 dB in the range of 140–160 GHz. We can also observe that the maximum of the path loss changes with the separation between the Tx and Rx.

Fig. 9(d)–(f) shows the scatter plot of the path loss as a function of T–R separation for glass, plastic, and ceramic OLoS environments, respectively. All 11 distances are used for the scatter plot to obtain the best linear regression fit. As in the LoS case, there are minimal discrepancies among ten consecutive measurements because the channel is quasi-static with no moving objects in the environment.

To estimate the path-loss model parameters $\gamma$ and $\sigma$ (dB) in (3), we have performed the least-squares linear regression fitting through the scatter of measured path loss points and the results are shown in Fig. 9(d)–(f) for glass, plastic, and ceramic, respectively. The path loss exponents ($\gamma$), standard deviations ($\sigma$), and the path losses at reference distance, 1 m, ($PL_0$) for all three obstruction materials are summarized in Table III. We can observe that the path loss exponent of plastic cup is the closest to the LoS path loss exponent value of 1.96, which is not surprising since plastic is very transparent at D-band frequencies. For glass and ceramic, due to the considerable blockage of LoS path, the path loss exponents have increased above the free-space value of 2. In OLoS scenarios, shadow fading becomes more dominant because of the presence of obstructions.
Fig. 10. Zero-mean Gaussian distributed shadow fading and measured shadow fading for OLoS scenarios. (a) Glass beaker. (b) Plastic cup. (c) Ceramic mug.

Fig. 11. Variation in path loss with varying height of the ceramic mug obstruction.

Fig. 12 plots the PDPs for three obstructions: glass, plastic, and ceramics, respectively. We can observe that all three PDPs have two distinct segments: one where the reflection peak appears at the same time delay regardless of the T–R separation distance (shown as 1 in the figures), followed by the reflection peaks whose positions depend on the T–R separation distance (shown as 2 in the figures). Here, we note that the difference between the first and the second arriving path is always equal to twice the cup diameter, regardless of the T–R separation distance, which explains why the multipath marked as 1 appears at the same excess delay for all distances. Furthermore, from the excess delay that corresponds to the first multipath (marked as 1 in the figures), we can conclude that this multipath corresponds to a ray that penetrated the cup, reflected off the wall closer to the Rx, reflected off the wall closer to the Tx, and traveled outside the cup to the Rx. Although the higher order of reflections might be present, the Rx sensitivity is not high enough to detect them.

From Fig. 12, we can observe that the PDP for the plastic cup has weaker reflected paths compared to the glass and ceramic mugs because most of the energy goes through the plastics and does not stay trapped inside the obstruction. Furthermore, we can observe that the PDP for the ceramic mug has significant reflections only at the distance of 35.56 cm, whereas for 45.72 and 55.88 cm, it is difficult to identify them because the reflections are significantly attenuated due to material properties. In the PDP section marked as 2 in Fig. 12(a)–(c), we can observe that the position of the multipath peak depends on the T–R separation. From the excess delay that corresponds to the second multipath, we can deduce that the signal has traveled through the obstruction, was reflected from the Rx probe head, was reflected once more off the obstruction, and then received with higher peaks. For this case, our experimental results and application of uniform geometrical theory of diffraction (UTD) have revealed the presence of diffraction at the convex surface of the cylindrical obstruction. The creeping waves or the surface-diffracted rays that travel around the cylinder in clockwise and counter-clockwise directions and their interference seem to be causing the variation in the measured $S_{21}$. Further characterization of this particular OLoS channel is one of our main future works.
by the $R_x$ antenna. Alternatively, the signal was reflected off obstruction, then reflected back from the $T_x$ probe head, and then traveled through obstruction to the $R_x$.

Note that the width of the main peak (first arriving path) is the widest for ceramic mug, which is followed by glass beaker and plastic cup, as observed in Fig. 12. This indicates that the ratio of the power associated with the strongest first arriving path to that of the following reflected paths is the highest for plastic, while the ratio is the lowest for ceramic. This agrees with the fact that glass is the most transparent to the waves, allowing most of the transmitted rays to pass through without multiple reflections. For ceramics, on the other hand, the transparency of the material is much lower than glass, which gives rise to more reflected paths that arrive with delays that are very close to each other. This high temporal proximity is manifested as clustering of the reflected paths, which leads to pulse broadening as shown in Fig. 12(c).

The multipath characterization parameters, $r_{\text{rms}}$, $\tau_{\text{rms}}$, and $B_c$, in the OLoS environment with the three different obstructions for the three $T$–$R$ spacings, 35.56, 55.88, and 76.2 cm, are summarized in Table IV. The OLoS channel obstructed by the plastic cup has the largest coherence bandwidth of almost 11 GHz at 35.56 cm, which is comparable with that of LoS environment for the same distance. Meanwhile, much narrower coherence bandwidths below 5 GHz are observed for glass and ceramic mug obstructions.

### V. CHARACTERIZATION OF D-BAND RNLOS CHANNEL

Another possible way of communication is through RNLOS paths. Since the effectiveness of communication will depend on the reflectivity of the material; here, we compare two different reflectors: aluminum plate and fiberboard. Furthermore, we investigate the effect of angular orientation of the $R_x$ on the received power levels. The $T_x$ is fixed at $\phi_T = 35^\circ$, and the $R_x$ is rotated between $\phi_R = 0^\circ$ and $\phi_R = 90^\circ$. The angles are measured from the direct LoS path. The $T$–$R$ separation distance has been fixed at $d = 76.2$ cm. The measured and theoretical (free-space) path loss for several angles $\phi_R$ with aluminum plate and fiberboard as reflectors are shown in Fig. 13. It is evident from the figure that the level of received power is closest to the theoretical LoS level when $\phi_R = \phi_T = 35^\circ$, since the condition $\phi_R = \phi_T$ ensures that the maximum power is transferred through specular reflection. The slight discrepancy from the LoS level can be attributed to the reflection coefficient of the aluminum plate. As the $R_x$ angle $\phi_R$, deviates from $35^\circ$, it is observed that reception becomes weaker and the path loss significantly increases. At the two extremes, $\phi = 0^\circ$ and $\phi = 90^\circ$, we can observe that the communication is essentially lost. Furthermore, we can observe that the path loss is higher when the fiberboard is used as the reflector. This is not surprising result because the fiberboard has lower reflectivity and higher surface roughness.

