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On the Potential of 5G mmWave Pencil Beam Antennas for UAV Communications: An Experimental Evaluation

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***Abstract*—Beamforming and pencil beam antennas are expected to become a major component of 5G mmWave networks. While spatial separation and high gains are anticipated benefits, the suitability of those new antenna types in highly dynamic scenarios, such as the use on Unmanned Aerial Vehicles (UAVs), requires appropriate real–time steering capabilities and needs to be proven in practice. In this paper we present results of lab experiments leveraging a wireless robotics testbed implementing a mmWave link at 28 GHz between a fixed base station equipped with a pencil beam antenna and an UAV. The setup allows the investigation of the beam tracking performance in terms of signal strength, quality and throughput for different antenna tapers, tracking algorithms and mobility patterns. This — to the best of our knowledge — first experiment applying mmWave communications at 28 GHz for air–to–ground communications confirms the potential and feasibility of pencil beam antennas for UAV communications. In case the antennas are aligned within a given error margin, a stable air–to–ground connection was observed during the flight experiments.**

I. Introduction

Recent developments in Unmanned Aerial Vehicle (UAV) technology enabled a wide set of applications reaching from remote sensing [1] up to providing coverage in disaster relief scenarios [2]. With the cost and size reduction of high quality sensors, the requirements for capable and reliable communication increase significantly and bear a challenge to a variety of research [3] ranging from basic considerations up to cognitive networking [4].

However, a number of challenges arise regarding swarm internal communications as well as air–to–ground (A2G) communication links. As depicted in Figure 1 (a), the employed public land mobile networks (PLMNs) indeed provide an exhaustive supply of wireless communications on the ground, but the radio channel available for the UAVs suffers from shadowing close to ground and from the decreasing antenna gain outside the main lobe at higher altitudes [5]. On the other hand, air–to–air (A2A) communications with respect to mesh networks are afflicted with height–selective fading [6], as shown in Figure 1 (b). Due to the widely used omnidirectional antennas on UAVs, interference further impacts the link performance.

In the context of the fifth generation of mobile communication (5G) [7], millimeter wave (mmWave) technology promises to overcome those challenging radio conditions by means of beamforming and tracking antennas. Considering Friis's transmission law, the frequency of 28 GHz appears to involve a by far higher path loss than the conventional sub 6 GHz mobile communication technologies. Nevertheless, smaller wavelengths allow for greater antenna gain with the same antenna size [8], [9]. Furthermore, deploying directional mmWave antennas at transmitting and receiving side may even allow more than a compensation of losses caused by the higher frequency [10].

Based on this background, the vision of mmWave beamforming and tracking systems appears to be very suitable for future UAV communications in 5G networks. As illustrated in Figure 1 (c), our vision of 5G focuses on pencil beams, which may be generated by phased array antennas (PAAs) and are therefore steerable to follow the UAV trajectories. With the help of beam tracking, the UAV may mostly find suited channel conditions with much less multi–path propagation effects or interference by surrounding UAVs, so that the overall communication quality can be kept on an appropriate level. The conducive effect of precise antenna alignment is evaluated experimentally at both static and dynamic UAV tracking scenarios. In the dynamic case, the UAV leverages antenna tracking for high data rate mmWave communication in flight. Consequently, the UAV would mostly operate in line–of–sight (LOS) conditions and scarcer shadowing environments may be handled by a communication–aware mobility control of the UAVs as a further approach [4].

The remainder of the paper is organized as follows: After discussing the related work in Section II, we present analytical considerations regarding the UAVs' communication channel in Section III. A description of our experimental testbed together with a presentation of our measurement results follow in Section IV. A summary concludes the paper in Section V.

