Experimental Investigation of 5G Positioning Performance Using a mmWave Measurement Setup

George Yammine¹, Mohammad Alawieh¹, Gregor Ilin¹, Mohammad Momani¹, Mostafa Elkhouly¹, Piotr Karbownik², Norbert Franke¹, Ernst Eberlein²

¹Fraunhofer Institute for Integrated Circuits (IIS) {firstname.lastname}@iis.fraunhofer.de
²{firstname.lastname}@iis-extern.fraunhofer.de

Abstract—Driven by an ever-increasing demand for higher data rates, 5G introduced communication over the millimeter-wave (mmWave) bands to fulfill this requirement. High data transmissions in this spectrum are enabled by beamforming massive MIMO antennas and the available allocated bandwidth. Of interest is the utilization of mmWave for high-accuracy positioning applications, motivated by the allocated bandwidth and beamforming characteristics of such systems. This paper provides numerical simulations on the 5G positioning reference signal reception and shows, for a real-world indoor environment, the promising performance results. The accuracy of ToA-based positioning in dependence of the beam shape and direction is determined to be at least within 6 cm for LOS scenarios. We also investigate the impact of LOS path obstructions on the performance. Achieving centimeter level accuracy is subject to improvements through continuing research and refinements.

Index Terms—5G mmWave, beamforming, over-the-air testing, massive MIMO, signal propagation, ranging accuracy, positioning, localization, 3GPP positioning service, phased-array antenna

I. INTRODUCTION

To address a need for ever-increasing data rates in cellular networks, 5G New Radio (5G NR) [9] supports the usage of frequency spectra known from previous generations (Frequency Range 1 (FR1), sub-6 GHz frequency bands), as well as the Frequency Range 2 (FR2) band [1], which includes frequencies in the millimeter-wave (mmWave) band [10], i.e., 24–100 GHz. Within the latter range, antenna arrays comprising very large number (in range of dozens or hundreds) of antenna elements, so-called massive multiple-input/multiple-output (MIMO) beamforming antennas, are being employed in 5G installations. Although, the deployment of those antennas is mainly motivated by data rate gain, their beamforming capabilities are of interest in the positioning application in 5G networks.

Precise positioning is of great significance in 5G NR, as many use cases and applications require accurate location awareness of user equipments (UEs) within the network. Radio signals propagating through an arbitrary channel convey direct or indirect information related to the direction or propagation delay properties that can be exploited for positioning [15]. This information can be extracted using a number of methods defined by 3rd Generation Partnership Project (3GPP) [3].

Despite vast research on mmWave together with positioning, relatively little information is available regarding real-life over-the-air (OTA) measurements. In this paper, we evaluate the performance for timing-based radio access technology (RAT)-dependent positioning by means of datasets acquired with the use of a 5G mmWave one-way ranging platform employing beamforming antennas.

This work is organized as follows. First, a review of the positioning signals in 5G NR is given in Section II. Next, in Section III, link budget considerations and related numerical simulation results are explored. After that, Section IV introduces the measurement setup. Following that, the system calibration and position estimation are described in Section V. Then, a description of the measurement campaign is given in Section VI, and the analysis of the results thereof is conducted in Section VII. Finally, conclusions and future work are given in Section VIII.

II. 5G POSITIONING SIGNALS

Release 16 in 5G introduced dedicated reference signals for positioning and defined related measurements and procedures such as time-based positioning techniques including downlink time difference of arrival (DL-TDOA), uplink time difference of arrival (UL-TDOA) and multi round-trip time (Multi-RTT), as well as angle-based positioning techniques including downlink angle of departure (DL-AoD) and uplink angle of arrival (UL-AoA). To that end, uplink sounding reference signals (UL-SRSs) and downlink positioning reference signals (DL-PRSs) which are transmitted by the user equipment (UE) and the base stations transmit receive points (TRPs) [2], [4], respectively, were defined. Both UL-SRS and DL-PRS are expected to produce similar performance for the evaluations within this paper. In this work, we use sounding reference signals (SRSs). Moreover, SRS, that is also used for communication (e.g., for channel state information) can be configured for positioning with additional properties. When used for positioning, the SRS is staggered over a configurable number of orthogonal frequency-division multiplexing (OFDM) symbols. Additionally, the SRS can be configured to begin on any symbol in the slot. In time domain, an SRS can span 1, 2, 4, 8, or 12 consecutive OFDM symbols for enhanced coverage in uplink (UL) multi-TRP positioning methods.