The PDPs for RNLOS channel with aluminum plate and fiberboard as the reflector for the angular positions, $\phi_R = 10^\circ$ and $35^\circ$ are presented in Fig. 14. The peaks that coincide at $\tau = 3.6$ ns represent the paths bouncing off the reflector, while an additional peak at $\tau = 2.7$ ns observed for $\phi_R = 10^\circ$ is a
VI. CONCLUSION
This paper presents measurements and characterization of D-band indoor channels. The measurements are performed in LoS, OLoS, and RNLoS environments. For OLoS scenario, cylindrical objects of different materials are used as obstructions. For RNLoS, different surfaces are used as reflectors. From the large set of LoS and OLoS measured data, the parameters for single-slope path loss model with shadowing are devised. Furthermore, the analysis of multipath propagation is performed. The rms delay spread, the mean excess delay, and the coherence bandwidth for LoS, OLoS, and RNLoS environments are calculated. In addition, the PDPs for LoS, OLoS, and RNLoS environments are analyzed. The results show that strong multiple reflections from the $T_x$ and $R_x$ electronics are present both in LoS and OLoS environments. Additionally, the results show that glass and ceramic objects in the propagation path produce surface-diffracted rays which clock-wise and counter-clock-wise superposition leads to frequency-dependent path loss. Finally, the results show that the RNLoS measured path loss with aluminum plate as a reflector is very similar to free-space path loss when the angle of incidence and the angle of reflection are equal.

REFERENCES

Seunghwan Kim was born in Seoul, South Korea, in 1986. He received the Bachelor of Applied Science degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 2009. He is currently pursuing the Ph.D. degree in electrical engineering at Georgia Institute of Technology, Atlanta, GA, USA.

During his degree, he worked as a Research Assistant with the Telecommunication Group, Korea Electrotechnology Research Institute (KERI), Changwon, Korea, and as a Hardware Engineer with Mitel Networks, Kanata, ON, Canada.

Wasif Tanveer Khan (S’10–M’15) received the B.Sc. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, in 2005, and the M.S. and Ph.D. degrees in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2010 and 2014, respectively.

From January 2006 to December 2008, he was a Lecturer with the National University of Computer and Emerging Sciences-FAST, Lahore, Pakistan. Since January 2015, he has been working as an Assistant Professor with the Department of Electrical Engineering, Lahore University of Management Sciences, Lahore, Pakistan. He has authored/coauthored more than 35 research papers in peer-reviewed conferences and journals. His research interests include the RF and microwave system design, millimeter wave circuit and package design, multilayer organic packaging, on-chip and off-chip antenna design, and phased array systems.

Dr. Khan has been the publications Chair for four IEEE conferences: RWS, PAWR, WiSiNet, and BioWirelesS, since 2010. Since 2011, he has also been a Technical Program Committee (TPC) member for IEEE Radio and Wireless Symposium (RWS). He was the recipient of a MS leading to Ph.D. fullbright Scholarship.

Alena Zaji´c (S’99–M’09–SM’13) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Belgrade, Belgrade, Serbia, in 2001 and 2003, respectively, and the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2008.

Currently, she is an Assistant Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology. Prior to that, she was a Visiting Faculty at the School of Computer Science, Georgia Institute of Technology, a Postdoctoral Fellow with the Naval Research Laboratory, and Design Engineer with Skyworks Solutions Inc. Her research interests include electromagnetics, wireless communications, signal processing, and computer engineering.

Dr. Zaji´c was the recipient of the Neal Shepherd Memorial Best Propagation Paper Award, the Best Paper Award at ICT 2008, the Best Student Paper Award at WCNC 2007, the Dan Noble Fellowship in 2004, awarded by Motorola Inc., and the IEEE VEHICULAR TECHNOLOGY SOCIETY for quality impact in the area of vehicular technology. Currently, she is an Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and the Chair of the IEEE MTT/AP Atlanta Chapter.

John Papapolymerou (F’xx) received the B.S.E.E. degree from the National Technical University of Athens, Athens, Greece, in 1993, and the M.S.E.E. and Ph.D. degrees from the University of Michigan, Ann Arbor, MI, USA, in 1994 and 1999, respectively. From 1999 to 2001, he was an Assistant Professor with the Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, USA, and during 2000 and 2003, he was a Visiting Professor at the University of Limoges, Limoges, France. From 2001 to 2005 and 2005 to 2009, he was an Assistant Professor and Associate Professor, respectively, with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA, where he is currently the Ken Byers Professor. He has authored or coauthored over 350 publications in peer-reviewed journals and conferences. His research interests include the implementation of micromachining techniques and MEMS devices in microwave, millimeter-wave and THz circuits and the development of both passive and active planar circuits and antennas on semiconductor (Si/SiGe, GaAs) and organic substrates (liquid crystal polymer-LCP, LTCC) for system-on-a-chip (SOC)/system-on-a-package (SOP) RFfrontend.

