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Cross–Bearing based Positioning as a Feature of 5G Millimeter Wave Beam Alignment

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***Abstract*—In the context of vehicle–to–everything (V2X) communications, a mobile subscriber positioning service is beneficial for locating e.g. motor vehicles on the road or unmanned aerial vehicles (UAVs) in the air. Current mobile networks process metrics like the receive power or the propagation delay to determine terminals' positions. With the introduction of millimeter wave (mmWave) communications, the electrically steerable directivity of phased arrays not only procure high gains on the radio link but also offer a direction finding (DF) to the terminals. Several DFs of located base stations could be merged in a cross–bearing manner to indicate the position of mobile devices. In this work, the suitability of DF for positioning of mobile subscribers is discussed based on latest standardization efforts and experimentally evaluated. Our extensive laboratory system consists of three software–defined radio mmWave transceiver platforms, phased array antennas and a tailored rail system allowing for reproducible mobility emulation, positioning and over–the–air testing at 28 GHz. The results show, that considering information about the directivity, a DF can be estimated precisely via the beam pointing direction. The mmWave V2X communications offer a possibility for a precise positioning service for mobile devices as well as to applications in the edge–cloud on the infrastructure side.**

I. Introduction

The millimeter wave (mmWave) spectrum forms a crucial part for satisfying growing mobile network throughput demands. Due to the necessarily directional communications, RF–based positioning services appear even more predestined than in previous mobile radio networks. With this, a mmWave–based positioning service is attractive for applications of 5G and beyond especially in the context of vehicular communications (Figure 1). Motor vehicles need to be located as part of the road traffic for tasks like navigation, remote control or even autonomous driving. At the same time, robotic vehicular systems on the ground and in the air may require position information as a fundamental component for supplying specific services.

Current global navigation satellite systems (GNSSs) are quite common, but also battery draining and tend to fail at obscured places like urban canyons and indoors. At the same time, deploying dedicated positioning infrastructure like e.g. ultra–wideband (UWB) anchors may not be affordable for comprehensive coverage. For this reason, positioning techniques focusing on exploiting communication interfaces (especially wifi and cellular) are widely established.

As an immanent feature of mmWave communications, proper directivity patterns (i.e. the beam directions) are negotiated between transmitter and receiver. In the context of mobile radio networks, this leads to knowledge of the base station's beam pointing direction which can be leveraged as bearing or direction finding (DF).

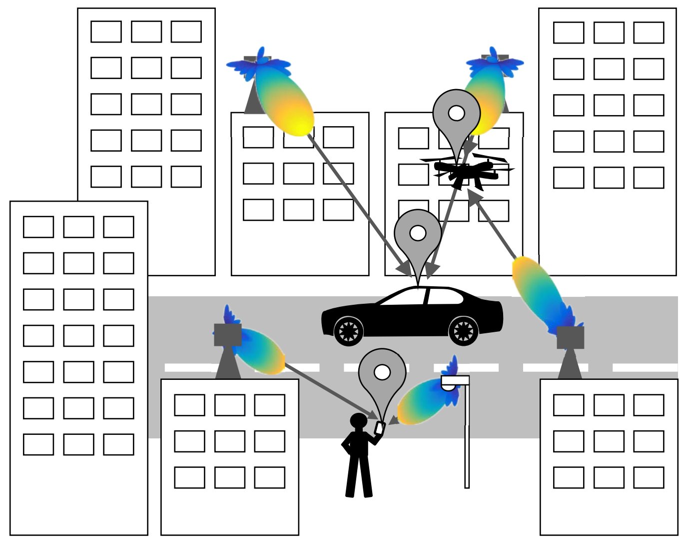

Fig. 1. In the exemplary context of road traffic, pedestrians, motor vehicles and Unmanned Aerial Vehicles (UAVs) as 5G mobile network subscribers may benefit from a mmWave–based positioning service, realizable by exploiting beam alignment information as bearing.

