

THz Band Channel Measurements and Statistical Modeling for Urban Microcellular Environments

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Abstract

The THz band (0.1-10 THz) has attracted considerable attention for next-generation wireless communications due to the large amount of available bandwidth that may be key to meet the rapidly increasing data rate requirements. Before deploying a system in this band, a detailed wireless channel analysis is required as the basis for proper design and testing of system implementations. One of the most important deployment scenarios of this band is the outdoor microcellular environment, where the Transmitter (Tx) and the Receiver (Rx) have a significant height difference (typically ≥ 10 m). In this paper, we present double-directional (i.e., directionally resolved at both link ends) channel measurements in such a microcellular scenario encompassing street canyons and an open square. Measurements are done for a 1 GHz bandwidth between 145-146 GHz and an antenna beamwidth of 13 degree; distances between Tx and Rx are up to 85 m and the Tx is at a height of 11.5 m from the ground. The measurements are analyzed to estimate path loss, shadowing, delay spread, angular spread, and multipath component

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(MPC) power distribution. These results allow the development of more realistic and detailed THz system performance assessment.

Index Terms

THz Channel Measurements, Outdoor Channel, Urban Scenario, Statistical Modeling, Microcellular

I. INTRODUCTION

A number of new and upcoming applications require ultra-high data rates that are beyond the capabilities of mmWave-based 5G communication systems. In order to meet these requirements, higher frequencies such as the THz band (0.1-10 THz) are being investigated because of the availability of considerable amounts of unused spectrum in these bands [1]–[4]. Therefore the THz band, especially the frequencies between 0.1-0.5 THz, has been explored by a number of studies, e.g., [5]–[8]. The recent decision of the Federal Communication Commission (FCC), the US spectrum regulator, to provide experimental licenses in this band has fostered additional research interest, and this band is widely expected to be an important part of 6G wireless systems [1], [9].

It is important to know the characteristics of a wireless channel before the design of a communication system that is to operate in it can proceed. Channel sounding measurements and their statistical analysis are an essential first step towards the understanding of a channel and consequently towards the design and deployment of a wireless system [10]. Since channel characteristics are highly dependent on the operating frequency range as well as the environment and the scenarios a wireless channel operates in, channel sounding campaigns need to be performed in the key scenarios of interest.

Existing channel measurements in the THz bands are mostly limited to short-distance indoor channels, see [6], [7], [11]–[14], usually as a result of measurement setup constraints; see also [15] and references therein. However, recently there has been some progress on longer distances and outdoor scenarios as well. These include the first long-distance (100 m) double-directional channel measurements for the 140 GHz band, which were reported in 2019 [16], [17] by our group, as well as our recent works [18]–[20] where we target device-to-device (D2D) scenarios, where both Tx and Rx are at about 1.6 m height. Another recent series of papers [8], [21], [22] also reported channel measurements, path loss and statistical modeling at 140 GHz over longer

channel lengths in an urban scenario; in those measurements the Tx is placed at 4 m above the ground (i.e., typical lamppost height). Our current paper aims to provide analysis for a scenario where the Tx is significantly higher, at 11.5 m, which is comparable to the height of a typical microcell base station. This paper presents the results of an extensive measurement campaign in this environment, with sufficient points to allow a meaningful statistical evaluation. To the best of our knowledge, such a detailed channel measurement campaign for cases where Tx is elevated more than 10 m above the ground has not been reported before in the THz band.

The results of this paper are based on ultra-wideband double-directional channel measurements for a 1 GHz bandwidth between 145-146 GHz ¹. Bands around 140 GHz band are of particular interest not only because of an interest from FCC [9], but also because of recent developments in design of antenna arrays in these bands [23]. Moreover, our previous device-to-device studies detailed in [20] also target the 145-146 band and thus allow us to compare across various scenarios. Measurements were conducted at 26 different transmitter (Tx) - receiver (Rx) location pairs. 13 of these represent line-of-sight (LoS) scenarios with direct Tx-Rx distances ranging from nearly 20 m to 83 m, while the other 13 are non-line-of-sight (NLoS) cases with direct Tx-Rx distances also in approximately the same range. Based on the nearly 110,000 directional impulse responses we collected from these measurements, we model the path loss, shadowing, delay spread, angular spread and multipath (MPC) power distribution for both LoS and NLoS cases. Our detailed analysis includes results both for the maximum-power-beam direction (max-dir) and the omni-directional characteristics as well as the distance dependence of the key parameters, and their relevant confidence intervals for the various model fits.

The remainder of this paper is organized as follows. In Section II, we describe the channel sounding setup and the measurement locations. Key parameters of interest and their processing is described in Section III. The results of the measurements and modeling are presented in Section IV. We finally conclude the manuscript in Section V.

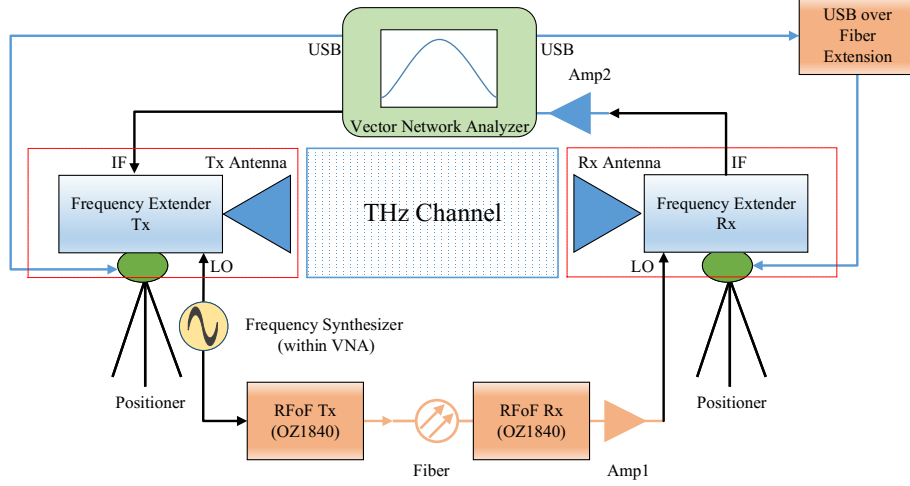


Fig. 1: Channel sounding setup.

TABLE I: Setup parameters.

Parameter	Symbol	Value
Frequency points	N	1001
Tx height	h_{Tx}	11.5 m
Rx height	h_{Rx}	1.7 m
Start frequency	f_{start}	145 GHz
Stop frequency	f_{stop}	146 GHz
Bandwidth	BW	1 GHz
IF bandwidth	IF_{BW}	10 KHz
THz IF	f_{THzIF}	279 MHz
Antenna 3 dB beamwidth	θ_{3dB}	13°
Tx Az rotation range	ϕ_{Tx}	$[-60^\circ, 60^\circ]$
Tx Az rotation resolution	$\Delta\phi_{Tx}$	10°
Rx Az rotation range	ϕ_{Rx}	$[0^\circ, 360^\circ]$
Rx Az rotation resolution	$\Delta\phi_{Rx}$	10°
Tx El rotation range	$\tilde{\theta}_{Tx}$	$[-13^\circ, 13^\circ]$
Tx El rotation resolution	$\Delta\tilde{\theta}_{Tx}$	10°
Rx El rotation range	$\tilde{\theta}_{Rx}$	$[-13^\circ, 13^\circ]$
Rx El rotation resolution	$\Delta\tilde{\theta}_{Rx}$	13°

II. MEASUREMENT EQUIPMENT AND SITE

A. Testbed description

The choice of channel sounding techniques is a trade-off among various factors such as measured bandwidth, speed, cost and complexity of the measurement system. A distinction can be

¹Some authors prefer to use the term "THz" to identify the frequency range > 300 GHz while using "high mmWave", "sub-THz" or "low-THz" for frequencies between 100-300 GHz. Other authors use the term "THz" for both these cases. Since the latter is the most widely used terminology, we will employ it in this paper as well

made between various measurement setups based on the way they excite the channel of interest. Frequency-domain measurement setups, in particular Vector Network Analyzer (VNA) based setups, sweep over frequencies of interest one tone at a time, while time-domain measurement setups are based on excitation of the channel by signals with instantaneously wide bandwidth (see [15] for more details). VNA-based setups are popular for channel measurements because they are based on well-calibrated, commercially available precision instrumentation, although the long duration implicit in stepping through the different tones limits the scenarios of interest to quasi-static cases. For this measurement campaign, a frequency-domain channel sounder outlined in Fig. 1) was used, similar to [20]; it is based on a VNA model PNAX N5247A from Keysight, which has a frequency range from 10 MHz to 67 GHz. Frequency extenders, WR-5.1 VNAX manufactured by Virginia Diodes, were used to increase the VNA's frequency range to the 140-220 GHz band, which encompasses the band of interest to us. The extenders were used with the "high sensitivity" waveguide option to improve the received Signal to Noise Ratio (SNR). The antennas (along with the extenders) are mounted on a rotating positioning system. A key aspect of this setup is the use of a RF-over-fiber (RFoF) link, which was originally introduced in [17]. The RFoF allows us to measure over longer distances than the typical 5-10 m range of similar systems without the link. The local oscillator signal required for the current sounder has a frequency between 11 and 18 GHz (12x multiplication factor in frequency extenders). For these frequencies, coaxial losses over the range of Tx-Rx separation distances typical for THz outdoor urban scenarios (up to 100 m) would be very high and thus require the use of a number of RF amplifiers along the cable. Among a host of other issues, this makes for a very bulky setup that is impractical to manage especially for outdoor measurements with elevated base station. The RFoF system we use eliminates these problems. For further details of the system please see [20].