Dr. Papapolymerou currently serves as Editor-in-Chief for IEEE Microwave and Wireless Components Letters (MWCL). He has also served as an Associate Editor for IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES from 2010 to 2012, and as Chair for Commission D of the US National Committee of URSI from 2009 to 2011. He was also an Associate Editor for IEEE MWCL (2004–2007), and IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (2004–2010). During 2004, he was the Chair of the IEEE MTT/AP Atlanta Chapter. He was the recipient of the 2012 IEEE ANTENNAS AND PROPAGATION SOCIETY (AP-S) H.A. Wheeler Prize Paper Award, the 2010 IEEE AP-S John Kraus Antenna Award, the 2009 IEEE MICROWAVE THEORY AND TECHNIQUES-SOCIETY (MTT-S) Outstanding Young Engineer Award, the 2009 School of ECE Outstanding Junior Faculty Award, the 2004 Army Research Office (ABO) Young Investigator Award, the 2002 National Science Foundation (NSF) CAREER award, the Best Paper Award at the 3rd IEEE International Conference on Microwave and Millimeter-Wave Technology (ICMWT2002), Beijing, China, and the 1997 Outstanding Graduate Student Instructional Assistant Award presented by the American Society for Engineering Education (ASEE), the University of Michigan Chapter.
Q1: Please provide issue number for Ref. [10].
Q2: Please provide page range for Ref. [22].
Q3: Please update Ref. [25].
Q4: Please provide field of studies for “B.S.E.E., M.S.E.E., and Ph.D.” degrees and membership history (year) of author “John Papapolymrou.”
D-Band Channel Measurements and Characterization for Indoor Applications

Seunghwan Kim, Student Member, IEEE, Wasif Tanveer Khan, Member, IEEE, Alenka Zajić, Senior Member, IEEE, and John Papapolymerou, Fellow, IEEE

Abstract—This paper presents measurements and characterization of D-band indoor channels. The measurements are performed in line-of-sight (LoS), obstructed-LoS (OLoS), and reflected non-LoS (RNLoS) environments. For OLoS scenario, cylindrical objects of different materials are used as an obstruction. For RNLoS, different surfaces are used as reflectors. From the large set of LoS and OLoS measured data, the parameters for single-slope path loss model with shadowing are devised. Furthermore, the analysis of multipath propagation is performed. The results show that strong multiple reflections from the transmitter and receiver electronics are present both in LoS and OLoS environments. Additionally, the results show that glass and ceramic objects in the propagation path produce surface-diffracted rays which clock-wise and counter clock-wise superposition leads to frequency-dependent path loss. Finally, the results show that the RNLoS measured path loss with aluminum plate as a reflector is very similar to free-space path loss when the angle of incidence and the angle of reflection are equal.

Index Terms—Channel measurements, channel modeling, D-band channels, indoor channels.

I. INTRODUCTION

ULTRA-WIDEBAND wireless communication systems are expected to help satisfy the ever-growing need for smaller devices that can offer higher speed wireless communications anywhere and anytime. In the past years, it has become obvious that wireless data rates exceeding 10 Gb/s will be required in several years from now [1]. To achieve this goal, several frequency bands have been explored. For example, propagation characteristics of 60 GHz with an unregulated bandwidth of 7 GHz have been presented in [2]–[10] and references therein. Similarly, propagation characteristics of 300 GHz with an unregulated bandwidth of 47 GHz have been presented in [11]–[25] and references therein. While 60-GHz communications have limited bandwidth, 300 GHz communications are limited in range.

As an alternative, the 60 GHz of spectrum from 110 to 170 GHz (D-band) offers a promising approach to provide sufficient bandwidth and range required for ultra-fast and ultrawideband data transmissions [26]. This frequency band is ideally suited for short- and medium-range communications. This large bandwidth paired with higher speed wireless links has potential applications in precision positioning and velocity sensors [27], passive millimeter-wave cameras [28] and can open the door to a large number of novel applications such as ultra-high-speed pico-cellular links, wireless short-range communications, and on-body communication for health monitoring systems. Note that this frequency band is currently unregulated for wireless communications, and is typically used for atmospheric applications.

To enable wireless communications in D-band, it is imperative to understand propagation mechanisms that govern communication at these frequencies. While D-band has been extensively used for microwave atmospheric sounding (e.g., [29]), to the best of our knowledge, no indoor D-band channel characterization based on measurements has been reported in the open literature. Although channel characterization at 120 GHz for an indoor office scenario has been reported in [30], the work only presents ray-tracing simulation results without channel measurements. While atmospheric absorption is the main focus of microwave atmospheric sounding, this loss plays minor role in indoor propagation. Reflections, diffraction, and scattering are more prevalent propagation mechanisms in indoor D-band channels.

As the first step toward characterizing D-band channel, we have performed line-of-sight (LoS), obstructed-LoS (OLoS), and reflected non-LoS (RNLoS) measurements at 140 with 60 GHz of bandwidth between the transmitter (Tx) and the receiver (Rx). The contributions of this paper are as follows.

1) Devised parameters for the single-slope path loss model with shadowing for LoS and OLoS environments. The results show that the path loss exponent is around 1.9 for LoS environment and the variations due to shadowing are negligible. Furthermore, the results show that the path loss exponent for plastic cup OLoS path is the closest to the LoS path loss exponent and that glass and ceramic OLoS path loss exponents increase to 3. Additionally, we find that glass and ceramics objects in the propagation path cause multiple strong reflections leading to higher frequency-dependent path loss. Finally, we observe that the RNLoS path loss with aluminum plate as a reflector is very similar to free-space path loss when the angle of incidence and reflection are equal. This indicates that communication is possible in RNLoS scenarios.
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II. MEASUREMENT SETUP

A. Equipment

The block diagram of the D-band measurement setup is shown in Fig. 1. The Agilent E8361C vector network analyzer is used for all measurements. The E8361C has a frequency range up to 67 GHz; therefore, the N5260A (millimeter-wave controller) and OML V06VNA2 (millimeter-wave test head modules) are used to extend the range to the D-band (110–170 GHz). The N5260A millimeter-wave controller provides radio frequency (RF) and local oscillator (LO) signals to the millimeter-wave test head modules and returns the down-converted reference and test IF signals to the VNA for process and display. The OML V06VNA2 frequency extension module has an LO multiplication factor of 10, which up-converts the input LO frequency from 11 to 17 GHz, supplied by the millimeter-wave controller, to the D-band (110–170 GHz).