II. Related Work

As higher frequencies lead to higher path losses, mmWave systems rely on antenna gains and the resulting strong directionality. With 5G the mobility aspect of mmWave communications become more important, because highly directional antennas need to track the moving devices precisely. A comprehensive survey on using of mmWave communication in future mobile networks is presented in [11], where the channel

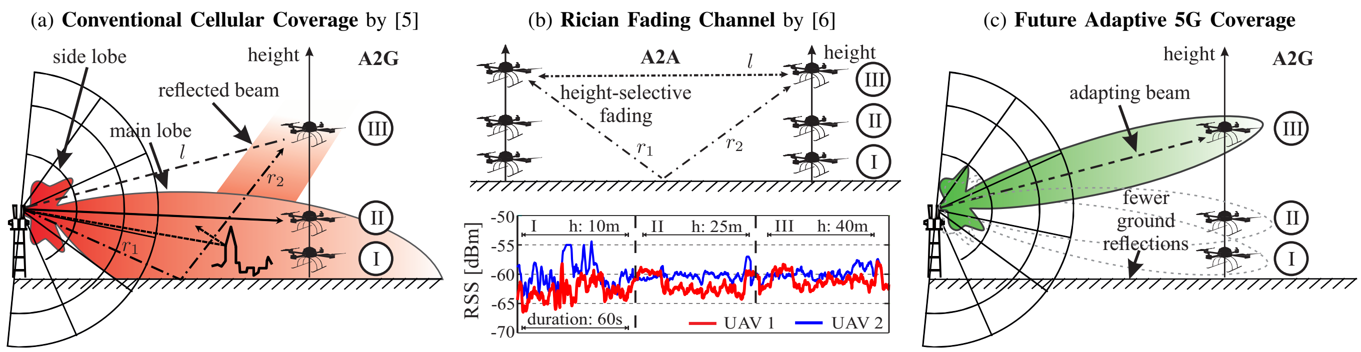

Fig. 1. Vision of pencil–beam–enabled 5G ultra–reliable, low latency communication for unmanned aerial vehicles.

characteristics and channel modeling are brought up as one of the main challenges. As recently pointed out in [12], there are several generic channel model approaches available.

In [13], the 3rd Generation Partnership Project (3GPP) has studied channel models from $0.5\,\mathrm{GHz}$ to $100\,\mathrm{GHz}$, including a list of further efforts like the mmMagic Project [14] or the NYU Wireless approach [15] to name a few. Especially in the context of UAVs, a supposed height dependence should be considered, but most of the channel model approaches are not designed for heights. Although 3GPP defines a 3D channel model for below $6\,\mathrm{GHz}$ frequencies in [16], the inclusion of the heights is even limited to outdoor–to–indoor scenarios with buildings with up to eight floors (i.e. maximum heights of $22.5\,\mathrm{m}$). Merely in [17] authors present some ray tracing results for UAV air–to–ground channels at $28\,\mathrm{GHz}$ and $60\,\mathrm{GHz}$.

Bringing together mmWave and UAVs to operate cellular networks is discussed in [8], whereas [18] addresses the use of relays to circumvent obstacles and therefore to overcome shadowing and non–LOS conditions. A phased array antenna (PAA) is used to detect missing people through UAVs in [19]. Simultaneously, [8] focuses on customization of the antenna pattern due to the use of PAAs: With a base station mounted on the flying vehicle, a wider beam facilitates the discovery of mobile stations during random access, whereas narrower beams qualify for payload transmissions. Simulations in [20] prove that flying base stations connote an alternative for dense small–cell networks. A small scale PAA is designed in [21] to fit into a metal cased mobile device with the dimensions of a common smartphone, which can probably be mounted on or integrated into an UAV, too. Apart from that, authors in [22] present a real–world experiment utilizing beam tracking at $28\,\mathrm{GHz}$ to run a wideband transmission to a moving motor vehicle. Up to now, to the best of our knowledge, no dedicated experiments combining UAVs and pencil beams at $28\,\mathrm{GHz}$ are documented.

In contrast to other work, this paper aims to experimentally analyze the tracking capabilities of modern 5G beamforming antenna systems for applications. Although it is currently not possible to fully integrate a mmWave system into the flying entity, a tethered–antenna testbed will be suitable to show the potential of the proposed approach on a mid–air UAV.

III. Observations on Air–to–Ground Link Quality

In the following subsections, we discuss existing analytical channel models for UAV–to–ground communications based on conventional cellular networks and the expected impact of mmWave communications under the use of pencil beams.