The SRS for positioning is based on Zadoff–Chu (ZC) sequences [6], [7] which have constant amplitude, leading to a low peak-to-average-power ratio (PAPR), and for a given fixed sequence index have zero autocorrelation for all time.

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shifts other than zero, otherwise one. However, when the bandwidth limitation is taken into account, the autocorrelation of a non-time-shifted ZC sequence is a sinc function. An example thereof is depicted in Figure 1. Note that the zero autocorrelation property applies to the OFDM symbol itself, and not the OFDM symbol with cyclic prefix.

For positioning, the SRS can have a comb size of 2, 4, or 8, stating which subcarriers are used. As an example, a comb factor of 2 means that every second subcarrier is used for SRS, and a comb factor of 8 means that every eighth one is. The comb factor can be utilized in different ways. The first allows different UEs to share the same OFDM symbol by assigning different sets of subcarriers for each user.

Another use of the comb factor, is to give a “power boosting gain”, whereby the available transmit power is distributed only among the active subcarriers. For example, with a comb factor of 4, the power allocated per fourth subcarrier is increased by a factor of 4 (6 dB). Additionally, for positioning, staggering was introduced. Instead of repeating the symbol over multiple slots, a comb offset is added, i.e., the utilized subcarriers in each slot are shifted. An example of staggering for an SRS using a comb factor of 4 can be seen in Figure 2. Other parameters to be defined are the number of OFDM symbols per slot and bandwidth used for the reference signal.

III. LINK BUDGET CONSIDERATIONS

For positioning applications, the time-of-arrival (ToA) of the first arriving path (FAP) is relevant. Three scenarios are considered. The first is good line-of-sight (LOS) conditions where the direct path between the transmitter (Tx) and receiver (Rx) is dominant, i.e., stronger (in terms of power) than the other multipath components.

The second scenario considers antennas with narrow beams, though with non-ideal beam pointing. This may significantly reduce the antenna gain for the LOS path, whereas the other multipath components may be received with a higher antenna gain. In this case the LOS path has a very low signal level, whereas the multipath components provide much higher correlation peaks.

The third is non-line-of-sight (NLOS) conditions, where the direct path may not exist or is heavily attenuated. Here, the goal of the ToA estimation is the detection of the path with the lowest delay, e.g., in case of diffraction the first arriving path may have only a low additional delay and would still be useful for time-of-flight (ToF) measurements. The detection of the FAP is limited by two factors, the signal power of the FAP, and the autocorrelation properties of the used sequence.

A. ToA and Power Budget

The required signal power in relation to the noise power of the measurement setup can be adjusted in a wide range by proper selection of the transmit sequence parameters. For the experiments, a configuration using 4 OFDM symbols with a comb factor of 4 was used. Examples of different possible configurations are given in Table I, where the number of resource blocks (RBs) is kept constant (by adjusting the number of resource elements (REs) per OFDM symbol) for all configurations (comb factor of 1 is added as a reference).

The ToA estimation accuracy depends mainly on the bandwidth and the effective SNR after processing. In this work, centimeter accuracy is targeted. To that end, the ToA must be detected with a resolution of approximately 1/50th of the sampling distance. For a signal with a bandwidth $B_w = 400$ MHz, the 5G nominal sampling frequency is $f_s = 491.52$ MHz. This results in a sampling distance of 2 ns (or equivalently, 61 cm). The estimates of the required SNR in Table I were verified against values obtained via simulations using an AWGN channel or more complex multipath channel model as defined by 3GPP [5]. To that end, two types of ToA estimators were used. The first method uses the inflection point of the rising edge of the first detected peak of the correlation function, and the second detects the peak itself. The latter performs well when no impairments (e.g., high delay spread) for the first peak are present, and when channels with a strong LOS path are considered. The simulation results, when an AWGN channel is used, are shown in Figure 3.

