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Measurement-Based Channel Characterization in a Large Hall Scenario at 300 GHz

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Abstract: Sub-terahertz (Sub-THz), defined as the frequency bands in 100-300 GHz, is promising for future generation communications and sensing applications. Accurate channel measurement and modeling are essential for development and performance evaluation of the future communication systems. Accurate channel modeling relies on realistic channel data, which should be collected by high-fidelity channel sounder. This paper presents the measurement-based channel characterization in a large indoor scenario at 299-301 GHz. We firstly review the state-of-the-art channel measurements at sub-THz frequency bands. We then presented a VNA-based channel sounder for long-range measurements, which uses the radio-over-fiber techniques. Channel measurements using this channel sounder are conducted in a large hall scenario. Based on the measurement data, we calculated and analyzed key propagation channel parameters, e.g., path loss, delay spread, and angular spread. The results are also analyzed both in the line-of-sight (LoS) and none-LoS (NLoS) cases. The large delay components in the measurements demonstrate the possibility of the long-range channel measurement campaign at 300 GHz.

Keywords: Channel measurement; Sub-Terahertz; 300 GHz; Channel characterization

I. INTRODUCTION

Future wireless communication systems, i.e., beyond fifth-generation (B5G), are attracting increasing attention worldwide as the demand for high data-rate in various applications continue to grow rapidly [1–3]. Sub-terahertz (sub-THz) technologies, which is defined as the frequency bands in 100-300 GHz, are foreseen to be one of the core radio technologies for B5G communication systems, due to their large unused and untapped frequency resource [4–7]. Sub-THz frequency bands can potentially support the opportunity for high data-rate. Nonetheless, this frequency band still faces many challenges. As demonstrated in [4], compared to the atmospheric attenuation at lower frequency bands, the atmospheric attenuation at sub-THz bands is much higher. Moreover, with the frequency goes higher, the wavelength of the sub-THz frequencies is close to the size of dust and rain, which makes the channel at sub-THz bands behave differently than the conventional low frequency spectrum [8].

The channel sounder is essential for recording reliable channel data in the channel measurements. We can classify the channel sounding systems presented in the literature into two types based on the channel sounding technologies, one is the time-domain channel sounders such as correlation-based sounder, and the other is the frequency-domain channel sounders. The vector network analyzer (VNA) is a widely used

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scheme for the frequency-domain sounder, since it offers many unique advantages, e.g., scalable operating bandwidth and easy calibration [9, 10]. Since the signal generator and analyzer are co-located in the VNA, the VNA requires cable connections to remote the antennas. However, the power loss through the coaxial cable increases with the frequency. Consequently, the reduced dynamic range results in the limited measurement range, especially at sub-THz bands. To address this issue, since the optical fiber cables has a low signal loss, radio-over-fiber (RoF) techniques are employed in VNA-based sounders, which uses an electrical-to-optical unit (i.e., laser) to modulate an electrical signal to optical, transmits the signal through an optical fiber cable, and demodulates the signal into electrical by an optical-to-electrical unit (i.e., photo detector) [11].

Numerous sub-THz measurement campaigns have been proposed in the recent literature. We can group the channel measurements into two categories in terms of the measurement distance and the size of the measurement scenarios, i.e., short-range measurements and long-range measurements. The high propagation loss at sub-THz bands and the hardware limitations limit the use of the sub-THz channel sounder. Therefore, many researchers are focusing on sub-THz channel in the short-range indoor scenarios, e.g., office and meeting room [7, 12, 13, 15, 16, 14, 17, 18]. Ultrawideband 300 GHz channel measurements in an indoor office room scenario were presented in [12], where key channel parameters, e.g., delay spreads and K -factors were analyzed. Channel measurements and comparison at three frequency bands, i.e., 10 GHz, 60 GHz, and 300 GHz, were carried out in [13] in an office room scenario, where the channel sounder was based on the correlation. The results illustrated the frequency-dependence of the multipath richness, and the 300 GHz multipath richness of the radio channel is much less than that at 60 GHz. The channel measurements at 304 GHz inside a train were presented in [15], and the key channel parameters, e.g., path loss, delay spread, and K -factor, were also presented. Furthermore, a ray-tracing method were proposed to simulate the intra-wagon channel model and verified from the measurement results. A measurement-based path loss model in a lecture room at 305 GHz was proposed in [14].

Only a handful of long-range measurements were reported in the long-range scenarios and mainly at

140 GHz [19–21, 23, 22]. VNA-based channel measurements at mmWave (i.e., 28 GHz) and sub-THz (i.e., 140 GHz) frequency bands, were performed in [19]. The measurement scenario is a large shopping mall and the measurement distance ranges from 3–65 m. The multipath components, delay spreads, and angular spreads of 28 GHz and 140 GHz were found to be similar. In [20, 21], 145 GHz outdoor channel measurements of up to 100 m measured distances were conducted. In [23], channel measurements at 140 GHz are performed in an outdoor urban environment. Moreover, path loss model, as well as a model of the penetration loss through foliage are provided. In [24], a long-range VNA-based channel sounder based on the radio-over-fiber techniques was developed. Besides, the channel measurements based on this channel sounder in a corridor scenario and the analyses of power angle spectrum, delay spread, and angular spread were presented, which is only a simple validation of the proposed long-range sounder. Table 1 provides the summaries of the channel measurements and modeling at sub-THz frequency bands. Note that this list is by no means complete and it is included here only to demonstrate some recent progress in the state-of-the-art works.

However, there is a lack of experimental studies on channels in long-range scenarios at 300 GHz. The high fidelity of our long-range channel sounder has been validated in [24]. However, the channel characteristics and channel models at 300 GHz are not further analyzed in [24] since the measured data were only collected at one measurement location. Therefore, in this study, channel measurements have been conducted using a double-directional scanning scheme (DDSS) to explore 300 GHz channel characteristics in a large hall scenario. Channel measurements are conducted with 8 different Transmitter (Tx)-Receiver (Rx) distance ranging from 3–15.6 m. Based on the large amount of the directional measurement data, i.e., 33120 channel frequency response (CFR), we calculate and analyze the power-angle-delay profiles (PADPs) and power-angle spectra (PAS). We also calculate and analyze key channel parameters including path loss, and dispersion spread in delay and angle domain.