A. *Conventional Cellular Mobile Networks*

The conventional PLMNs are designed for good coverage on the ground. As shown in Figure 1 (a), this is done by using directional sector antennas with tilt down. To describe the specific characteristics of cellular network coverage for UAV communications, the Height and Distance Dependent Air–to–Ground channel model (HD2–A2G) has been introduced in [5]. The HD2–A2G model has been derived from flight experiments measuring the connectivity of real–life cellular networks in heights up to $500\,\mathrm{m}$ and has been validated by ray tracing simulations. While located in the main lobe, shadowing of the existing development impairs the channel at small altitudes near ground (Zone I). From a certain height, the shadowing is reduced while the main lobe is still present (Zone II). At even higher altitudes, only main lobe reflections and some side lobes are available (Zone III). The HD2–A2G model defines the received signal strength (RSS) based on the two–ray ground model, where the gains of the direct and the reflected path as well as the path loss exponent are height–dependent. With increasing height, i.e. leaving zone I, the gains of both paths decrease. There is no direct path in zone III because of the down tilt angle of the base station. Nevertheless, the reflected path persists with linear decreasing gain. Additionally, the path loss exponent is higher at the two lower zones I and II and becomes equal to free space propagation at higher altitudes in zone III.

The interrelation between the height and a normalized path gain derived from the HD2–A2G model is shown in Figure 2. The additional graphs are created with the quadriga channel model generator [23], and all the curves are post processed by a moving average filter for better readability of the large–scale effects. At this point, base station and mobile station are $1500\,\mathrm{m}$ horizontally apart from each other and an operating frequency of $2.1\,\mathrm{GHz}$ is assumed (for more details, see [5]). To facilitate the comparison, the curves are normalized to start from the beginning of zone III at a gain of $0\,\mathrm{dB}$. This is

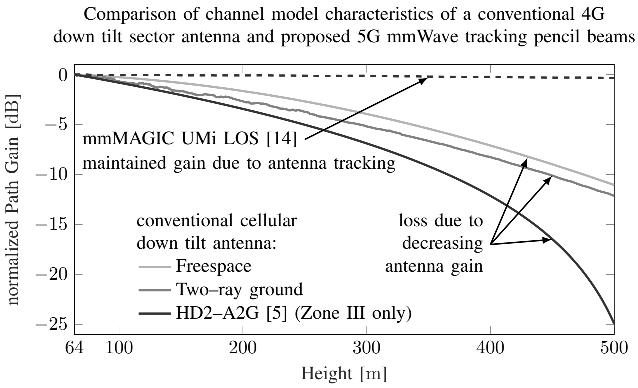

Fig. 2. Normalized path gain vs. height at a horizontal distance of 1500 m and with a base station height of 32 m. Whereas the lower three graphs show results for a conventional cellular down tilt antenna, a precise pencil beam steering is deployed for the mmWave approach.

to focus on the expected impact of mmWave beamforming antennas for LOS connections at heights beyond the main lobe of the conventional cellular base station antennas. The impact of buildings and other ground objects will be addressed in future work.

The HD2–A2G path gain declines gradually in the depicted Zone III, as on these heights side lobes as well as reflections from the ground dominate, while the main lobe is no longer available. For comparison, the two–ray ground model and the free space attenuation curves are displayed at the same assumed frequency and with the mentioned scaling, too.

Additionally, as modeled in [6], there might be a height dependency in the rician fading channel as depicted in Figure 1 (b). The bottom graph illustrates the higher variance of the received signal strength (RSS) at low altitudes, since the amount and the impact of reflecting surfaces might vary at different altitudes.

Based on the aforementioned observations, conventional cellular mobile networks are not ideally suited to provide coverage for UAVs in heights above 100 m, as they focus on ground coverage and are not intended for A2G communication. While it is technically possible to close this gap by adding additional antennas with fixed orientation to cellular networks, pencil beams enable a much more tailored coverage to UAVs. At the same time, pencil beams also address the interference issues introduced by UAVs [24], [25].

B. Upcoming 5G mmWave Mobile Networks

The upcoming fifth generation of mobile communication will focus on frequencies above 6 GHz, especially on wavelengths in the millimeter domain.