Table I shows the configuration parameters for the sounder. The IF bandwidth of the VNA was selected to provide a compromise between the dynamic range and the measurement duration, namely such that the duration of a measurement sweep is lower than the mechanical movement of the horn, and therefore has only a minor impact on the total measurement time. Each sweep of the VNA contains 1001 frequency points over the 1 GHz bandwidth, therefore allowing unambiguous measurement of maximum excess delay of up to 1 μ s. In other words, the maximum measurable excess runlength for multipaths is 300 m, a reasonable distance considering the scenarios and the frequency band being sounded. A major consideration in the selection for 1 GHz

of measurement bandwidth is measurement time: for our VNA-based setup, measurement time increases with increasing bandwidth (for a given maximum excess delay and dynamic range). Furthermore, higher *instantaneous* bandwidths result in a higher noise floor [24]; averaging can help in regaining the dynamic range, however, it also increases the measurement time. Finally, given that the measurements take a significant amount of time, they were conducted at night while ensuring the scenario remains static/quasi static.

The measurement locations were selected to be typical of a "microcellular" scenario. The Tx for the current measurements is set at a height of 11.5 m above the ground while the Rx is placed 1.7 m high from the ground. These parameters have been selected following the 3GPP UMi Street Canyon model, (3GPP TR 38.901 version 14.0.0 Release 14 suggests $h_{Tx} = 10m$ and $1.5m \leq h_{Rx} \leq 22.5m$). Additionally, to extract the double-directional characteristics of the channel, the frequency sweeps of the VNA were repeated with sets of different orientations of the antennas. The positioners were oriented to ensure that the azimuth angle zero at both ends (Tx and Rx) corresponded to the LoS direction, irrespective of whether an unblocked optical LoS connection between Tx and Rx actually exists or not. We anticipated that multiple elevation scans are required to properly analyze the scenario, due to the different heights of the link ends, therefore, three elevation cuts are scanned on both the Tx and Rx. The Tx azimuth will scan a 120° sector from -60° to 60° with 10° of azimuthal resolution, meanwhile, the Rx will carry out a complete azimuth scan, from 0° to 360° in steps of 10° , similar to Tx. In elevation, Tx and Rx are aligned so that when both antennas are facing ($\tilde{\theta}_{Tx} = \tilde{\theta}_{Rx} = 0^\circ$), they are in the same elevation cut. After that, both ends will make additional scans 13° above and 13° below the "alignment", giving a total of 9 elevation scans per Tx-Rx location (3 elevation scans at the Tx and 3 for the Rx).²

The measurements were performed on different days, due to the long measurement time per point (nearly 4 hours per measurement point). For each day a calibration of the VNA, an over-the-air calibration (OTA) with the Tx and Rx at a LoS location was performed. OTA calibration (as opposed to back-to-back calibration) is necessitated by our current setup since the high-sensitivity waveguide we use on the Rx-end of our setup to improve dynamic range does not allow us to connect the RF heads directly (device damage is caused otherwise). Additional details

²It is important to mention that $\tilde{\theta} = 0^\circ$ is not equivalent to $\theta = 90^\circ$ in elevation, i.e. it is not the horizontal. $\tilde{\theta} = 0^\circ$ is different on each point in an absolute elevation reference.

of the setup are described in [17]–[19]. The OTA is performed by aligning the Tx and Rx and performing a sweep over all the frequencies while placing them with a clear LoS and ensuring no reflectors are present within a small distance around the Rx (usually around 2 m). The results are then delay-gated to ensure all reflections from environmental objects are discounted and instead we are left with the system's response.

Finally, we note that the frequency domain-sounder provides a high phase stability which allows to conduct Fourier analysis and High Resolution Parameter Extraction (HRPE). Although HRPE can provide more accurate results, the current paper only uses Fourier analysis; HRPE analysis will be discussed in future work.

B. Measurement locations

An important step in the measurement campaign is the selection of suitable locations so that we can measure realistic samples of LoS and NLoS scenarios. For this purpose we selected an area inside the University Park Campus of the University of Southern California (USC) in Los Angeles, California, USA, that is located in the center of the city and can be characterized as an urban environment. Fig. 2 shows the scenario and locations of the Tx and Rx locations. As can be seen, the measurement campaign is divided into 6 routes with LoS or NLoS points each corresponding to a unique Tx location. For all 6 Tx locations (corresponding to the 6 yellow dots in Fig. 2), the positioner was placed on the edge of the Downey Way Parking Structure (PSA) building on the third floor.

Route One (corresponding to Tx1 in Table II) contains 6 LoS points aligned on the walkway of the Andrus Gerontology Center (GER) on the McClintock side of the building, covering a distance range from 33.5 to 81.7 m (see Fig. 3a). Ronald Tutor Hall (RTH) and the Hughes Aircraft Electrical Engineering Center (EEB) together with the GER building create a "street canyon" for Route One points. It is important to note that the LoS was not obstructed or partially obstructed by foliage or other environmental objects. The three NLoS points were placed under the portico of the GER building (see Fig. 3b). Apart from the roof of the building, the pillars provide additional obstructions to the LoS. The second route is at the opposite side of PSA on a parking lot surrounded by Ray Irani (RRI) and Michelson Hall (MCB). While the photo of Fig. 2 shows cars, no cars were present during the measurement. Rx points 10, 11 and 13 were set on a straight line aligned to the Tx and Rx 12 was set 30 meters north of Rx 11. For Route Three, the Tx is moved 40 meters along PSA parallel to Downey Way. Here, MCB's side corner



Fig. 2: Microcellular campaign measurement scenario.

completely blocks the LoS components for Rx points 14-16. The distances for this route are approximately in the range of 40 to 60 meters.

Route Four places the Tx in the northwest corner of PSA, the three Rx locations are placed in an alley between Technical Theatre Laboratory (TTL) and the Scene Dock Theatre (SCD) buildings at distances ranging from 35 to 65 meters approximately. Route Five places the Tx 15 meters south of the Tx location in Route Four and the four Rx locations were placed in the same alley between SCD and TTL as Route Four. The obstruction for this route is provided by the TTL building and foliage as shown in Fig. 2³.

Finally, for Route Six, the points are located on the McClintock side of PSA, approximately 10 meters behind the location of the Tx on Route One. The Rx locations were placed on the sidewalk next to McClintock Ave. Similar to the points in Route One, Olin Hall of Engineering (OHE), and RTH building (together with PSA and GER) create a "street canyon" environment for this route. The main obstruction of the LoS is provided by the PSA building itself (pillars) as well as the foliage between the Tx and Rx locations. A sample point (Tx6-Rx24) is shown in

³Delay domain results for the subset of measurements on Route Four and Five were presented in [25]. This analysis is significantly different from the statistical analysis of the current work, which is based on a large set of measurements.

(a) Tx1-Rx1 LoS; $d = 81.7m$.(b) Tx1-Rx7 NLoS ; $d = 83.2m$.

Fig. 3: LoS and NLoS measurement points for Route One.

Fig. 4c. Table II shows a summary of the routes, locations and distances for all the measurement points of the campaign.

TABLE II: Description of Tx-Rx links and their respective direct distances.

