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# Experimental 5G mmWave Beam Tracking Testbed for Evaluation of Vehicular Communications

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***Abstract*—Upcoming 5G technology has a great potential to enhance cellular networks especially in the field of vehicular communications. Utilizing millimeter wave (mmWave) spectrum benefits the ever–growing mobile data traffic, but the more challenging radio channel requires the use of tracking directional antennas. In this paper, we address beamforming and beam tracking to maintain highly capable and robust links to vehicles on the road or rail and in the air as well as in the context of networked indoor robotics. For this reason, a real–time, no overhead tracking method, which focuses on consistently selecting the most promising beam direction as result of a proximity search, is implemented and evaluated on a modular 5G mmWave software–defined radio (SDR) platform. To achieve a controlled environment providing very accurate ground truth of the vehicular movement, we emulate typical mobilities with a mechanical testbed, capable of providing a variety of movement dynamics in a reproducible manner. The experimental setup consists of the high performance SDR radio system operating at 28 GHz including an 8 by 8 beamforming antenna and a specifically developed mechanical testbed. The results demonstrate the feasibility of reliably providing multi–gigabit network access to vehicles with various mobilities by wireless links at mmWave frequency.**

## I. INTRODUCTION

The upcoming fifth generation of mobile communication (5G) will make use of millimeter wave (mmWave) frequencies to satisfy the growing demand of high data rates. Especially vehicular applications on the road or rail, in the air and in the context of networked indoor robotics could profit from this so–called enhanced mobile broadband (eMBB), since mobile devices may act as multi–sensor platforms, in case of Unmanned Aerial Vehicles (UAVs) for surveillance purposes or even to operate a mobile base station supplying network coverage e.g. for passenger devices on a high–speed train.

Here, the vehicle mobility is the greatest challenge, because mmWave frequencies require highly directional antennas and their *beams* have to be aligned accurately to ensure a stable communication link. As widely discussed in literature (e.g. [1], [2]), particularly the initial access to the network and with this the initial discovery of the right alignment of the antenna beams is challenging on the one hand, and on the other hand, the alignment needs to be maintained also for network subscribers with high mobility.

To achieve a proper beam orientation, phased array antennas can be used since their main lobe direction is electronically steerable. With a great number of antenna elements, a high gain can be reached through a very small beam width. This high gain overcomes the higher path loss of the mmWave frequency compared to the traditional sub 6 GHz frequencies [3], but the narrow beam width is a blessing and a curse: Very directional beams enable a high spatial reuse, but apart from that, precise beam steering and continuously accurate alignment of the beams of both the base station and the mobile station is crucial as has been shown in our previous work [4]. For this reason, beam management approaches are a major study item in recent years as surveyed in [5]. For example, in [6] authors suggest to use different beam widths during random access and payload transmissions, whereas in [7], [8] the potential benefit of utilizing Kalman filter based algorithms is proven by simulations and in [9] a particle filter based method is opposed. Recent experiments are mainly conducted for fundamental research of the mmWave propagation channel to derive channel models. Comprehensive surveys of these works can be found in [10], [11]. However, testbeds and field trials are very important steps towards the realization and approval of those concepts. Although measurement campaigns were carried out in some vehicular contexts like in [12], there is a deficiency of scientific, highly reproducible experiments related to mmWave communications in UAV as well as ground vehicle scenarios.

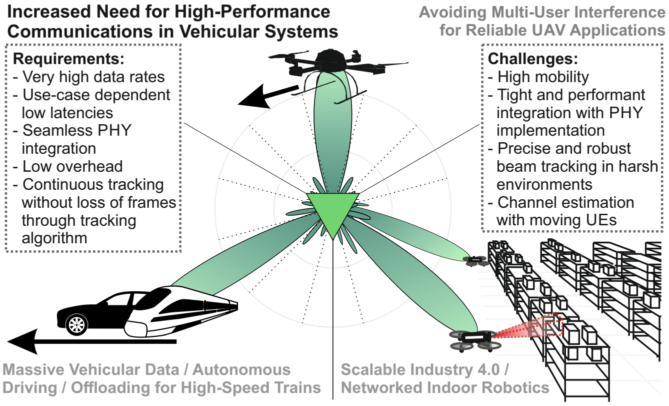

Fig. 1. Vehicular application scenarios. A base station equipped with a phased array antenna needs to precisely align the pencil beam during the vehicular movement on road, rail and in the air. Despite various mobility patterns, an appropriate radio link quality needs to be ensured.

