

Characterization of Propagation Phenomena Relevant for 300 GHz Wireless Data Center Links

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Abstract— This paper presents details about an extensive channel measurement campaign and subsequent statistical channel models for the characterization of 300 GHz channels for wireless rack-to-rack (R2R) and blade-to-blade (B2B) communications in a data center-like environment. Measurements were conducted in various scenarios such as R2R line-of-sight (LoS), R2R obstructed-LoS (OLoS), R2R reflected-non-LoS (RNLoS), R2R obstructed-RNLoS (ORNLoS), B2B RNLoS, B2B ORNLoS, and B2B LoS scenarios. In the aforementioned scenarios, we explored the impact of transmitter (T_x)/receiver (R_x) misalignment and obstructions such as cables, metal cabinets, and mesh structures on THz propagation, as well as feasibility of using existing metal objects as reflectors for NLoS links. For the R2R LoS scenario, an optical lens was used to extend the T_x - R_x separation distance. This led to a waveguide effect in the channels measured thereby resulting into a path loss exponent (PLE) of 1.48 with a shadowing gain of 0.7 dB. When obstructions of cables are present, ORNLoS link outperforms OLoS link with 2.5 dB lower shadowing gain and weaker multipath. Reflector in the RNLoS link has reflection coefficients very close to 1 for all incident angles. For the B2B scenario, a dual-reflector THz transceiver rack system is proposed to enable wireless links across vertically stacked servers and allow easy maintenance and repair of servers. The measured path loss closely follows the Friis values in the LoS link and in the RNLoS link with hollow vertical ground plane. When obstructions of cables are present, the ORNLoS link experiences 5–10 dB higher path loss and on average 0.25 GHz lower coherence bandwidth than the RNLoS link. Measured statistical channel properties show that the shadowing gain caused by cable clusters follows the log-normal distribution.

Index Terms— THz propagation, wireless propagation in data centers, channel sounding, channel characterization.

I. INTRODUCTION

Data centers play an important role in cloud computing and storage [1], [2]. An essential need inside data centers is high-speed and reliable connectivity between servers [3]. Optical waveguides and metal wires are conventionally used in data centers, but they increase the service time and the cost of operation, maintenance, and assembly, and degrade cooling efficiency, etc. [1]–[10]. Cabling cost may take up to 3–8% of the overall infrastructure budget, according to [11]. Cable bundles between server racks and blades can lead to blockages of airflow, which may increase power consumption for cooling or cause failure of components [12], [13].

One potential solution for data center rack-to-rack (R2R) and blade-to-blade (B2B) links is to use wireless communications, which will not only alleviate packaging constraints,

cable management, serviceability, but also provide direct wireless communication with lower latency [1]–[10], e.g., from one rack to the next-aisle rack, as opposed to common approaches of routing cables down to the floor or above racks where they are connected to routers and switches. One major challenge for wireless data centers is to provide high data rates in the range of hundreds of gigabits per second required in existing systems [14]. Terahertz (THz) wireless communication is an ideal candidate to provide ultra high data rates and has the following advantages to facilitate wireless data centers: sufficient available bandwidth [9], [10]—an IEEE 802.15.3d [15] standard for THz communication proposes data rates up to 100 Gbit/s at 252–325 GHz using eight different bandwidths between 2.16 GHz and 69.12 GHz. Smaller antennas and antenna spacing at THz frequencies enables miniaturization of phased arrays for beamsteering to provide more MIMO (multiple input multiple output) channels within the same array aperture that can reach Tbit/s data rates. Directional beams at THz frequencies lead to increased isolation and reduced interference [16], [17]. Moreover, controllable environmental conditions in data centers such as limited nodes mobility and a low moisture atmosphere can be favorable for THz wave propagation. The frequency-dependent path loss at THz corresponding to various frequencies and relative humidity levels is presented in [18], [19]. Highly directional antennas can be used to overcome the molecular absorption losses at the THz bands [20]. In addition, optimal carrier frequency selection strategies can reduce path loss and improve throughput [9], e.g., there are several transmission windows around 300 GHz with low atmospheric losses.

To develop THz R2R and B2B wireless data centers, THz channel measurements need to be conducted in a data center environment. Since data exchange demands high reliability at data centers, the effects of blockage of cables, humans, and small-scale mobility (e.g. rack vibrations) on THz propagation need to be studied. The blockage caused by cables has been discussed in this paper. Human blockage can cause additional attenuation around 35 dB at 300 GHz [21]. While the effect of rack vibrations depends on antenna beamwidth [22] because rack vibrations may cause T_x - R_x misalignment up to 0.25 mm [23], however, we have verified that given a THz antenna with a beamwidth at around 10 degrees, a 0.25 mm T_x - R_x misalignment does not cause any observable time-domain or frequency-domain differences at $d = 20$ – 210 cm and thus the effect of rack vibrations is not discussed in this paper. Scattering effect is another important propagation property that needs to be considered for THz communications as wavelength approximates the surface roughness of the reflecting medium

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[24]. [25] provides detailed modeling of the diffuse scattering loss and shows that THz wireless links can be established via scattered paths. In our measurements, the R2R RNLoS link experiences scattering of the metal reflector. While the concept of THz wireless data centers has been mentioned in [9], [10], [19], [26] and stochastic channel models for THz wireless data centers have been presented in [10], no channel measurements for THz R2R or B2B scenarios have been conducted. In our prior work [27], THz channel measurements have been conducted in a data center-like environment. However, the study was limited to the R2R scenario without further investigating the B2B scenario and the impacts of obstructions of server racks and their mesh structures on THz propagation. Moreover, no statistical channel properties have been developed, which are crucial for building channel models.

This paper presents detailed characterization of 300 GHz channels for wireless R2R and B2B communications in a data center-like environment. We envision that future THz wireless data centers will leverage the integration of B2B and R2R links such that B2B links will provide short-range communication between servers within the same rack, while R2R links with optical lenses enable long-range communication across multiple racks. We have performed measurements in seven different wireless data center scenarios: 1) R2R line-of-sight (LoS); 2) R2R obstructed-LoS (OLOs) with obstructions of cables, metal cabinets, and mesh structures; 3) R2R reflected-non-LoS (RNLoS) link, where an aluminum reflector is used to redirect signals in NLoS links; 4) R2R obstructed-RNLoS (ORNLoS) where cables are placed between the transmitter (T_x)/receiver (R_x) and the reflector as obstruction; 5) B2B RNLoS, where two metal reflectors are used to direct waves vertically across servers; 6) B2B ORNLoS, where the B2B RNLoS link is obstructed by cables; 7) B2B LoS, where the T_x and R_x are horizontally placed on a rack server. We consider these seven scenarios to evaluate the impact of T_x/R_x misalignment and obstructions such as cables on THz propagation, as well as possibility of using existing metal objects as reflectors that guide signals in desired directions.

The rest of the paper is organized as follows. Section II presents our THz channel sounding system and PTFE optical lens configuration. Section III describes seven measurement scenarios. Section IV introduces the analysis methodology. Sections V and VI present measurement and analysis results for R2R and B2B links, respectively. Last, Section VII provides concluding remarks.

II. MEASUREMENT SETUP

Our channel sounding system includes a Keysight N5224A PNA vector network analyzer (VNA) for recording the frequency-domain channel sounding measurement, a Virginia Diodes, Inc. (VDI) Tx210 transmitter and a VDI Rx148 receiver [28] with T_x output power of around -15 dBm. A vertically polarized pyramidal horn with gain that varies from 22 to 23 dBi from 300 GHz to 312 GHz, and with theoretical half-power beamwidth (HPBW) of 10° in azimuth and elevation is used in our measurement. Detailed instrument description and measurement parameters can be found in

TABLE I
MEASUREMENT PARAMETERS

Parameter	Symbol	Value
Measurement points	N	801
Intermediate frequency bandwidth	Δf_{IF}	20 kHz
Average noise floor	P_N	-90 dBm
Input signal power	P_{in}	0 dBm
Start frequency	f_{start}	10 MHz
Stop frequency	f_{stop}	12 GHz
Bandwidth	B	11.99 GHz
Time domain resolution	Δt	0.083 ns
Maximum excess delay	τ_m	20 ns

Table I and [14]. Two plano-convex Polytetrafluoroethylene (PTFE/Teflon) lenses [29] with a diameter of 5 cm and a focal length of 7.5 cm are used in the R2R scenario to give additional gain. The configuration of THz lenses is presented in Fig. 1. Note that when changing the T_x - R_x distance, only the distance between two lenses (d') varies, while the distance between horns and lenses is fixed at 6 cm.

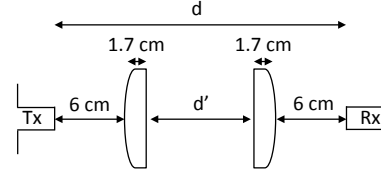


Fig. 1. Polytetrafluoroethylene (PTFE) lenses configuration for the R2R scenario.

III. MEASUREMENT SCENARIOS

In this measurement campaign, seven wireless data center scenarios have been considered. We envision that future THz wireless data centers will leverage the integration of blade-to-blade (B2B) and rack-to-rack (R2R) links such that B2B links provide short-range communication between servers within the same rack, while R2R links enable long-range communication across multiple racks, and that future THz wireless data center will be equipped with optical lenses and THz transceivers that are miniaturized and integrated into the server chassis. THz beam alignment and beam steering techniques with the use of lenses have been introduced in [30]. The measurement designs and results provided in this paper are the starting point and proof-of-concept for realistic performance evaluations and designs and prototyping of THz communications systems in wireless data center environments. Note that “blade” represents a server mounted on a rack, and the B2B link represents communication link among different servers placed in vertical and horizontal positions on one rack.