Route identifier	Tx identifier	LoS Rx identifier	d_{LoS} (m)	NLoS Rx identifier	d_{NLoS} (m)
Route One	Tx_1	1-6	82.5, 64.5, 40.8, 72.3, 49.8, 32.1	7-9	83.2, 73.6, 46.4
Route Two	Tx_2	10-13	20.4, 33.9, 45.9, 54.3	-	-
Route Three	Tx_3	-	-	14-16	62.6, 53.4, 40.7
Route Four	Tx_4	17-19	36.3, 57.9, 65.7	-	-
Route Five	Tx_5	-	-	20-23	35, 58.5, 66.8, 45.5
Route Six	Tx_6	-	-	24-26	20.8, 30, 20

III. PARAMETERS AND PROCESSING

A. Data processing

The VNA-based measurement setup explained in Section II produces a collection of frequency scans for each Tx-Rx geographical location. Each measurement can be described as a five-



(a) Tx4-Rx19 LoS $d = 64.6m$. (b) Tx5-Rx23 NLoS $d = 45.5m$. (c) Tx6-Rx24 NLoS $d = 20.4m$

Fig. 4: LoS and NLoS sample points for Routes Four, Five and Six.

dimensional tensor $H_{meas}(f, \phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}; d)$ where f denotes the frequency points over the 1 GHz bandwidth (145-146 GHz), ϕ_{Tx} and ϕ_{Rx} denote the azimuth orientation of the Tx and Rx, respectively, $\tilde{\theta}_{Tx}$ and $\tilde{\theta}_{Rx}$ denote elevation orientation of the Tx and Rx, respectively, and d is the Tx-Rx distance. Each tensor, H_{meas} , has dimensions of $N \times N_{Tx}^{\tilde{\theta}} \times N_{Tx}^{\phi} \times N_{Rx}^{\tilde{\theta}} \times N_{Rx}^{\phi}$ where N is the number of frequency points per sweep (1001), N_{Tx}^{ϕ} and N_{Rx}^{ϕ} are the number of azimuth directions at the Tx (13) and Rx (36), and $N_{Tx}^{\tilde{\theta}}$ and $N_{Rx}^{\tilde{\theta}}$ are the number of elevation directions at the Tx (3) and Rx (3), respectively. Before the processing and parameter analysis we calibrate the measurement (eliminating the effects of the system and antennas) transfer functions. The OTA calibration $H_{OTA}(f)$ is used to obtain the calibrated directional channel transfer function by dividing the measured channel transfer function by the OTA calibration: $H(f, \phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}; d) = H_{meas}(f, \phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}; d) / H_{OTA}(f)$. The calibrated channel frequency response is used to compute different parameters such as the directional power delay profile (PDP) as

$$P_{calc}(\tau, \phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}, d) = |\mathcal{F}_f^{-1}\{H(f, \phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}, d)\}|^2, \quad (1)$$

where $\mathcal{F}_f^{-1}$ is the inverse fast Fourier transform (IFFT) with respect to f . To minimize the effects of noise, thresholding and delay gating are applied similar to [19], [26] that is expressed as

$$P(\tau) = [P_{calc}(\tau) : (\tau \leq \tau_{gate}) \wedge (P_{calc}(\tau) \geq P_\lambda)] \quad (2)$$

or 0 if it does not fulfill these conditions. The value τ_{gate} is the delay gating threshold set to avoid using long delay bins or points with the "wrap-around" effect of the IFFT. P_λ is the noise threshold that is selected to ignore the power of delay bins with noise which could particularly distort delay spread and angular spread. For the current measurements, τ_{gate} is set to 966.67 ns (corresponding to 290 m excess runlength) and P_λ is selected to be 12 dB above the noise floor (average noise power) of the PDP to reduce the impact of noise in the results. Please note that, for the current campaign, the peak to noise threshold range for all measurement points is more than 25 dB.

From the collection of directional PDPs we selected the strongest beam as the beam-pair with the highest power (max-dir) as

$$P_{max}(\tau) = P(\tau, \phi_i, \tilde{\theta}_j, \phi_k, \tilde{\theta}_l, d); (\hat{i}, \hat{j}, \hat{k}, \hat{l}) = \max_{i,j,k,l} \sum_{\tau} P(\tau, \phi_i, \tilde{\theta}_j, \phi_k, \tilde{\theta}_l, d). \quad (3)$$

Finally, an "omni-directional" PDP is constructed by first combining all the elevations by summing over different elevations for each delay bin, and then selecting the azimuth with the strongest contribution. The selection of the strongest azimuth direction per delay bin to reconstruct a PDP is similar to [18], [27]. Overall, this process can be summed up as

$$P_{omni}(\tau; d) = \max_{\phi_{Tx}, \phi_{Rx}} \sum_i \sum_j P(\phi_{Tx}, \tilde{\theta}_{Tx}^i, \phi_{Rx}, \tilde{\theta}_{Rx}^j; d). \quad (4)$$

where $i, j \in \{1, 2, 3\}$ represents the elevations ($\tilde{\theta}_{Tx}^i, \tilde{\theta}_{Rx}^j \in \{-13^\circ, 0^\circ, 13^\circ\}$) for Tx and Rx, respectively. The adding of the different elevation cuts is meaningful because the spacing of the cuts in the elevation domain was taken as 13° , which is identical to the (full width half maximum (FWHM)) beamwidth. Thus, the effective elevation pattern of the sum is approximately constant in the range $-13^\circ \leq \tilde{\theta}_{Tx} \leq 13^\circ$, and has a FWHM of 39° , and similar at the Rx. Please also note that the omni-directional PDPs and subsequent parameter calculations based on them were corrected by a factor of 1.96 dB. This factor comes from the fact that we are adding different elevations to construct an omni-directional PDP. Even though the elevations were taken at 13 degrees (1 HPBW) spacing, when adding them together, the combine effect produces an extra gain of 0.98 dB (ideally it should be 0 dB), at each of Tx and Rx.

B. Parameter computation

Similar to the analysis performed in [20], we use the directional and omni-directional PDPs described in the previous section to compute several condensed parameters in order to characterize the propagation channels. The computations are based on the noise-thresholded and delay-gated PDPs calculated as described above.

1) *Path loss and shadowing*: The first parameter to be computed is the path loss. By definition (see [10]), the path gain is computed as the sum of the power on each delay bin in the PDP.

$$PG_i(d) = \sum_{\tau} P_i(\tau, d), \quad (5)$$

where i can denote omni-directional (omni) or the strongest beam (best-dir). The path loss ($PL_i(d) = PG_i^{-1}(d)$) is obtained as the inverse of the path gain. To model its behavior as a function of distance, we use the classical single slope "power law" also known as $\alpha - \beta$ model, such that the pathloss in dB is

$$PL_{\text{dB}}(d) = \alpha + 10\beta \log_{10}(d) + \epsilon, \quad (6)$$

where α and β are the estimated parameters, and ϵ represents the "Shadowing" or random variation of the data with respect to its mean. It is assumed to follow a zero-mean normal distribution $\epsilon \sim N(0, \sigma)$, where σ is the standard deviation of the distribution. To obtain the parameters of the model, we can use approaches such as maximum likelihood estimation (MLE) or ordinary least squares (OLS) [10], [28]. Following common assumptions in the modeling of path loss, the procedure is separated between the ensemble of LoS and NLoS measurement points.

An analysis carried out in [29] describes the challenges of an uneven density of distances between the Tx and Rx (in linear and logarithmic scale). This non-uniformity can lead to an increasing in the leverage of some points in the regression analysis compared to others. To compensate for this effect, [29] implemented a weighted regression model for path loss modeling. Each weight (w_i) is computed according to the density of points along the distance in $\log_{10}$ scale. So, w_i will be larger for points located in low density areas and vice versa. While multiple weighting methods are described in the paper, however, we adopt the approach of "equal weights to N bins over $\log_{10}(d)$ ($w_i \propto \log_{10}(d)$)", because this strategy corresponds to a least square fitting of "dB vs $\log_{10}(d)$ ".

2) *Delay spread*: The rms delay spread (RMSDS) is calculated as the second central moment of the PDP [10]:

$$\sigma_\tau = \sqrt{\frac{\int_\tau P_i(\tau) \tau^2 d\tau}{\int_\tau P_i(\tau) d\tau} - \left(\frac{\int_\tau P_i(\tau) \tau d\tau}{\int_\tau P_i(\tau) d\tau} \right)^2}, \quad (7)$$

where i can be "omni" or "max-dir". Noise and delay thresholding are essential for reducing the impact of long-delayed artefacts. Since this parameter is defined for continuous waveforms, therefore to approximate it, we increase the number of samples in the PDPs by oversampling them. Additionally, the PDPs shown are windowed. Different window types have been proposed in the literature, including the here-used Hann window [30], Hanning [31] and Kaiser [32], which represent different tradeoffs between broadening of the main lobe in the delay domain and the sidelobe level. Since our measurements have a very high dynamic range, we opted for strong suppression of the sidelobes, which is provided by Hann windowing.