In this work, a communication link at 28 GHz is set up for experimental analysis of the tracking capabilities of modern 5G beamforming antenna systems (Figure 1). With this, a simple beam tracking procedure according to the traditional lobe switching principle is carried out to estimate the vehicle's direction. In doing so, existing reference signals are reused to measure the signal quality so that no additional overhead occurs. The indoor testbed allows for experimental link evaluation of highly reproducible vehicular movement patterns, although a complete integration of the mmWave system into a lightweight airborne or vehicular system is currently not yet possible. Results prove, that the experimental testbed allows for the assessment of different parameterizations and that our implemented, simple tracking approach already performs well, since a high data rate communication link can be maintained even in demanding scenarios with high mobility.

The remainder of the paper is organized as follows: In Section II the overall concept is introduced by considerations on tracking algorithms and key performance indicators. The laboratory testing environment, the experimental setup as well as the realization of the self–contained beam tracking functionality is discussed in Section III, before results follow in Section IV. A summary concludes this work in Section V.

## II. OVERVIEW OF CONSIDERATIONS ON TRACKING ALGORITHMS AND KEY PERFORMANCE INDICATORS

The fundamental concept of tracking antennas in the context of vehicular communications has been analyzed on the basis of UAV flight experiments in our previous work [4]. Misalignments caused by incorrect position information or noisy measurements lead to severe implications on the link performance. However, precisely aligned beams at both the airborne UAV and the ground station permit a stable communication link even in mobile scenarios. This implies a continuous tracking of the beam alignment to ensure connectivity.

To enable self–contained beam tracking, a quality measure of a chosen beam direction as well as the ability to change the beam direction must be integrated into MAC procedures. For an exhaustive search, different beam directions need to be defined to cover the complete search space. Since an analog beamforming architecture is used in this work, only one single beam direction can be applied at a time and all defined directions must be evaluated consecutively. Considering hybrid or digital beamforming architectures, this effort could be parallelized by using more than one RF chain. However, having multiple beams would indeed accelerate the search, but a high amount of RF chains is very costly and power consuming. It is believed that at least fully digital beamforming is not yet applicable for mmWave communications with regard to the proposed large antenna arrays.

Subsequently, a measurand usable as quality indicator is introduced, before further considerations on beam sweeping and tracking mechanisms follow.

### A. Signal or beam quality indicator

The error vector magnitude (EVM) describes the divergence of a received symbol from the nearest point of the constellation diagram which is its expectation. Calculating the EVM from the demodulation reference signal (DM–RS) is particularly promising, because DM–RS is meant to be transmitted robustly modulated (in the present implementation, QPSK) compared to other data like the payload. So a mean EVM value from DM–RS may be available every subframe, as long as the receiver can synchronize to the signal. Additionally, as the name suggests, DM–RS is transmitted anyway as demodulation reference so that no further signal and thus no signaling overhead is introduced to gather a signal quality indicator for beam alignment applications.