The full available bandwidth of 60 GHz is used in all measurements, which provides the spatial and temporal resolution of 5 mm or 0.0167 ns. Due to input power restrictions of the mixers, a test signal with a power of 0 dBm is used, providing a dynamic range of approximately 90 dB for the chosen intermediate frequency filter bandwidth of $\Delta f_{IF} = 100$ Hz. The number of sweep points is set to 801, and the maximum excess delay is 13 ns. All measurement parameters are summarized in Table I.

B. Antenna Characteristics

The antenna used in the measurement is a pyramidal horn with gain that varies from 22 to 28 dBi from 110 to 170 GHz, respectively. Both $T_x$ and $R_x$ antennas are vertically polarized and have theoretical half-power beamwidth (HPBW) of 12° and 13.5° in E- and H-plane, respectively, at 110 GHz. The E- and H-plane beamwidths also decrease to 9° and 12°, respectively, toward higher frequencies. Furthermore, antennas have sidelobes that are at least 25 dB below the main beam and all possible reflectors on the sides of the channel have been covered with absorbers as shown in Fig. 3, to ensure that any paths resulting from the sidelobes are suppressed. The measured $S_{11}$ and the frequency-dependent gain of the horn antenna are presented in Fig. 2. Note that the return loss shown here includes the reflections at the interfaces between cable and test head, as well as test head and the antenna due to mismatches between them. Nevertheless, we can observe that the $S_{11}$ is below $-25$ dB across the entire bandwidth. In further analysis, antennas are considered to be part of the channel impulse response, which is typically the case in wireless communication applications.
C. Measurement Scenarios

In this measurement campaign, three different scenarios have been considered: LoS scenario shown in Fig. 3(a), OLoS scenario shown in Fig. 3(b), and RNLoS scenario shown in Fig. 3(c).

Considering the short-range of D-band applications, the T_x–R_x separation distance d shown in Fig. 1, has been varied from 35.56 (14") to 86.36 cm (34") in 5.08 cm (2") increments, giving a total of 11 different distances for LoS scenario. Furthermore, to mitigate the reflections from the ground and the metallic transceiver cases, the T_x and R_x test heads have been placed on top of a supporting plastic container, and all possible reflecting surfaces, including the ground, the equipment rack cabinet, and the front faces of the test heads, have been covered with absorbers as shown in Fig. 3(a). For OLoS scenario, obstructions of circular cylinder shape, i.e., cups, have been used as typical objects present on desk tops. To study the impact of different materials on propagation in D-band, three different types of material, i.e., glass, plastic (polystyrene), and ceramic have been considered. The same 11 T_x–R_x separations as in LoS scenario have been used for OLoS scenario. Each obstruction is placed such that the cylinder’s center coincides with the midpoint of the separation distance, and its top edge is 3.5 cm above the LoS path. Furthermore, to investigate the effect of obstruction height on path loss, we have varied the positions of the top rim of the cylinders, or h in Fig. 1, from 14.3 to 21.9 cm. The obstruction height has been varied by having different number of styrofoam pads (which have been tested to cause minimal reflections at the frequencies of interest) underneath the cylinder obstruction, as shown in Fig. 1. Note that the centers of the horn antennas are located 20.6 cm above the table. Finally, in RNLoS scenario, we use reflection as the main mechanism of wave propagation. Two types of reflecting surfaces, aluminum plate and fiberboard, having different reflectivity and surface roughness, have been used. Furthermore, by varying the angular position of the R_x, while keeping the T_x position fixed, the range of R_x angular offsets at which the R_x can detect the reflected signal is studied. For RNLoS, the LoS separation distance was fixed to 76.2 cm.

III. CHARACTERIZATION OF D-BAND LO S CHANNEL

A. LoS Path Loss and Shadowing

In this paper, we refer to mean path loss as the transmit power multiplied by the transmit and receive antenna gains divided by the mean received power, i.e.,

$$PL = \frac{P_t \cdot G_t \cdot G_r}{\overline{P_r}} = \left(\frac{4\pi d}{\lambda}\right)^2.$$  (1)

The mean path loss is obtained by averaging a swept continuous wave over time and frequency, i.e.,

$$PL(d) = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} |H(f_i, t_j, d)|^2$$  (2)

where $H(f_i, t_j, d)$ is the measured complex frequency response data matrix, $N$ is the number of observed frequencies, $M$ is the number of frequency-response snapshots over time, and $d$ is the distance in meters.

Fig. 4 compares the measured path loss with the theoretical path loss calculated using (1). We plot only 5 out of 11 separation distances to avoid clutter. We can observe that the measured path loss curves very closely follow the theoretical lines. The oscillations observed in the path loss curves have been found to be a result of multiple reflections between the front faces of the T_x and R_x test heads. Although they were covered with a layer of absorbing material, as shown in Fig. 3(a), it was apparently not thick enough to completely mitigate the reflections. This resulted in the constructive and destructive interference between the direct and reflected rays, which led to the oscillation in the measured S21.

Fig. 5 shows the scatter plot of the mean path loss as a function of transmitter-receiver (T-R) separation on a desktop for an LoS environment. We can observe that the variation between different frequency-response snapshots over time is minimal. This is because there are no temporal or spatial variations nor additional clutter in the channel that would cause significant variations in the measured path loss. Note that this finding is significantly different from typical indoor measurements, where path loss significantly varies around the mean value. This finding leads us to conclude that the number of frequency-response snapshots over time does not have to be large and we have found that ten measurements are sufficient to capture all temporal variations in the signal.

Path loss over distance can be modeled by the path loss exponent model [31], i.e.,

$$PL(d) = 10\gamma \log_{10} \left(\frac{d}{d_0}\right) + PL(d_0) + X_o$$  (3)

where $PL(d)$ is the average path loss in dB at the distance $d$, $PL(d_0)$ is the free-space path loss at the reference distance $d_0$, $\gamma$ is the path loss exponent that characterizes how fast the path loss increases with the increase in the separation between the T_x and the R_x, and $X_o$ represents shadow fading that can be modeled as a zero-mean Gaussian distributed random variable (in dB) with standard deviation $\sigma$. Single slope path loss model
Fig. 3. Photographs of measurement scenarios. (a) LoS. (b) OLoS, glass as obstruction. (c) RNLoS, aluminum plate as reflector.