3) *Angular spread*: The measurement campaign creates a "virtual" MIMO scenario for each location pair, allowing angular analysis. A way to quantify the dispersion of power over different angular directions is the angular spread. The starting point of its computation is the double-directional angular power spectrum ($DDAPS_{full}$), a function of the power concentration over different directions (particular azimuth, elevation directions) at Tx and Rx. The DDAPS is computed as

$$DDAPS_{full}(\phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}; d) = \sum_{\tau} P(\tau, \phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}; d). \quad (8)$$

Similar to the delay spread analysis, noise and delay gating are important before the computation of $DDAPS_{full}$ to minimize noise accumulation in directions where no significant MPC is observed. Using the $DDAPS_{full}$, we add the contribution of different elevations from both ends to have a similar DDAPS as [20].

$$DDAPS(\phi_{Tx}, \phi_{Rx}; d) = \sum_{\tilde{\theta}_{Tx}} \sum_{\tilde{\theta}_{Rx}} DDAPS_{full}(\phi_{Tx}, \tilde{\theta}_{Tx}, \phi_{Rx}, \tilde{\theta}_{Rx}; d). \quad (9)$$

We combine the different elevations we measured since the limited number of elevation cuts (which was imposed by limits on the measurement duration) is insufficient for a detailed elevation analysis. Moreover, since the direction of the primary propagation is well covered, it is expected that there will be less information in other elevation cuts. Finally, to compute the (azimuthal)

angular power spectrum (APS) at the Tx, we integrate over ϕ_{Rx} , and do the same for the APS at the Rx. Using the APS, we compute the angular spread by applying Fleury's definition [33]:

$$\sigma^\circ = \sqrt{\frac{\sum_\phi |e^{j\phi} - \mu_\phi|^2 APS_k(\phi)}{\sum_\phi APS_k(\phi)}}, \quad (10)$$

where k can be Tx or Rx indicating departure or arrival APS and μ_ϕ can be computed as

$$\mu_\phi = \frac{\sum_\phi e^{j\phi} APS_k(\phi)}{\sum_\phi APS_k(\phi)}. \quad (11)$$

It is important to mention that the obtained values will be an upper bound for the actual angular spreads of the channel due to the finite horn antenna beamwidth [20].

4) *Power distribution over MPC*: In channel analysis, it is important to examine the power distribution of MPCs over the delay domain. Specially, the concentration of power in the "strongest" MPC versus the rest of the MPCs in the channel. Thus, we define κ_1 , a parameter computed as follows:

$$\kappa_1 = \frac{P_i(\tilde{\tau}_1)}{\sum_{\tilde{\tau}=\tilde{\tau}_2}^{\tilde{\tau}_N} P_i(\tilde{\tau})}, \quad (12)$$

where i can be "omni" or "max-dir", and $\tilde{\tau}_k$ is the delay bin of the k -th local maximum of the PDP $P_i(\tilde{\tau})$, ordered by magnitude, so that $\tilde{\tau}_1$ signifies the location of the largest local maximum.

As explained in [13], κ_1 is different from the "Rice Factor" because it is not possible to differentiate between closely spaced MPCs, therefore, the local maximum of the PDP is not strictly identical to an MPC. To perform the most accurate Rice Factor analysis, HRPE can be used so that MPCs are properly identified, and this will be presented in future work. Similarly as σ_τ we apply oversampling and a Hann window to avoid the sidelobe effects and to have a better estimation of the parameter. Please note that this processing can affect the values of κ_1 . More specifically, since κ_1 values depend on local maxima to extract components, if MPCs are merged into the envelope of nearby stronger components, they will not be detected as peaks in the oversampled waveform. Thus, both peak detection, filtering, and oversampling play a part here. We plan to conduct HRPE analysis in future studies where after the extraction of MPCs, the calculation of Rice factor can be independent of these issues.

In the next section, regression analysis will be added in the estimation of the parameters σ_τ , κ_1 similar to [20]. These regressions reveal their behavior with respect to the distance between Tx and Rx. Note that the linear regression model is with respect to logarithmic quantities, i.e., $Z = \alpha + \beta \log_{10}(d)$.

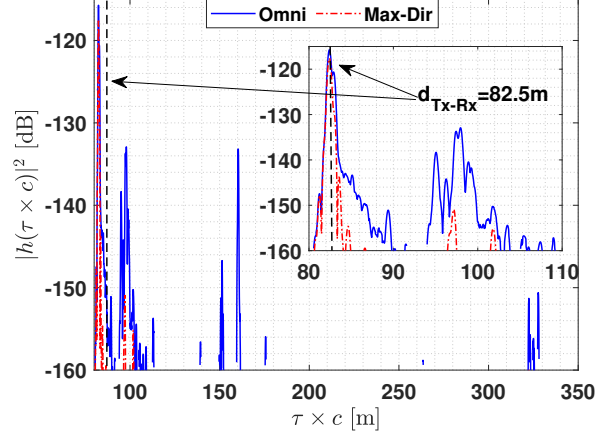


Fig. 5: LoS case with $d = 82.5m$ (Tx1-Rx1).

IV. MEASUREMENT RESULTS

In this section, we discuss the results of our measurement campaign.

A. Power delay profiles

To start with the measurement analysis, we first present some sample PDPs, characterizing one LoS and two NLoS location pairs. These results are shown in Fig. 5 and Fig. 6. Please note that the delay on the x-axis is in the units of meters, which correspond to runlength (delay $\times c$ where c represents the speed of light with a value equal to 3×10^8 m/s). We use this transformation since runlength provides an easier comparison with physical positions and objects in the scenario.

The LoS measurement whose omni-directional and max-dir PDPs are shown in Fig. 5, was taken at a distance of 82.5 m. In this case, the LoS MPC is clearly observed in both the max-dir and omni-directional PDPs. Apart from the LoS MPC, we observe multiple MPCs with runlength ≤ 160 m with powers only up to 30 dB lower than the LoS. While the powers of these "extra" components is much lower in comparison to the strongest components, they nevertheless affect channel parameters such as delay spread and angular spread; they are diminished in the max-dir as a result of the spatial filtering effect provided by the antennas. In this particular case, for the omni-directional case, we observed several (very weak) MPCs arriving before the LoS MPC. As explained in Section II, the maximum measurable excess delay of the system is $1 \mu\text{s}$ which leads to 300 m of maximum runlength. Any MPC with delay of $1 \mu\text{s}$ is wrapped around in delay

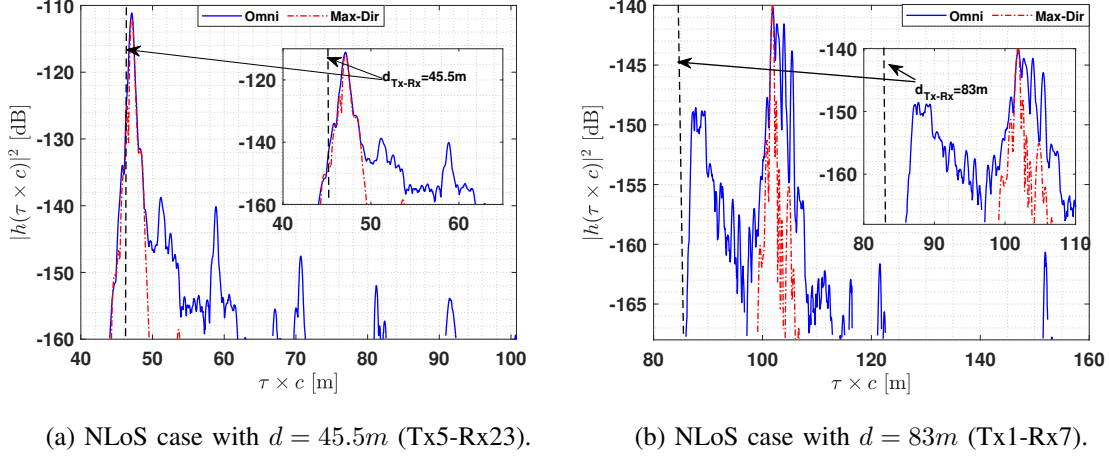


Fig. 6: PDP for two sample NLoS measurement cases.

domain and thus may appear as (small) peak before the line of sight. This effect is corrected for all figures by a circular shift on the x-axis.

For the NLoS case, we present two location pairs with Tx-Rx distances of 45.5 and 83 m, respectively. A richer multipath scenario is expected because of the attenuation of the LoS component and the increase of additional MPCs that arrive at the Rx. In the case of the 45.5 m measurement, we see a concentrated max-dir PDP, and a small quantity of additional MPCs with power ≤ 30 dB, similar to a LoS scenario. The scenario for this measurement is shown in Fig. 4b, and as can be seen, the Tx is set in the PSA building and the Rx is located in the alley between TTL and SCD, creating a "street-canyon" and concentrating (in the delay domain) the power reaching the Rx, since all MPCs guided by the canyon have fairly similar delays, only distinguished by different number of reflections on the housewalls, which are just a street width apart. We also note that while the first pronounced peak in the PDP is the strongest one, it is *not* a quasi-LoS (as often observed at low frequencies), as shown by the fact that its associated delay is *much* longer than that of the (theoretical) LoS. The delay of the expected LoS is calculated based on measurement of the physical distance of a direct Tx-Rx link on the map while assuming the speed of light to be fixed at 3×10^8 .