TABLE I
PARAMETER CONFIGURATION

| **Parameter** | **Value** |
|---|---|
| Key Performance Indicator | |
| **EVM** | $-60\,\text{dB}$ to $-20\,\text{dB}$ |
| Modulation | QPSK |
| Periodicity of DM–RS | $5\,\text{kHz}$ |
| Configuration of mmWave Transceiver System | |
| Center frequency | $28.5\,\text{GHz}$ |
| System bandwidth | 8x100 MHz |
| Waveform | CP–OFDM |
| FFT size | 2048 |
| Subcarrier spacing | $75\,\text{kHz}$ |
| MCS (payload) | 64QAM, code rate $\frac{7}{8}$ |
| TX power | $3\,\text{dBm}$ |
| TX antenna gain, HPBW (horn) | $10\,\text{dBi}$, 54° |
| TX cable length, loss | $3\,\text{m}$, $16\,\text{dB}$ |
| RX phased array antenna | 8 by 8 elements |
| RX antenna gain, HPBW (phased array) | ≈37 dBi, ≈13° |
| RX cable length, loss | $1.5\,\text{m}$, $4\,\text{dB}$ |
| Beam Tracking Algorithm | |
| **Best Choice (BC)** | (az $\pm$ $\Delta$az, el $\pm$ $\Delta$el) |
| Pattern | square (3x3 grid) |
| Spacing $\Delta$(azimuth, elevation) | 1° to 11° each |

Since the current implementation of the testbed is based on specifications from 5GTF[1], the rate of available EVM values is $r = 5\,\text{kHz}$ in the proposed setup. Further parameters are given in Table I.

### B. Beam Sweep

Switching through every adjustable beam direction is very time consuming, since large antenna arrays allow for very narrow beams whose high gains are required for sufficient signal strengths. Considering that both transmitter and receiver use directional antennas, the number of possible beam combinations multiplies. For an exhaustive search, a coarse grid can be defined that covers the entire search space by considering the half power beam width (HPBW). Here, the grid spacing embodies a trade–off between a comprehensive coverage and the required time for the sweep: Generally applies, the denser the grid, the more accurate the resulting beam direction. However, this is not the case with a considerable relative velocity of the vehicle, as it might move into an already scanned area during the sweep. The exploration may then be less accurate.

Additionally, in case of vehicular communications the mobile device as part of the vehicle could be aware of the base station positions. This corresponds to the context information based search described in [13]. Knowing the own pose and the coordinates of nearby base stations, the vehicle would be able

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[1] Verizon 5G technical forum (5GTF), http://5gtf.org/ [Accessed Aug 19, 2019]

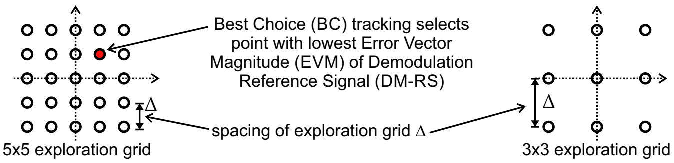

Fig. 2. The implemented tracking algorithm cycles through an exploration grid defined in the azimuth and elevation plane and selects the best measured direction as the center of the subsequent iteration.

to align its antenna to the base station reducing the problem of antenna alignment. In this case, only the base station would need to find the appropriate beam direction to notice a vehicle. Multi–rotor UAVs like quadcopters are even able to align their antenna mechanically at least in the azimuthal plane. This means that an antenna system mounted on UAVs may be kept lightweight and power–saving for example by using a horn antenna, whereas ground vehicles like trains may not have such constraints.

Although this exhaustive search approach might be well suited for obtaining a first fix without prior knowledge, it inhibits a continuous connection and is thus less appropriate for tracking.

### *C. Tracking*

Once a rough direction has been obtained, tracking of the vehicle can mainly focus on maintaining the connectivity. This first direction may be determined or estimated by a sweeping procedure such as just discussed or by means of external knowledge (e.g. GPS position). According to [5], the tracking mechanism constitutes *beam measurement* and *beam determination* procedures.

Considering the mobility, it is supposed that there are no dashes to completely other directions, so tracking may be viable by only exploring (measuring) the adjacent beam directions in case of line–of–sight (LOS) as depicted in Figure 2. The main advantage of focusing on exploring the proximity for *beam measurement* is twofold: The receive quality is supposed to stay good, so that the connection may remain at a proper link quality and the search space is greatly reduced compared to a full sweep approach. In this respect, beam tracking shall be conducted in a self–contained manner without any feedback by only using signal or beam quality measurements at the receiver station.