Fig. 4. Measured and theoretical path loss for five separation distances.

Fig. 5. Scatter plot of the LoS path loss.

Fig. 6. Confirming the log-normality of the shadow fading caused by variations in T–R alignment in LoS environment.

is a statistical method used to estimate the path-loss slope and the variation from the mean path loss. This is an important tool when designing communication systems. More advanced statistical models can be devised from the measurements if the single slope model does not produce adequate fit, which is not the case in our paper. Alternative approach is a deterministic approach (e.g., ray-tracing [22] and diffraction modeling [23]), which is expected to produce more repeatable results; however, it depends on the detailed and accurate description of all objects in the propagation space.

To estimate the path loss model parameters $\gamma$ and $\sigma$ (dB) in (3), we have performed the least-squares linear regression fitting through the scatter of measured path loss points in decibels such that the root mean square (rms) deviation of path loss points about the regression line is minimized. The reference distance is $d_0 = 1$ m and the free-space path loss at the reference distance $d_0$ is $PL(d_0) = 75.19$ dB. The found path loss exponent is around $1.97$ and the variations due to shadowing are around $\sigma = 0.12$ dB. To confirm that shadowing can be modeled as a zero-mean Gaussian distributed random variable, Fig. 6 compares the measured distribution of shadow fading with the Gaussian distribution. This shadowing is due to misalignment between the $T_x$ and $R_x$ antennas. While this may not be a conventional shadowing process, it is still a random process that causes variations of received power at a given distance.
TABLE II
T2:2 MEAN EXCESS DELAY, RMS DELAY SPREAD, AND COHERENCE BANDWIDTH FOR DIFFERENT T–R SEPARATION DISTANCES

| d (cm) | Without absorbers | | | | | With absorbers | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | \(\tau_m\) (ps) | \(\tau_{rms}\) (ps) | \(B_c\) (GHz) | \(\tau_m\) (ps) | \(\tau_{rms}\) (ps) | \(B_c\) (GHz) | | | | | |
| 35.56 | 17.18 | 32.12 | 4.95 | 16.92 | 12.00 | 13.26 | | | | | |
| 55.88 | 17.08 | 30.50 | 5.22 | 16.95 | 12.84 | 12.40 | | | | | |
| 76.2 | 17.04 | 31.28 | 5.09 | 16.87 | 10.03 | 15.87 | | | | | |

B. LoS Multipath Characterization

Multipath propagation is the propagation mechanism manifested when the transmitted signal reaches the receive antenna along two or more paths. Such waves typically arrive at the \(R_x\) from many different directions and with different delays, and combine vectorially at the \(R_x\) antenna. Such channel impulse response can be characterized as [31]

\[
h(t, \tau, d) = \sum_{k=1}^{L} a_k(t, d) \exp(j\theta_k(t, d))\delta(t - \tau_k)
\]  

where \(L\) is the number of multipath components, \(a_k\) represents the amplitude of the \(k\)th multipath component, \(\theta_k\) is the associated phase, and \(\tau_k\) is the excess delay of the \(k\)th path relative to the first arrival, and \(\delta(\cdot)\) denotes the Dirac delta function.

An estimate of the channel impulse response is made by taking the inverse discrete Fourier transform (IDFT) of the measured frequency response. The impulse response is then normalized such that the area under the squared magnitude of the power-delay response is equal to one. We refer to a normalized squared magnitude of the impulse response as the multipath intensity profile (MIP) at the single point in space. The noise floor of the MIP is set to 10 dB above the average \(R_x\) noise floor. Part of the MIP characterization is based on rms delay spread \(\tau_{rms}\), which is a measure of multipath spread within the channel. It is an important parameter for characterizing time dispersion or frequency selectivity. It is the square root of the second central moment of the MIP and is given by [31]

\[
\tau_{rms} = \sqrt{\sum_{k=1}^{L}(\tau_k - \tau_m)^2|h(t, \tau_k, d)|^2}
\]  

where \(\tau_m\) is the mean excess delay (the first moment of the MIP) and is defined as

\[
\tau_m = \sum_{k=1}^{L} \tau_k \cdot |h(t, \tau_k, d)|^2.
\]

The rms delay spread, mean excess delay, and the coherence bandwidth \((B_c = 1/(2 \cdot \pi \cdot \tau_{rms}))\) for three separation distances with and without the absorbers are presented in Table II. It is observed that the coherence bandwidths have almost doubled, or even tripled, when the absorbers are in place.

For the distance of 35.56 cm, the delay spread \(\tau_{rms}\) is expected to be lower, or equivalently, the coherence bandwidth is expected to be higher than that of the 76.20 cm, but the opposite is observed in Table II. This is because the distance of 35.56 cm is short enough for the second reflected path to be captured within the maximum excess delay of 6.67 ns. This detection of an extra reflected signal results in the increase in the delay spread, which leads to the decrease in the coherence bandwidth. When the absorbers are used to cover the \(T_x/R_x\) test head’s front face, we can observe that, while the reflections are almost completely removed for 76.20 cm, there are still some weak reflections observed for 35.56 cm. This has again resulted in a slightly narrower coherence bandwidth for 35.56 cm then that for 76.20 cm.

The PDP of the three separation distances in LoS environment with and without the absorbers that cover the \(T_x\) and \(R_x\) test heads is shown in Figs. 7 and 8. Note that all PDP’s are normalized, and referenced to the first incoming path. We can observe that the later arriving paths caused by reflections off the metallic test head cases can be attenuated using the absorbers. It is also observed that the reflected paths have increasing excess delay, more delay spread, and decreasing signal power with
increasing T–R separation as they travel further distances with more power spreading. In summary, the unwanted reflections from the transceiver electronics will have a profound impact on the channel, and attenuating these reflected signals below certain threshold could be an important issue when building the transceiver systems.