In addition to the large bandwidth, one of the major prospects of mmWave comes with the viable antenna directivity with less space requirements at those wavelengths. By means of PAAs, beam steering can be applied to keep the mobile station mostly in the main lobe of the pencil beam and find appropriate channel conditions as depicted in Figure 1 (c). Particularly UAVs, as flying participants of the mobile network, might benefit from the tracking capabilities of PAAs, since they might experience a high LOS probability at higher altitudes. Even the scalability of these networks rises using the focused lobe of the pencil beam for multi–user MIMO and space division multiplex (SDM) approaches. On the other hand, a precise antenna tracking is needed, where the pencil beams pursue each participant.

Considering the pencil beams with the mmMagic model from [14] at 28 GHz, Figure 2 shows that their use indicates stable air–to–ground links for UAVs which may fly at different heights. Here, directional tracking antennas with a half power beam width (HPBW) of approximately 13° are selected at the transmitter as well as the receiver. Since in this scenario the distance between transmitter and receiver (i.e. the length of the direct path) only varies by less than 5 %, the normalized path gain with the tracked antennas appears constant (less than 0.5 dB with pathloss exponent $\gamma = 2$). In contrast to the curves considering a conventional down tilt antenna, the use of directional tracking antennas enables a continuously maintained path gain.

Regarding the mentioned height–dependent rice fading according to Figure 1 (b), the high directivity due to utilizing pencil beams also diminishes the interferences of multipath propagation. Fewer non–LOS components consequently induce a less pronounced distribution of the short–term fading channel.

Conclusively, if there is a precise tracking of the mobile station, the utilization of highly directional beams promises advantages for UAV channels.

IV. Experimental Evaluation

To evaluate the stated observations, we present our mmWave test system utilizing a tracking pencil beam in a mobile UAV context. The general experimental setup is described, before first results are presented.

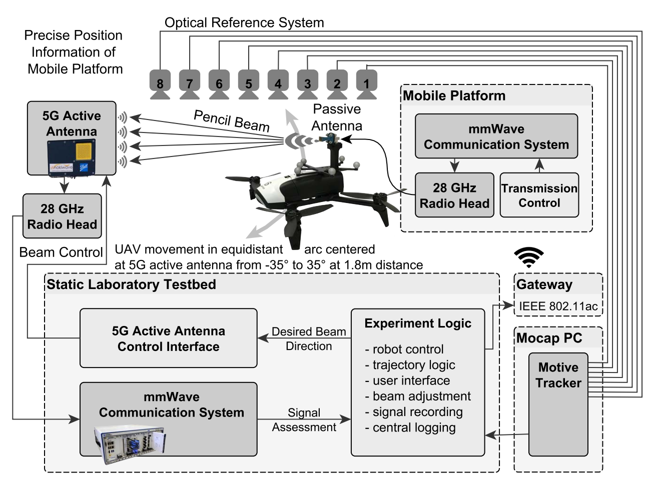

Fig. 3. Schematic illustration of the experimental setup. The highly directional pencil beam follows the mobile platform using precise feedback from an optical reference system.

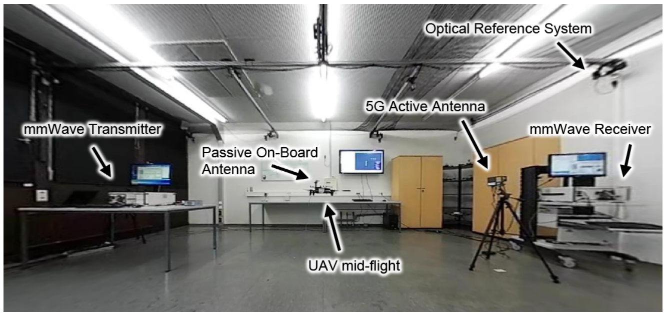

Fig. 4. The experimental setup in our UAV lab. The optical reference system acquires precise position information of the transmitting UAV. The UAV's horn antenna is connected to the mmWave transmitter, whereas the pencil beam antenna on the right–hand side is connected to the mmWave receiver.