The novelties of this study are outlined in the following aspects:

1. geometric

Table 1. Recent studies on sub-THz short- and long-range channel measurement.

| Ref. | Frequency (GHz) | Sounder | Scenario | Distance (m) | Channel parameters |
|-------------|-----------------|--------------|------------------------------|--------------|---|
| Short-range | | | | | |
| [7] | 250 - 300 | VNA | Lab | 2.3 | Power angle spectrum. |
| [12] | 275 - 325 | VNA | Office | 1.8 - 2.9 | K -factors, delay and angular spread. |
| [13] | 300 - 308 | Correlation | Office | 4 | Power angle spectrum. |
| [14] | 300 - 310 | VNA | Lecture room | 2 - 5 | Path loss |
| [15] | 300 - 308 | Correlation | Intrawagon | 5.3 | Path loss, delay and angular spread, polarization. |
| [16] | 280 - 320 | VNA | Data center | 1.8 | Path loss, shadowing, cluster number and power. |
| [17] | 126 - 156 | VNA | Lab, office, conference room | 1.8 - 10.6 | Path loss, delay spread, angular spread, cluster. |
| [18] | 130 - 143 | VNA | Meeting room | 1.4 - 8.0 | Path loss, delay and angular spread, cluster. |
| Long-range | | | | | |
| [19] | 141.1 - 145.1 | VNA with RoF | Shopping mall | 3 - 65 | Path loss, delay and angular spread. |
| [20] | 141 - 148.5 | VNA with RoF | Outdoor urban | 104 | Path loss, angular spread, and cluster spread. |
| [21] | 141 - 148.5 | VNA with RoF | Outdoor urban | 15.9 - 34.2 | Path loss, angular spread. |
| [22] | 141.5 - 142.5 | Correlation | Office floor | 3.9 - 39.2 | Path loss, number, delays, and powers of clusters. |
| [23] | 142 | Correlation | Outdoor | up to 117.4 | Path loss, penetration loss through foliage. |
| [24] | 299-301 | VNA with RoF | Corridor | 27 & 43 | Power angle spectrum, delay spread, and angular spread. |

2. We calculate and analyze the key measurement-based channel characteristics, i.e., PAS, PADP, path loss, delay and angular spread, in the LoS and NLoS cases. We also plotted the ray trajectories for the considered measurement locations.

The reminder of this paper is organized as follows. Section II illustrates the VNA-based sounder structure and the description of the measurement scenario. Section III gives the signal model and key channel parameters. Section IV highlights the results of this 300 GHz channel measurements. Conclusion are finally drawn in Section V.

II. CHANNEL SOUNDER DEVELOPMENT AND MEASUREMENT SCENARIO

2.1 Channel Sounder Development

Fig. 1 and Table 2 depict the structure of the 300 GHz VNA-based sounder with RoF schemes and the components employed in the sounder, respectively. This channel sounder consists of two parts, i.e., VNA-based sounding system and RoF scheme. In the first part, we used a four-port VNA from Keysight (N5227B) and

frequency extenders from VDI Inc. (VDI WR 3.4). An radio frequency (RF) signal at 12.22-18.33 GHz is sent from the VNA to the Tx extender. In the Tx extender, the RF signal then passes through a multiplier with a factor of 18 and is converted to 220-330 GHz. A coupler is used to split the sub-THz signal, one of the split signals is used for transmission over the channel which needs to be measured. Note that the other split signal is demodulated to a 7.438 MHz signal and sent back to VNA for reference. The VNA also sends a local-oscillator (LO) signal at 9.12-13.75 GHz. The LO signal is then split into two signals by a power splitter and sent to the LO port in the Tx and Rx extenders. The LO signals are multiplied by a factor of 24 to demodulate the sub-THz signals. Finally, the 7.438 MHz reference signal and the demodulated received signal is sent to Port A and Port B, respectively.

The dynamic range of this sounder is limited due to the high power loss through the coaxial cables, thus constraining the measurement distance of this channel sounder. Therefore, we develop an RoF extension scheme in this work. The main idea is to raise the dynamic range and extend the measurement range us-

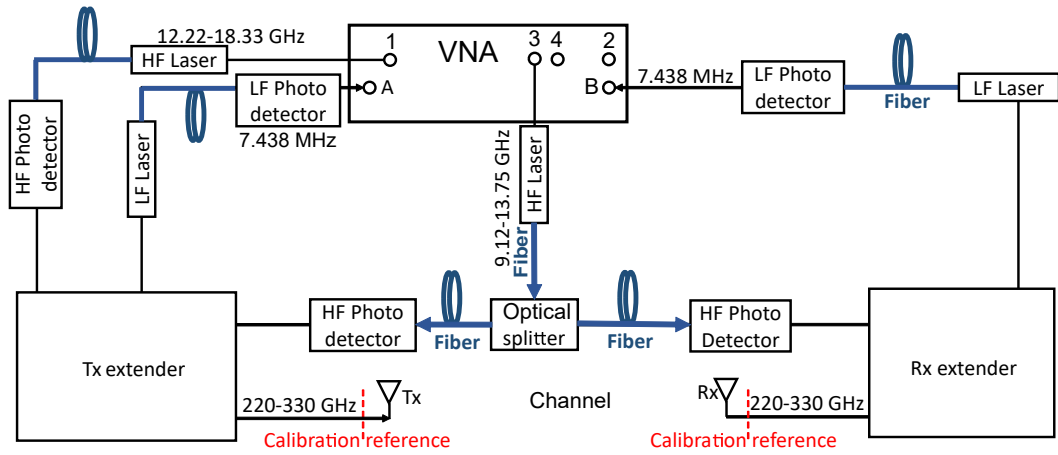


Figure 1. Schematic diagram of the channel sounder using the RoF techniques.

ing optical fiber cable which has a negligible signal loss (i.e., 0.8 dB/km). In the RoF system part, two RoF system working at two different frequency bands, i.e., high frequency (HF) for 0-50 GHz and low frequency (LF) for 0-6 GHz, are utilized. By using an electric-optical modulator, i.e., laser, the electrical signal is modulated to optical signal with the wavelength of 1550 nm. The optical signal is transmitted through an 300 m optical fiber cable and demodulated into an electrical signal. In principle this long-range channel sounder could reach to 600 m Tx-Rx separation. However, the measurement range might be limited by the measurement scenario in practice. In practical measurements, we must also consider over-the-air free space propagation loss and antenna misalignment loss (e.g., antenna alignment and polarization alignment).

To combat the high path loss, highly directive antennas are used in sub-THz channel measurements. In this work, the antenna gain for both sides is 26 dBi. The measured antenna pattern at 300 GHz is depicted in Fig. 2. The radiation pattern measurements were conducted in the anechoic chamber in Aalborg University, with a measurement distance of 9 m (i.e., direct far-field setup). Dynamic range is 50 dB in these measurements with the intermediate frequency bandwidth (IFBW) of 1 kHz. If we decrease IFBW to 10 Hz, we could get a higher dynamic range of 70 dB, however, the measurement time will explode. The measured half-power beamwidths (HPBW) in the H-plane and E-plane are 8° and 6°, respectively. Higher sidelobes is observed in the E-plane and the sidelobe level is seen to be -7.7 dB. Note that only vertically polarized channels are investigated in this study.