B. Setup-Specific Parameters

In our measurement setup, a digital spectrum analyzer with wideband in-phase and quadrature (I/Q) signal recording

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Fig. 1. An example of the autocorrelation function of a Zadoff–Chu sequence in a band-limited system. The red markers indicate the samples (obtained at $f_s = 491.52$ MHz) of the autocorrelation function, and the blue line (---) is the interpolated version thereof.

Fig. 2. Example of staggering. Here, two resource blocks are shown. A comb factor of 4 is utilized. The used subcarriers (per symbol) are shown in yellow (●) and the unused in blue (●).
Assuming an additional low-noise amplifier (LNA) and taking into account the required SNR at the input, the margin at a distance of 30 m (free-space loss of 90.9 dB) is 68 dB. This is equivalent to an effective total distance of 72 km (free-space loss of 158.5 dB). Further increase in the link-budget margin can be achieved by increasing the equivalent isotropically radiated power (EIRP). The transmit antenna which was used supports an EIRP of up to 54 dBm, i.e., an additional increase of 27 dB, leading to a theoretical distance (for positioning) under ideal LOS conditions of up to 1600 km. With this coverage range, communication with satellites operating in low Earth orbit seems to be feasible.

For indoor measurements, the EIRP was set to a low value, in this case 23 dBm. In the context of 5G system deployments, EIRP values of up to 39 dBm are typically considered for indoor applications.

### IV. 5G mmWave Setup Design

In the proposed mmWave setup, we use the ToA approach to estimate the position of the moving receiver, cf. Section II. The main purpose of the experiments was the feasible distance accuracy. The setup shown in Figure 4 allows the measurement of ToF using a coaxial cable with a constant propagation delay as reference. A full list of the components are summarized in Table III. The signal goes through multiple stages, starting with signal generation at the transmitter side, followed by signal acquisition at the receiving end, then data preprocessing, ToA estimation and finally distance calculation.

#### A. mmWave Transmitter Setup

For high accuracy measurements, we derived two RF output signals at different center frequencies from one baseband signal. The Rohde & Schwarz SMW200A vector signal generator (VSG), which embodies the actual signal source, delivers both the baseband signal and the RF one. To obtain the second RF signal, an external mixer upconverts the baseband signal to a carrier frequency different from the first one. The carrier frequencies are selected to allow the digitization of the signal.

![Plot of the standard deviation ToA error (in ns) vs. the SNR (in dB)](image)

**Fig. 3.** Plot of the standard deviation ToA error (in ns) vs. the SNR (in dB) at the input, obtained from numerical simulations using an AWGN channel, for the 4/4 and 8/8 configurations from Table I. Inflection-point-based method (IFP) and the correlation peak search method (PEAK) curves are given.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Power boosting gain [dB]</th>
<th>Total gain [dB]</th>
<th>Required SNR at input [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/4</td>
<td>6</td>
<td>41</td>
<td>-26</td>
</tr>
<tr>
<td>8/8</td>
<td>9</td>
<td>44</td>
<td>-29</td>
</tr>
<tr>
<td>1/1</td>
<td>9</td>
<td>44</td>
<td>-29</td>
</tr>
</tbody>
</table>

TABLE I

**EXAMPLE OF DIFFERENT TRANSMIT SEQUENCE PARAMETERS.** The number of RBs is kept constant for all configurations, which are denoted using comb factor/OFDM symbols.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Comb factor</th>
<th>Number of OFDM symbols</th>
<th>REs per OFDM symbol</th>
<th>Configuration</th>
<th>Used RBs</th>
<th>Effective sequence length (REs)</th>
<th>Bandwidth ($B_{aw}$) [MHz]</th>
<th>Subcarrier spacing [kHz]</th>
<th>Correlation gain [dB]</th>
<th>Target SNR after processing [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/4 8/8</td>
<td>4 8 4</td>
<td>4 8 4</td>
<td>4 8 4</td>
<td>4/4 8/8</td>
<td>264</td>
<td>3168</td>
<td>400</td>
<td>120</td>
<td>35</td>
<td>15</td>
</tr>
</tbody>
</table>