A. Experimental Setup

In order to analyze the capabilities of state of the art 5G hardware, this work performs experiments with an actual UAV. The overall structure of our experimental setup is depicted in Figure 3. The communication link is built upon the National Instruments mmWave transceiver system, as presented in [26]. Since the aim is an evaluation of the tracking capabilities in an UAV scenario, a simple transmitter–receiver scheme is used by sending from the mobile drone–based platform to the static infrastructure side. The system operates at a center frequency of $28.5\,\mathrm{GHz}$ with a bandwidth of $800\,\mathrm{MHz}$, divided into eight component carriers, each with $100\,\mathrm{MHz}$ bandwidth. A 64QAM with a code rate of $\frac{7}{8}$ is used as modulation and coding scheme (MCS).

As a lightweight UAV system is chosen for this experiment, it is equipped with a passive antenna only, while the active antenna is representing the ground station. In order to have a ground–truth for the tracking performance evaluation and to control the 5G active antenna, an optical reference system is used to obtain highly accurate position and orientation information of the UAV and hence of the passive antenna.

The pencil beam antenna[1] is located at a certain distance and height pointing towards the moving UAV. The antenna taper has a HPBW of approximately $13°$ and the UAV can be precisely controlled to move along predefined tracks facing towards the beamforming antenna. Based on that, the setup allows the investigation of the received signal quality at different poses of the UAV and at different angles of the pencil beam. Figure 4 shows the flying UAV with a mounted lightweight horn antenna directed to the pencil beam antenna on the receiver side. The horn antenna has a HPBW of approximately $54°$ and contributes $10\,\mathrm{dBi}$ to the link budget. While the horn antenna is azimuthally aligned to the receiver by the UAV's yaw orientation, the pencil beam antenna tracks positioning information provided by the optical reference system. In the long term, the alignment of the pencil beam should be independent of any auxiliary system, for example via a RSS scan functionality and controlling in MAC layer.

[1]The used pencil beam antenna is an AnokiWave AWMF-0129 (c.f. http://www.anokiwave.com/products/awmf-0129/index.html [Accessed Nov. 6, 2017]).

Besides the position and orientation information, the receive gain of the automatic gain control (AGC), the error vector magnitude (EVM) and the achieved data rate are recorded for the following evaluation.

B. Experimental Results

Below, first results of an actual $28\,\mathrm{GHz}$ mmWave test system, as presented in [26], used together with the mentioned pencil beam PAA are presented. Three experiments have been carried out in both static and dynamic UAV setups.

1) Study of the pencil beam alignment: First, the characteristic of the used PAA is studied in a static environment. The transmitting horn antenna is located at boresight of the pencil beam antenna, which itself is in receive mode at a distance of $1.8\,\mathrm{m}$. During the experiment, the pencil beam is azimuthally steered from $-15°$ to $15°$. Figure 5 shows the measurement results with respect to the controlled absolute azimuthal misalignment $|\chi|$ of the beam–steering, as the setup is symmetric around the boresight angle of $0°$. Starting from the right–hand side of the figure at $|\chi| = 15°$, there is no communication possibility due to the significant misalignment. When the misalignment decreases to $|\chi| < 7°$, the achievable data rate increases abruptly within a range of $\Delta\chi = 2°$. That is caused by the EVM decreasing below $-24\,\mathrm{dB}$, which in turn is obtained by the now present antenna gain. From here on, the used MCS seems to be robust enough to enable a communication link. In the range of $|\chi| \leq 5°$, the maximum data rate of $2.8\,\mathrm{Gbit/s}$ for this MCS is reliably achieved.

All in all, the alignment of the pencil beam turns out to be the crucial point in terms of feasibility of mmWave communication. For this reason, the following experiment focuses on a prove of concept for tracking on flight.