The second PDP shown in Fig. 6b (where the physical location is shown earlier in Fig. 3b) is an 83.2 m link (see Table II). In this case it is observed that there is a larger number of MPCs, especially for the omni-directional PDP, compared to the previous NLoS case. A number of MPCs are received around 90 m, 105 m, 110 m and 150 m while the strongest component is

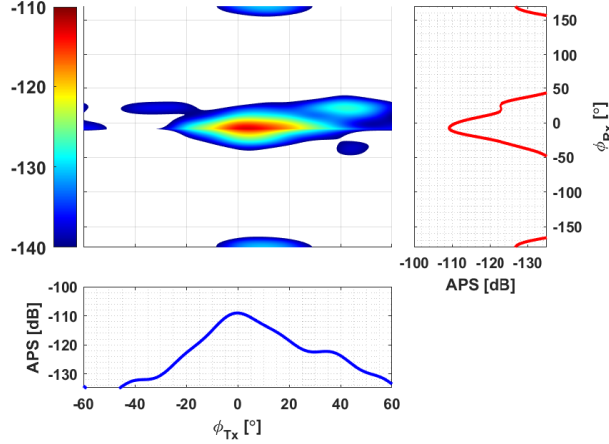


Fig. 7: LoS APS for $d = 82.5m$ (Tx1-Rx1).

located around 102 m. These MPCs are a product of reflections coming from the RTH building. This effect can be noticed in Fig. 6b, and we see that the first significant MPC is not the strongest one. More details of this scenario will be discussed in the next subsection.

B. Angular power spectrum

This section discusses the Angular Power Spectrum (APS) of the selected sample LoS and NLoS location pairs provided in Fig. 7 and Fig. 8. To assess these results, we compare the APS results against the map of the locations shown in Fig. 2. as well as the subsequent location images.

For the LoS case, we observe a large concentration of MPCs in the LoS direction, an additional concentration of MPCs can be observed at $\phi_{Tx} = 37, \phi_{Rx} = 35$. These MPCs correspond to reflections coming off the RTH building, additionally, we can also observe MPCs at angles close to $\phi_{Tx} = 0, \phi_{Rx} = 180$.

The NLoS points have a different behavior compared to LoS. In the case of the point Tx5-Rx23 shown in Fig. 8a, we see a large concentration of MPCs in one main direction, similar as in the sample LoS. However, the center of this concentration is not in the LOS direction, but rather in the direction of the street, with $\phi_{Tx} = -15, \phi_{Rx} = -27$. This concentration of MPCs are a product of the "street canyon" effect created by the SCD and the TTL building (see Fig. 4b). An additional concentration of MPCs can be observed at $\phi_{Tx} = -15, \phi_{Rx} = 47$; in this

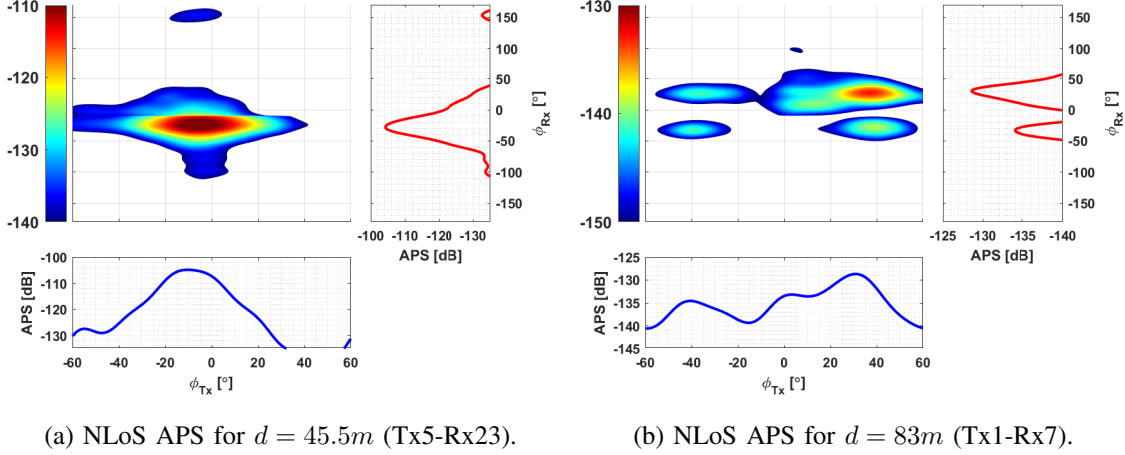


Fig. 8: Sample NLoS APSes for two cases.

case, the Tx horn is still facing towards the canyon but the receiver collects a weaker reflection inside it. For the NLoS location pair (Tx1-Rx7), which has a distance of ($d = 83$ m), the APS in Fig. 8b shows several maxima in the APS, with the strongest one at $\phi_{Tx} = 37^\circ, \phi_{Rx} = 28^\circ$. This corresponds to Tx and Rx looking towards the RTH building, and is thus congruent with the scenario observed in Fig. 3b. As can be seen in the picture, the LoS is blocked by the pillars in front of the receiver and the right-hand side of the receiver has an opening facing towards McClintock Ave, the OHE, RTH and EEB buildings. Moreover, additional weaker MPCs (approx. 8 dB weaker than the strongest MPCs) are observed at $\phi_{Tx} = -38^\circ, \phi_{Rx} = 27^\circ$. These MPCs are reflections from RTH, similar to the previous MPCs, however they reach the receiver from the left hand side gap observed between the inner wall of GER building and the pillar, which means additional attenuation.

The above discussions not only provide a description of relevant propagation effects, but also support the correctness of the measurements, as the extracted MPCs are in agreement with the geometry of the environment. Further verifications, not shown here for space reasons, were done for other location pairs as well.

C. Path loss and shadowing

In this section, we start the analysis of the ensemble of measurement locations. For the analysis, the points will be separated into LoS and NLoS to analyze their characteristics separately. For the LoS case, Fig. 9a shows the path loss analysis using "max-dir", "omni-directional" and the Friis

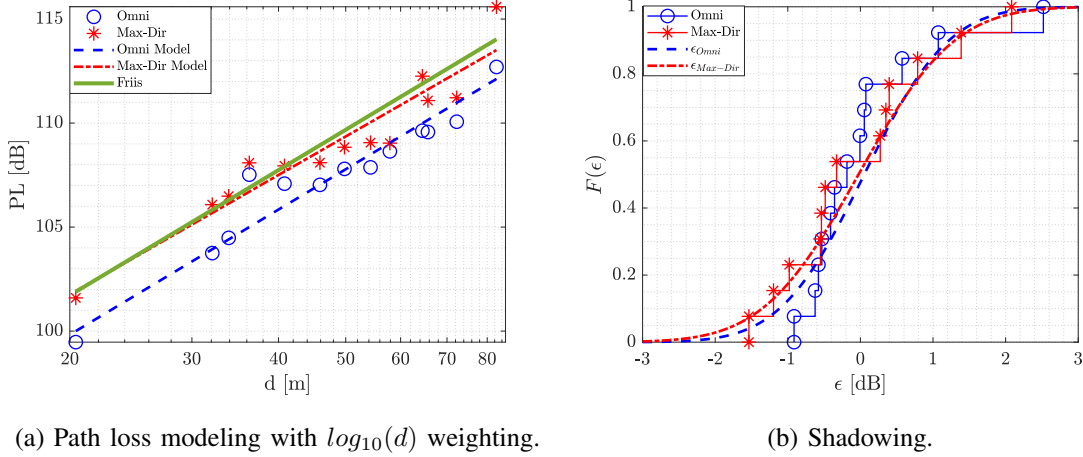


Fig. 9: Path loss and shadowing models for LoS points.

Model. For all points it can be observed that the path loss for the "max-dir" is larger or equal to the "omni" path loss points ($PL_{max-dir} \geq PL_{omni}$). Max-dir and omni-directional PL models are close to, or lower than, the Friis (free-space) model. The PL exponent is $\beta \approx 1.9$, slightly below the free space model. These effects are congruent with the scenario because the LoS points in Routes One and Four are in "street canyon" LoS environments (9 of 13 locations), therefore the "waveguiding" effect will produce a path loss lower than the free space [10, Chapter 4]. We see similar results for the THz band urban device-to-device scenarios discussed in [20]. Moreover, a more detailed description for Route 4 points is given in [25]. The parameters extracted by the *weighted* regression and the OLS are similar because of the low variations of the points against their linear models, additionally the shadowing shows the same variance in both cases and has a small difference in the mean value.