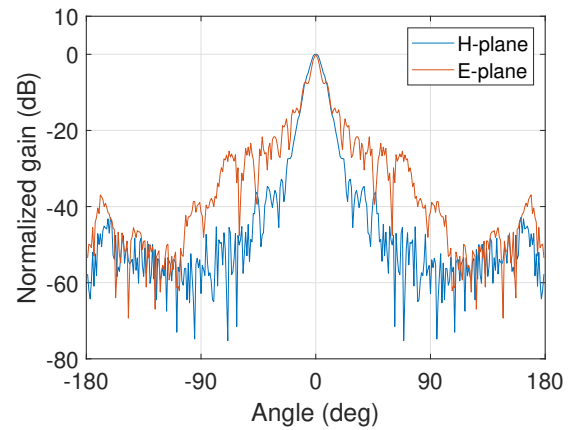


Figure 2. Measured radiation pattern of the 300 GHz antenna.

Table 2. Components for the channel sounder

| Component | Type | Frequency/wavelength |
|--------------------|-----------------------|----------------------|
| VNA | Keysight N5227B | 0.01-67 GHz |
| Frequency extender | VDI WR 3.4 | 220-330 GHz |
| HF laser | QMOD XMTQ-C-A-24 | 0 – 50 GHz |
| HF photo detector | QMOD XMRQ-C-A-24 | 0 – 50 GHz |
| LF laser | RFOF6T3FR-PA-11 | 0 – 6 GHz |
| LF photo detector | RFOF6R3FR-PA-11 | 0 – 6 GHz |
| Optical splitter | JDS FFC-CKH12B105-003 | 1550 nm |

2.2 Measurement Scenario

Fig. 3 illustrates the measurement deployment. These channel measurements are carried out in a large hall with a size of $42 \times 25 \text{ m}^2$. Note that the size of the corridor in this scenario is $43.4 \times 3.7 \text{ m}^2$. Fig. 4 illustrates the pictures in the real scenario. In these measurements, the Tx is deployed near the wall to mimic the base station, while four Rx measurement points are deployed to investigate the NLoS scenarios, (i.e., Rx 2 and Rx 4) as well LoS scenario (i.e Rx 1 and Rx 3). Note that Rx 4 is under the stairs and the LoS is completely blocked, while the NLoS case of Tx-Rx 2 is created by adding a metallic plate with the dimension of $56 \times 85 \text{ mm}^2$, as depicted in Fig. 4 (a) and (c). Besides, we also conduct four channel measurements with different Tx-Rx distances in the LoS cases, i.e., Rx 5 - 8, to model the channel parameters.

To capture the channel information in the spatial domain, the DDSS was used in the measurements. Note that we performed an over-the-air (OTA) calibration to eliminate the effect of the system, which uses 1 m LoS channel measurement results as a reference to calibrate the system and antenna response. The picture of the channel sounder incorporated with the turntables is depicted in Fig. 5. As shown in Fig. 5, we mounted the Tx and Rx extenders to two turntables. The Tx and the Rx are programmed to rotate the azimuth in the range of $[-90^\circ, 90^\circ]$ and $[-180^\circ, 176^\circ]$, respectively. The rotation step is set to be 4° at both sides. According to [25], the 4° rotation angle step is sufficient for wide-band channel spatial profile reconstruction. Thus, the number of channel frequency responses we obtained for each measurement point is $45 \times 90 = 4140$. In total, we obtained 33120 CFR (i.e., number of Tx-Rx pairs \times number of measurement locations). The detailed measurement specifications are demonstrated in Table 3.

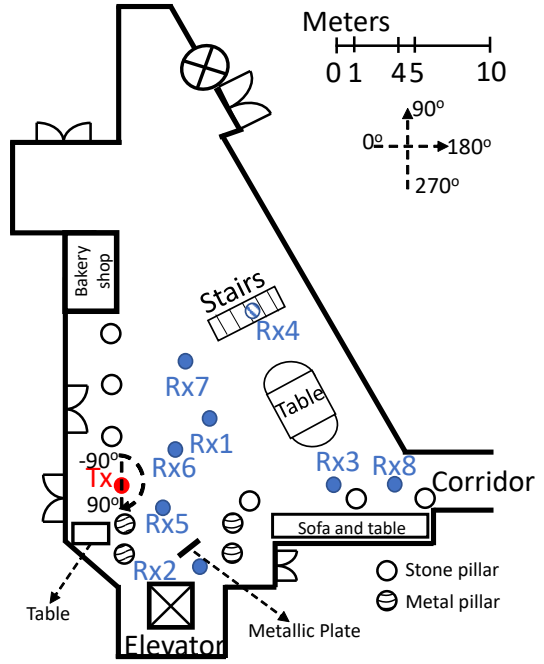
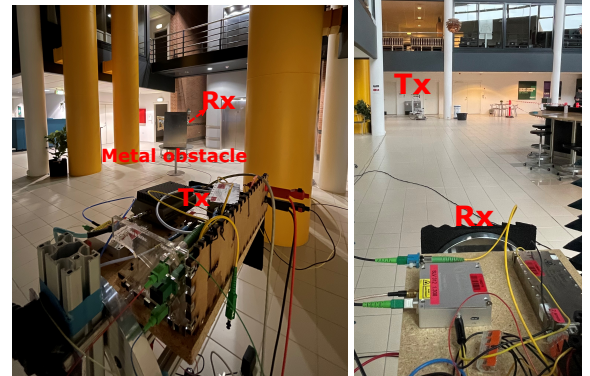


Figure 3. Top view of the large hall scenario.



(a)

(b)



(c)

Figure 4. Photos of the measurement scenario. (a) Tx-Rx 2; (b) Tx-Rx 3; (c) Tx-Rx 4.

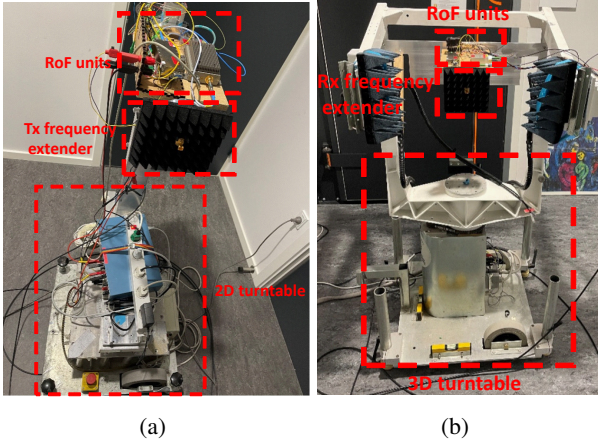


Figure 5. Photos of the channel sounder mounted on the turntables. (a) Tx side; (b) Rx side.