IV. CHARACTERIZATION OF D-BAND OLoS CHANNEL

A. OLoS Path Loss and Shadowing

The OLoS environment is created by placing a glass beaker, a plastic cup, and a ceramic mug in the midpoint of the separation distance, and its top edge is 3.5 cm above the LoS path. The measured path losses for these three scenarios and three different separation distances are presented in Fig. 9(a)–(c), respectively. The measured results are compared with the free-space theoretical path loss obtained using (1). The plots show that the measured path loss is much higher than the free-space path loss, which is an expected result since the OLoS has higher losses due to obstructions in LoS. Furthermore, we can observe that the plastic cup introduces the least amount of attenuation compared to free-space path loss and that the variation of path loss across frequencies is minimal. The glass beaker introduces higher attenuation and as the distance increases, the path loss variations as the function of frequency become more pronounced. Finally, the ceramic mug introduces the highest attenuation and the path loss variations as the function of frequency become dominant. We can observe that ceramic material introduces similar attenuation as a glass at lower frequencies, i.e., 110–130 GHz, but then the loss increases to over 100 dB in the range of 140–160 GHz. We can also observe that the maximum of the path loss changes with the separation between the T_x and R_x.

Fig. 9(d)–(f) shows the scatter plot of the path loss as a function of T–R separation for glass, plastic, and ceramic OLoS environments, respectively. All 11 distances are used for the scatter plot to obtain the best linear regression fit. As in the LoS case, there are minimal discrepancies among ten consecutive measurements because the channel is quasi-static with no moving objects in the environment.

To estimate the path-loss model parameters $\gamma$ and $\sigma$ (dB) in (3), we have performed the least-squares linear regression fitting through the scatter of measured path loss points and the results are shown in Fig. 9(d)–(f) for glass, plastic, and ceramic, respectively. The path loss exponents ($\gamma$), standard deviations ($\sigma$), and the path losses at reference distance, 1 m, ($PL_0$) for all three obstruction materials are summarized in Table III. We can observe that the path loss exponent of plastic cup is the closest to the LoS path loss exponent value of 1.96, which is not surprising since plastic is very transparent at D-band frequencies. For glass and ceramic, due to the considerable blockage of LoS path, the path loss exponents have increased above the free-space value of 2. In OLoS scenarios, shadow fading becomes more dominant because of the presence
Fig. 10. Zero-mean Gaussian distributed shadow fading and measured shadow fading for OLoS scenarios. (a) Glass beaker. (b) Plastic cup. (c) Ceramic mug.

Fig. 11. Variation in path loss with varying height of the ceramic mug obstruction.

KIM et al.: D-BAND CHANNEL MEASUREMENTS AND CHARACTERIZATION FOR INDOOR APPLICATIONS 7

of obstructions. To confirm that shadowing can be modeled as a zero-mean Gaussian distributed random variable, we have compared the measured distribution of shadow fading with the Gaussian distribution in Fig. 10. Table III shows that standard deviation around the mean path loss is the smallest with plastic obstruction and similar (but much higher) for glass and ceramic obstructions.

Fig. 11 shows variation in OLoS path loss with varying height of the obstruction, while the T–R separation is fixed at 86.36 cm. As described in Section II-C, the LoS is 20.6 cm above the table, while $h$ is varied from 14.3 to 21.9 cm. In Fig. 11, we can see that the path loss closely follows the theoretical free-space path loss curve when the LoS path is clear of obstruction, which corresponds to $h = 14.3$ cm in the figure. One interesting observation here is that the path loss curve for $h = 18$ cm is about 2 dB below the free-space curve. Geometrical optics simulations reveal that the ceramic mug height of 18 cm at separation distance of 86.36 cm places the top rim of the mug on the boundary of the beam. This results in the second ray that reflects off the mug’s top edge, which combines vectorially with the first LoS path, leading to a slight gain in the received power, and therefore slightly lower path loss than predicted by (1). On the other hand, as $h$ increases, or as the mug obstructs more of the LoS path, it is observed that the path loss increases and becomes more frequency-dependent with higher peaks. For this case, our experimental results and application of uniform geometrical theory of diffraction (UTD) have revealed the presence of diffraction at the convex surface of the cylindrical obstruction. The creeping waves or the surface-diffracted rays that travel around the cylinder in clockwise and counter-clockwise directions and their interference seem to be causing the variation in the measured $S_2$. Further characterization of this particular OLoS channel is one of our main future works.

B. OLoS Multipath Characterization

Fig. 12 plots the PDPs for three obstructions: glass, plastic, and ceramics, respectively. We can observe that all three PDPs have two distinct segments: one where the reflection peak appears at the same time delay regardless of the T–R separation distance (shown as 1 in the figures), followed by the reflection peaks whose positions depend on the T–R separation distance (shown as 2 in the figures). Here, we note that the difference between the first and the second arriving path is always equal to twice the cup diameter, regardless of the T–R separation distance, which explains why the multipath marked as 1 appears at the same excess delay for all distances. Furthermore, from the excess delay that corresponds to the first multipath (marked as 1 in the figures), we can conclude that this multipath corresponds to a ray that penetrated the cup, reflected off the wall closer to the $R_x$, reflected off the wall closer to the $T_x$, and traveled outside the cup to the $R_x$. Although the higher order of reflections might be present, the $R_x$ sensitivity is not high enough to detect them.

From Fig. 12, we can observe that the PDP for the plastic cup has weaker reflected paths compared to the glass and ceramic mugs because most of the energy goes through the plastics and does not stay trapped inside the obstruction. Furthermore, we can observe that the PDP for the ceramic mug has significant reflections only at the distance of 35.56 cm, whereas for 45.72 and 55.88 cm, it is difficult to identify them because the reflections are significantly attenuated due to material properties.