A. R2R LoS Link

In the R2R link [4], T_x and R_x are mounted on top of server racks to enable wireless communication between racks. Fig. 2 (a) presents the measurement setup for R2R LoS link, where THz T_x/R_x and lenses are placed on top of two separate metal cabinets, acting as server racks in a data center. Measurements were taken at T_x - R_x distances of 40–210 cm

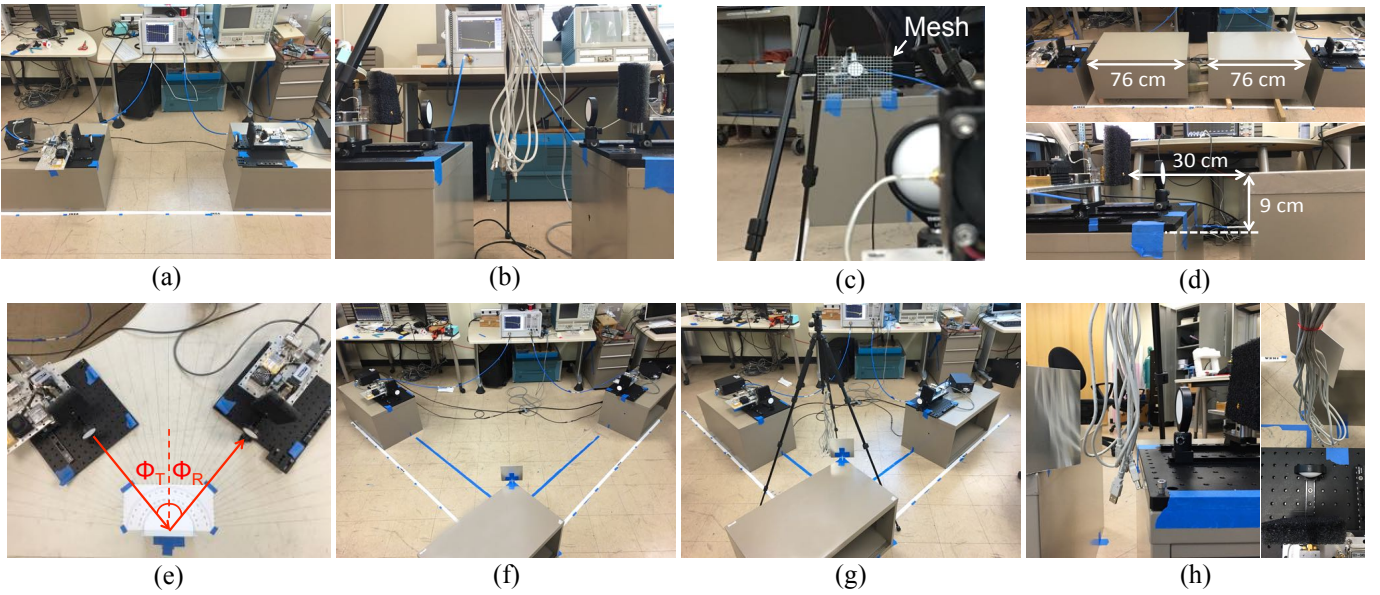


Fig. 2. Measurement scenarios of the R2R link: (a) LoS; OLoS with (b) cables, (c) mesh, and (d) metal cabinets serving as obstructions; (e) RNLoS reflection coefficient measurement; (f) RNLoS; (g)/(h) ORNLoS with cables serving as an obstruction.

in 5 cm increments. The maximum distance of 210 cm is constrained by the length of the synchronization cable that connects the T_x and R_x . We use the R2R LoS scenario both as a potential data center link as well as validation of our measurement setup in the R2R obstructed-LoS scenario.

B. R2R OLoS Link

In this section, we study a scenario where the wireless link is obstructed by cables, server racks and their mesh structures, which are common objects in data centers. According to [4], [12], long cables in data centers require overhead cable trays, where cables may be exposed to the R2R link between the overhead cable trays and the racks. The measurement setup for R2R OLoS link with cables as obstruction is presented in Fig. 2 (b). Following the same setup in Section III-A, the LoS channel is now obstructed by a cluster of cables hung in the air from a tripod. We use a tripod to hold cables such that cables can be fixed at the same position (midpoint between T_x/R_x) while T_x/R_x were being moved. The R2R OLoS measurements with cables as obstruction have been recorded at $d = 40\text{--}210$ cm with 10 cm increments. Furthermore, in a data center for an R2R scenario with a maximum distance of 210 cm, there will be multiple server racks between the T_x and R_x . Multiple metal cabinets and their mesh structures might have an influence on the channel. We have investigated R2R links with metal cabinets and mesh structures placed between the T_x and R_x that partially block the channel. The measurement setups for R2R OLoS link with mesh structures and metal cabinets as obstructions are presented in Figs. 2 (c) and (d), respectively. Measurements have been recorded at $d = 210$ cm.

C. R2R RNLoS Link

R2R RNLoS links are proposed to increase transmission range and allow T_x/R_x to bypass obstructions and establish direct links without multi-hop relays [4]. Most of the existing

RNLoS links in wireless data centers [2], [4]–[6], [10] use entire ceiling in server rooms as reflectors, which increases cost and occupies huge space. Our configuration in Fig. 2 (f) shows that a palm-sized compact reflector would be sufficient for R2R RNLoS links in THz wireless data centers due to the very focused THz beam. If more links are required, we may increase the size of the reflector or cover the ceiling/wall with reflecting material and use them as reflectors [2], [4]–[6], [10]. Note that the dimension of the reflector needs to accommodate lens size. We design an aluminum square-shape reflector with length of 15 cm (roughly twice the lens diameter). R2R RNLoS measurements are recorded at T_x horn-to-reflector-to- R_x horn distance = 40–210 cm with 5 cm increments with equal T_x/R_x -to-reflector distances and equal transmitting and receiving angles (ϕ_T/ϕ_R) at 45° . We use the R2R RNLoS scenario as validation of our measurement setup for the R2R RNLoS that we later used for the obstructed-RNLoS scenario. Furthermore, we also characterized the reflection coefficient and the angular misalignment tolerance range of the aluminum reflector used in the R2R RNLoS link with the measurement setup in Fig. 2 (e). In the reflection coefficient measurement, to ensure specular reflection, the angle of incidence (ϕ_T) is set equal to the angle of reflection (ϕ_R) in the range from 20° to 85° in 5° increments with T_x horn-to-reflector-to- R_x horn distance fixed at 90 cm. This setup is chosen to test the stability of the reflector’s reflection coefficient in various T_x/R_x angular setups since in reality the R2R RNLoS link may not be able to position the reflector at exact $\phi_T = \phi_R = 45^\circ$, e.g., obstructions or location of the racks may vary. In the angular misalignment measurement, ϕ_T is fixed at 45° while ϕ_R varied from 5° to 85° in 5° increments with T_x horn-to-reflector-to- R_x horn distance fixed at 90 cm. This setup is chosen to test the angular misalignment tolerance range.

D. R2R ORNLoS Link

Figures 2 (g) and (h) present the measurement setup for the R2R ORNLoS link with cables as obstruction. Similar to

Section III-C, here we position a tripod with obstructing cables between the T_x and the reflector. R2R ORNLoS measurements are recorded at $d = 40\text{--}210$ cm with 10 cm increments.

E. B2B RNLoS Link

In the B2B RNLoS scenario, rack-mounted reflectors are used to enable wireless links across vertically stacked servers. Optical lenses are not applied due to shorter communication range and limited space in a B2B environment. Fig. 3 (a) and Figs. 4 (a)–(d) present schematics and measurement setup of the B2B RNLoS link. Note that the rack in Fig. 4 is a mock-up of a real server rack. T_x is placed at the lower blade (blade 2) and R_x is placed at the upper blade (blade 1), both of which are facing toward the vertical metal panel of the cabinet. To enable a link between T_x and R_x , we position two rack-mounted reflectors in a similar manner as in a periscope, i.e., two reflectors are positioned at 45° to the direction where T_x and R_x are pointed to, such that the transmitted signal can reach the R_x via a vertical channel between two vertically aligned reflectors. Using metal reflectors for communication between two blades can be extended to multiple blades by having longer metal reflectors. Many of the datacenter racks come with metal enclosure that can be leveraged as a reflector. Data exchange at each server node is typically point-to-point communication, where a switch will be used to connect multiple servers onto the network. Interference may need to be handled for the coexistence of multiple B2B links. Fortunately, due to the narrow beamwidth at THz frequencies, interference can be better managed compared to lower frequencies. One advantage of using rack-mounted reflectors as compared to waveguides is that it allows easy maintenance and repair of blades. In addition, we want to test the possibility of using reflectors for NLoS type of link inside a server rack since there may be obstacles inside server compartments blocking the propagation path, which require redirecting the THz beam. Reflectors will provide more flexibility for realizing NLoS type of links inside a server rack. In Fig. 3 (a), $d_1 = d_3$ are the T_x/R_x -to-reflector distance, $d_2 = 15$ cm is the distance between the T_x - and R_x -reflectors (roughly twice/four times of the height of the 2U/1U rackmount servers [31]), $d_4 = 4$ cm is the gap between rack's vertical ground plane and the edge of the reflector, $d_5 = 2.2$ cm is the distance between the horizontal ground plane and the horn center. We have found that reflection can be generated from both vertical and horizontal ground planes inside the rack (paths 1, 2, and 3 in Figs. 3 (b) and (c)) and can lead to significant path loss variation as distance increases. To better understand the reflection in a B2B environment, we conducted our experiments with three vertical ground plane designs in a server compartment: 1) solid metal (Fig. 5 (a)), 2) hollow (Fig. 5 (b)), and 3) mesh (Fig. 5 (c)) structures. Since we want to focus on analyzing reflection from the vertical ground plane, we limit the total distance ($d = d_1 + d_2 + d_3$) to within 49 cm such that the reflection interference from blade 2's horizontal ground plane (path 3 in Fig. 3 (c)) can be minimized. The server rack we use has a dimension of 130 cm x 75 cm x 45 cm. The opening window of the vertical ground plane (Fig. 5) has a size of 12 cm x 10 cm. The T_x/R_x reflectors are made of aluminum and have dimensions of 15 cm x 5

cm. Note that the size of reflectors should accommodate the height and the beamwidth of the T_x/R_x antennas, and that the alignment of T_x/R_x reflectors is critical since the received signal is extremely sensitive to the positioning of the reflectors. We briefly discuss the consequences of misaligned reflectors in the following paragraphs. The B2B RNLoS measurements have been recorded as the total horn-to-horn distance ($d = d_1 + d_2 + d_3$) varied from 20 cm to 49 cm with 1 cm increments (both d_1 and d_3 change and $d_1 = d_3$).