Table 3. The measurement configuration in the large hall scenario.

| Parameter | Value |
|------------------------------|-------------------------|
| Frequency range (GHz) | 299-301 |
| Bandwidth (GHz) | 2 |
| Frequency point | 2001 |
| Max. detectable distance (m) | 300 |
| IFBW (kHz) | 2 |
| Transmitted power (dBm) | 10 |
| Antenna height (m) | 1.25 |
| LoS Tx-Rx distance (m) | 5.9 (Rx 1), 11.4 (Rx 3) |
| NLoS Tx-Rx distance (m) | 6.2 (Rx 2), 12 (Rx 4) |
| Tx-Rx distance (m) | 3 (Rx 5), 4.2 (Rx 6) |
| Tx-Rx distance (m) | 8.1 (Rx 7), 15.6 (Rx 8) |
| Tx rotation range (deg.) | $[-90, 90]$ |
| Rx rotation range (deg.) | $[-180, 179]$ |
| Rotation step (deg.) | 4 |

III. CHANNEL PARAMETER CHARACTERIZATION

3.1 Signal Model

The double-directional channel impulse response (CIR) $h(\tau)$ in this work is written as:

$$h(\tau, \phi_{AoD}, \phi_{AoA}) = \sum_{\ell=1}^L \alpha_{\ell} \delta(\tau - \tau_{\ell}) \delta(\phi - \phi_{AoD, \ell}) \cdot \delta(\phi - \phi_{AoA, \ell}), \quad (1)$$

where α_{ℓ} and τ_{ℓ} denote the complex amplitude and the delay of the ℓ th propagation path, respectively. $\phi_{AoD, \ell}$ and $\phi_{AoA, \ell}$ represent the angle-of-departure (AoD) and the angle-of-arrival (AoA) the ℓ th path. And L represents the total number of propagation paths.

3.2 DDPAS

From the measurements, we obtain the radio CFR $H(f, \phi_{AoD}, \phi_{AoA})$. The power delay profiles $h(\tau, \phi_{AoD}, \phi_{AoA})$ can be obtained using inverse fast Fourier transform (IFFT), where f , τ , ϕ_{AoD} , and ϕ_{AoA} denote the frequency, delay, AoD, and AoA, respectively.

The double-directional PAS (DDPAS) $P(\phi_{AoD}, \phi_{AoA})$ can show the power distribution of the measured channel as a function of AoD ϕ_{AoD} and AoA ϕ_{AoA} . The DDPAS is calculated as:

$$P(\phi_{AoD}, \phi_{AoA}) = \sum_{\tau} |h(\tau, \phi_{AoD}, \phi_{AoA})|^2 \quad (2)$$

Note that in this paper, 10 dB higher than the noise floor is chosen to be the signal threshold for both LoS and NLoS cases.

3.3 Omnidirectional PDP

In this paper, we analyze the omnidirectional power delay profile (PDP) by reconstructing the omnidirectional pattern from the full bidirectional capture. In this approach, we choose the direction with the highest power in each delay, similar to [26]:

$$P_{\text{omni}}(\tau) = \max_{\phi_{AoD}} \max_{\phi_{AoA}} |h(\tau, \phi_{AoD}, \phi_{AoA})|^2 \quad (3)$$

3.4 Path Loss

Path loss is a channel parameter that characterizes the power of the received signal as a function of distance. In this paper, path loss is calculated as the power summation of the omnidirectional PDP:

$$PL = \sum_{\tau} P_{\text{omni}}(\tau) \quad (4)$$

We fit the empirical path loss by two log-distance dependent path loss model, i.e., alpha-beta-gamma (ABG) model and close in (CI) model, which is widely used in[27–29]. The ABG model can be written as:

$$PL_{ABG}(d)[\text{dB}] = 10n_{ABG} \log_{10}\left(\frac{d}{d_0}\right) + PL(d_0) + \chi_{\sigma}^{ABG} \quad (5)$$

where $PL_{ABG}(d)$ (in dB) denotes the ABG path loss model over distance. d (in meter) represents the Tx-Rx distance with $d \geq 1$ m and $d_0 = 1$ m; n_{ABG} and $PL(d_0)$ are the path loss exponent and the optimized offset value for path loss, respectively. χ_{σ}^{ABG} represents the large-scale signal fluctuations.

The CI model is given as:

$$\begin{aligned} PL_{CI}(d) [\text{dB}] &= 20 \log_{10} \left(\frac{4\pi f_c}{c} \right) + 10n_{CI} \log_{10}(d) \\ &+ \chi_{\sigma}^{CI} \\ &= 10n_{CI} \log_{10}(d) + 81.98 + \chi_{\sigma}^{CI} \end{aligned} \quad (6)$$

where $PL_{CI}(d)$ (in dB) denotes the CI path loss model over distance. n_{CI} and χ_{σ}^{CI} are the path loss exponent and the large-scale signal fluctuations, respectively.

3.5 Delay Spread

Delay spread is a channel parameter that describes the delay span of the channel path. Note that we compute and analyze the delay spread based on the omnidirectional PDP $P_{\text{omni}}(\tau)$. In this study, the root-mean-square (RMS) delay spread of the channel τ_{rms} is computed as

$$\tau_{\text{rms}} = \sqrt{\frac{\sum_{\tau} (\tau - \bar{\tau})^2 P_{\text{omni}}(\tau) d\tau}{\sum_{\tau} P_{\text{omni}}(\tau) d\tau}}, \quad (7)$$

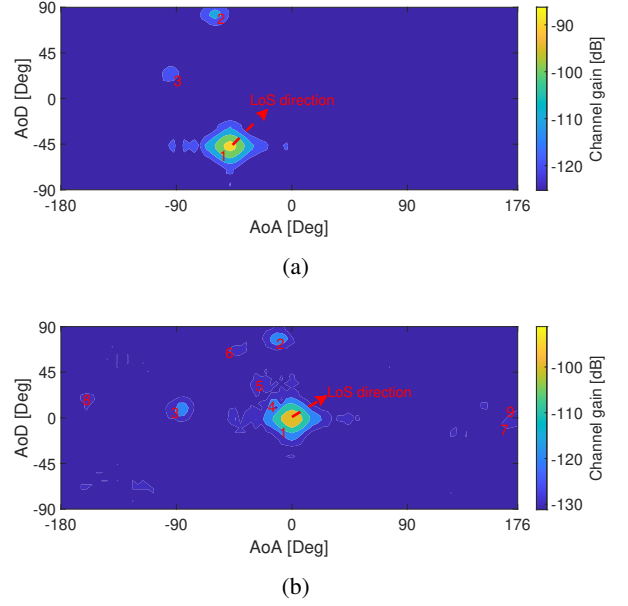


Figure 6. Exemplary DDPAS for the LoS measurement locations. (a) Tx-Rx 1 (LoS); (b) Tx-Rx 3 (LoS).

where τ_{max} is the maximum delay, i.e., 750 ns, and $\bar{\tau}$ is the average delay spread that is calculated as

$$\bar{\tau} = \frac{\sum_{\tau} \tau P_{\text{omni}}(\tau) d\tau}{\sum_{\tau} P_{\text{omni}}(\tau) d\tau} \quad (8)$$