TABLE II

**PARAMETERS OF THE MEASUREMENT SETUP USED THROUGHOUT THE CAMPAIGN.**

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Center frequency [MHz]</th>
<th>Transmit power (RMS) [dBm]</th>
<th>Power loss from cable [dB]</th>
<th>Transmit antenna gain (incl. amplifier gain) [dB]</th>
<th>EIRP [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>Distance [m]</td>
<td>Free-space loss [dB]</td>
<td>Effective received power at LOS [dBm]</td>
<td>Receive antenna gain [dB]</td>
<td>Noise power at receiver input [dBm/($B_{aw}$)]</td>
</tr>
<tr>
<td>Receiver</td>
<td>30</td>
<td>90.9</td>
<td>-67.9</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>Noise &amp; SNR</td>
<td>Bandwidth $B_{aw}$ [MHz]</td>
<td>G/T [dB/K]</td>
<td>SNR derived from G/T [dB]</td>
<td>Noise power at receiver input [dBm/($B_{aw}$)]</td>
<td>Receiver noise power [dBm/($B_{aw}$)]</td>
</tr>
<tr>
<td>400</td>
<td>40</td>
<td>42.6</td>
<td>-64.6</td>
<td>-54</td>
<td>-53.6</td>
</tr>
</tbody>
</table>

TABLE III

**LIST OF THE mmWave SETUP HARDWARE COMPONENTS.**
using an analog-to-digital converter (ADC). This minimizes the calibration effort and measurement errors resulting from non-ideal synchronization of several receive chains. Table IV summarizes the configuration parameters of the setup.

### B. mmWave Receiver Setup

The receiver setup consists of the Rohde & Schwarz FSW85 signal and spectrum analyzer (SSA) and RTO2004 oscilloscope. The configuration parameters of the receiver setup are given in Table IV. The oscilloscope acts as an ADC, increasing the available recording analysis bandwidth of the SSA. The SSA downconverts the signal to an intermediate frequency (IF), then the oscilloscope digitizes the signal with a sampling frequency of up to 20 GHz and transfers it back to the SSA via an Ethernet-based connection [12], [11]. This high recording bandwidth allows the digitizing of several signals with different center frequencies with one ADC.

### V. System Calibration and Position Estimation

The focus of the measurement was the evaluation of the impact of beam steering on the ToA measurement accuracy. When the distance and transmit time is known, the ToA measurement error can be calculated. A typical method for the generation of high accuracy transmit time is using high performance clocks such as rubidium clocks. In our case we target an accuracy of 100 ps (equivalently 3 cm).

The impact of beam sweeping using many steering angles is of interest. This results in long measurement times. To main-

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Rx</th>
<th>Tx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>AWA-0134</td>
<td>AWMF-0129</td>
</tr>
<tr>
<td>Operation frequency [GHz]</td>
<td>26.5–29.5</td>
<td>27.5–30</td>
</tr>
<tr>
<td>Number of elements</td>
<td>256</td>
<td>64</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear (Horizontal)</td>
<td>Linear (Horizontal)</td>
</tr>
<tr>
<td>3 dB beamwidth</td>
<td>7°</td>
<td>13°</td>
</tr>
<tr>
<td>2D scan volume</td>
<td>60°</td>
<td>314°</td>
</tr>
</tbody>
</table>

The OTA signal and the reference one (with constant delay stemming from the cable length) are combined via frequency multiplexing before analysis. Figure 5 shows an example snapshot of the combined signals’ spectrum. The lower frequency signal represents the reference signal (transmitted over a coaxial cable), and the upper one represents the OTA signal. After this stage, post-capture analysis is performed on a PC, including data preprocessing, and ToA estimation for both the reference signal and the one received by the antenna. The difference between the two ToA values represents the ToF. An initial calibration measurement with a known distance is used to estimate all equipment internal delays, and the offset can be cancelled out.