By means of context information like a map of base stations including their orientations, the intersection of at least two DFs is supposed to serve as position estimate. At this, the position estimation can take place at the operator network side in case of feedback from the user equipment (UE). Alternatively, even an internal positioning is conceivable in case of the operator sharing the base station map with subscribers, so that information converges in the UE.

For this reason, this work focuses on an internal positioning approach for geographically positioning a mobile radio network subscriber by means of mmWave communications within a cellular mobile radio network.

The remainder of the paper is organized as follows: In Section II, related work is briefly surveyed. Section III elaborates on the practicality of a 5G mmWave, cross–bearing based positioning service by considering current standardization efforts. Subsequently, the proposed methodology and the designed experimental measurement setup are presented in Section IV. In Section V, results are interpreted for DF and the positioning performance is classified. Section VI concludes this work by wrapping up the outcome of the measurement campaign and pointing out the subsequent applicability of the results achieved.

II. Related Work

In standardization [1], UE positioning capabilities are grouped by technology. The most prominent ones are probably GNSS and enhanced cell ID (E–CID), where E–CID contains UE measurements like reference signal received power (RSRP) and reference signal received quality (RSRQ) as well as network–based measurements like for example timing advance and angle of arrival (AoA). Currently, the standard states the E–CID positioning feature only based on long term evolution (LTE) signals. However, beam–based metrics like for example uplink angle of arrival (UL–AoA) and downlink angle of departure (DL–AoD) are expected to be introduced with upcoming release 16.[1]

In literature, RF–based positioning is discussed based on various signal features and metrics like observed time difference of arrival (TDoA), AoA, time of flight (ToF) and received signal strength (RSS) [2], [3]. One major field of research focuses on exploiting multipath effects by digital or hybrid beamforming. For example, promising approaches in the regime of massive multiple input multiple output (MIMO) are surveyed in [4].

In the analog beamforming domain, it is time–consuming to profit from multipath propagation, since there is only one RF signal at a time. However, E–CID methods are predominantly based on metrics gathered from radio link measurements. For this reason, the proposed method is considered part of the E–CID group, since beam directions can be regarded as narrow cell sectors with the synchronization signal/physical broadcast channel (SS/PBCH) blocks representing their respective identity [5].

Authors in [6] merge ToF and angle of departure (AoD) with raytracing estimates utilizing a 3D area map to also handle none–line–of–sight (NLOS) environments. In [7], numerical results of 3D positioning based on beam–RSRP reporting are presented by also accounting for base station orientation uncertainties. Reversely in [8], authors propose to accelerate initial beam alignment by exploiting position information.

However, this work focuses on UE positioning based on beam signal quality measurements as introduced by our previous work [9].

III. Positioning Capabilities of 5G NR by Direction Finding as Feature of mmWave Communications

Ranging–based positioning approaches consider some distance, range or pseudo–range measure to perform a lateration. In contrast, angular directions are determined with DF. These solely can lead to a position estimate by means of cross bearing, or by combination with ranging measures.

In the following, we focus purely on leveraging DFs for position estimation as illustrated in Figure 2. Against this background, the UE could locate itself with the aid of base station beacons, but also a network–based positioning is conceivable as soon as there is some signaling from a UE.

[1] 3GPP Work Item #830077 — "NR positioning support" (RP–192581 as of Jan. 14, 2020)

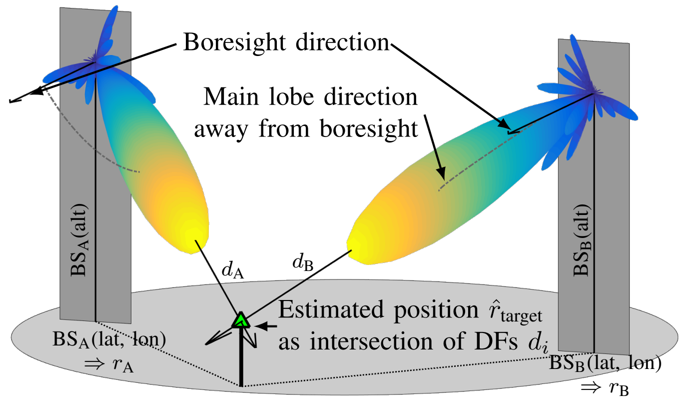

Fig. 2. Cross–bearing as a basic principle of the proposed positioning. The intersection (or its least squares approximation) of at least two base station DFs (denoted as d_i) embodies the estimated mobile device position. The base station positions r_i and orientations are assumed as given for the computation.