As a first step, the given (determined/estimated) direction is used as the center of the subsequent exploration. Although more extensive stateful approaches might be considered to enhance the direction estimation and reduce the tracking error, they will needlessly overuse time and computational resources especially on FPGA hardware if even a resource efficient *Best Choice (BC)* routine similar to the traditional *lobe switching* technique performs the task appropriately. Furthermore, the exploration beam grid might be varied in its spread, directions and amount of points depending on the last changes of the beam directions to improve the system performance once more. In any case, the exploration results, i.e. the directions with associated EVM measurements, are incorporated into the target direction estimation.

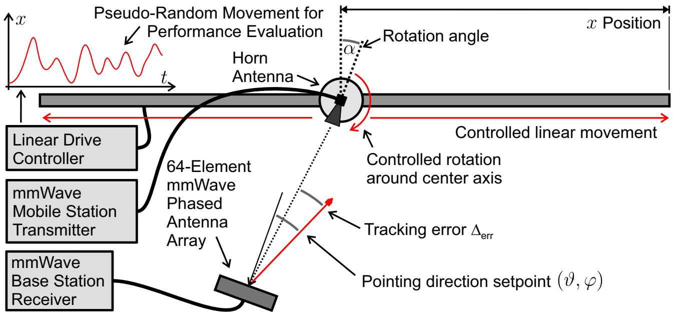

Fig. 3. Schematic illustration of the experimental setup.

In the event of a changeover to a none–line–of–sight (NLOS) condition, an appropriate reflected path is likely to have a quite different direction than the former LOS. Hence, a more comprehensive exploration or even a complete beam sweep may be performed to recover the connection through a reflected path. Nevertheless, another base station with LOS condition could be available and a handover could be conducted to recover a better link quality.

Issues such as line–of–sight obstruction, resource sharing, medium access and the related control links will be addressed in future work, especially integrating the herein presented testbed and the results of this work into our end–to–end system architecture as presented in [14].

## III. EXPERIMENTAL TESTBED AND IMPLEMENTATION OF BEAM TRACKING ALGORITHM

In Figure 3, the experimental testbed is schematically illustrated, while Figure 4 shows a photo of the laboratory measurement setup using the mmWave transceiver system as described in [15]. The base station performs beam tracking by using a 64–element phased array antenna at 28 GHz as presented in [16]. While in our recent work [4], UAV flight experiments have been carried out relying on virtually perfect external positional knowledge for the purpose of prove–of–concept evaluation, the vehicle trajectory and further, more accelerated motions emulated by a linear guide on a truss are now being tracked self–contained. This setup allows for safe and highly reproducible experiments at higher motion

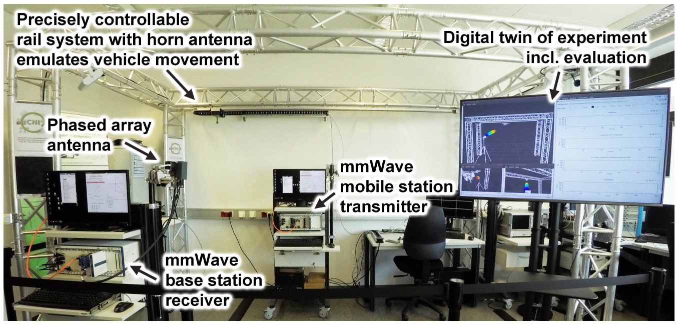

Fig. 4. Illustration of experimental setup. The indoor testbed allows for experimental link evaluations of highly reproducible measurements with a linear guide.