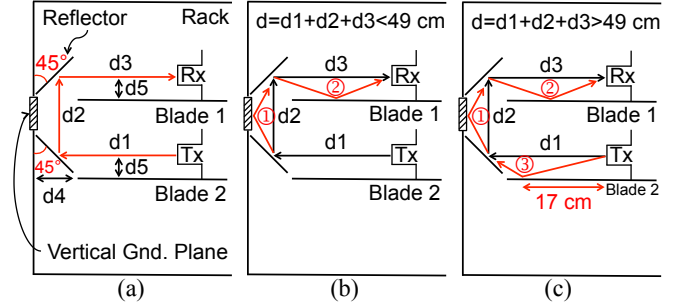


Fig. 3. (a) Schematics of B2B RNLoS measurement setup. Analysis of reflection interference in B2B environment at (b) $d < 49$ cm and (c) $d > 49$ cm.

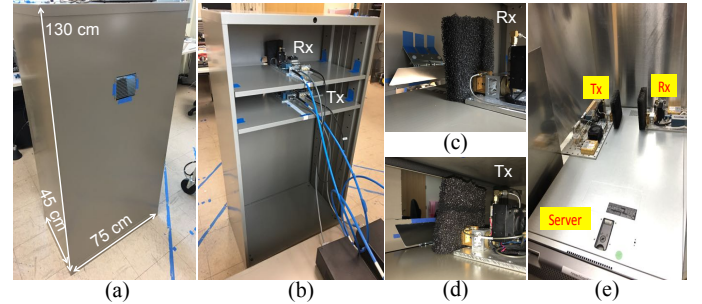


Fig. 4. Measurement setup of the vertical B2B link: (a) back and (b) front sides of the rack, (c) R_x and R_x -reflector at the upper blade, (d) T_x and T_x -reflector at the lower blade; (e) measurement setup of the B2B LoS link.

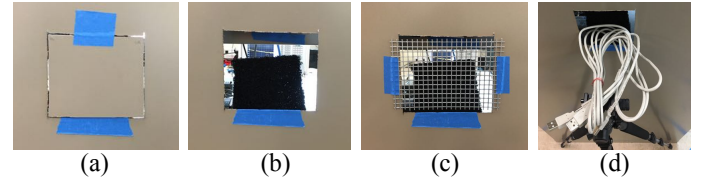


Fig. 5. Vertical ground plane designs in B2B server compartments: (a) solid metal, (b) hollow structure, and 3) mesh structure; (d) hollow structure with cables as obstruction.

F. B2B ORNLoS Link

Our measurement setup for the B2B ORNLoS link is presented in Fig. 5 (d). Similar to the setup in Section III-E, here we place the obstructing cables supported by a tripod through the opening window of the vertical ground plane between the T_x - and R_x -reflectors. B2B ORNLoS measurements are recorded at $d = 20\text{--}49$ cm with 1 cm increments.

G. B2B LoS Link

Our measurement setup for the B2B LoS link is presented in Fig. 4 (e), where the T_x and R_x are placed on a rack server and aligned horizontally as common blade servers are placed on a rack. Aluminum plates are placed around the rack

server to mimic a rack compartment environment. The B2B LoS measurements have been recorded at $d = 12, 14, 16,$ and 18 cm. T_x - R_x distances are selected such that they are greater than the thickness of one blade server (4.4 cm for one blade according to [31]) or multiple blade servers.

IV. ANALYSIS METHODOLOGY

A. Path Loss and Multipath Characterization

For our analysis, we calculate the mean of measured path loss (\overline{PL}) by averaging a continuous wave over frequency and time,

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

where M is the number of snapshots of frequency-response over time, N is the number of frequency tones. $H(f_i, t_j, d)$ is the measured complex frequency response data (transfer function) and d is the T_x - R_x distance. We use the single-frequency floating-intercept (FI, the 3rd Generation Partnership Project 3GPP, or alpha-beta) path loss model to model the mean path loss due to its better susceptibility to measurement errors [32]. FI path loss model is defined as [33, pp. 16–21]:

$$PL^{FI}(d) = \alpha + 10\beta \log_{10} \left(\frac{d}{d_0} \right) + X_{\sigma}^{FI}, d \geq d_0, \quad (2)$$

where $PL^{FI}(d)$ is the dB-scale path loss as a function of d , α is a floating intercept (in dB) representing the path loss in the free-space at reference distance $d_0 = 20$ cm. According to [34], d_0 should always be in the far-field of the antenna so that the near-field effects do not alter the reference path loss. The far-field boundary in our work was estimated as 4.23 cm at 300 GHz according to the Fraunhofer distance given that the largest physical dimension of the horn aperture is 4.6 mm. We set d_0 as 20 cm since it falls within the far-field range and it is also the first distance measured in our work. β is the path loss exponent, PLE, that characterizes the path loss dependency on d . X_{σ}^{FI} is the large-scale shadowing gain that can be modeled by zero-mean Gaussian distributed random variable with standard deviation σ (dB). Least-squares linear fitting is applied on the measured path loss data to estimate path loss model parameters (α , β , and σ) such that the RMS deviation from the mean path loss is minimized.

We obtain the channel impulse responses by conducting the inverse discrete Fourier transform (IDFT) over the measured channel frequency responses. RMS delay spread is estimated by the calculation of the square root of the second central moment of the normalized squared magnitude of the channel impulse response, i.e.,

$$\tau_{rms} = \sqrt{\frac{\sum_{k=1}^L (\tau_k - \tau_m)^2 |h(t, \tau_k, d)|^2}{\sum_{k=1}^L |h(t, \tau_k, d)|^2}}, \quad (3)$$

where τ_k is the excess delay of the k^{th} path relative to the first arrival, $|h(t, \tau_k, d)|^2$ is the squared magnitude of the channel impulse normalized by the sum of PDPs over delay bins, L is the number of multipath components, and τ_m is the mean excess delay defined as

$$\tau_m = \sum_{k=1}^L \tau_k \cdot |h(t, \tau_k, d)|^2. \quad (4)$$

The coherence bandwidth (B_c) with a correlation coefficient of 0.9 is estimated as [34],

$$B_c \approx 1/(2 \cdot \pi \cdot \tau_{rms}). \quad (5)$$

B. Reflection Coefficients

The reflection loss of the aluminum reflector in the R2R link is obtained by calculating the difference between the R2R LoS received power at $d = 90$ cm and the R2R RNLoS received power with $\phi_T = \phi_R = 45^\circ$ and T_x horn-to-reflector-to- R_x horn distance at 90 cm. The reflection coefficient is found from the reflection loss,

$$RL = -20 \log_{10} |\Gamma|, \quad (6)$$

where Γ is the reflection coefficient and RL is the reflection loss in dB, which is calculated from the link budget equation,

$$RL = P_t - P_r + G_t + G_r - \overline{PL} \text{ [dB]}. \quad (7)$$

Note that similar characterization of the reflectors in the B2B RNLoS link without T_x/R_x optical lenses can be found in [35].

V. R2R RESULTS

A. Characterization of R2R LoS and R2R RNLoS Links

Here we characterize the relationship between T_x - R_x distance and path loss, PDPs, and B_c in the R2R LoS and R2R RNLoS scenarios as introduced in Figs. 2 (a), (f) and Sections III-A and III-C.

Figures 6 (a) and (b) present the measured path loss with T_x - R_x distances at 50–210 cm in R2R LoS and R2R RNLoS scenarios, respectively. Similar path loss values that range between 50–64 dB have been observed in the LoS and RNLoS links at distances between 50–210 cm. Friis theoretical path loss at $d = 50$ cm is also presented in Figs. 6 (a) and (b) to demonstrate that more than 25 dB additional gain can be obtained with the use of optical lenses. Note that due to the very focused beam created by the lenses, the channel characteristics (e.g. multipath, ripples in transfer function) in the R2R scenarios are dominated by the effects of the lenses rather than the surrounding environment. As a result, we will include the lenses as part of the propagation channel rather than part of the measurement system. We can observe that periodic ripples in the measured path loss curves are the strongest at near distances and slowly attenuate as distance increases. The reason is that ripples result from multiple reflections between horns and lenses, and the reflections gradually decay as distance increases. Note that the periodic path loss ripples are not caused by the antenna gain diagram since antenna's peak-to-peak gain variations over frequency are only around 0.6 dB while the measured path loss ripples have peak-to-peak values up to 4 dB.