In the PDP section marked as 2 in Fig. 12(a)–(c), we can observe that the position of the multipath peak depends on the T–R separation. From the excess delay that corresponds to the second multipath, we can deduce that the signal has traveled through the obstruction, was reflected from the $R_x$ probe head, was reflected once more off the obstruction, and then received...
by the $R_\alpha$ antenna. Alternatively, the signal was reflected off obstruction, then reflected back from the $T_x$ probe head, and then traveled through obstruction to the $R_x$.

Note that the width of the main peak (first arriving path) is the widest for ceramic mug, which is followed by glass beaker and plastic cup, as observed in Fig. 12. This indicates that the ratio of the power associated with the strongest first arriving path to that of the following reflected paths is the highest for plastic, while the ratio is the lowest for ceramic. This agrees with the fact that glass is the most transparent to the waves, allowing most of the transmitted rays to pass through without multiple reflections. For ceramics, on the other hand, the transparency of the material is much lower than glass, which gives rise to more reflected paths that arrive with delays that are very close to each other. This high temporal proximity is manifested as clustering of the reflected paths, which leads to pulse broadening as shown in Fig. 12(c).

The multipath characterization parameters, $\tau_m$, $\tau_{rms}$, and $B_c$, in the OLoS environment with the three different obstructions for the three T–R spacings, 35.56, 55.88, and 76.2 cm, are summarized in Table IV. The OLoS channel obstructed by the plastic cup has the largest coherence bandwidth of almost 11 GHz at 35.56 cm, which is comparable with that of LoS environment for the same distance. Meanwhile, much narrower coherence bandwidths below 5 GHz are observed for glass and ceramic mug obstructions.

### V. CHARACTERIZATION OF D-BAND RNLoS CHANNEL

Another possible way of communication is through RNLoS paths. Since the effectiveness of communication will depend on the reflectivity of the material; here, we compare two different reflectors: aluminum plate and fiberboard. Furthermore, we investigate the effect of angular orientation of the $R_\alpha$ on the received power levels. The $T_x$ is fixed at $\phi_T = 35^\circ$, and the $R_\alpha$ is rotated between $\phi_R = 0^\circ$ and $\phi_R = 90^\circ$. The angles are measured from the direct LoS path. The T–R separation distance has been fixed at $d = 76.2$ cm. The measured and theoretical (free-space) path loss for several angles $\phi_R$ with aluminum plate and fiberboard as reflectors are shown in Fig. 13. It is evident from the figure that the level of received power is closest to the theoretical LoS level when $\phi_R = \phi_T = 35^\circ$, since the condition $\phi_R = \phi_T$ ensures that the maximum power is transferred through specular reflection. The slight discrepancy from the LoS level can be attributed to the reflection coefficient of the aluminum plate. As the $R_\alpha$ angle $\phi_R$ deviates from $35^\circ$, it is observed that reception becomes weaker and the path loss significantly increases. At the two extremes, $\phi = 0^\circ$ and $\phi = 90^\circ$, we can observe that the communication is essentially lost. Furthermore, we can observe that the path loss is higher when the fiberboard is used as the reflector. This is not surprising result because the fiberboard has lower reflectivity and higher surface roughness.

The PDPs for RNLoS channel with aluminum plate and fiberboard as the reflector for the angular positions, $\phi_R = 10^\circ$ and $35^\circ$ are presented in Fig. 14. The peaks that coincide at $\tau = 3.6$ ns represent the paths bouncing off the reflector, while an additional peak at $\tau = 2.7$ ns observed for $\phi_R = 10^\circ$ is a

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**TABLE IV**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\tau_m$ (ps)</th>
<th>$\tau_{rms}$ (ps)</th>
<th>$B_c$ (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass beaker</td>
<td>35.56</td>
<td>18.06</td>
<td>3.99</td>
</tr>
<tr>
<td>Plastic cup</td>
<td>55.88</td>
<td>18.31</td>
<td>4.63</td>
</tr>
<tr>
<td>Ceramic mug</td>
<td>76.2</td>
<td>18.72</td>
<td>5.19</td>
</tr>
</tbody>
</table>

**Fig. 12.** PDPs for OLoS scenarios. (a) Glass beaker. (b) Plastic cup. (c) Ceramic mug.

**Fig. 13.** Measured RNLoS path loss for different $R_\alpha$ angles with aluminum plate; measured RNLoS path loss with fiberboard, and the theoretical free-space path loss for $d = 76.2$ cm.
result of the direct LoS path that arrives before the reflected path. Note that for the same $R_x$ angle of $\phi_R = 35^\circ$, aluminum plate and fiberboard produce similar PDPs with a single reflected path and no higher order reflections due to the high directivity of the antenna.

Table V presents the mean excess delay, rms delay spread, and coherence bandwidth for different $R_x$ angular positions in RNLos environment. As expected, we can observe the largest coherence bandwidth for $\phi_R = 35^\circ$, at which maximum power transfer occurs. At the same angle, when the reflecting surface is fiberboard, the coherence bandwidth is four times smaller. It is also observed that the coherence bandwidth reduces rapidly as the $R_x$ angle deviates from $35^\circ$, dropping to megahertz range at $\phi_R = 90^\circ$.

**VI. CONCLUSION**

This paper presents measurements and characterization of D-band indoor channels. The measurements are performed in LoS, OLoS, and RNLos environments. For OLoS scenario, cylindrical objects of different materials are used as obstructions. For RNLos, different surfaces are used as reflectors. From the large set of LoS and OLoS measured data, the parameters for single-slope path loss model with shadowing are devised. Furthermore, the analysis of multipath propagation is performed. The rms delay spread, the mean excess delay, and the coherence bandwidth for LoS, OLoS, and RNLos environments are calculated. In addition, the PDPs for LoS, OLoS, and RNLos environments are analyzed. The results show that strong multiple reflections from the $T_x$ and $R_x$ electronics are present both in LoS and OLoS environments. Additionally, the results show that glass and ceramic objects in the propagation path produce surface-diffracted rays which clock-wise and counter-clock-wise superposition leads to frequency-dependent path loss. Finally, the results show that the RNLos measured path loss with aluminum plate as a reflector is very similar to free-space path loss when the angle of incidence and the angle of reflection are equal.