3.6 Angular Spread

In this study, angular spread is referred to as the AoD spread and the AoA spread denoted with $\sigma_{\phi \text{AoD}}$ and $\sigma_{\phi \text{AoA}}$, respectively. In this work, the angular spread σ_{ϕ} is calculated approximately as the second central-moment of the azimuth-power spectrum $P(\phi)$:

$$\sigma_{\phi} \approx \sqrt{\frac{\sum_{\phi} (\phi - \mu_{\phi})^2 \cdot P(\phi)}{\sum_{\phi} P(\phi)}}, \quad (9)$$

where μ_{ϕ} represent the mean angle, and it is calculated as,

$$\mu_{\phi} = \frac{\sum_{\phi} \phi \cdot P(\phi)}{\sum_{\phi} P(\phi)}. \quad (10)$$

IV. MEASUREMENT RESULTS

In this section, channel parameters at 300 GHz are presented, including DDPAS, delay spread, angular spread, and path trajectory.

4.1 DDPAS

Fig. 6 and Fig. 9(a) and (c) depict the exemplary DDPASs $P(\phi_{Tx}, \phi_{Rx})$ and the PADPs of the measured LoS channel, respectively. Note that we use 40 dB threshold from the peak power value in the spectra, and the gain of the horn antenna has not been removed in the results. In the Tx-Rx 1 scenario, the LoS path has the delay of 20 ns, the AoD of -46° , and the AoA of -48° , which matches the geometry of the transceiver deployment. While the LoS component in the Tx-Rx 3 LoS scenario has the delay of 38 ns, the AoD of 0° , and the AoA of 0° . The power is observed to be highly concentrated around the LoS direction, while several additional reflection contributions from various directions are identified. Besides, the LoS path power decreases from -40.4 dB to -45.3 dB with the measurement distance increasing from 5.9 m to 11.4 m. The number of multipath components (MPCs) in these two LoS scenarios are seen to be 2 and 8, respectively. Note that path 9 is found to be the reflection from the window structure of the corridor. The multipath is shown to be specular and sparse from the measured results. Furthermore, Fig. 7 depicts the relation of the main paths in the channel to the room geometry, the delays, AoDs, AoAs of the main paths in the LoS scenarios match the room geometry.

The DDPAS and PADP in the Tx-Rx 2 NLoS scenario are depicted in Fig. 8 (a) and Fig. 9 (b), respectively. The LoS path can still be observed with the delay of 21 ns (which matches the Tx-Rx 2 distance of 6.2 m) and power of -77.2 dB, which to our postulation, is due to the diffraction from the edge of the metal obstacle. Besides, the MPCs are mainly concentrated in the AoD range of $[0^\circ, 90^\circ]$. In the Tx-Rx 4 NLoS scenario, the LoS path is observed to be totally blocked by the stairs, and the MPCs in this case are mainly concentrated in the AoA range of $[-180^\circ, 0^\circ]$, as illustrated in Fig. 8 (b) and Fig. 9 (d). Furthermore, compared with the DDPAS from the LoS scenario in Fig. 6, the MPCs in the NLoS cases are richer compared to those in the LoS cases due to the fact that the dominant LoS components are blocked and thus, the difference in power between various MPCs is less.

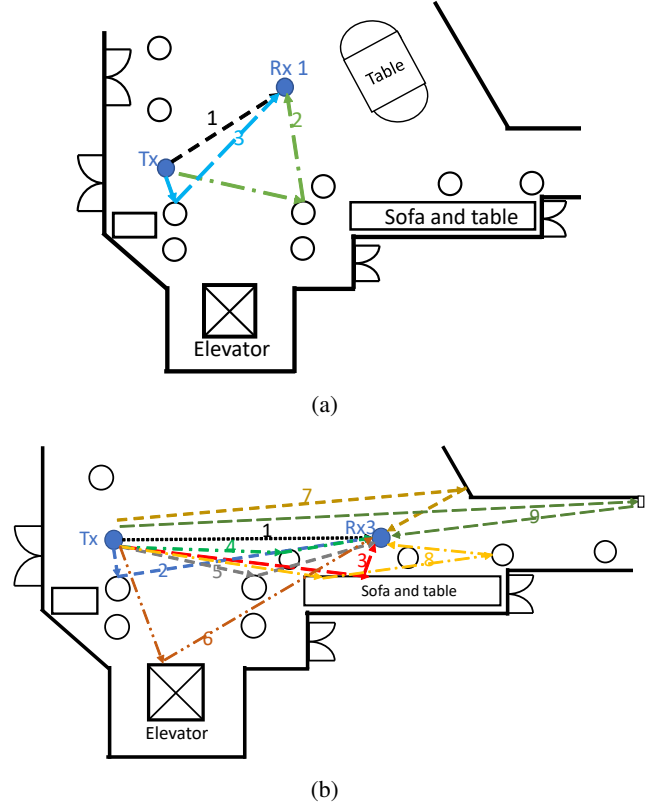


Figure 7. Relationship between the main paths and the room geometry. (a) Tx-Rx 1; (b) Tx-Rx 3.

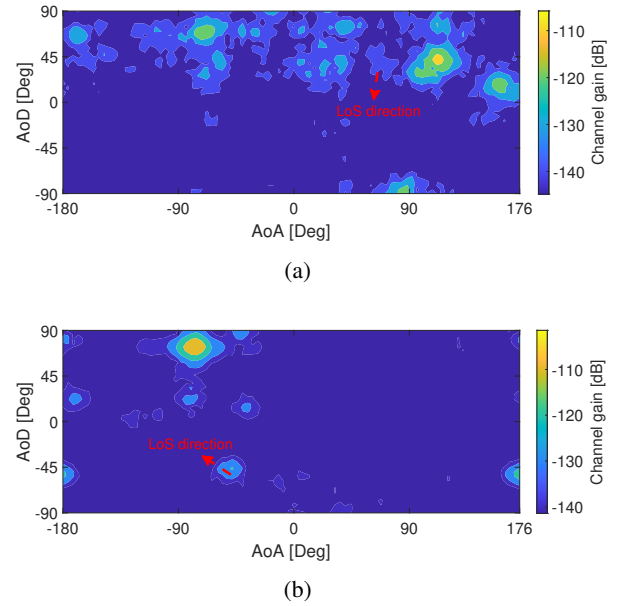


Figure 8. DDPAS for the NLoS measurement locations. (a) Tx-Rx 2; (b) Tx-Rx 4.