Figure 7 presents a comparison of FI path loss models and the measured mean path loss for the R2R LoS and R2R RNLoS scenarios at $d = 40$ –210 cm. Detailed path loss model parameters are summarized in Fig. 7. It can be observed that

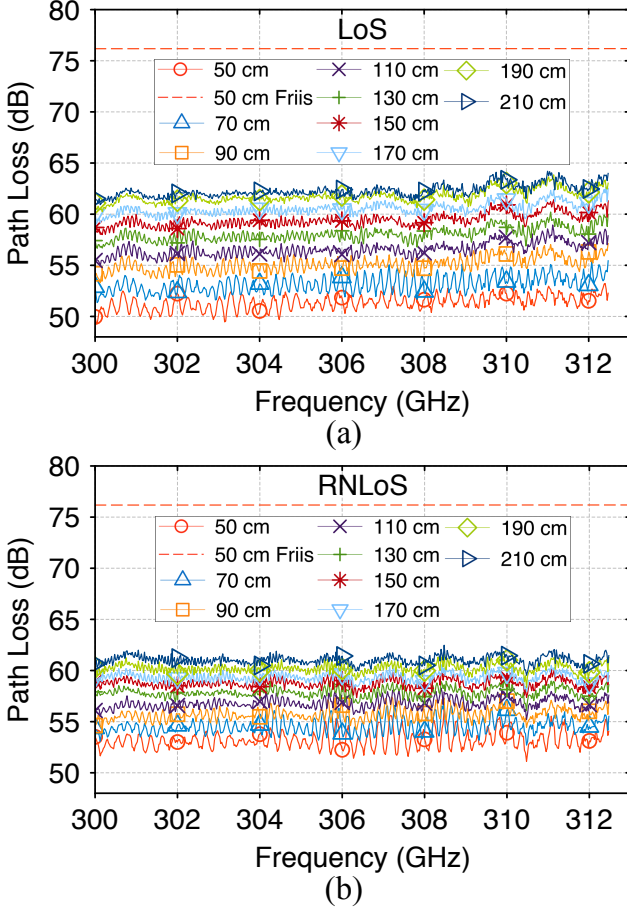


Fig. 6. Measured path loss curves in (a) R2R LoS and (b) R2R RNLoS scenarios at $d = 50, 70, 90, 110, 130, 150, 170, 190, 210$ cm along with Friis theoretical path loss at $d = 50$ cm.

the R2R RNLoS link has similar path loss values as the R2R LoS link. We can also observe that both the R2R LoS and the R2R RNLoS links act as waveguides with PLEs of 1.48 and 1.25 due to the use of optical lenses. Interestingly, we found that both R2R LoS link (red triangles in Fig. 7) and R2R RNLoS link (blue cross signs in Fig. 7) seem to have two trends of slopes (PLE): one from 3 to 6 dB of x-axis and the other from 6 to 10 dB of x-axis. From 3 to 6 dB of x-axis, both R2R LoS and R2R RNLoS links have similar slopes of around 0.5. From 6 to 10 dB of x-axis, the R2R LoS link has a slope of around 2, whereas the slope is around 1.6 in the R2R RNLoS link. We conclude that two trends of slopes in the R2R LoS and R2R RNLoS links result from the diverging of the beam given the fact that the collimated beam created by the lenses is not perfectly parallel. At distance between 40 cm and 80 cm (from 3 to 6 dB of x-axis), the diverging of the collimated beam is less significant and thus the R2R LoS link and the R2R RNLoS link have similar path loss values and slopes. In contrast, at distance between 80 cm and 210 cm (from 6 to 10 dB of x-axis), the collimated beam diverges to an extent such that the received signal starts to decay at a faster rate for both R2R LoS and R2R RNLoS links. Specifically, for the R2R LoS link, the received signal decays at a rate similar to in a free space with a path loss slope (PLE) of around 2, while for the R2R RNLoS link, a lower PLE of around 1.6 is observed, which is due to the fact that reflector helps

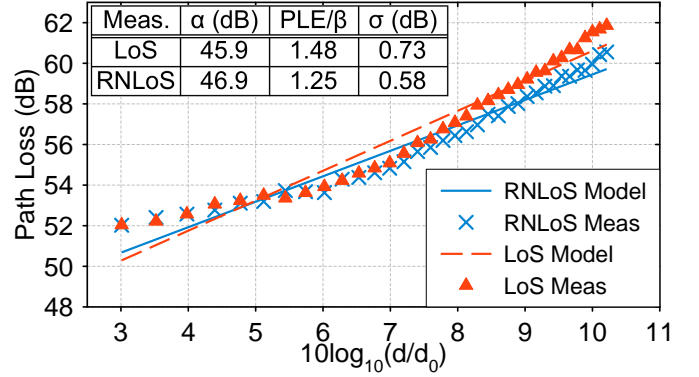


Fig. 7. Measured mean path loss for the R2R LoS (red triangles) and R2R RNLoS (blue cross signs) scenarios and FI path loss models for the R2R LoS (red dash line) and the R2R RNLoS (blue solid line) scenarios at $d = 40$ – 210 cm and $d_0 = 20$ cm.

to “collect” the diverged waves and transmit back to the R_x , resulting in lower path loss values.

Figure 8 shows the measured PDPs for R2R LoS and R2R RNLoS scenarios at $d = 50$ – 210 cm. We categorize multipaths into three clusters as shown in Figs. 8 (a) and (b). Cluster 1 results from reflections between (T_x lens and T_x horn) and (R_x lens and R_x horn), where a time delay of 0.8 ns corresponds to four times of lens-horn distance. Note that cluster 1’s time delay does not change as distance increases because the horn-lens distance is always 6 cm (please refer to Fig. 1). Cluster 2 results from reflections between T_x lens and R_x horn and between R_x lens and T_x horn. Take the R2R LoS 50 cm PDP curve (red curve in Fig. 8 (a)) for example, cluster 2 has a delay about 3 ns corresponding to an additional delay path of 90 cm that is roughly twice the distance from the R_x horn to the T_x lens plus multiple reflected paths within the R_x lens. Cluster 3 is due to R_x horn-to- T_x horn reflection. Take the R2R LoS 50 cm PDP curve (red curve in Fig. 8 (a)) for example, it can be observed that cluster 3 has a delay around 3.7 ns corresponding to an additional delay path of 111 cm that is roughly twice the distance from the R_x horn to the T_x horn plus multiple reflected paths within the R_x lens and the T_x lens. Since the surrounding area of the T_x and R_x horns are covered with absorbers, we can conclude that the tips and internal surfaces on the horns are the cause of horn-related multiple reflections. From Figs. 8 (a) and (b), we can observe that as distance gradually increases, clusters 2 and 3 in the R2R LoS link and cluster 3 in the R2R RNLoS link gradually decayed below the noise floor (cluster 3 decreased at a faster rate than cluster 2), while cluster 2 in the R2R RNLoS link remained visible. As distance increases to 185–210 cm, only cluster 1 in the R2R LoS link remained as shown in Fig. 8 (a). On the contrary, both clusters 1 and 2 in the R2R RNLoS link remained observable at around 12–14 ns at distance up to 210 cm as shown in Fig. 8 (b). The comparison in Figs. 8 (a) and (b) shows that the reflector in R2R RNLoS link preserved reflections between T_x lens and R_x lens and sustained cluster 2 in PDPs over distances of 50–210 cm. This difference in PDPs between R2R LoS and R2R RNLoS links has an impact on the B_c values and the maximum data rate as discussed in the next paragraph. In addition, we can infer that reflections from server rack frames (metal cabinets in our mock-up) are

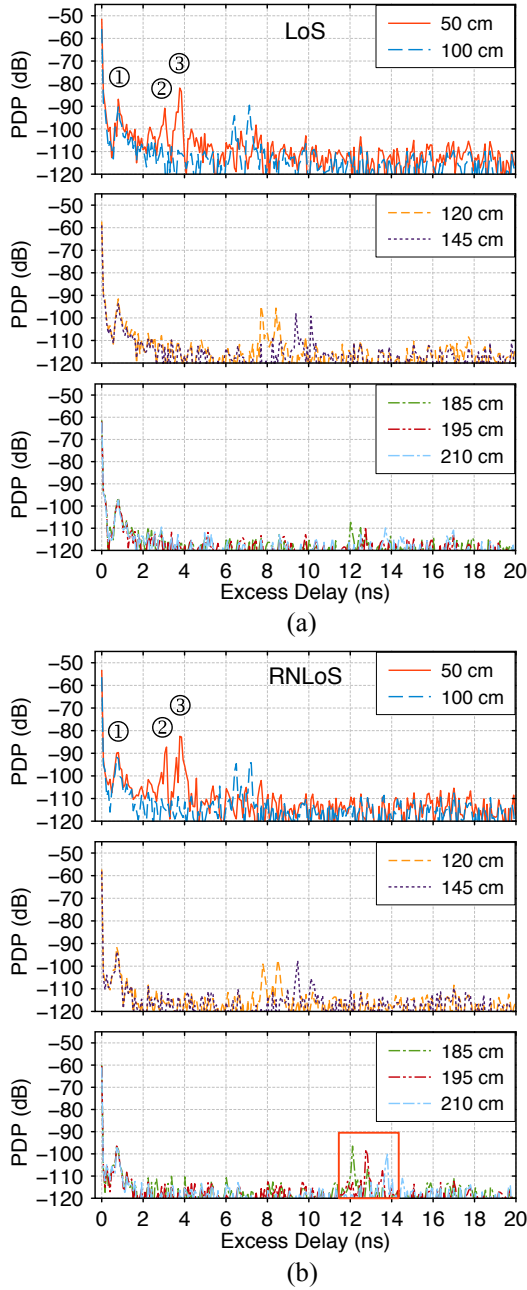


Fig. 8. Measured PDPs for (a) R2R LoS and (b) R2R RNLoS scenarios at $d = 50, 100, 120, 145, 185, 195, 210$ cm.

insignificant in the R2R LoS and R2R RNLoS links since the dominant multipath clusters 1, 2, and 3 are from reflections between the lenses.