A. Self–Positioning at UE

In 5G new radio (NR), the 5G base station (gNB) broadcasts SS/PBCH bursts, where each containing SS/PBCH block corresponds to a distinct beam direction, i.e. DL–AoD. These bursts are especially used during cell search procedure, so the UE may still be in *radio resource control (RRC) idle* state (i.e. not yet attached). To support mobility, UEs keep determining receivable cells. Thus, the cell search procedure is an enduring mechanism.

The SS/PBCH beams are potentially wider than the beams used for the physical downlink shared channel (PDSCH). This is because the focus is on spreading robustly modulated control information instead of providing high gains, which may permit an increased payload data throughput.

Positioning based on SS/PBCH tends thus to be less precise, but does not require an active connection to the network. However, for locating within e.g. a world geodetic system (WGS), the UE needs to know the gNBs' coordinates and orientations, which may have been provided beforehand.

As soon as there is an ongoing downlink transmission e.g. during *RRC Connected*, narrow beams with high gain are formed supplying not only a higher throughput but also an increased accuracy (e.g. by exploiting channel state information reference signals (CSI–RSs)).

B. Network–based Positioning

Beside the network–based positioning service as has already been offered for a long time, positioning is believed to further enhance by means of beamforming and highly directional mobile communications especially in the mmWave domain.

While several metrics like RSRP and the timing advance parameter may be combined, we initially concentrate on a DF–only approach based on DL–AoD or UL–AoA and leave ensemble methods for future work. Although the current E–CID positioning service is claimed to rely on LTE signals

[1], information of SS/PBCH block direction received by a connecting UE is known on the network side. During beam refinement, DF can be further improved by utilizing reference signals of the UE's uplink transmission (UL–AoA). Additionally, measurement reports may also support reporting of DL–AoD as a result of the UE's continuous cell search procedure. With this, multiple DFs are available on network side to serve for positioning. Depending on the use case, the location estimate can be offered as a service to the UE itself as well as to cloud– or edge–hosted applications (e.g. considering vehicle–to–everything (V2X) communications).

Since DF to at least two gNBs is necessary for positioning, dual connectivity operation to multiple gNBs is beneficial in either case. This is again because an ongoing data transmission utilizes narrower beams, which may lead to a more accurate positioning based on CSI–RS instead of SS/PBCH blocks.

IV. Direction Finding with Pencil Beam Pattern and Subsequent Positioning by Cross–Bearing

In the following, the proposed methodology is detailed by explaining the three stages from measuring signal or beam quality over determining the DF to estimating the target position. An overview is shown in Figure 3.

A. Measurement Setup

Exemplary measurements are conducted based on our mmWave experimental platform as presented in [9]. Therein, the error vector magnitude (EVM) of the demodulation reference signal (DM–RS) has been chosen as signal or beam quality indicator, which is also used for the following study. The described setup is extended by a second base station with an equal, 64–element phased array antenna system operating eight by eight elements at 28.5 GHz, whereas the mobile unit's antenna is replaced by a passive omnidirectional (azimuthal) antenna with 3 dBi. The developed linear drive system emulates the mobile UE by moving its antenna along a rail supplying a reproducible position reference. The positioning task is done for three arbitrary locations on the rail. The redesigned arrangement of the base stations and the mobile station is illustrated in Figure 4.

For the subsequent measurements, the base stations determine the UL–AoA during a lasting uplink transmission for the network–based positioning. A self–positioning UE would determine the reciprocal DL–AoD in an analogous manner and is not considered individually.