### C. mmWave Antennas

The platform is designed to support various types of mmWave antennas. For the purposes of the measurement campaign, two models of Anokiwave beamforming phased antenna arrays were used, the AWMF-0129 [13] at the Tx, and the AWA-134 [14] at the Rx. The Tx and Rx antenna arrays comprise 64 and 256 steerable antenna elements, respectively. For simplicity, we will refer to those systems as the Tx and Rx antennas. The key features of the antennas, such as the operation frequency and 3 dB beamwidth, are summarized in Table V.

![Figure 4. Overview of the proposed mmWave setup. A full list of the components are summarized in Table III.](image)

**TABLE IV**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td></td>
</tr>
<tr>
<td>IF baseband [GHz]</td>
<td>2</td>
</tr>
<tr>
<td>RF frequency [GHz]</td>
<td>28</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
</tr>
<tr>
<td>IF antenna [GHz]</td>
<td>3.5</td>
</tr>
<tr>
<td>Sample rate [MHz]</td>
<td>491.52</td>
</tr>
<tr>
<td>Recording time [µs]</td>
<td>100</td>
</tr>
</tbody>
</table>
tain the target precision over a measurement time of one hour, a reference clock with a precision of $10^{-14}$ is required. This accuracy is only feasible with high performance cesium clocks. Instead, we used a cable for the reference signal. The transmit signal arrives over the air with a delay according to the distance and with a constant delay through the cable at the receiver. The ToF (and distance) can be calculated from the difference between the ToAs. Using the same signal for both paths and the same ToA estimation method minimizes the measurement errors. Moreover, if the temperature is kept largely constant, changes in, e.g., the propagation delay variation of the cable are negligible. For the calibration we used reference point with nearly ideal LOS conditions and ideal beam steering.

To estimate the ToA, first, synchronization of the OFDM symbol timing is performed at the Rx. Then, the cyclic correlation of the SRS is calculated. Next, the ToA is determined from the correlation. To that end, two methods are employed, a peak search in the oversampled signal, or the determination of the inflection point of the rising edge of the first peak.

VI. Measurement Campaign

In order to generate realistic indoor datasets for positioning analysis, a measurement campaign was executed in the L.I.N.K. hall at Fraunhofer IIS in Nuremberg. The hall itself is approximately 44 m long, 30 m wide and 11.7 m high, and allows for measurements under reproducible environmental conditions. The OTA measurements were executed under two groups of environmental conditions, i.e., obstructed line-of-sight (OLOS) and LOS.

Throughout the whole measurement campaign, the position and the orientation of the Rx antenna (imitating a 5G indoor access point) were kept fixed at a position typical for indoor positioning applications. The position and orientation of the Tx antenna however, were changed according to each scenario.

During the OLOS scenario, the Tx antenna was mounted at a height of 8 m and separated by a distance of approximately 26 m. Due to the high height of the Tx, the signal reflected from the ground is received by an additional delay equivalent to app. 4.2 m. Both units were fixed on the guard rail, and several measurements were performed by placing different obstacles in the hall. In order to achieve OLOS conditions, we placed an RF absorber of 0.5 m × 1.0 m size between the antennas. This setup can be seen in Figure 6.

To execute measurements for a scenario evaluating the achievable distance accuracy under LOS condition, we moved the Tx antenna to ground level. The antenna was fixed approximately at 1 m above the floor while the position and orientation of the Rx antenna were unchanged. During this scenario, eight measurement positions of the Tx antenna, depicted in Figure 7, were considered. At each of considered measurement position, we roughly mechanically pointed the Tx antenna in the direction of the Rx one.