B_c is a key parameter whose value is relative to the available bandwidth and data rate of the transmitted signal, thereafter determines the need for employing channel protection techniques, e.g., channel equalization, channel coding, or channel diversity to overcome the dispersive effects of multipaths [36]. In this paper, B_c is estimated from τ_{rms} with a correlation coefficient of 0.9 using (5). When calculating τ_{rms} from PDP, we perform noise filtering on PDP to remove unwanted noise by setting a threshold level at 8 dB above the noise floor, where PDP values below this threshold are considered as noise and equaled to zero. Fig. 9 shows the measured B_c for R2R LoS and R2R RNLoS scenarios at $d = 40\text{--}210$ cm. An overall

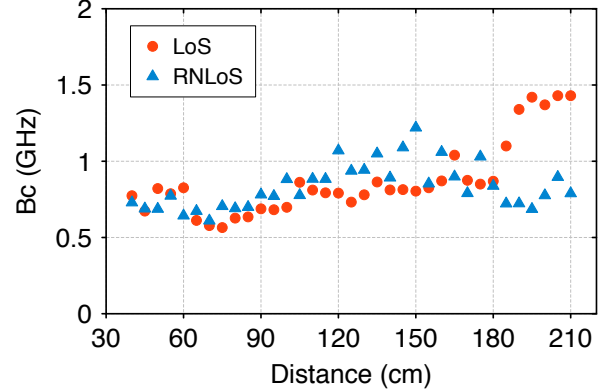


Fig. 9. Measured B_c for R2R LoS and R2R RNLoS scenarios at $d = 40\text{--}210$ cm.

trend of increasing B_c as distance increases is observed in both LoS and RNLoS links, which is counterintuitive because τ_{rms} is expected to increase as distance increases due to wider beamwidth coverage of surrounding objects at further distance, resulting in decreased B_c . This counterintuitive observation results from the highly focused beam created by the lenses used in our measurement. Optical lenses effectively collimate the beam such that the propagating wave stays within the “cylindrical tube” created by the lenses. Because of this confined “tube-like” propagation channel, even though the distance increases, there is no additional multipath involved in the channel except for clusters 1, 2, and 3 shown in Fig. 8. As distance increases, the existing clusters 1, 2, and 3 are attenuated thereby leading to a reduction in τ_{rms} and an increment in B_c . If we look into Fig. 9 more carefully, at distance around 60-180 cm, the RNLoS link has a slightly higher B_c than the LoS link. This is mostly due to reflector’s reflection loss (shown in Fig. 16). At $d = 60\text{--}180$ cm, the amplitude of multipath clusters 1, 2, and 3 in the RNLoS link in Fig. 8 (b) is slightly lower than that in the LoS link in Fig. 8 (a) due to reflection loss of the reflector. The attenuated multipath in the RNLoS link leads to a slightly lower τ_{rms} and slightly higher B_c . Similar observation is found in the obstructed R2R links in Fig. 12, where on average B_c in the ORNLoS link is slightly higher than the OLoS link due to suppressed multipath. Now if we compare the B_c in Fig. 9 at distance beyond 180 cm, it is observed that the B_c in the LoS link is higher than the RNLoS link by approximately 1 GHz. The suppressed B_c in the RNLoS link is caused by the scattering effect of the metal reflector. According to [37], metal objects can be viewed as perfect electrical conductors with a slightly rough surface and can cause scattering in the THz frequencies. The reflector in the RNLoS link slightly scatters the beam such that the beam is no longer ideally confined within the “tube-like” propagation channel and is reflected off of the metal rim of the lenses. As a result, multipath cluster 2 in the RNLoS link remains observable even at distances beyond 180 cm (highlighted in Fig. 8 (b)) due to reflections from the lens rim, resulting in higher τ_{rms} and lower B_c . Narrower B_c in the R2R RNLoS link may limit the maximum data rate.

B. Characterization of R2R OLoS and R2R ORNLoS Links

Here we investigate the relationship between $T_x\text{--}R_x$ distance and path loss, PDPs, and B_c in the R2R OLoS link with

cables, mesh structures, and metal cabinets as obstructions and the R2R ORNLoS link with cables as obstruction introduced in Figs. 2 (b), (g), (h), and Sections III-B and III-D.

Figures 10 (a) and (b) compare the Friis path loss and the measured path loss in R2R OLoS and R2R ORNLoS links with cables as obstruction at $d = 50, 110, 150, 210$ cm. We

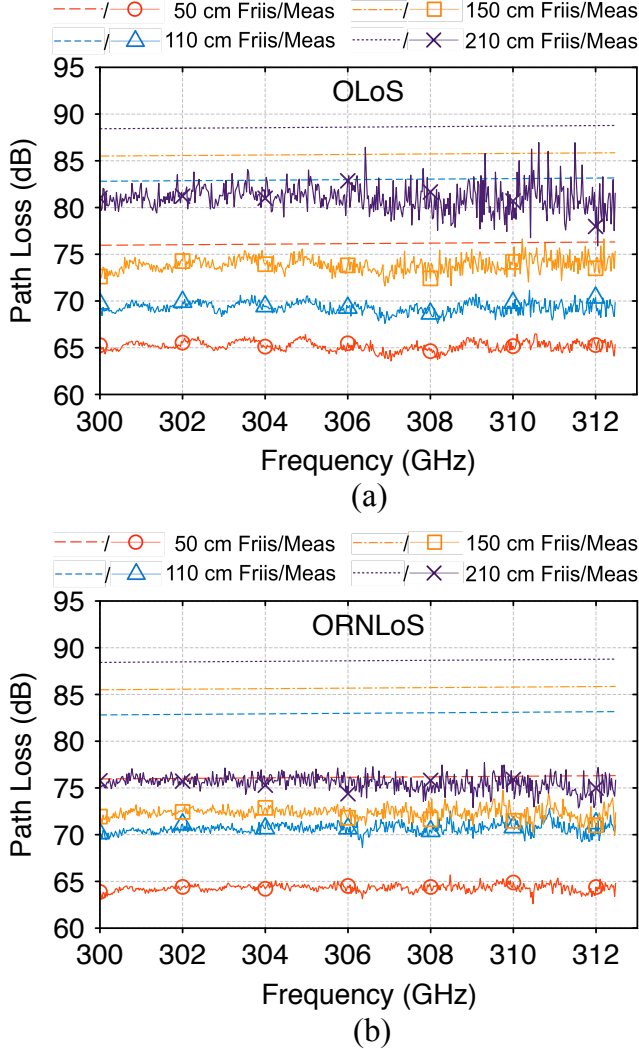


Fig. 10. Measured path loss curves in (a) R2R OLoS and (b) R2R ORNLoS scenarios with cables as obstruction at $d = 50, 110, 150, 210$ cm.

can observe that the R2R ORNLoS link has lower path loss (5 dB lower at distance beyond 1.3 m) and less path loss fluctuations with frequency than the R2R OLoS link. The THz wave experiences both diffraction and reflection as propagating through cable clusters due to the fact that the radius of cables' curvature is comparable to the wavelength at 300 GHz. These diffracted and reflected waves are "collected" by the reflector in the R2R ORNLoS link and transmitted from the T_x to the R_x , resulting in lower path loss as compared to the R2R OLoS link. Measured PDPs for R2R OLoS and R2R ORNLoS links at $d = 50, 110, 150, 210$ cm are presented in Figs. 11 (a) and (b). It has been observed that in the presence of obstructing cables, most of major multipath clusters (2 and 3) in Figs. 8 (a) and (b) are no longer visible. Measured B_c for R2R OLoS and R2R ORNLoS scenarios at $d = 40\text{--}210$ cm is presented in Fig. 12. We can observe that as distance increases from

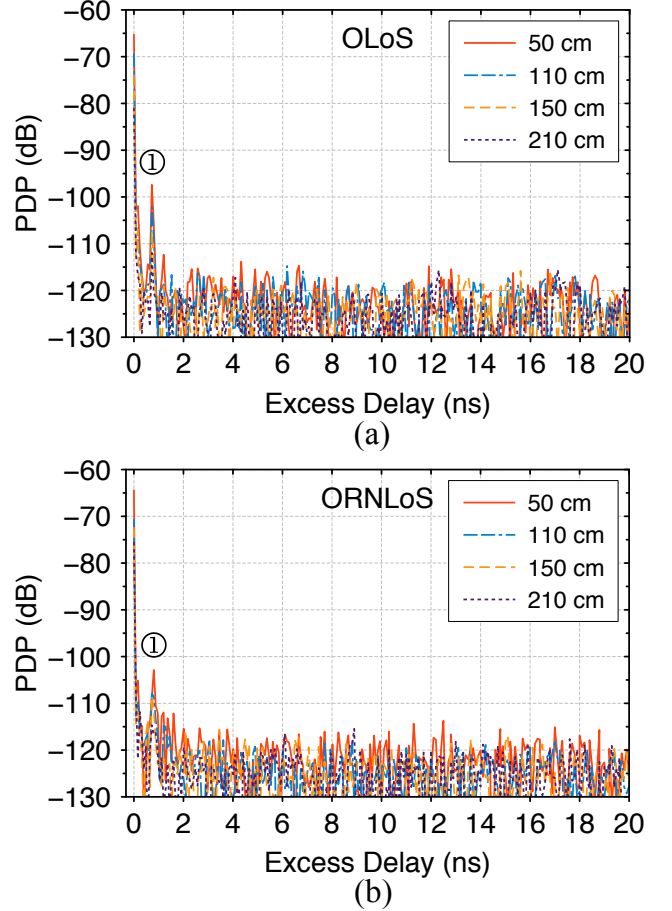


Fig. 11. Measured PDPs for (a) R2R OLoS and (b) R2R ORNLoS scenarios with cables as obstruction at $d = 50, 110, 150, 210$ cm.

40 cm to 210 cm, B_c decreases from around 1.5–1.8 GHz to around 0.3–0.8 GHz. The R2R ORNLoS link has a wider B_c than the R2R OLoS link, corresponding to a relatively flat frequency domain response in Fig. 10 (b) compared to Fig. 10 (a), due to R2R ORNLoS link's suppressed multipath as shown in Figs. 11 (a) and (b).