Fig. 10a shows the regression modeling for the NLoS case. The max-dir results show large values of PL compared to the omni-directional results, since in this case a significant percentage of energy is contained in MPCs whose directions are different from the max-dir horn orientations. For a similar reason, the path loss exponent for the max-dir and omni-directional case are different ($\beta = 2.5, \beta = 1.87$ respectively). The omni-directional case has a smaller slope due to more MPCs from different directions providing energy at large distances. The shadowing oscillates between -15 and 15 dB for the omni and max-dir cases. The observed shadowing standard deviations are 7.34 and 6.11 for the max-dir and omni-directional cases, respectively. A summary of the estimated regression parameters for path loss and statistical parameters for

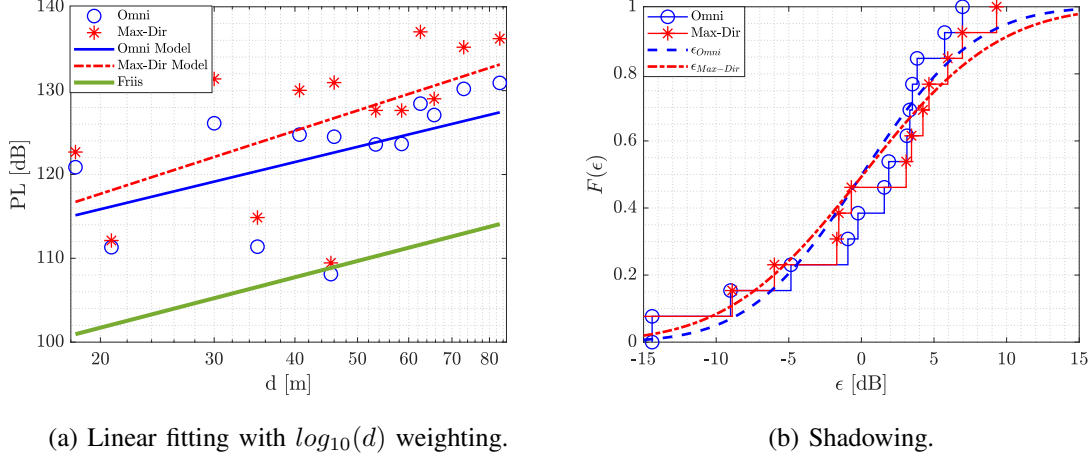


Fig. 10: Path loss and shadowing models for NLoS points.

TABLE III: Path loss parameters with 95% confidence interval.

Parameter	Linear model parameters estimated with 95% CI					
	α	$\alpha_{min,95\%}$	$\alpha_{max,95\%}$	β	$\beta_{min,95\%}$	$\beta_{max,95\%}$
PL_{omni}^{LoS}	73.84	69.01	78.67	2.00	1.70	2.30
$PL_{max-dir}^{LoS}$	76.92	71.74	82.10	1.91	1.59	2.23
$PL_{omni}^{LoS} OLS$	75.73	69.83	81.63	1.89	1.54	2.24
$PL_{max-dir}^{LoS} OLS$	77.19	70.34	84.04	1.89	1.48	2.30
PL_{omni}^{NLoS}	91.53	63.59	119.47	1.87	0.10	3.63
$PL_{max-dir}^{NLoS}$	85.21	52.06	118.36	2.50	0.40	4.59
$PL_{omni}^{NLoS} OLS$	87.15	53.98	120.33	2.14	0.14	4.59
$PL_{max-dir}^{NLoS} OLS$	82.57	42.65	122.5	2.66	0.29	5.07

the shadowing with their respective 95% confidence interval is shown in Tables III and IV.

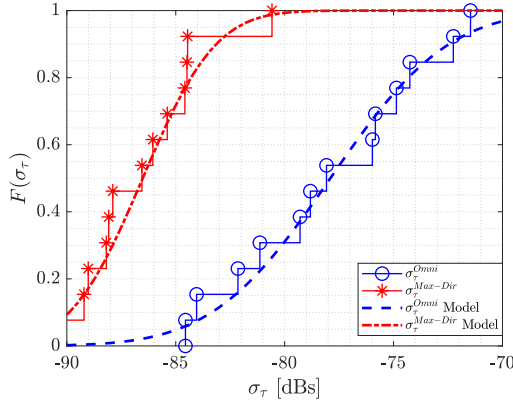
In the NLoS case, we observed path loss values larger compared to Friis, except for the point (Tx5-Rx23). This point is located in a corridor between SCD and TTL buildings, (see Fig. 4b). In this case there exists a very strong reflection, and the associated directional pathloss equals Friis, while the omni-directional pathloss is lower due to the existence of additional MPCs; similar to the LoS situation, this is *not* unphysical.

D. RMSDS

The next parameter to evaluate is the RMSDS. In the LoS case, we expect lower values for the max-dir evaluation due to the spatial filtering. Similarly, an increase in the RMSDS with

TABLE IV: Shadowing model parameters with 95% confidence interval.

Parameter	Statistical model parameters estimated with 95% CI					
	μ	$\mu_{min,95\%}$	$\mu_{max,95\%}$	σ	$\sigma_{min,95\%}$	$\sigma_{max,95\%}$
ϵ_{omni}^{LoS}	0.05	-0.50	0.60	0.91	0.65	1.50
$\epsilon_{max-dir}^{LoS}$	-0.03	-0.65	0.60	1.04	0.74	1.71
$\epsilon_{omni}^{LoS OLS}$	0.00	-0.54	0.54	0.89	0.64	1.47
$\epsilon_{max-dir}^{LoS OLS}$	0.00	-0.63	0.63	1.04	0.74	1.71
ϵ_{omni}^{NLoS}	0.04	-3.65	3.74	6.11	4.38	10.09
$\epsilon_{max-dir}^{NLoS}$	0.13	-4.31	4.56	7.34	5.26	12.11
$\epsilon_{omni}^{NLoS OLS}$	0.00	-3.68	3.68	6.09	4.37	10.05
$\epsilon_{max-dir}^{NLoS OLS}$	0.00	-4.43	4.43	7.33	5.26	12.1



(a) CDF of delay spread.

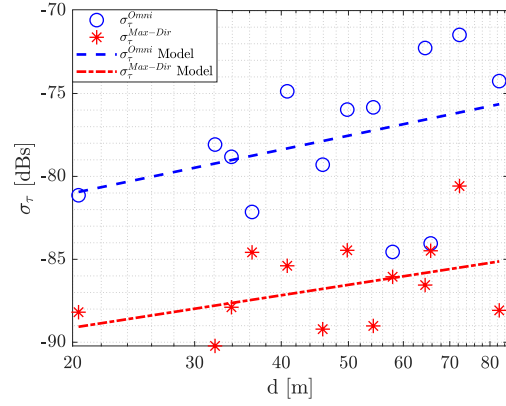
(b) Linear modeling of σ_τ with weighting.

Fig. 11: Modeling of delay spread for LoS cases.

increasing distance between the Tx and Rx is expected, due to a larger number and differences in runlength of the MPCs. Fig. 11a shows the probability density function of the RMSDS. It is plotted on a logarithmic scale, i.e., dBs ($10\log(\text{Delay Spread}/1\text{second})$), as is common in the channel modeling literature such as in 3GPP. This representation also allows to easily see the excellent fit of a lognormal distribution to the measurement results. The variance of the max-dir points is approximately 62% the value of the omni-directional case.

Fig. 11b shows the RMSDS as a function of distance and the linear regression, showing an increase with distance, as anticipated (and also in agreement with experimental results at lower frequencies). It is also observed that for all measurement points the max-dir values are smaller than the omni-directional.

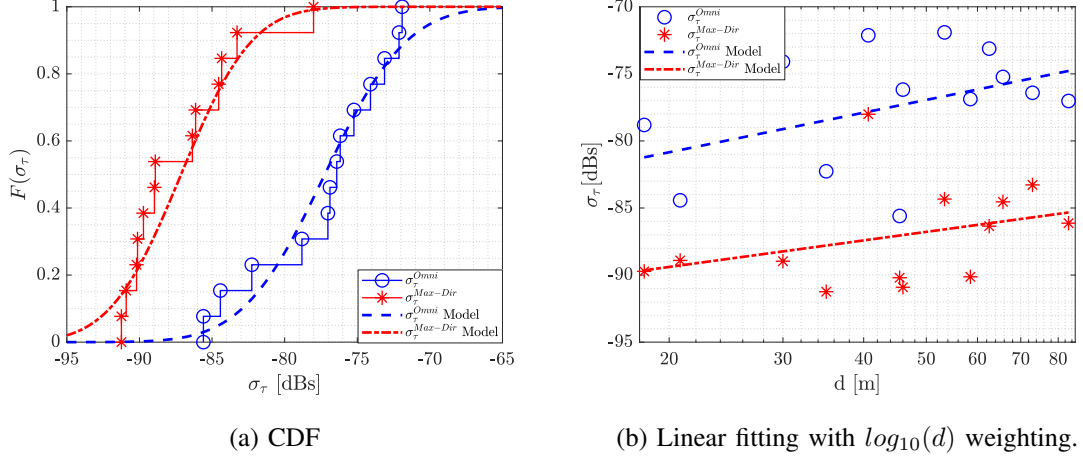


Fig. 12: Modeling of delay spread for NLoS points.