2) Precise tracking of UAV in flight: After discussing the directivity at a static setup, for this experiment the UAV flies a circular sector of $60°$ with a fixed distance of $1.8\,\mathrm{m}$ to the receiving pencil beam antenna. The movement of the UAV over time is shown in Figure 6 (a)–(c). The top figure illustrates the time–dependent movement on the horizontal

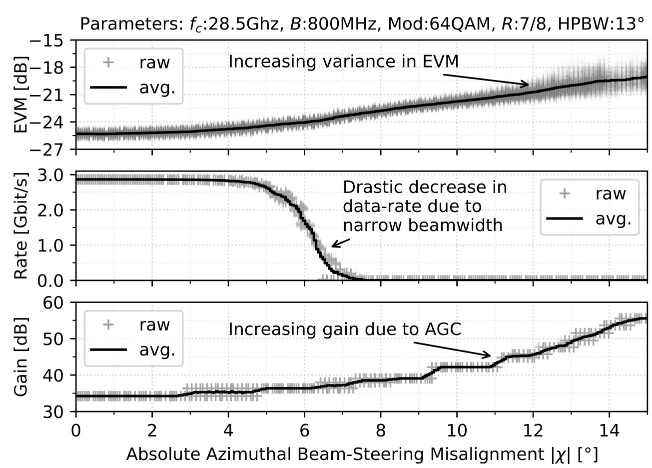

Fig. 5. Alignment study: The used pencil beam has a HPBW of approximately $13°$. Thus, a precise alignment of the pencil beam is crucial, as the diagram shows.

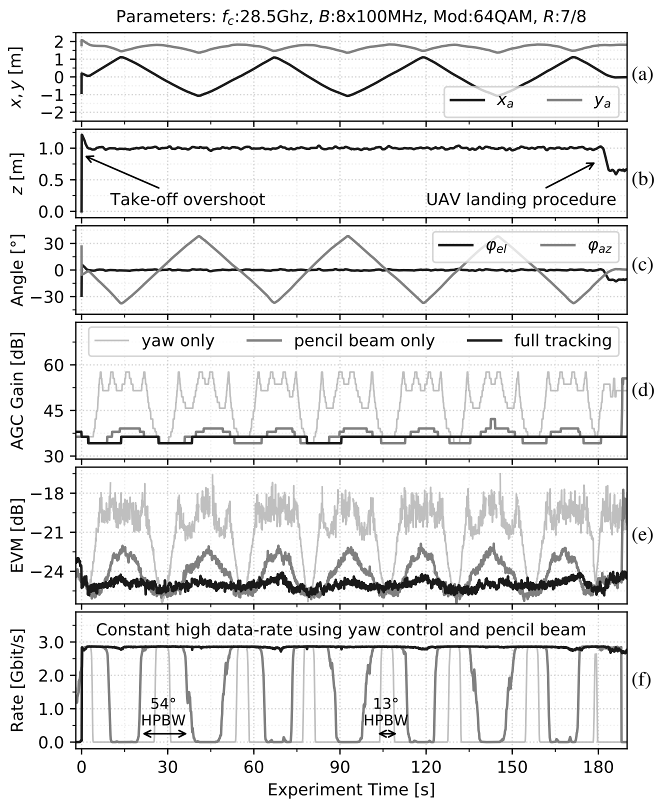

Fig. 6. While the top three axes display the course of the UAV, the bottom three present the measurement results depending on the tracking entity.

plane with the pencil beam antenna position defining the origin. While the y coordinate describes the displacement in boresight direction, the x coordinate represents the orthogonal deflection. For better readability, the derived azimuthal angle of deviation φ_{az} is shown in the third axis. Here, the circular sector of $60°$ (i.e. $\pm 30°$ from boresight) becomes visible, as the UAV moves back and forth on the $30°$ deviation three times and returns to boresight before landing. The second axis shows the Cartesian height coordinate z, whose origin is defined on the ground below the pencil beam antenna. Starting from ground, the UAV aims to hold a height of $z = 1\,\mathrm{m}$, as this is the altitude of the stationary receiving antenna. The derived elevation angle φ_{el} relative to the pencil beam antenna is also presented in the third axis and is almost $0°$ over the entire experimental procedure, except for takeoff and landing.

This experimental procedure has been performed three times to cover all three tracking modes: *yaw only*, *pencil beam only*, *full tracking*. Initially, the UAV repositions its azimuthal orientation (i.e. its yaw angle) to align the mounted horn antenna to the receiver, while the receiving pencil beam stays aligned to boresight (called "yaw only" in Figure 6). In a second run, the UAV's yaw angle is fixed during a whole flight, while the pencil beam tracks the UAV continuously ("pencil beam only"). At last, a "full tracking" is done, where both participants align the main lobes to each other as this promises the highest antenna gains. Therefor, the horn antenna is aligned through a tracking yaw angle of the UAV and the PAA receives pointing commands derived by the optical reference system information.