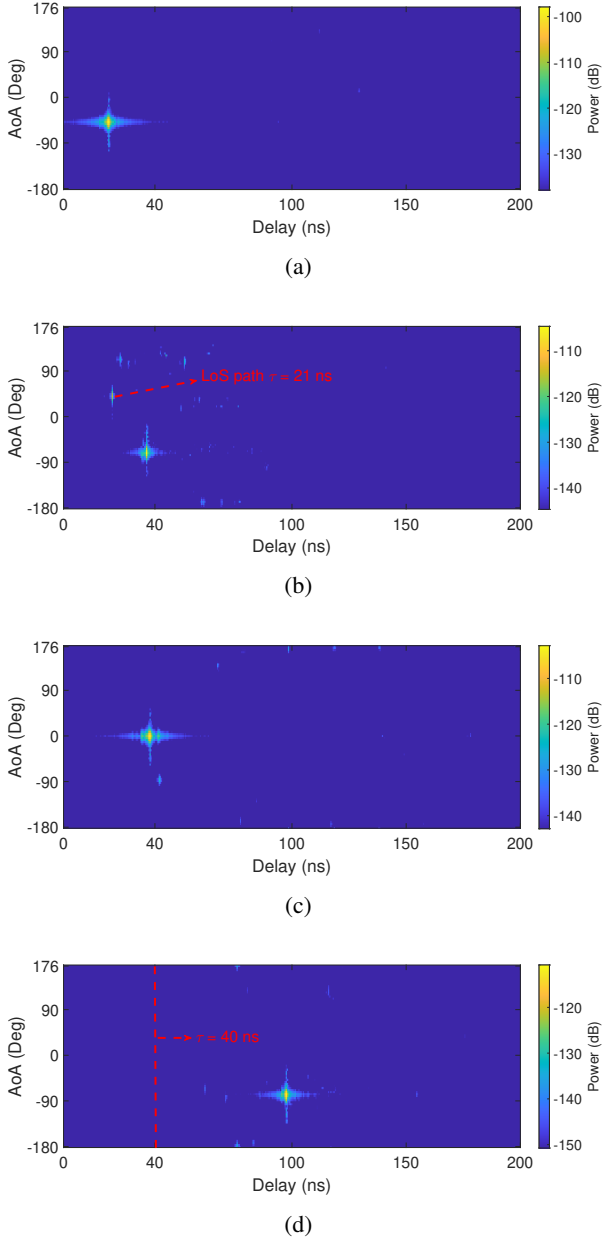


Figure 9. Exemplary PADP for NLoS locations at the LoS direction. (a) Tx-Rx 1 ($\phi_{Tx} = -46^\circ$); (b) Tx-Rx 2 ($\phi_{Tx} = 50^\circ$); (c) Tx-Rx 3 ($\phi_{Tx} = 0^\circ$); (d) Tx-Rx 4 ($\phi_{Tx} = -50^\circ$).

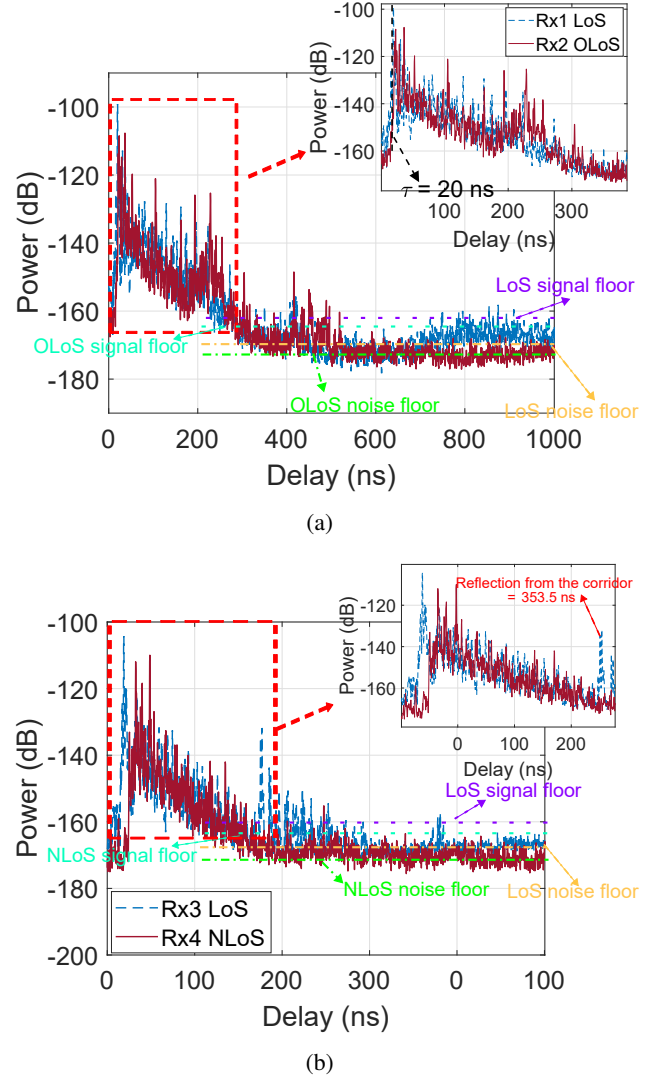


Figure 10. Exemplary omnidirectional PDP comparison. (a) Rx 1 and Rx 2. (b) Rx 3 and Rx 4.

4.2 Omnidirectional PDP and Path Loss

Fig. 10 illustrates an exemplary omnidirectional PDP comparison. In Fig. 10(a) (Rx 1 and Rx 2 cases), we observe that the LoS path in the OLoS case is blocked and the power decreases from -40.4 dB to -67.7 dB compared to that in the LoS case. We observe that the MPCs are rich for both cases. The MPCs mainly appear in the delay range of $[21, 250]$ ns (corresponding to the propagation distance range of $[6.3, 75]$ m). Furthermore, several weak paths over 400 ns (corresponding to the propagation distance of 120 m) can still be identified in both cases. In Fig. 10(b) (Rx 3 and Rx 4 cases), the LoS path in the NLoS case (i.e., Rx 4) is completely blocked and the power reduction is 58.5 dB compared to LoS case. The MPCs in NLoS case mainly appear in the delay range of $[50.5, 270]$ ns (corresponding to the propagation distance range of $[15, 81]$ m), while the omnidirectional PDP in the LoS case is seen to have a longer decay in the delay range of $[37.5, 446.5]$ ns. Note that we also identify one reflection path from the wall at the end of the corridor with the power of -79.0 dB and the delay of 353.5 ns.