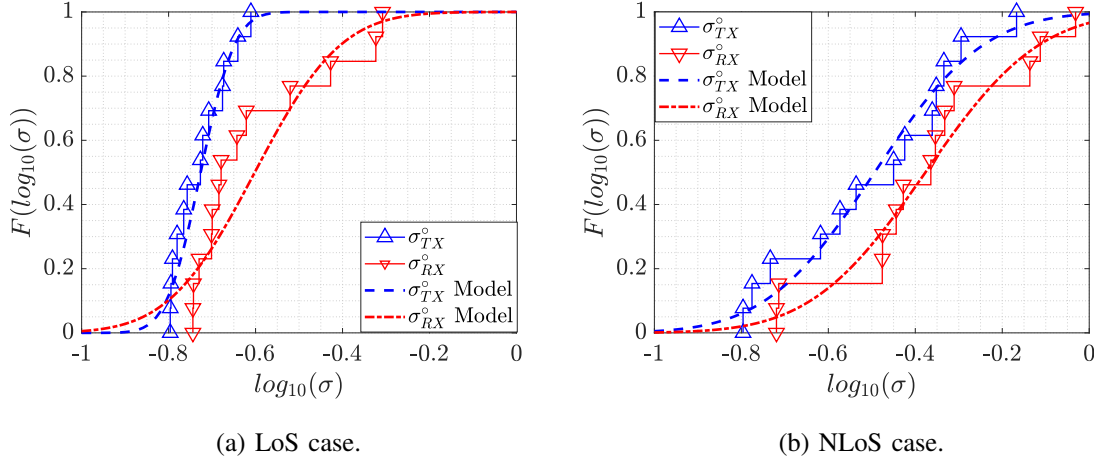
TABLE V: Linear model parameters for σ_τ with 95% confidence interval.

Parameter	Linear model parameters estimated with 95% CI					
	α	$\alpha_{min,95\%}$	$\alpha_{max,95\%}$	β	$\beta_{min,95\%}$	$\beta_{max,95\%}$
$\sigma_{\tau_{omni}}^{LoS}$	-88.16	-107.62	-68.7	6.29	-5.7	18.28
$\sigma_{\tau_{max-dir}}^{LoS}$	-96.41	-109.03	-83.79	5.96	-1.81	13.74
$\sigma_{\tau_{omni}}^{NLoS}$	-93.61	-111.78	-75.44	9.81	-1.68	21.31
$\sigma_{\tau_{max-dir}}^{NLoS}$	-97.94	-112.8	-83.08	6.57	-2.83	15.97

Fig. 12 shows the RMSDS analysis for the NLoS case. It is observed that the CDFs have a different slope ($\beta_{omni}^{NLoS} = 9.81, \beta_{max-dir}^{NLoS} = 6.57$). This behavior can be related to the "street-canyon" scenarios of Routes One, Four, and Six. The waveguiding effect as a result of the street canyons constrains the propagation through streets and allows the concentration of power in a small set of delay and angle bins - angular bins because of the limitation of how the waves are guided along the street canyon, and delay because the excess delay acquired during waveguiding is small, and the only "far reflectors" than can work are ones that are in a line with the street canyon. A special case of the "waveguiding" effect is the point Tx5-Rx23 ($d = 45.5m$), in which the σ_τ values for the omni-directional and max-dir cases are almost equal. A summary of the estimated regression parameters and the statistical analysis are shown in Tables V, VI.

TABLE VI: Statistical model parameters for σ_τ with 95% confidence interval.

Parameter	Statistical model parameters estimated with 95% CI					
	μ	$\mu_{min,95\%}$	$\mu_{max,95\%}$	σ	$\sigma_{min,95\%}$	$\sigma_{max,95\%}$
$\sigma_{\tau_{omni}}^{LoS}$	-77.76	-80.28	-75.24	4.17	2.99	6.89
$\sigma_{\tau_{max-dir}}^{LoS}$	-86.22	-87.71	-84.74	2.45	1.76	4.05
$\sigma_{\tau_{omni}}^{NLoS}$	-77.24	-79.92	-74.55	4.44	3.18	7.33
$\sigma_{\tau_{max-dir}}^{NLoS}$	-87.13	-89.45	-84.81	3.84	2.75	6.34

Fig. 13: Modeling of σ° for all points.

E. Angular spread

The next parameter to analyze is the angular spread. In this case, the analysis is separated between the Tx and Rx end. As explained in Section II, the scan ranges for Tx and Rx are different, so our conjecture is to observe a larger angular spread in the Rx side for both LoS and NLoS cases. Furthermore, the richer number of scattering objects at street level is expected to compound this effect.

Fig. 13 shows the CDF for LoS and NLoS cases. In both cases, the data confirm our hypothesis. For example, in the LoS case the Tx points show a smaller spread compared to the Rx ($\sigma_{NLoS}^{Tx} < \sigma_{NLoS}^{Rx}$). This result is related to the fact that reflected MPCs are reflected in the vicinity of the Rx, and are "seen" by the Tx under angles similar to that of the LoS. On the other hand, the NLoS points show AS points with a similar spread (i.e. $\sigma_{NLoS}^{Tx} \approx \sigma_{NLoS}^{Rx}$). A possible cause for this behavior is the waveguiding in the "street canyon" environments, which

TABLE VII: Statistical model parameters for σ° with 95% confidence interval.

Parameter	Statistical model parameters estimated with 95% CI					
		$\mu_{min,95\%}$	$\mu_{max,95\%}$	σ	$\sigma_{min,95\%}$	$\sigma_{max,95\%}$
$\sigma_{LoS}^\circ Tx$	-0.73	-0.76	-0.69	0.06	0.04	0.10
$\sigma_{LoS}^\circ Rx$	-0.6	-0.7	-0.51	0.16	0.11	0.26
$\sigma_{NLoS}^\circ Tx$	-0.49	-0.61	-0.37	0.20	0.14	0.33
$\sigma_{NLoS}^\circ Rx$	-0.38	-0.50	-0.25	0.21	0.15	0.34

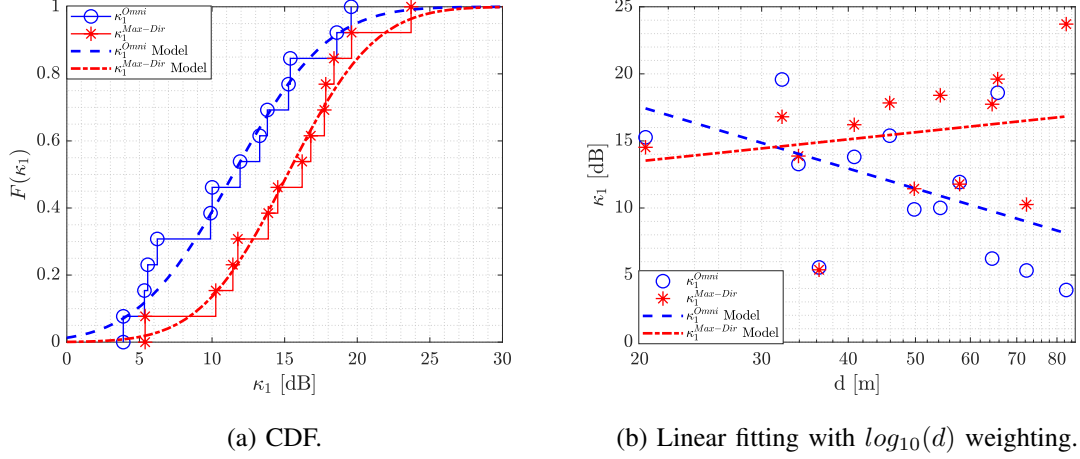
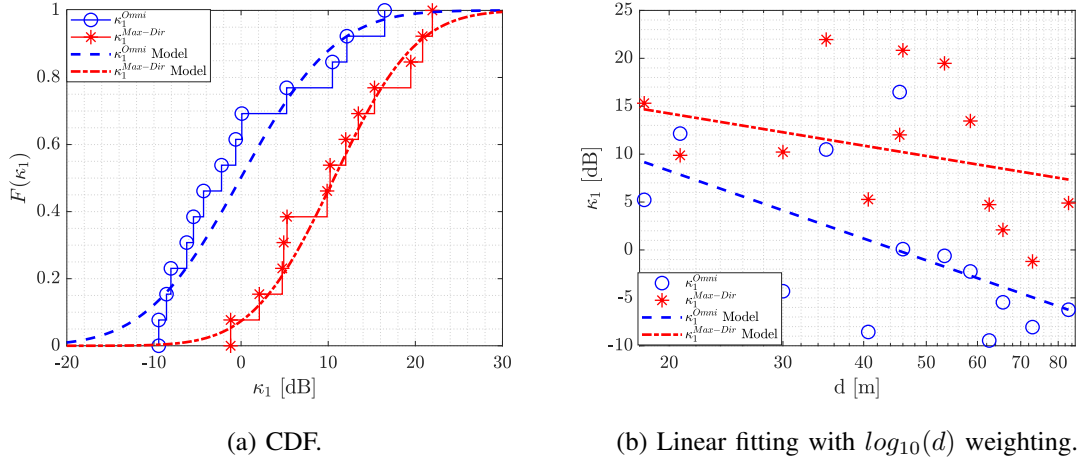
concentrates the MPCs in a narrower angular range. A summary of the estimated statistical parameters with their 95% confidence interval is shown in Table VII.