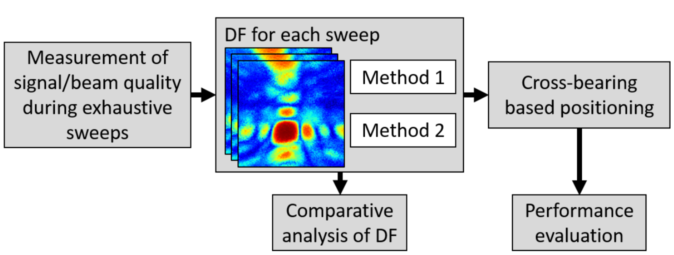

Fig. 3. Methodology of experimental evaluation. Based on the measurement results, DF is computed with the described methods. Finally, the target position is estimated by cross–bearing and the performance is evaluated.

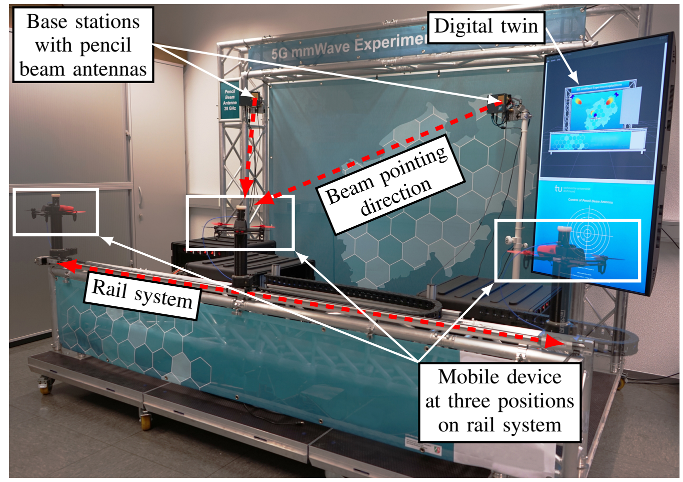

Fig. 4. Laboratory setup for experimental evaluation. The *pencil beams* of two phased array antennas are directed towards the mobile device at the three indicated positions.

B. Direction Finding

For DF, the angular direction from a known location (i.e. UL–AoA or DL–AoD) needs to be determined. Thus, DF requires beam quality measurements to estimate the best beam pointing direction. In this work, measurements are conducted as exhaustive sweeps, i.e. the complete coverable angular area is scanned. As shown in [9], this time–consuming procedure could be replaced by beam tracking algorithms, which reduce the necessary amount of measurements for estimating a proper beam pointing direction. However, the extensive scans allow for a comprehensive analysis of the signal quality based direction estimation, the subsequent DF and finally the positioning within a stationary setup. The evaluation of positioning during tracking of moving UEs will be addressed in future work.

This work considers the following DF estimation methods:

Method 1: Highest signal quality (M1)
: This first method takes the direction measuring the highest signal quality (i.e. the lowest EVM). Due to measurement noise, this might be rather inaccurate, when only considering a single scan.

Method 2: Centroid of the main region (M2)
: The second estimation method determines the centroid of the spot with the highest signal quality. This is done by converting the scan result to a binary image by applying a threshold. The threshold value is chosen to ensure the separation of the main lobe region from the side lobe regions within the binary image ($\mathrm{EVM}_{\mathrm{thr}} = -50\,\mathrm{dB}$). Finally, the centroid of the main lobe region containing the highest signal quality is used as the direction estimate.

C. Cross–Bearing

Cross-bearing is a well–known positioning method of terrestrial navigation, where two (or more) bearings of known locations are used to locate a target. In this work, the mobile network base stations are assumed to embody the known locations ($\mathrm{BS_A}$ and $\mathrm{BS_B}$, cf. Figure 2). Within a shared (cartesian) coordinate system, the i–th base station location is given by the position vector r_i in 3D space. Further, the corresponding i–th bearing is defined as azimuth and elevation angle $(\mathrm{az}, \mathrm{el})_i$ subsequently represented by a cartesian unit direction vector d_i. To map a bearing to its unit direction vector, the orientation of the corresponding base station needs to be taken into account. The reference location r_i and pointing direction d_i define a line in 3D space per base station i.