Fig. 11 depicts the comparison of the empirical path loss and the modeled path loss. Note that the antenna gain is removed from the omnidirectional PDP before the calculation. The empirical path loss in the NLoS scenarios is also illustrated in Fig. 10. The empirical path loss is well-fitted to the ABG path loss model of $2.1 * 10 * \log_{10}(d) + 79.6$ with the root-mean-square error (RMSE) of 0.9 dB, and is also well-fitted to the CI model of $1.8 * 10 * \log_{10}(d) + 82.0$ with the RMSE of 1.1 dB. The ABG model has higher accuracy compared to the CI model. We also compare the measured path loss with the free space path loss (FSPL) model. The fitted path loss exponent for ABG model $n_{ABG} = 2.1$ matches the theoretical FSPL value. However, measured $PL(d_0)$ is 1.6 dB less than the theoretical value due to the fact that the omnidirectional path loss is a wideband path loss. While the fitted exponent for CI model $n_{CI} = 1.8$ is slightly lower than the theoretical value. Compared the NLoS path loss (i.e., Rx 2 and Rx 4) with the LoS path loss in the same Tx-Rx distance (i.e., Rx 1 and Rx 3), the path losses increase 3.3 dB and 4.7 dB, respectively.

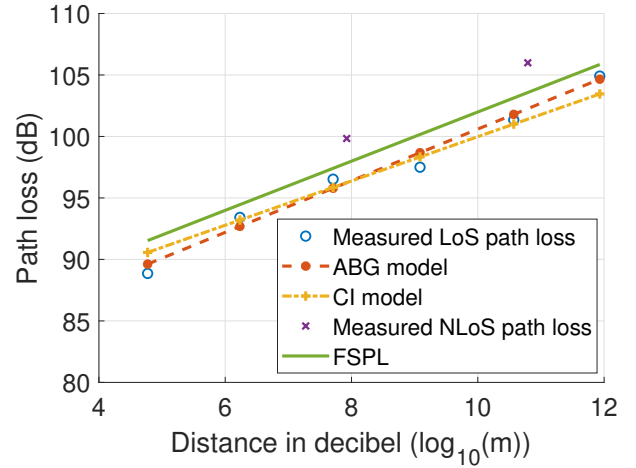


Figure 11. Path loss models for these measurement results.

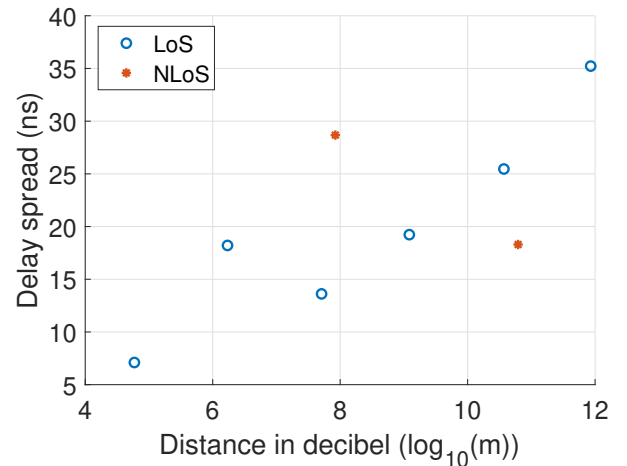


Figure 12. Relation of the delay spread to the Tx-Rx distance.

4.3 Delay Spread

Fig. 12 depicts the comparison of the empirical delay spread. As illustrated in Fig. 12, the empirical delay spreads in the LoS cases range within $[7.5, 35.6]$ ns. Besides, the LoS delay spreads increase with the link distance between the Tx and the Rx, which is due to the fact that as the LoS power decreases with the increasing distance, the power of MPCs becomes comparable to that of the LoS path. In the NLoS cases, the delay spread of the Rx 2 is 14.8 ns higher than that of Rx 1, while the delay spread of the Rx 4 is 7.6 ns lower than that of Rx 3. However, due to the lack of sufficient NLoS measurements, we cannot draw any conclusions for the NLoS delay spreads and further measurements should be carried out to investigate it.

4.4 Angular Spread

The relation of the empirical angular spread to the link distance between the Tx and Rx is depicted in Fig. 13. We observe that the LoS AoA spreads are ranging in $[18^\circ, 43^\circ]$ and increases with the distance. Moreover, the LoS AoD spreads are seen to increase with the measurement distance range of $[3, 8.1]$ m, and decrease in the Tx-Rx distance range of $[8.1, 15.6]$ m. Fig. 14 illustrates the power-angle-spectrum (PAS) comparison of the Rx 3, Rx 7, and Rx 8. We observed that the Rx 7 has a larger AoD difference between the LoS direction and the mean AoD compared to those of the Rx 3 and Rx 8, which means that the MPCs contribute more to the angular spread in the Rx 7 case. For the NLoS scenarios, the AoA spreads of the two NLoS cases, i.e., Rx 2 and Rx 4, are 88.0° and 115.2° , respectively, which are observed to be much higher than those AoA spreads at the same distance. Fig. 15 illustrates the comparison of the PAS in azimuth and the mean azimuth in LoS and NLoS cases. It is observed that the mean AoA appears near the LoS peak in Rx 1 and Rx 3 (LoS cases), as shown in Fig. 15(a), and the LoS power contributes dominantly to the angular spread, which leads to a small angular spread around the mean AoA (i.e., LoS) direction. Meanwhile, the LoS path is blocked in Rx 2 and Rx 4 (NLoS cases), and the MPCs and angle differences of the paths to the mean angle contributed more significantly to the angular spread. The AoD spread of the Rx 4 is 43.6° higher than that of Rx 3 and the AoD spread of the Rx 2 is found to be close to that of Rx 1.

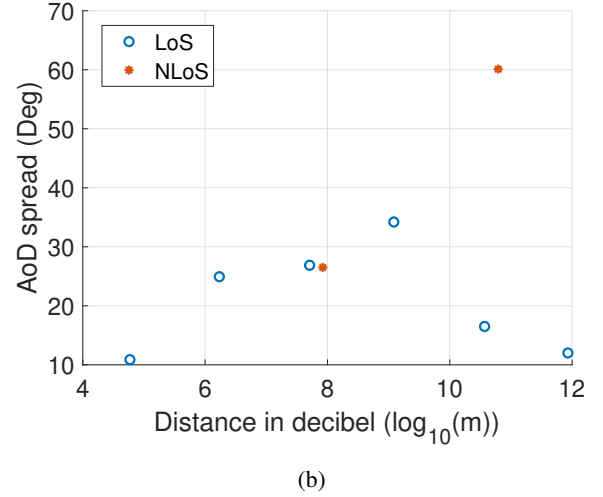
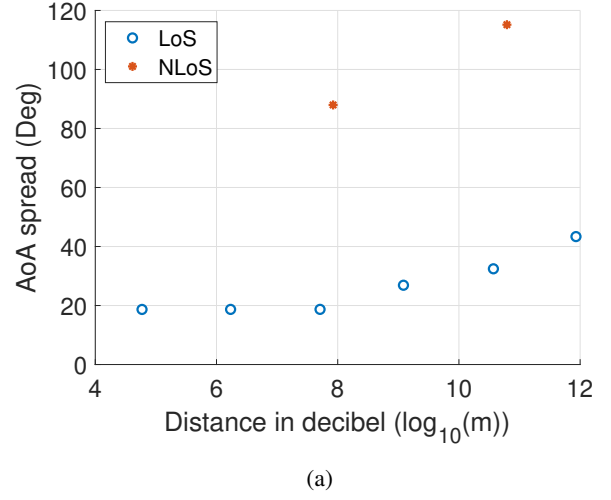


Figure 13. Relation of the angular spread to the Tx-Rx distance. (a) AoA spread; (b) AoD spread.