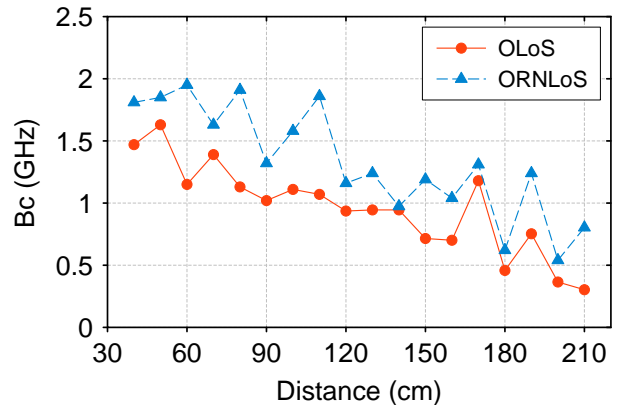


Fig. 12. Measured coherence bandwidth (B_c) for R2R ORNLoS and R2R OLoS scenarios with cables as obstruction at $d = 40\text{--}210$ cm.

We have further investigated the shadowing gain (X_σ) in the R2R OLoS and the R2R ORNLoS links with cables as obstructions by repeating the measurements with three cable thickness sizes and ten cable positions at $d = 40\text{--}210$ cm to have enough ensemble to perform a statistical evaluation.

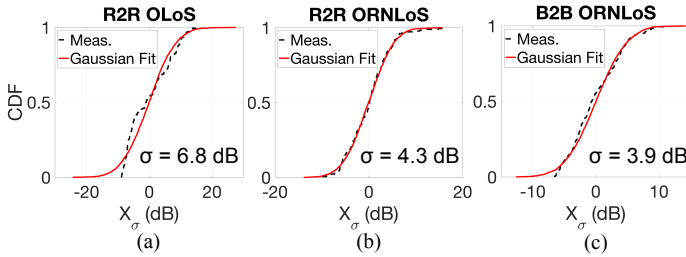


Fig. 13. CDFs of the shadowing gain (X_σ) for (a) R2R OLoS link at $d = 40\text{--}210$ cm, (b) R2R ORNLoS link at $d = 40\text{--}210$ cm, (c) B2B ORNLoS link at $d = 20\text{--}49$ cm, all measured with three cable thickness sizes and ten cable positions.

We found that the shadowing gain of both R2R OLoS and the R2R ORNLoS links follow log-normal distribution with its logarithmic equivalent having a zero-mean (in dB) and standard deviations (σ) of 6.8 dB and 4.3 dB, respectively. Cumulative distribution functions (CDFs) of X_σ for both links are presented in Figs. 13 (a) and (b) to confirm the log-normality of the shadowing gain.

Figure 14 presents the measured path loss at $d = 210$ cm in the R2R LoS link (scenario in Fig. 2 (a); red circles) and in the R2R OLoS links with obstructions of mesh structures (scenario in Fig. 2 (c); green cross signs) and metal cabinets (scenario in Fig. 2 (d); blue triangles). Friis path loss at $d = 210$ cm is presented alongside as a reference (red dash curve). Additional path loss of around 3 dB and 10 dB were observed due to the obstructions of mesh structures and metal cabinets, respectively. Fig. 15 shows the measured PDPs at $d = 210$ cm in the R2R LoS link (red curve) and in the R2R OLoS links with obstructions of mesh structures (blue dash curve) and metal cabinets (purple dot curve). Two dominant multipaths have been observed: 1) multipath 1 is located at around 0.8 ns (same cause as cluster 1 in Fig. 8) and is present in all scenarios; 2) multipath 2 is only present in the R2R OLoS link obstructed by metal cabinets and is located at around 2 ns, which corresponds to two times of the distance (30 cm) between the middle cabinets and the T_x/R_x racks as shown in Fig. 2 (d).

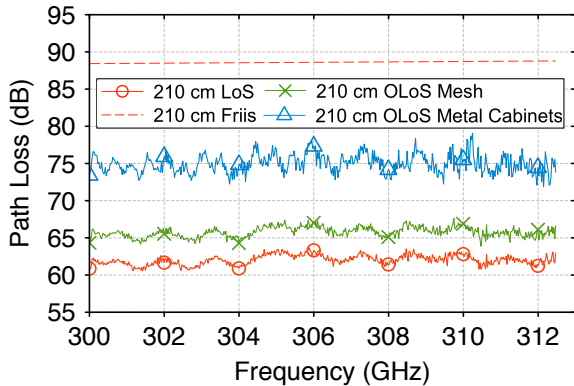


Fig. 14. Measured path loss curves at $d = 210$ cm in the R2R LoS link (red circles) and in the R2R OLoS links with obstructions of mesh structures (green cross signs) and metal cabinets (blue triangles). Friis path loss at $d = 210$ cm is presented alongside as a reference (red dash curve).

C. Characterization of Reflection Coefficients of Reflectors

In this section, we characterize the reflection loss and the reflection coefficient of the aluminum reflector used in the

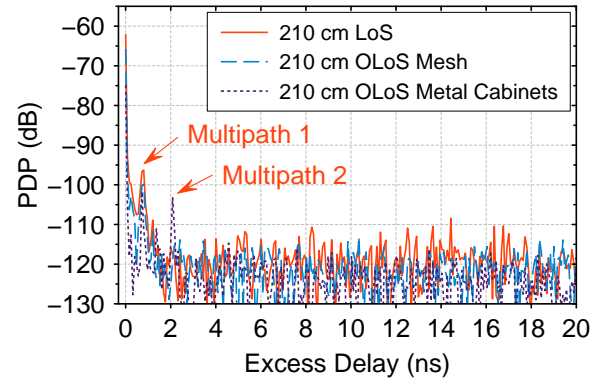


Fig. 15. Measured PDPs at $d = 210$ cm in the R2R LoS link (red curve) and in the R2R OLoS links with obstructions of mesh structures (blue dash curve) and metal cabinets (purple dot curve).

R2R RNLoS link with optical lenses applied to the T_x/R_x . Similar characterization of the reflectors in the B2B RNLoS link without T_x/R_x optical lenses can be found in [35]. Our measurement setup is introduced in Fig. 2 (e) and Section III-C. Calculation of reflection loss and reflection coefficient is explained in Section IV-B.

Figure 16 presents the measured reflection loss of the aluminum reflector used in the R2R RNLoS link. Averaged reflection loss is calculated as 0.6 dB across the measured frequencies (from 300 GHz to 312 GHz). Fig. 17 (a) and

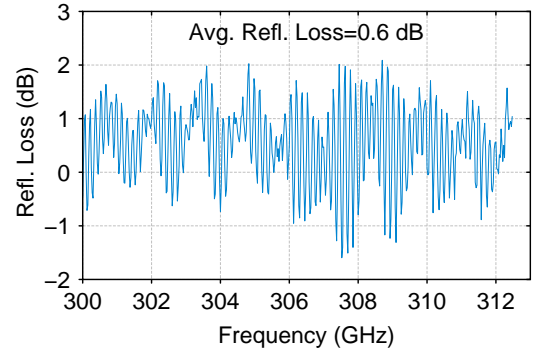


Fig. 16. Measured reflection loss of the aluminum reflector used in the R2R RNLoS link. The averaged reflection loss is calculated as 0.6 dB.

Fig. 18 (red circles) present the measured path loss and the magnitude of reflection coefficient of the aluminum reflector used in the R2R RNLoS link with $\phi_T = \phi_R = 20^\circ, 40^\circ, 45^\circ, 50^\circ, 70^\circ$. It is observed that the measured path loss values approximate 55 dB, which result in reflection coefficients very close to 1 across all ϕ_T and ϕ_R angles. Fig. 17 (b) and Fig. 18 (blue triangles) present the measured path loss and the magnitude of reflection coefficient of the aluminum reflector used in the R2R RNLoS link with ϕ_T fixed at 45° while ϕ_R varies at $20^\circ, 40^\circ, 45^\circ, 50^\circ, 70^\circ$. It is observed that as ϕ_R deviates from ϕ_T by only 5° (from $\phi_R = 45^\circ$ to 40° or 50°), path loss increases more than 20 dB and reflection coefficient decreases from around 1 to less than 0.1 due to very focused beam. We can conclude that the reflector serves as a good reflecting surface for reliable RNLoS links at all angles ($\phi_T = \phi_R$). However, angular misalignment ($\phi_T \neq \phi_R$) requires careful attention in RNLoS links in THz wireless data centers given that the angular misalignment tolerance range is less

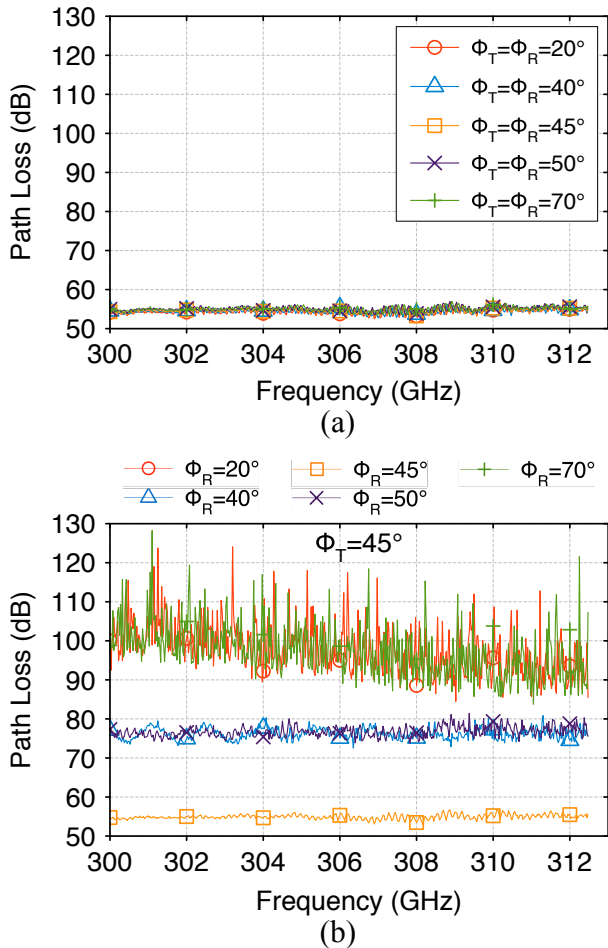


Fig. 17. Measured path loss in the R2R RNLoS link at $d = 90$ cm with (a) $\phi_T = \phi_R = 20^\circ, 40^\circ, 45^\circ, 50^\circ, 70^\circ$; (b) $\phi_T = 45^\circ, \phi_R = 20^\circ, 40^\circ, 45^\circ, 50^\circ, 70^\circ$.

than 5° .