Since we are considering cm level ranging accuracy, accurate ground-truth position and orientation determination of the antennas and their phase center play a crucial role. For that purpose, we chose as an optical reference system a Leica MS50 total station, with a typical 3D accuracy being better than 3 mm.

VII. Results

A. Line-of-Sight Scenario

In this scenario, the Tx is sequentially placed at different positions, marked (P1–P8), as shown in Figure 7. The Rx array was always at the same position and orientation and the beam angles are adjusted electrically, by means of analog beamforming. We assume previous knowledge on the Tx position for the beam steering. The nominal beam angle for the Rx was calculated using a model of the antenna array. For the Tx array, we assume a coarse manual pointing towards the Rx. We electrically swept the beams, in steps of ±10° and ±20° for the Rx and the Tx arrays, respectively, in azimuth and elevation relative to the nominal pointing angle. This resulted in 81 beam pairs. We analyzed the received signal strength (reference signal received power (RSRP)) and the ToA estimation accuracy of the beam pairs to study the impact of non-ideal beam pointing.

Fig. 6. Overview of the deployment setup for the OLOS scenario. The Tx and Rx antennas are fixed on the guard rail approximately at 8 m above the floor level, and separated by a distance of approximately 26 m. Additionally, the RF absorber used to create OLOS conditions is shown.
The expected signal strength covering the pathloss according the distance and the effective antenna pattern of the beamformed Rx antenna array is exemplary depicted in Figure 8. The plot represents the path gain assuming ideal pointing of the Tx antenna or an ideal omni-directional antenna. It is observed that, for beams having pointing angles with a high offset to the axis perpendicular to antenna surface more side lobes are shown.

The measured RSRP for the 81 beam pairs is given as the cumulative distribution function (CDF) of the correlation peak representing the received signal strength of the direct path in Figure 9. For ideal pointing the peak value, depending on the position, is in the range 45 dB to 53 dB. Due to the narrow beam width, the RSRP drops down to 10 dB or lower. These signals are still useful due to the high dynamic range of the measurement. Assuming that invalid measurements can be detected by comparing the ToA estimations for several beam pairs, it is observed that for app. 60% (CDF value 0.6), the error is in the range of 10 cm, even with non-ideal beam pointing as seen in Figure 10. Noteworthy, P7 shows a higher error. This was caused by ground reflections arriving with a low delay. If the delay is lower than the correlation peak width, then several correlation peaks overlap. This requires more advanced ToA estimators. In general, multipath components with a low delay (in our case an additional path length less than 1 m relative to LOS) have a high impact to the ToA estimation accuracy. Nevertheless, by only considering the beam pairs with the highest RSRP for each position, cm-level positioning error was observed, cf. Table VI.

B. Obstructed Line-Of-Sight Scenario

Each beam pair in Table VI was selected by measuring the highest received signal strength at a given Tx position. If the LOS path is attenuated by obstacles, multipath components may be much stronger. This may require advanced beam sweeping strategies to allow the detection of weak FAPs. To demonstrate these effects, LOS and OLOS conditions were compared. For the OLOS case, an obstacle in form of an absorber, was placed to (partly) block the LOS link, as can be seen in Figure 11. We recorded the correlation function for different settings of the Tx and the Rx beam angles.

The correlation function is calculated as the cyclic correlation at the nominal sampling frequency $f_s = 491.52$ MHz.

<table>
<thead>
<tr>
<th>Position</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error [cm]</td>
<td>-0.36</td>
<td>-1.2</td>
<td>1.67</td>
<td>0.53</td>
<td>5.68</td>
<td>4.02</td>
<td>1.05</td>
<td></td>
</tr>
</tbody>
</table>
and the plot is resampled (interpolated) to a higher resolution, which is shown in Figure 12. Each row represents a different beam angle setting, and the columns compare LOS (left) and OLOS (right). The red dashed curves show the correlation of the estimated LOS peak. The x-axis is normalized to the true distance and scaled in meters. At $f_s = 491.52$ MHz, one sample corresponds to 0.61 m. The y-axis represents the magnitude of the complex valued correlation function. Please note the different scaling of the y-axis.