The target position is regarded as point with the minimum squared Euclidian distance to each of these skew lines, i.e. the centroid of skew lines is computed as least squares approximation of the intersection of given bearings:

$$\hat{r}_{\text{target}} = \left(\sum_i I - d_i d_i^T \right)^{-1} \left(\sum_i (I - d_i d_i^T) r_i \right) \quad . \tag{1}$$

With I as the identity matrix, the resulting target position estimate is denoted as $\hat{r}_{\text{target}}$ and is subsequently evaluated in relation to the true target position in terms of accuracy and precision.

V. Experimental Results and Performance Evaluation

In the following, the explained approach of cross–bearing based positioning by means of DFs is experimentally evaluated within our presented laboratory setup. Results are analyzed in two stages by first focusing on the DF performance and secondly assessing the position estimates.

A. Assessment of Proposed DF Methods

In a first step, the accuracy and precision of DF are evaluated by analyzing the directional signal quality measured in the azimuth and elevation plane with a grid spacing $\Delta = 1°$, i.e. the antenna's steerable pointing direction is incremented in 1° steps within its angular coverage area from –60° to 60° in both dimensions. The measurements in form of exhaustive sweeps of both base station antennas are repeated one hundred times at each of three different mobile device positions as depicted in Figure 4. The DF is subsequently estimated per iteration by means of the described methods.

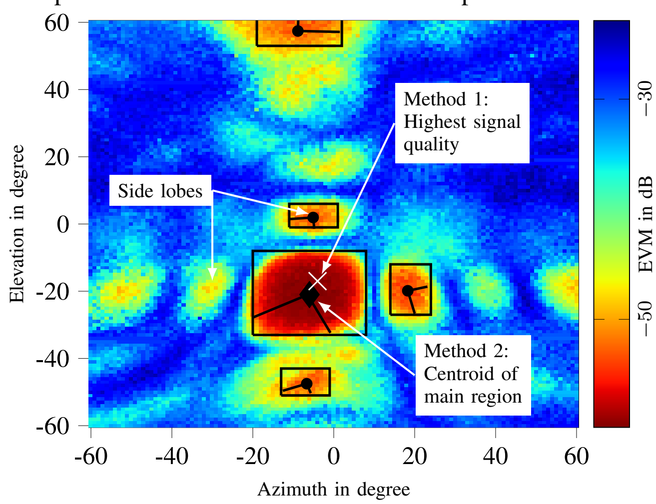

Fig. 5. Heat map of measured EVM of DM–RS as signal direction quality indicator of one exemplary exhaustive sweep. The direction estimates determined by the two proposed methods are marked as white cross and black diamond respectively and could be considered as bearing direction for subsequent cross–bearing positioning.

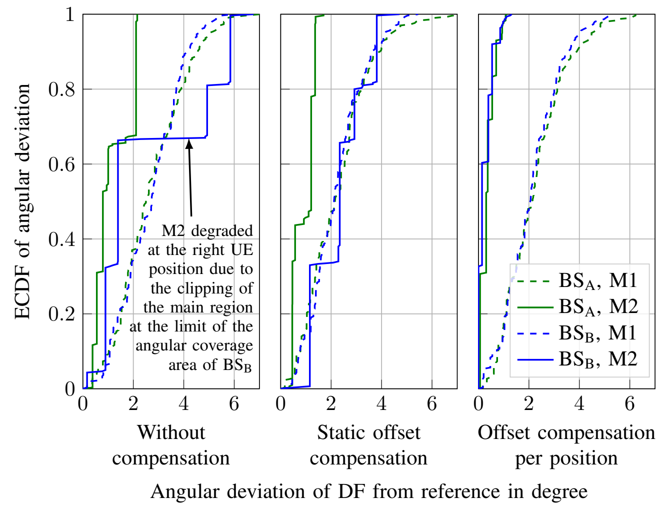

Fig. 6. ECDF of the achieved DF precision in terms of the angular deviation from reference pointing directions of both antennas BS_A and BS_B and the two discussed estimation methods M1 and M2. The precision is slightly increased by static offset compensation and further enhanced by an individual offset compensation per UE position. Especially the centroid method (M2) performs well with a maximum deviation of 1.38°.