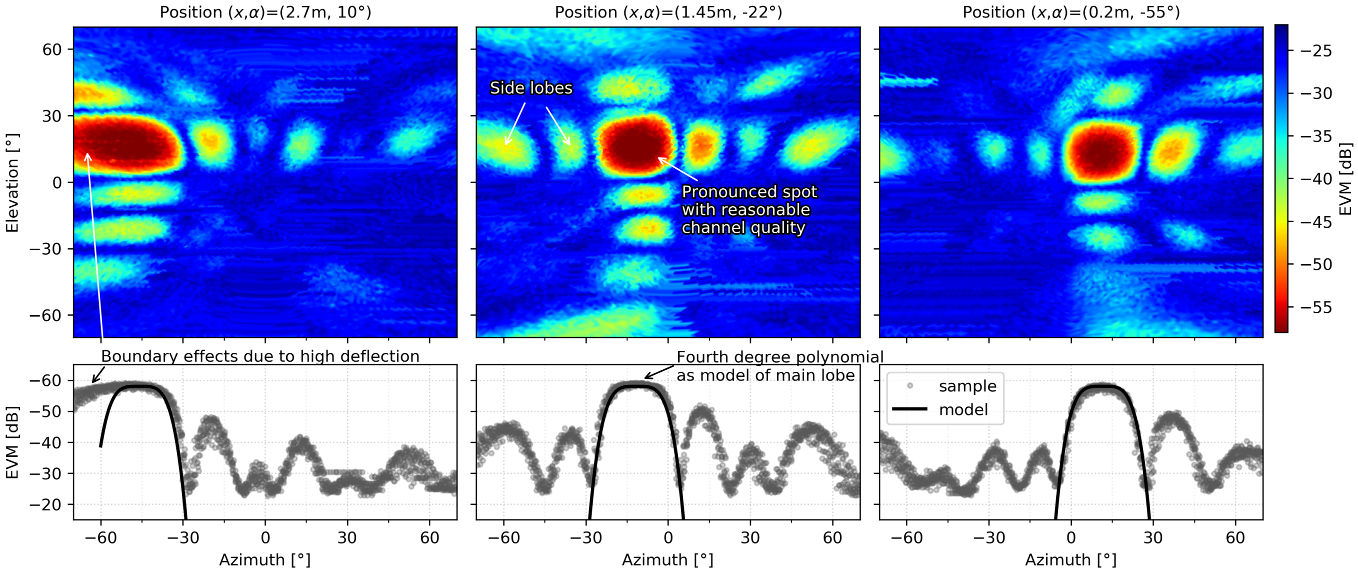

Fig. 5. Top row: Scan results of the complete search space on arbitrary transmitter positions along the movement trajectory. Bottom row: Associated main lobe modelling exemplarily in azimuthal dimension at elevation of $15°$.

dynamics as well as a subsequent meaningful statistical evaluation. During the entire movement along the axis, the mounted horn antenna is continuously mechanically aligned to the base station antenna.

The pose of the base station's phased array antenna hardware is assumed static, as if mounted onto a building, light pole or other infrastructure facility in real world scenarios. Thus, the vehicle's playground is restricted to the area coverable by the base station's beam. To further extend the mobility support, handover procedures will be addressed in a subsequent work. However, several velocities and acceleration patterns are examined, whereas the vehicle's antenna is constantly directed towards the base station like described before. For this reason, a horn antenna with a HPBW of about $54°$ is used, so that the required alignment precision of the vehicle is drastically reduced compared to the strong directivity of the base station's beam.

### A. Ground Truth

As a reference, the appropriate LOS beam direction is computed by considering the target's current relative position. This may also refer to application scenarios with external positioning of the vehicle or frequent feedback about its current position (in case of a UAV e.g. via ADS–B[2]). Here, sharing position information is time critical and requires a high precision to ensure proper alignment.

Due to the need for a precise position reference for comparison and evaluation of different configurations, the experiments are conducted slowed down. This includes the tracking algorithm's speed (beam update rate). Since the implementation is capable of a 50–fold increased beam update rate, it may support accordingly higher angular velocities.