**REFERENCES**


et al. (S’09–M’10–SM’13) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Belgrade, Belgrade, Serbia, in 2001 and 2003, respectively, and the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2008.

Currently, she is an Assistant Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology. Prior to that, she was a Visiting Faculty at the School of Computer Science, Georgia Institute of Technology, a Postdoctoral Fellow with the Naval Research Laboratory, and Design Engineer with Skyworks Solutions Inc. Her research interests include electromagnetics, wireless communications, signal processing, and computer engineering.

Dr. Zajić was the recipient of the Neal Shepherd Memorial Best Propagation Paper Award, the Best Paper Award at ICM 2007, the Dan Noble Fellowship in 2004, awarded by Motorola Inc., and the IEEE Vehicular Technology Society for quality impact in the area of vehicular technology. Currently, she is an Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and the Chair of the IEEE MTT/AP Atlanta Chapter.

John Papapolymerou (’Fx’x) received the B.S.E.E. degree from the National Technical University of Athens, Athens, Greece, in 1993, and the M.S.E.E. and Ph.D. degrees from the University of Michigan, Ann Arbor, MI, USA, in 1994 and 1999, respectively.

From 1999 to 2001, he was an Assistant Professor with the Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, USA, and during 2000 and 2003, he was a Visiting Professor at the University of Limoges, Limoges, France. From 2001 to 2005 and 2005 to 2009, he was an Assistant Professor and Associate Professor, respectively, with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA, where he is currently the Ken Byers Professor. He has authored or coauthored over 350 publications in peer-reviewed journals and conferences. His research interests include the implementation of micromachining techniques and MEMS devices in microwave, millimeter-wave and THz circuits and the development of both passive and active planar circuits and antennas on semiconductor (Si/SiGe, GaAs) and organic substrates (liquid crystal polymer-LCP, LTCC) for system-on-a-chip (SOC) and system-on-a-package (SOP) RF front ends.

Dr. Papapolymerou currently serves as Editor-in-Chief for IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS (MWCL). He has also served as an Associate Editor for IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES from 2010 to 2012, and as Chair for Commission D of the US National Committee of URSI from 2009 to 2011. He was also an Associate Editor for IEEE MWCL (2004–2007), and IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (2004–2010). During 2004, he was the Chair of the IEEE MTT/AP Atlanta Chapter. He was the recipient of the 2012 IEEE ANTENNAS AND PROPAGATION SOCIETY (AP-S) H.A. Wheeler Prize Paper Award, the 2010 IEEE AP-S John Kraus Antenna Award, the 2009 IEEE MICROWAVE THEORY AND TECHNIQUES–SOCIETY (MTT-S) Outstanding Young Engineer Award, the 2009 School of ECE Outstanding Junior Faculty Award, the 2004 Army Research Office (ARO) Young Investigator Award, the 2002 National Science Foundation (NSF) CAREER award, the Best Paper Award at the 3rd IEEE International Conference on Microwave and Millimeter-Wave Technology (ICM2002), Beijing, China, and the 1997 Outstanding Graduate Student Instructional Assistant Award presented by the American Society for Engineering Education (ASEE), the University of Michigan Chapter.


Seunghwan Kim (S’14) was born in Seoul, South Korea, in 1986. He received the Bachelor of Applied Science degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 2009. He is currently pursuing the Ph.D. degree in electrical engineering at Georgia Institute of Technology, Atlanta, GA, USA.

During his degree, he worked as a Research Assistant with the Telecommunication Group, Korea Electrotechnology Research Institute (KERI), Changwon, Korea, and as a Hardware Engineer with Mitel Networks, Kanata, ON, Canada.

Wasif Tanveer Khan (S’10–M’15) received the B.Sc. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, in 2005, and the M.S. and Ph.D. degrees in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2010 and 2014, respectively.

From January 2006 to December 2008, he was a Lecturer with the National University of Computer and Emerging Sciences–FAST, Lahore, Pakistan. Since January 2015, he has been working as an Assistant Professor with the Department of Electrical Engineering, Lahore University of Management Sciences, Lahore, Pakistan. He has authored/coauthored more than 35 research papers in peer-reviewed conferences and journals. His research interests include the RF and microwave system design, millimeter wave circuit and package design, multilayer organic packaging, on-chip and off-chip antenna design, and phased array systems.

Dr. Khan has been the publications Chair for four IEEE conferences: RWS, PAWR, WisNet, and BioWireless, since 2010. Since 2011, he has also been a Technical Program Committee (TPC) member for IEEE Radio and Wireless Symposium (RWS). He was the recipient of a MS leading to Ph.D. fullbright Scholarship.

Alenia Zajić (S’09–M’09–SM’13) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Belgrade, Belgrade, Serbia, in 2001 and 2003, respectively, and the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2008.

John Papapolymerou (’Fx’x) received the B.S.E.E. degree from the National Technical University of Athens, Athens, Greece, in 1993, and the M.S.E.E. and Ph.D. degrees from the University of Michigan, Ann Arbor, MI, USA, in 1994 and 1999, respectively.

From 1999 to 2001, he was an Assistant Professor with the Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, USA, and during 2000 and 2003, he was a Visiting Professor at the University of Limoges, Limoges, France. From 2001 to 2005 and 2005 to 2009, he was an Assistant Professor and Associate Professor, respectively, with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA, where he is currently the Ken Byers Professor. He has authored or coauthored over 350 publications in peer-reviewed journals and conferences. His research interests include the implementation of micromachining techniques and MEMS devices in microwave, millimeter-wave and THz circuits and the development of both passive and active planar circuits and antennas on semiconductor (Si/SiGe, GaAs) and organic substrates (liquid crystal polymer-LCP, LTCC) for system-on-a-chip (SOC) and system-on-a-package (SOP) RF front ends.

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