In Figure 5, this process is exemplarily illustrated for one sampling run with the mobile unit at a central position of the rail from the perspective of base station A. While the pointing direction with highest signal quality (M1) lies somewhere within the main region as a result of the measurement noise, the centroid of the strongest detected region (M2) occurs to be a more precise estimate as further validated in the following.

In Figure 6, the DF estimation of both methods and antennas is analyzed in terms of the ECDF of the angular deviation from the respective reference pointing direction. On the left–hand side, the raw deviation is illustrated. Due to the mobile device reaching the limit of base station B's angular coverage area, the second method degrades because of its main region beeing clipped and the centroid computation is inevitably distorted.

In center diagram, the mean deviation from the reference angles is subtracted from the DF estimates for both antennas as a fixed value. However, this measure only slightly improves the error of base station B's estimated DF, since its deviation is more strongly distorded for one single position. Hence, the estimated DF has a different offset for this pointing direction, which could be compensated by individual offset values per mobile device position as shown on the right–hand side subfigure. With this post–processing, the second method achieves a maximum angular deviation of only 1.12° and 1.32° for base station A and B, respectively.

Against the background of the used sampling resolution of 1°, this accuracy seems quite appropriate. Additionally, its standard deviation is $\sigma_{\text{M2, BS}_\text{A}} = 0.27°$ and $\sigma_{\text{M2, BS}_\text{A}} = 0.28°$ in case of offset compensation per position, which can be considered as reasonable precision. Consequently, within its operating range, the centroid method (M2) significantly out-

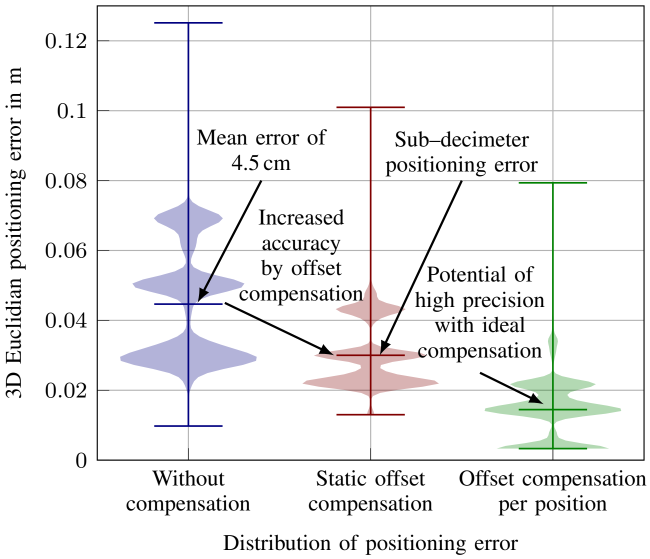

Fig. 7. Statistical evaluation of achieved positioning performance using the second proposed DF method. Compensation is applied in post–processing to account for the mean angular offset in total and individually per mobile device position, respectively.

performs the one purely based on the highest signal quality (M1) and is used for positioning.

B. Positioning Performance

With the determined DFs of the second method, the mobile device position is finally computed using Equation 1 and the assumed known poses of base station A and base station B. Due to one reference position being outside the acceptable operation range of BS_B, it is excluded from subsequent analysis. The results are analyzed in terms of the three dimensional euclidian positioning error as depicted in Figure 7.

While a mean positioning error of 4.5 cm is achieved with raw DF values, the positioning performance is further improved by offset compensation. The center violin diagram illustrates the results with a static angular offset per antenna, whereas an individual offset compensation is applied for each user device position at the rightmost diagram. The offset is computed as the mean angular offset in each case. With a mean position error of 1.4 cm and a standard deviation of 0.9 cm, the results achieve a quite promising positioning performance in terms of accuracy and precision.