The experimental results are presented in Figure 6 (d)–(f): In this scenario, the system is designed in such a way that the additional gain of both antennas decides on the feasibility of data transmissions. Especially the different beam widths of the used antennas become clear in the bottom axis as the range of a functioning transmission is similar to the beam width of the not tracking antenna. The advantage of the higher antenna gain of the pencil beam becomes clear in the fourth axis, as the AGC needs to increase the RX gain much less with tracking pencil beam and misaligned horn antenna than vice versa.

On the other hand, the bottom axis highlights, when tracking on both sides, a continuously high data rate can be maintained throughout the entire measurement period.

3) Effects of the tracking precision: The optical reference system delivers positions with an accuracy in millimeter range. However, a greater blur could possibly be tolerated, too. To analyze this factor, the required tracking precision is evaluated in the next run. The static setting of the first experiment is reestablished, so that the UAV is at boresight in a distance of $1.8\,\mathrm{m}$ from the receiving pencil beam antenna, again.

In the course of a precisely aligned horn antenna, the pencil beam antenna gets pointing commands with noisy direction information. Thus, the ideal pointing angle of $0°$ in azimuth and elevation is superposed by a normally distributed, zero mean error with a defined standard deviation σ.

Figure 7 plots the empirical cumulative distribution function (CDF) of the achieved data rate depending on the chosen standard deviation σ. In the ideal case ($\sigma = 0°$) the curve has a defined peak only at the maximum data rate, i.e. no lower data rate was achieved in this optimal run. With $\sigma = 2°$, the achieved data rate is below the maximum for just $20\,\%$ of measuring data. As σ rises, the data rate succumbs the more frequent misalignments, which leads to an outage of $20\,\%$ to $80\,\%$ with $\sigma = 4°$ to $\sigma = 10°$, respectively. The experiment shows the need for an accurate antenna alignment, as even a standard deviation of a few degrees leads to unstable communication.

The results allow to quantify the requirements for accurate beam tracking and alignment algorithms in order to leverage the full benefit of pencil beam antennas.

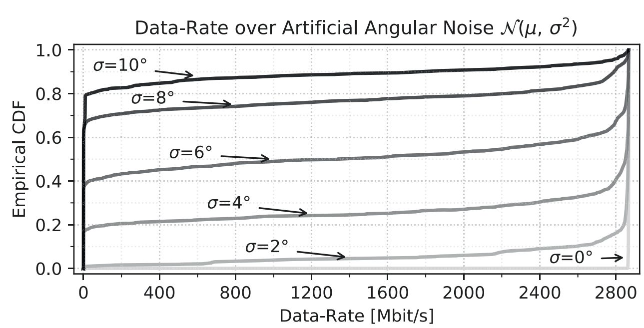

Fig. 7. Results of sensitivity analysis regarding the accuracy of the antenna aligment: CDF of data rate achieved with various angular noise.

V. Conclusion

Future mmWave technology employing directional beams promises to overcome the limitations of current UAV–based mobile networks. Not only the limits of current cellular systems are expected to be improved, but also the challenging multi–user mid–air channel will gain significantly through the obtained spatial diversity. This paper focuses on an analysis of the dynamics of the beam–steering versus the tracking and communication quality. The lab platform presented in this paper allows for experimental analysis of the beam tracking performance in UAV environments.

In our experiments, the benefits of tracking the highly directive mmWave antennas are illustrated as first results. A qualitative evaluation of the tracking precision is done to provide the basis for defining the requirements of future self–contained UAV platforms utilizing 5G mmWave communication with the aid of tracking pencil beams.

In future work, we will further investigate the characteristics of 5G mmWaves by means of pencil beams in an outdoor mobile environment. In addition, the depicted platform is planned to be extended to support multiple beams and bidirectional communication in the near future. Finally, we plan to investigate the impact of pencil beams on the interference with ground networks in UAV communication scenarios.

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