F. Power distribution of MPCs

The final parameter estimated is the κ_1 . Our hypothesis is to observe larger values of κ_1 in max-dir cases compared the omni-directional ones. Fig. 14 shows the estimated values for the LoS case. As can be observed in Fig. 14a the LoS points for the omni-directional case have a similar spread compared to the max-dir cases, but significantly smaller mean. Fig. 14b shows the regression analysis of the power distribution. The observed range oscillates between 4 and 23 dB. As observed in the plot, κ_1 for the max-dir grows as the distance increases, however, for the omni-directional case, it shows a decreasing trend. The filtering effects of the antenna attenuate MPCs received by it from directions away from its beam direction. As the distance increases, additional MPCs (coming from reflections) suffer from further attenuation and only those in the LoS directions are boosted by the antenna gain. On the other hand, in the omni-directional case, the value of κ_1 decreases because as the distance increases more MPCs will be collected from different direction apart from the LoS⁴. A summary of the parameters see Tables VIII, IX.

In the NLoS case, we observed the values with a range from -10 to 22 dB. This high variability can be related to the multiple points in "street canyon" scenarios (Routes One, Five, and Six). The "street canyon" filters/concentrates the MPCs arriving at the Rx. Furthermore, κ_1 is reduced when the distance increases, both for the omni- and the max-Dir case. Similarly to the RMSDS analysis, the points Tx5-Rx23 and Tx6-Rx24 shows a different behavior ($\kappa_{1_{omni}}^{NLoS} > \kappa_{1_{max-dir}}^{NLoS}$).

⁴An unusual behavior is observed in point Tx1-Rx6 where ($\kappa_1^{omni} > \kappa_1^{max-dir}$), though the difference is small. We conjecture that this is caused by imperfections in the calibration procedure and the generation of omni-directional PDPs from the directional PDPs.

Fig. 14: Modeling of κ_1 for LoS points.Fig. 15: Modeling of κ_1 for NLoS points.

This is related to the fact that the strongest MPC angle is between two azimuthal captures, which produces this unusual behavior. More details about the regression analysis and statistical modeling and estimation are shown in Tables VIII, IX.

G. Summary of results

In this section, a summary of the estimated parameter for a systems design or channel simulation are shown in Tables X, XI. Table X shows the regression analysis (i.e. linear modeling) for the distance dependence of the parameters for both LoS and NLoS cases. Table XI shows the estimated parameters for the statistical fits/modeling carried out in this analysis for both

TABLE VIII: Linear model parameters for κ_1 with 95% confidence interval.

Parameter	Linear model parameters estimated with 95% CI					
	α	$\alpha_{min,95\%}$	$\alpha_{max,95\%}$	β	$\beta_{min,95\%}$	$\beta_{max,95\%}$
$\kappa_{1_{omni}}^{LoS}$	37.51	12.85	62.19	-15.34	-30.55	-0.14
$\kappa_{1_{max-dir}}^{LoS}$	6.43	-16.76	29.62	5.42	-8.87	19.71
$\kappa_{1_{omni}}^{NLoS}$	38.80	8.27	69.33	-23.47	-42.79	-4.16
$\kappa_{1_{max-dir}}^{NLoS}$	28.78	0.85	56.70	-11.17	-28.83	6.50

TABLE IX: Statistical model parameters for κ_1 with 95% confidence interval.

Parameter	Statistical model parameters estimated with 95% CI					
	μ	$\mu_{min,95\%}$	$\mu_{max,95\%}$	σ	$\sigma_{min,95\%}$	$\sigma_{max,95\%}$
$\kappa_{1_{omni}}^{LoS}$	11.44	8.34	14.55	5.14	3.69	8.49
$\kappa_{1_{max-dir}}^{LoS}$	15.20	12.34	18.05	4.72	3.39	7.8
$\kappa_{1_{omni}}^{NLoS}$	-0.04	-5.20	5.12	8.55	6.13	14.11
$\kappa_{1_{max-dir}}^{NLoS}$	10.69	6.23	15.14	7.37	5.29	12.17

LoS and NLoS cases. Please note that the presented statistical results are valid for the ranges of distances we measured over ($\approx 20 \sim 85$ m).

It is important to note that the parameters obtained in the analysis are directly related to the number of points and the selection of measurement locations. In other words, this analysis is impacted by the fact that the measurement locations were chosen such that reasonable Rx power could be anticipated. An analysis of outage probability should consider a "blind" selection of points, e.g., on a regular grid, that would allow an assessment of the percentage of points that cannot sustain communications at a given sensitivity level. Also other parameters, which might be correlated to the received power, might conceivably be influenced by the selection of the points. The results in this paper should thus be interpreted as "conditioned on the existence of reasonable Rx power".

Furthermore, while in the current campaign more than 100,000 transfer functions were measured, the number of measured *location pairs* is still somewhat limited. Hence, this model is based on a relatively small number of points to provide an initial channel model to give a realistic analysis and model for system design. A larger number of measurement locations will obviously increase the number of measurement locations and increase the validity of the analysis. However, the time required to perform the current campaign was quite significant (several months), and it

TABLE X: Linear model parameters summary.

Parameter	α	β
PL_{omni}^{LoS}	73.84	2.00
$PL_{max-dir}^{LoS}$	76.92	1.91
$PL_{omni}^{LoS}OLS$	75.73	1.89
$PL_{max-dir}^{LoS}OLS$	77.19	1.89
$\sigma_{\tau_{omni}}^{LoS}$	-88.16	6.29
$\sigma_{\tau_{max-dir}}^{LoS}$	-96.41	5.96
$\kappa_{1_{omni}}^{LoS}$	37.51	-15.34
$\kappa_{1_{max-dir}}^{LoS}$	6.43	5.42
PL_{omni}^{NLoS}	91.53	1.87
$PL_{max-dir}^{NLoS}$	85.21	2.50
$PL_{omni}^{NLoS}OLS$	87.15	2.14
$PL_{max-dir}^{NLoS}OLS$	82.57	2.66
$\sigma_{\tau_{omni}}^{NLoS}$	-93.61	9.81
$\sigma_{\tau_{max-dir}}^{NLoS}$	-97.94	6.57
$\kappa_{1_{omni}}^{NLoS}$	38.80	-23.47
$\kappa_{1_{max-dir}}^{NLoS}$	28.78	-11.17

is among the largest double-directional campaigns ever performed in the THz regime (for any type of environment). Future measurements will be added to improve the model further.

V. CONCLUSIONS

In this paper, we presented the results of the first extensive wideband, double-directional THz outdoor channel measurements for microcell scenarios with Tx heights of more than 10 m above the ground. We provide an overview of the measurement methodology and environments, as well as the signal processing to extract parameters characterizing the channels. Most importantly, we provided a parameterized statistical description of our measurement results that can be used to assess THz systems. The key parameters discussed in the current paper include path loss, shadowing, angular spread, delay spread and MPC power distribution. These results are an important step towards drawing some important first conclusions about the implications on system design and deployment in the THz regime.

TABLE XI: Statistical model parameters summary.

Parameter	μ	σ
ϵ_{omni}^{LoS}	0.05	0.91
$\epsilon_{max-dir}^{LoS}$	-0.03	1.04
$\epsilon_{omni}^{LoS} OLS$	0	0.89
$\epsilon_{max-dir}^{LoS} OLS$	0	1.04
$\sigma_{LoS}^{\circ} Tx$	-0.73	0.06
$\sigma_{LoS}^{\circ} Rx$	-0.6	0.16
$\sigma_{\tau_{omni}}^{LoS}$	-77.76	4.17
$\sigma_{\tau_{max-dir}}^{LoS}$	-86.22	2.45
$\kappa_{1_{omni}}^{LoS}$	11.44	5.14
$\kappa_{1_{max-dir}}^{LoS}$	15.2	4.72
ϵ_{omni}^{NLoS}	0.04	6.11
$\epsilon_{max-dir}^{NLoS}$	0.13	7.34
$\epsilon_{omni}^{NLoS} OLS$	0	6.09
$\epsilon_{max-dir}^{NLoS} OLS$	0	7.33
$\sigma_{NLoS}^{\circ} Tx$	-0.49	0.2
$\sigma_{NLoS}^{\circ} Rx$	-0.38	0.21
$\sigma_{\tau_{omni}}^{NLoS}$	-77.24	4.44
$\sigma_{\tau_{max-dir}}^{NLoS}$	-87.13	3.84
$\kappa_{1_{omni}}^{NLoS}$	-0.04	8.55
$\kappa_{1_{max-dir}}^{NLoS}$	10.69	7.37

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