C. Relevance for Real–World Deployment

Public road traffic services based on subscriber positioning like e.g. navigation or alerting may tolerate even higher uncertainties than the herein achieved performance. In the context of mmWave aided mobile networks, utilizing SS/PBCH signals may suffer from a few non–overlapping and unaligned beams. However, the achieved resolution is rather expected during active data transmissions, which necessitate continuous beam refinement with an order of magnitude in the range of a few degrees. As mentioned earlier, more sophisticated approaches may even fuse several position estimates from different technologies to balance between energy efficiency, resource utilization and positioning resolution.

VI. Conclusion

Vehicular systems on the road and in the air tend to necessitate position information for supplying various services. Positioning technologies like GNSS or UWB may have an advantageous performance within suited environments. However, they require dedicated infrastructure and also suffer from shortcomings in specific settings.

With V2X communications leveraging 5G mmWave, the radio communication link is supposed to be exploited to additionally provide a positioning service. While a mobile radio network hosted positioning service is no new idea at all, the introduction of mmWave spectrum and electronically steerable antenna directivity constitutes a notable positioning precision gain. A cross–bearing approach based on base stations' mmWave beam management has been expounded for self as well as network–based positioning. By means of our advanced mmWave experimental platform, the performance of an exemplary positioning method proposal is evaluated in a laboratory experiment. The results prove, that the mobile devices can be located within a mean deviation of about 1 cm with proper offset compensation.

In future work, an outdoor measurement campaign is planned to further validate the results by positioning motor vehicles and UAVs on the road and in the air, respectively.

Acknowledgment

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References

[1] 3GPP, "Stage 2 functional specification of user equipment (UE) positioning in NG-RAN," 3rd Generation Partnership Project (3GPP), TS 38.305 V15.4.0, Tech. Rep., 2019.

[2] F. Lemic, J. Martin, C. Yarp, D. Chan, V. Handziski, R. Brodersen, G. Fettweis, A. Wolisz, and J. Wawrzynek, "Localization as a feature of mmWave communication," in *International Wireless Communications and Mobile Computing Conference (IWCMC)*, Sep. 2016, pp. 1033–1038.

[3] O. Kanhere and T. S. Rappaport, "Position locationing for millimeter wave systems," in *IEEE Global Communications Conference (GLOBECOM)*, Dec. 2018, pp. 206–212.

[4] F. Wen, H. Wymeersch, B. Peng, W. P. Tay, H. C. So, and D. Yang, "A survey on 5G massive MIMO localization," *Digital Signal Processing: A Review Journal*, vol. 94, pp. 21–28, Nov. 2019.

[5] 3GPP, "NR and NG-RAN overall description," 3rd Generation Partnership Project (3GPP), TS 38.300 V15.7.0, Tech. Rep., 2019.

[6] O. Kanhere, S. Ju, Y. Xing, and T. S. Rappaport, "Map-assisted millimeter wave localization for accurate position location," in *IEEE Global Communications Conference (GLOBECOM)*, Dec. 2019.

[7] E. Rastorgueva-Foi, M. Costa, M. Koivisto, J. Talvitie, K. Leppänen, and M. Valkama, "Beam-based device positioning in mmWave 5G systems under orientation uncertainties," in *52nd Asilomar Conference on Signals, Systems, and Computers*, Oct. 2018.

[8] I. Orikumhi, J. Kang, C. Park, J. Yang, and S. Kim, "Location-aware coordinated beam alignment in mmWave communication," in *2018 56th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, Oct. 2018, pp. 386–390.

[9] K. Heimann, J. Tiemann, D. Yolchyan, and C. Wietfeld, "Experimental 5G mmWave beam tracking testbed for evaluation of vehicular communications," in *IEEE 2nd 5G World Forum (5GWF)*, Sep. 2019, pp. 382–387.