With $(\theta_{\text{ref}}, \varphi_{\text{ref}})$ as ground truth direction, the absolute alignment error $\Delta_{\text{err}}$ of the actual beam is computed by

$$\begin{aligned}\cos\left(\Delta_{\text{err}}\right) = \sin\left(\theta\right) \cdot \sin\left(\theta_{\text{ref}}\right) \cdot \cos\left(\varphi - \varphi_{\text{ref}}\right) \\ + \cos\left(\theta\right) \cdot \cos\left(\theta_{\text{ref}}\right) \quad . \end{aligned} \tag{1}$$

The actual beam direction is expressed by $(\theta, \varphi)$. In this representation, a straight ahead direction (boresight) is achieved with $\theta = 0°$ and the deflection increases with increasing $\theta$, while $\phi = 0°$ points to the left and increments clockwise.

Knowledge of the subscriber's position may considerably accelerate initial access procedures, as the time–consuming beam sweep can be superseded. In case of proportionally rare position update messages, a signal quality based, self–contained tracking may additionally be performed in the meantime to allow for a continuous alignment and thus maintaining an appropriate link quality.

### B. Signal quality modelling and grid spacing configuration

To clarify the behaviour of the EVM as signal quality indicator, it is analyzed for selected static transmitter positions throughout the whole search space coverable by the phased array antenna in Figure 5.

In the top three diagrams, scan results show a pronounced minimum of the EVM where a good signal quality is achievable. Further spots are particularly visible horizontally and vertically from the absolute minimum, which result from the side lobes of the receiving antenna's directional radio pattern.

With these measurements, a model of the EVM characteristic in relation to angle variation is created as can be seen in the bottom three diagrams of Figure 5 in the azimuthal plane for a selected elevation angle of $15°$. It turns out, that the area with suited conditions or *main lobe* can be approximated by a fourth degree polynomial. Due to a reasonable operating range of the phased array antenna of about $\pm 60°$, boundary effects are visible in the left diagram.

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[2] Automatic Dependent Surveillance - Broadcast currently used in commercial aviation, more scalable traffic management systems are in the conception phase