VI. B2B RESULTS

A. Characterization of B2B RNLoS and B2B ORNLoS Links

In this section, we investigate the reflection from vertical ground planes of different structures and how T_x - R_x distance relates to the path loss, PDPs, and B_c in the B2B RNLoS and B2B ORNLoS scenarios as introduced in Figs. 3–5 and Sections III-E and III-F.

Figure 19 presents the Friis theoretical path loss (red line) and the measured mean path loss with different vertical ground plane structures: 1) solid metal (yellow circles), 2) hollow structure (blue triangles), 3) mesh structure (purple squares), and 4) hollow structure with cables as obstruction (green diamonds) in the vertical B2B link at $d = 20$ – 49 cm. It is observed that path loss fluctuates around the theoretical values as distance increases. Specifically, the hollow structure causes the least path loss fluctuation, closely followed by mesh structure, while solid structure creates the most unwanted path loss fluctuation around 4 dB above the Friis path loss. This path loss fluctuation is mainly caused by constructive and destructive interference from two reflected paths: 1) vertical ground plane (path 1 in Fig. 3 (b)) and 2) horizontal ground plane (path 2 in Fig. 3 (b)). Our measurement results show that the vertical ground plane has more dominant effects on the path loss fluctuation than the horizontal ground plane

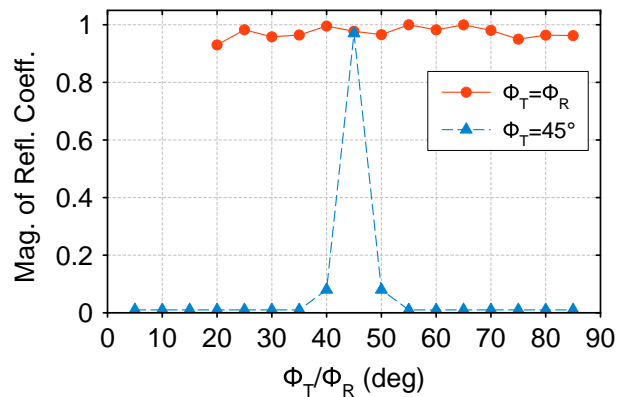


Fig. 18. Measured magnitude of the reflection coefficient of the aluminum reflector used in the R2R RNLoS link: 1) $\phi_T = \phi_R$ in a range from 20° to 85° (red circles); 2) ϕ_T is fixed at 45° while ϕ_R varies from 5° to 85° (blue triangles).

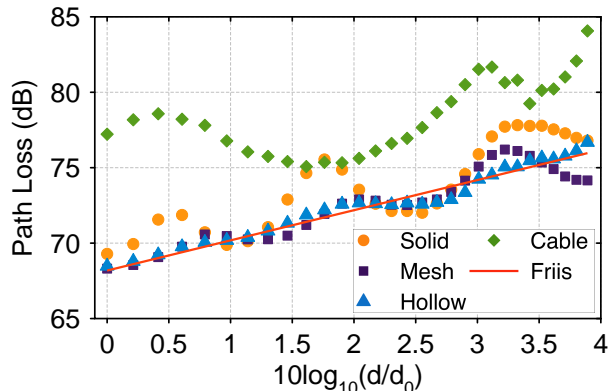


Fig. 19. Friis theoretical path loss (red line) and the measured mean path loss with different vertical ground plane structures: 1) solid metal (yellow circles), 2) hollow structure (blue triangles), 3) mesh structure (purple squares), and 4) hollow structure with cables as obstruction (green diamonds) in the vertical B2B link at $d = 20$ – 49 cm and $d_0 = 20$ cm.

in vertical B2B links since strong path loss fluctuation is observed when solid vertical ground plane is applied (yellow circles in Fig. 19), while without solid vertical ground plane, only slight path loss fluctuation is observed (blue triangles in Fig. 19). As a result, for future THz B2B communication system design, we recommend to use hollow structure instead of solid metal for vertical ground planes on server racks to minimize path loss fluctuation. The following comparisons of measured path loss, PDPs, and B_c for the B2B RNLoS and B2B ORNLoS links are based on the hollow structure design in Fig. 5 (b) since it has the least path loss interference from vertical ground plane.

Note that besides vertical ground plane design, one of the key challenges in designing vertical B2B links is the positioning of the T_x/R_x reflectors. Misaligned reflectors may increase path loss and path loss fluctuation, or even cause complete signal loss. Here we briefly discuss the consequences of misaligned reflectors. We use the same hollow vertical ground plane design in Fig. 5 (b) but intentionally tilt the R_x reflector around 1° away from the original 45° position. Fig. 20 shows the Friis theoretical path loss (red line) and the measured mean path loss with misaligned R_x reflector (blue triangles) at $d = 20$ – 49 cm. It is observed that the misaligned reflector can cause up to 4 dB path loss deviation

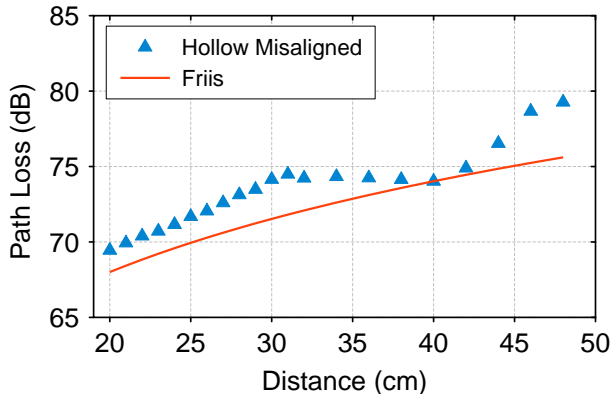


Fig. 20. Friis theoretical path loss (red line) and the measured mean path loss with R_x reflector tilted (misaligned) by around 1° away from the original 45° position (blue triangles) in the vertical B2B link at $d = 20\text{--}49$ cm.

from the Friis values. Therefore, for future THz B2B link design, we recommend to integrate the T_x/R_x reflectors into the server racks for better alignment since the received signal is extremely sensitive to the positioning of the reflectors.

Next, we compare the measured path loss, PDPs, and B_c between B2B RNLoS and B2B ORNLoS links with hollow vertical ground plane design. Fig. 19 compares the Friis theoretical path loss (red line) and the measured path loss curves in B2B RNLoS (blue triangles) and B2B ORNLoS (green diamonds) scenarios over distances at $d = 20\text{--}49$ cm. Figs. 21 (a) and (b) present the Friis theoretical path loss curves and the measured path loss curves over frequencies in B2B RNLoS and B2B ORNLoS scenarios at $d = 24, 32, 42$ cm. In Fig. 19 (blue triangles) and Fig. 21 (a), the measured path loss curves in the B2B RNLoS link closely follow the Friis values in both distance and frequency domains. In Fig. 19 (green diamonds) and Fig. 21 (b), the measured path loss curves in the B2B ORNLoS link show that cables as obstruction can increase path loss by around 5–10 dB as compared to the B2B RNLoS link and the frequency-dependent path loss fluctuation becomes more prominent at higher frequencies. Note that path loss values in the B2B ORNLoS link in Fig. 19 (green diamonds) and Fig. 21 (b) decrease as distance increases from 24 cm (red circles in Fig. 21 (b)) to 32 cm (blue triangles in Fig. 21 (b)). This is because signals in the direct $T_x\text{--}R_x$ path and reflected path caused by the cables arrive within the same delay bin, i.e., their time difference of arrival (or path length difference) is smaller than the minimum time domain resolution (or spatial resolution) of the measurement system, where signals add up either in-phase or out-of-phase and result in constructive or destructive interference. We have further investigated the shadowing gain (X_σ) in the B2B ORNLoS link by repeating the measurements with three cable thickness sizes and ten cable positions at $d = 20\text{--}49$ cm to have enough ensemble to perform a statistical evaluation. We found that the shadowing gain follows a log-normal distribution with the logarithmic equivalent having a zero-mean (in dB) and standard deviation (σ) of 3.9 dB. A CDF of X_σ for the B2B ORNLoS link is presented in Fig. 13 (c) to confirm the log-normality of the shadowing gain.