When ideal beam pointing is at hand (first row), in case of OLOS (Figure 12b), the direct path is attenuated by approximately 22 dB compared to the LOS scenario (Figure 12a).

The effect of using narrow beams for the Tx with non-ideal beam pointing is demonstrated in the middle row. The Rx uses ideal beam pointing (highest antenna gain for the direct path). For LOS, the signal of the sidelobes of the Tx antenna is sufficient and the impairments caused by multipath components are marginal (observed as small differences between the calculated correlation and the estimated LOS peak). For OLOS, the power of direct path is further reduced and now received with a signal strength 40 dB below the ideal LOS condition. The first lobe of the correlation peak is now impaired by multipath components with low additional propagation delay, but the signal is still sufficient for ToA estimation with low error. The ground reflection is received through the sidelobe of the Rx antenna (correlation peak at app. 4.2 m offset) and other multipath components are observed as well.

Now, when both the Tx and Rx beams are pointed to the ground (Figure 12c), two things are observed. First, the characteristic of the correlation peak is identical to the ideal LOS case, attenuated by app. 7.5 dB only. Second, the peak is shifted by approximately 4.2 m (normalized distance), i.e., the additional path length compared to the direct link. Without further analysis, a receiver may consider this path as an ideal LOS path. If the direct path is blocked, the Rx can detect the direct path only if the beam sweep searches for a weak direct path, as demonstrated in the middle row. Here, the ground reflection signal was 13 dB stronger than the obstructed LOS path. In the OLOS case (Figure 12f), the picture is similar to LOS, albeit with an additional 2 dB loss in comparison. This difference may have resulted from a re-adjustment of the antenna panel with limited accuracy before the last measurement.

VIII. CONCLUSION AND OUTLOOK

FR2 frequency bands are typically combined with massive MIMO antenna arrays and larger bandwidth signals which improve the positioning accuracy. The related positioning algorithms and beam management procedures are subject of ongoing research activities. For communication purposes, the beam pair may be identified typically from the ones that provide the highest RSRP. For positioning purposes, other criteria may apply. This is especially true in scenarios where the direct path is attenuated by obstacles, as it may be difficult to identify the most reliable beams.

We designed a setup supporting 5G compliant reference signals for the detailed analysis of the signal characteristics and the verification of ToA estimation accuracy. The 5G positioning reference signals based on Zadoff–Chu sequences allow measurements with very high dynamic range. This enables the detection of very weak first arriving paths, or the identification of reflected signals useful for positioning in the NLOS scenarios. Advanced positioning algorithms, combined with beamforming, can provide estimates on the angle of departure (AoD) or angle of arrival (AoA). In this paper, the system setup and measurement results were presented.

We used beamforming-capable antennas for the Tx and Rx with a beam width of 13° and 7°, respectively. For each position, many beam pairs provide a useful signal. For example, a signal received through the sidelobes of the antenna pattern, or reflected signals may be already comparable or much stronger than an attenuated direct path. Therefore, advanced beam management procedures shall be studied to minimize the beam sweep effort.

In particular, our measurements demonstrated that, for LOS reception the distance error was less than 6 cm. For OLOS, the beam pair selection plays a more significant role. If the RSRP beam pair criterion is applied, the Tx and Rx beams might point to a NLOS beam direction which results in high timing errors. Further measurements with environments close to typical usage scenarios are subject to future work.

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[5] Study on channel model for frequencies from 0.5 to 100 GHz. Technical Report (TR) 38.901, 10, version 16.1.0., 3rd Generation Partnership Project (3GPP).
Fig. 12. Plots of the correlation function vs. normalized distance (in m). Two cases: LOS (left column); OLOS (right column). Three scenarios: ideal beam pointing (top row); ideal pointing at the Rx and non-ideal pointing at the Tx (middle row); Tx and Rx both pointing to the ground (bottom row). The measured correlation is plotted in solid blue (●), and the estimated LOS (or ground reflection for the last row) correlation in dashed red (○).