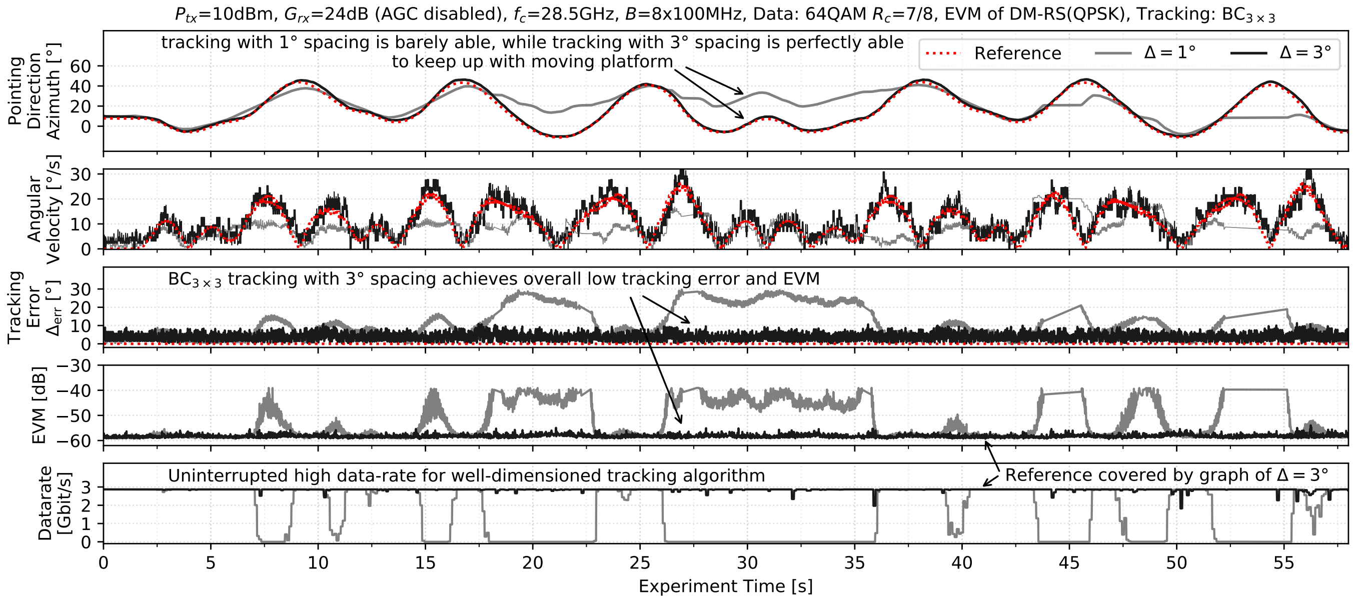

Fig. 6. Exemplary link performance measurement with exploration grid spacing of $\Delta = 1°$ and $\Delta = 3°$. While the trackable velocity is superseded with $\Delta = 1°$, a stable communication link is maintained throughout the whole run with $\Delta = 3°$. Refer to Fig. 2 and 3 for quantity definitions. Due to the need for a precise position reference, the experiments are conducted slowed down. To gain representable results, this includes the tracking algorithm's speed (beam update rate). Since the implementation is capable of a 50–fold increased beam update rate, it may support accordingly higher angular velocities.

As discussed, the Best Choice (BC) method measures the signal quality along an exploration grid similar to traditional *lobe switching* techniques and the direction with the lowest EVM is subsequently selected as estimated target direction. This approach is time and resource efficiently realizable on FPGA hardware allowing for fast beam updates and thus supporting high mobile speeds.

In the following, different spacings $\Delta$ of the exploration grid are examined. Since a 3 by 3 grid is applied, eight additional directions with an offset defined by the spacing $\Delta$ are considered besides the assumed best direction. To evaluate the influence of the intended misalignment during the exploration, EVM and data rate are surveyed for spacings of $\Delta = 1°$ up to $\Delta = 11°$ in Figure 7. For these measurements, the transmitter is fixed at the center position of the guide rail, and the system is configured to transfer payload data with a 64QAM modulation and a code rate of $\frac{7}{8}$ using OFDM and $800\,\mathrm{MHz}$ of bandwidth (see also Table I), while the illustrated EVM is still related to the QPSK modulated DM–RS signals.

The violin plots prove, that in case of a static transmitter a stable and high–rate communication link is only viable with spacings up to $\Delta = 3°$, while greater spacings lead to more frequent drops and worse mean data rates.

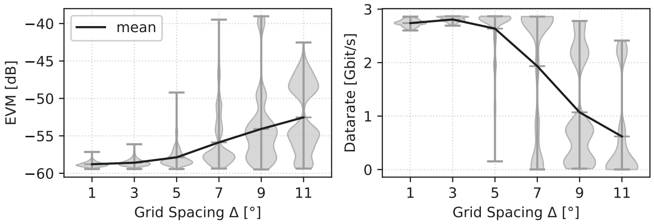

Fig. 7. Comparison of different exploration grid spacings $\Delta$.

## IV. RESULTS OF TRACKING EXPERIMENTS

Taking the previous considerations into account, several experiments with reasonable exploration grid spacings $\Delta$ and different acceleration patterns are conducted. Exemplary time series of two different measurement runs are depicted in Figure 6. The top diagram displays the angular movement of the emulated vehicle as reference and of the beam in the two configurations. In the one run, the motion is partially more rapid than trackable with a spacing of $\Delta = 1°$, so that the target leaves the coverage area which leads to a sharp degradation of signal quality and finally to a link failure. When the vehicle is within range again, a sufficient signal quality is achieved and the maximum data rate is restored, before it is leaving the main lobe once more. Simultaneously, a negatively correlated pattern is identifiable in the tracking error diagram, because the beam appears to hurry after the faster vehicle. With this $\Delta = 1°$ configuration, the system boundary of the maximum trackable mobile speed is exceeded. On the contrary, the second run illustrates, that with a pitched spacing of $\Delta = 3°$ the proposed tracking leads to a reliably high signal quality and thus to a stable communication link. The maximum system capacity of about $2.8\,\mathrm{Gbit/s}$ is maintained throughout the complete measurement series.