Figures 22 (a) and (b) show the measured PDPs for B2B

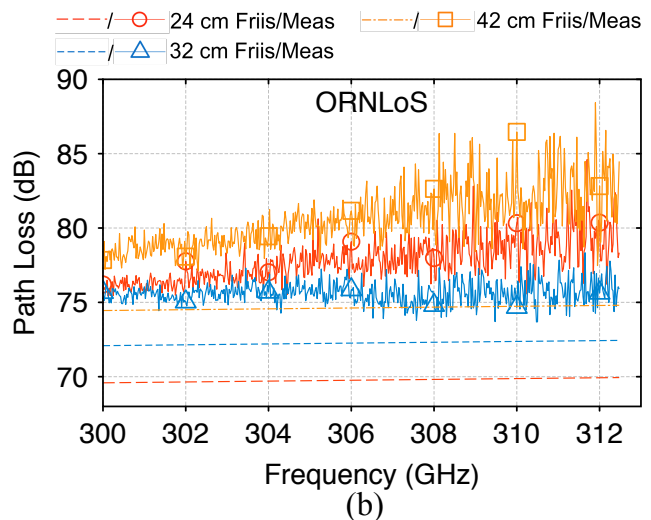
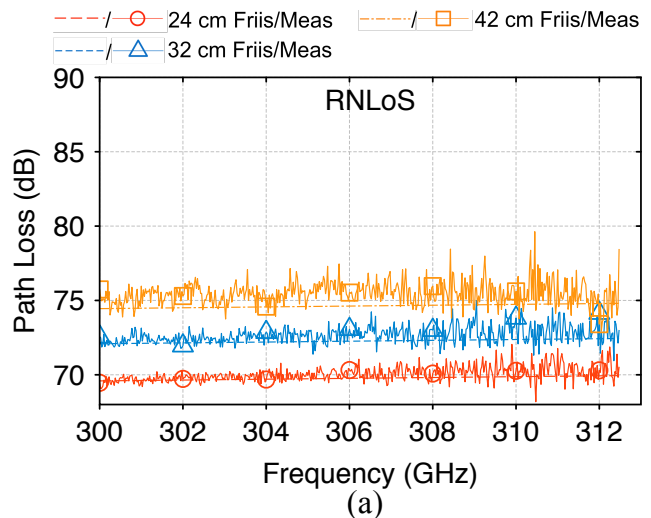


Fig. 21. Measured path loss curves and Friis theoretical path loss curves in (a) B2B RNLoS and (b) B2B ORNLoS scenarios at $d = 24, 32, 42$ cm.

RNLoS and B2B ORNLoS links at $d = 24, 32, 42$ cm. In Fig. 22 (a), a dominant multipath cluster at around 1 ns is observed in the B2B RNLoS link, which results from multiple reflection between T_x/R_x blades since 1 ns corresponds to twice the vertical distance between two blades. In contrast, with cables as obstruction, the multipath cluster at around 1 ns is no longer observable in the B2B ORNLoS link as shown in Fig. 22 (b). In addition, the first arriving peak in Fig. 22 (b) is followed by a “long tail” over 0–0.5 ns, which is a result of multiple reflection between cables that arrives in several adjacent delay bins. A “long tail” in PDPs will generally act as interference and weaken communication performance [38].

Figure 23 shows the measured B_c for B2B RNLoS and B2B ORNLoS scenarios at $d = 20\text{--}49$ cm. We can observe that as distance increases from 20 cm to 49 cm, B_c stays relatively constant at around 0.2–0.5 GHz in the ORNLoS link while decreases from around 1 GHz to around 0.4 GHz in the RNLoS link. Results imply that the B2B RNLoS link can achieve higher peak data rate as compared to the B2B ORNLoS link while the data rate in the B2B RNLoS link may fluctuate more as distance varies.

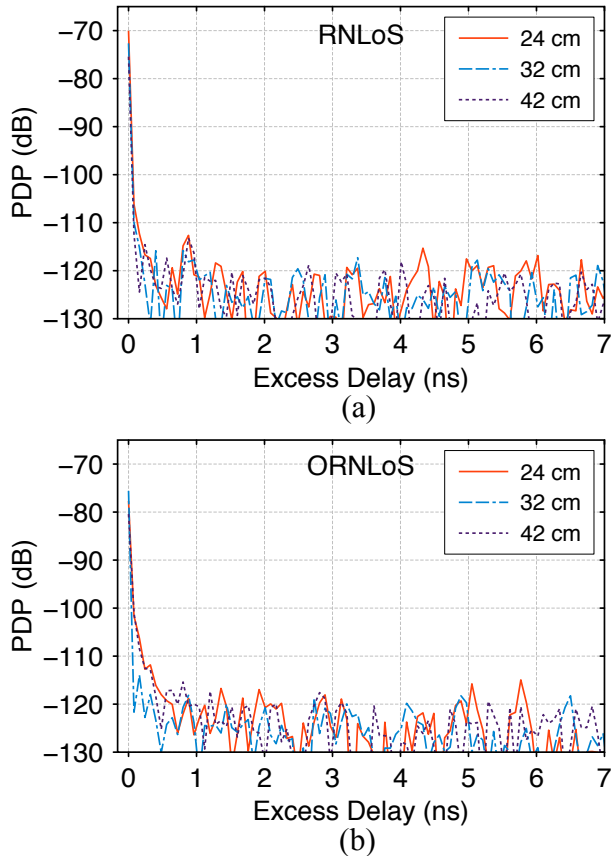


Fig. 22. Measured PDPs for (a) B2B RNLoS and (b) B2B ORNLoS scenarios at $d = 24, 32, 42$ cm.

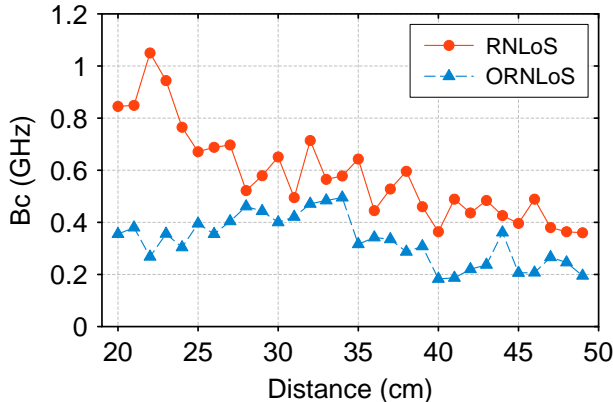


Fig. 23. Measured B_c for B2B RNLoS and B2B ORNLoS scenarios at $d = 20-49$ cm.

B. Characterization of B2B LoS Link

In this section, we study the relationship between T_x - R_x distance and the corresponding path loss and PDPs in the B2B LoS scenario as introduced in Fig. 4 (e) and Section III-G.

Measured path loss curves and Friis theoretical path loss values for the B2B LoS link are presented in Fig. 24 (a). It can be observed that the measured path loss values closely follow the theoretical values across all distances. The corresponding measured PDPs are presented in Fig. 24 (b). Although being surrounded by metal plates, there is no observable multipath cluster in the PDPs of the B2B LoS link due to very focused beamwidth at THz frequencies. In summary, the B2B LoS link is comparable to the LoS propagation in a free space. Similar measurement results can be found in [32].

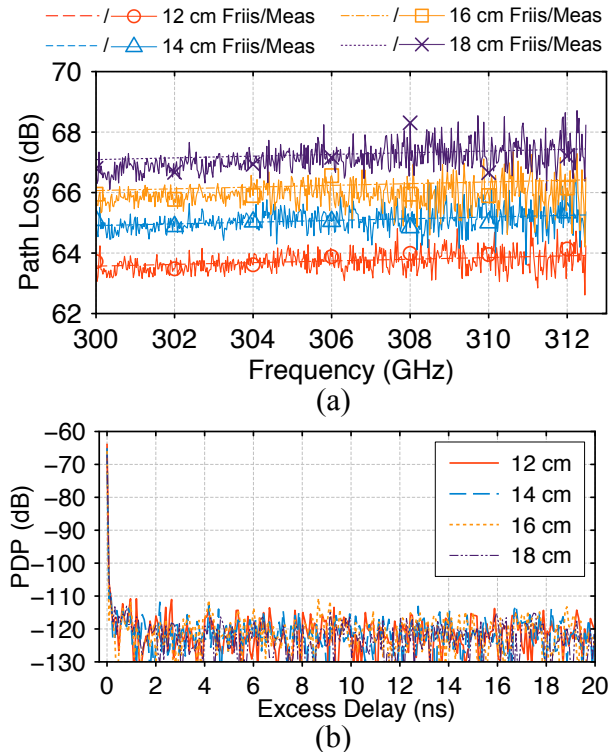


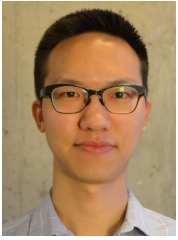
Fig. 24. (a) Measured path loss curves and Friis theoretical path loss values and (b) measured PDPs for the B2B LoS scenario at $d = 12, 14, 16, 18$ cm.

VII. CONCLUSIONS

This paper presents detailed characterization of 300 GHz channels for wireless R2R and B2B communications in data centers. Measurements are conducted in R2R LoS, R2R OLoS, R2R RNLoS, R2R ORNLoS, B2B RNLoS, B2B ORNLoS, and B2B LoS scenarios, which evaluate the impact of T_x/R_x misalignment and obstructions such as cables, metal cabinets, and mesh structures on THz propagation, as well as possibility of using existing metal objects as reflectors that guide waves for NLoS type of links. For the R2R LoS scenario, the channel with optical lenses acts as a waveguide with a PLE of 1.48 and the optical lenses provide additional gain of more than 25 dB. PDPs reveal that optical lenses can cause additional multiple reflections. When obstructions of cables are present, ORNLoS link outperforms OLoS link with 2.5 dB lower shadowing gain and weaker multipath. Multi-band spectrum utilization [15] may be required in the OLoS link since the lowest B_c is only around 0.3 GHz. Reflector in the RNLoS link has reflection coefficients very close to 1 for all incident angles. For the B2B scenario, a dual-reflector THz transceiver rack system has been proposed to enable wireless links across vertically stacked servers and allow easy maintenance and repair of servers. The measured path loss approximates the Friis values in the LoS link and in the RNLoS link with hollow vertical ground plane. Hollow rack structure is preferred over solid metal due to its minimum reflection interference. When obstructions of cables are present, the ORNLoS link experiences 5–10 dB higher path loss and on average 0.25 GHz lower B_c than the RNLoS link. Measured statistical channel properties show that the shadowing gain caused by cable clusters follows the log-normal distribution.

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