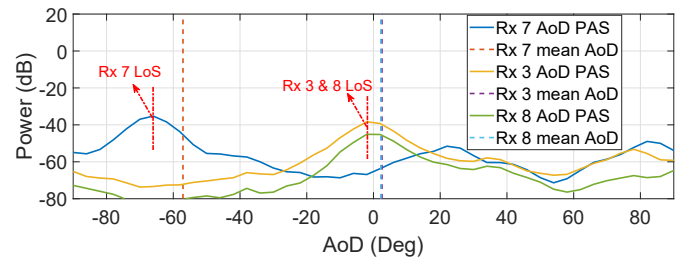


Figure 14. The AoD PAS with the mean elevation and LoS direction.

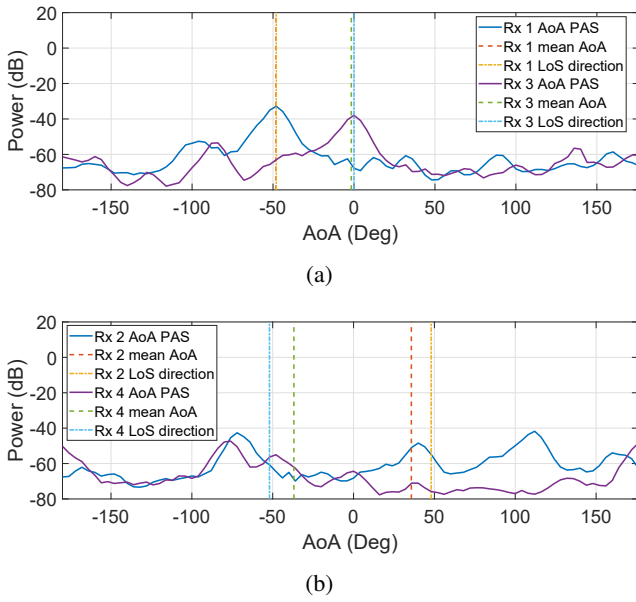


Figure 15. The AoA PAS with the mean azimuth and LoS direction. (a) LoS cases. (b) NLoS cases.

4.5 Observation and Model Comparison to Existing Counterpart

- **The measured channels are seen to be specular and sparse.** The diffuse components are predicted to be more important in principle as the frequency goes up, since the wavelength is getting close to the surface smoothness [30, 31]. However, this is not our observation here both for the LoS and NLoS scenarios, the measured channels are shown to be highly specular and sparse, due to its susceptibility to high transmission loss, blockage loss, and high diffraction loss. Furthermore, the wavelength at 300 GHz is around 1 mm, which is still much larger than the typical indoor surface roughness.
- In the 3GPP channel models, a channel modeling framework with cluster-level parameters is typically adopted for 3GPP SCME channel model and 3GPP 38.901 channel model [32]. The measured data can provide realistic inputs on the channel parameter settings for the simulation.
- With respect to path loss, two widely-used log-distance path loss models are used and compared in this study. In the state-of-the-art, there are only a few literature reporting directional/double-directional channel models at 300 GHz frequency bands [15, 33, 34]. Table 4 illustrates the compari-

son of the path loss model to the existing 300 GHz channel models. The fitted ABG model is found to be closed to that in [15] and the offset $PL(d_0)$ in this study is seen to be 3.2 dB higher than that in [33]. The exponent of the fitted CI model is 0.4 higher than that in [34]. As for other parameters, the delay spread in this work is much higher than that in [15, 33, 34], which is due to the bigger scenario size and richer scatterer in our measurements. The AoA spread are observed to be close compared to those in [34] in the similar Tx-Rx distance.

V. CONCLUSIONS

In this paper, we present the measurement results of the double-directional sub-THz channel measurements at 300 GHz bands in a large hall scenario. Firstly, we summarize the sub-THz channel measurements in the literature. A VNA-based channel sounder using RoF scheme at 300 GHz is then proposed and channel measurements are performed in a large hall scenario. The Tx-Rx distances are from 3-15.6 m. We also consider LoS and NLoS cases in the measurements. Channel characteristics, i.e., DDPAS, PADP, path loss, delay spread, and angular spread, are calculated and analyzed in the aforementioned scenario. The DDPAS results show a good agreement with the room geometry, which demonstrates the accuracy of the measurements. The DDPAS results in the LoS scenario also illustrates the sparsity of the multipaths at 300 GHz. The empirical path loss related to the measurement distance in decibel is well-fitted by the ABG model and found to be close to the theoretical FSPL model. The LoS delay spread is observed to increase with the Tx-Rx distance. Compared with the low angular spreads in the LoS cases, the angular spreads at NLoS cases are found to be much higher. Moreover, MPCs are observed in the omnidirectional PDP over 200 ns (which corresponds to 60 m). This result indicates the possibility of long-range channel measurement campaign at 300 GHz. Further long-range 300 GHz channel measurements should be conducted in the future.

Table 4. The Comparison of Path Loss Models at 300 GHz bands.

| Ref. | Frequency (GHz) | Conditions | Path loss model | Delay spread | AoA spread |
|--------------|-----------------|---------------------------------------|---|-------------------|----------------|
| Fitted model | 299-301 | Large hall, $3 \leq d \leq 15.6$ m | $PL_{ABG}(d) = 2.1 * 10 * \log_{10}(d) + 79.6$ $PL_{CI}(d) = 1.8 * 10 * \log_{10}(d) + 82.0$ | [7.1, 35.2] ns | [18.7°, 43.4°] |
| [15] | 300-308 | Intra-wagon, $d = 5.3$ m | $PL_{ABG}(d) = 2.2 * 10 * \log_{10}(d) + 79.8$ | [1.2, 2.6] ns | 22.8° |
| [33] | 270-300 | Office room, $1 \leq d \leq 6.6$ m | $PL_{ABG}(d) = 1.9 * 10 * \log_{10}(d) + 82.8$ | [2.3, 7.9] ns | - |
| [34] | 306-321 | Corridor, $7.7 \leq d \leq 18.5$ m | $PL_{CI}(d) = 1.4 * 10 * \log_{10}(d) + 82.4$ | [10.19, 20.69] ns | [20.0°, 52.1°] |

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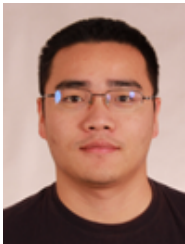
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