The experiments are conducted with exploration grid spacings $\Delta$ of 1°, 3° and 5° and at different dynamics of the emulated vehicle's trajectory. Figure 8 depicts the empirical evaluation of EVM and data rate in relation to grid spacing and tracking dynamics (maximum angular speed). The latter are derived from the velocity and the physical test setup. As also seen at the time series, with a spacing of only $\Delta = 1°$, the beam cannot follow the vehicle because of the slower angular speed. However, increasing the grid spacing to $\Delta = 3°$

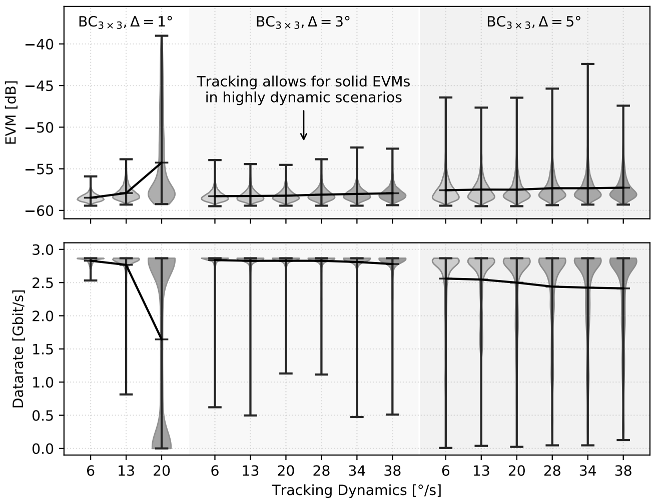

Fig. 8. Comparison of the achievable data rate at different maximum speeds and exploration grid spacing configurations. (Slowed down in the same way as described in Figure 6.)

already ensures a stable communication link with only short impairments. Even greater grid spacings like $\Delta = 5°$ still improve the limit of the maximum supported angular speed, but they also lead to a reduced overall link performance in terms of data rate.

In summary, the experimental results display that a high data rate communication link can be reliably maintained during high angular speeds of the emulated vehicle by applying an appropriate, time and resource efficient tracking approach. A video illustrating the setup as well as the conducted measurements is provided alongside this work in [17].

## V. CONCLUSION

The mmWave frequencies offer high bandwidth, which may be also suited for several vehicular applications. In the course of this, the major challenge arises from the essential directionality of the antennas and the assumed high vehicular mobility considering networked indoor robotics, UAVs, connected cars and high–speed trains. The need for precise beam alignment has been elaborated experimentally in our recent work, so that this work focuses on its exploration and tracking.

Signal quality measurements can be leveraged to evaluate each single beam direction, but an exhaustive search proves to be time–consuming. For this reason, knowledge of the vehicular mobility can be incorporated to drastically reduce the search space. Reusing available reference signals like DM–RS, no additional signalling overhead may be required.

Our 5G mmWave beam tracking testbed allows for the reproducible emulation of various vehicle trajectories and a signal quality as well as data link based evaluation of a proposed tracking method. Extensive experimental evaluation results show, that a time and resource efficient search pattern applying a 3 by 3 exploration grid with a spacing of 3° delivers sufficient quality even in challenging mobility scenarios.

In future work, this testbed will be extended by link recovery methods to cope with blockage and it will be integrated into our software–defined end–to–end system from [14].

## ACKNOWLEDGMENT

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