Concept Design and Performance Evaluation of UAV-based Backhaul Link with Antenna Steering

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Abstract: **At present, cellular coverage in many rural areas remains intermittent. Mobile operators may not be willing to deploy expensive network infrastructure to support low-demand regions. For that reason, solutions for the rapid deployment of base stations in areas with insufficient or damaged operator infrastructure are emerging. Utilization of unmanned aerial vehicles (UAVs) or drones serving as data relays holds significant promise for delivering on-demand connectivity as well as providing public safety services or aiding in recovery after communication infrastructure failures caused by natural disasters. The use of UAVs in provisioning high-rate radio connectivity and bringing it to remote locations is also envisioned as a potential application for fifth-generation (5G) communication systems. In this study, we introduce a prototype solution for an aerial base station, where connectivity between a drone and a base station is provided via a directional microwave link. Our prototype is equipped with a steering mechanism driven by a dedicated algorithm to support such connectivity. Our experimental results demonstrate early-stage connectivity and signal strength measurements that were gathered with our prototype. Our results are also compared against the free-space model. These findings support the emerging vision of aerial base stations as part of the 5G ecosystem and beyond.**

Index Terms: **Drone, antenna steering, prototype, measurements.**

I. Introduction

MOBILE traffic demand has been dramatically increasing over the past decades [1] and is predicted to continue growing with the evolution of the next-generation (5G) wireless networks [2, 3]. Even though demand for cellular coverage in rural areas is high, access therein is still limited for many people [4]. According to BusinessLIVE, this is primarily because cellular operators focus on developing/upgrading their installations in metropolitan areas, where demand for spectrum is higher [5].

From another perspective, a natural disaster may occur and damage infrastructure anywhere, thus leaving certain areas without sufficient connectivity [6, 7]. Such scenarios require efficient and easy-to-deploy solutions that deliver temporary connectivity to these regions. As an example, one may conventionally consider a relay [8–10], utilization of vehicular networks [11, 12], or a stand-alone base station (BS) [13]. In present-day networks, such solutions are mostly facilitated by cell relays, referred to as cell on trucks (COT) or cell on wheels (COW) [14]. Many remote areas have low cellular coverage or no coverage. These areas may be affected to a greater extent as the demand for coverage in such locations is insufficient over extended periods of time and soars in cases of emergency.

However, the use of a relay BS mounted on a ground vehicle is rather expensive due to its large dimensions and the need for personnel to operate it. Usually, a team of at least a driver and a telecommunications technician is required [15]. This motivates companies to consider more flexible approaches such as small cells and relays [16]. Recently, research attention was drawn to the development of cheaper and easier to deploy 5G-grade solutions. One of these solutions involves the use of unmanned aerial vehicles (UAVs) [17, 18].

Initially exploited by the military, UAVs are currently gaining interest from civilian users due to rapid developments in electronics and mobile communications. A flying device without a human pilot on-board is a flexible solution that is suitable for a broad range of applications [19–21], such as goods delivery, video surveillance, anti-drone monitoring, and aerial mapping, among many others. In fact, UAVs have become so popular that the Federal Aviation Administration in the United States demands mandatory registration of new drones and has restricted their commercial use until thorough regulations are issued. In 2018, it was estimated that the number of commercial aerial drones will reach about 600,000 units [22].

UAVs (or drones) have already been studied by the research community from different perspectives [13]. Several companies propose deploying air balloons to provide extended cellular coverage in remote areas affected by natural disasters [23]. These are called low or high altitude platforms (LAPs or HAPs, respectively). A company by the name X Development LLC is also running a project where air balloons operate in the stratosphere and bring cellular coverage to remote locations [24]. The mobile company EE (formerly Everything Everywhere) implemented a similar solution for rural coverage and disaster recovery, known as Air Mast [25]. This drone-based communication network is potentially suitable for deployment during emergencies and critical public safety situations, as well as in high-density metropolitan scenarios. Both cases are of interest for emerging 5G systems [26–28].

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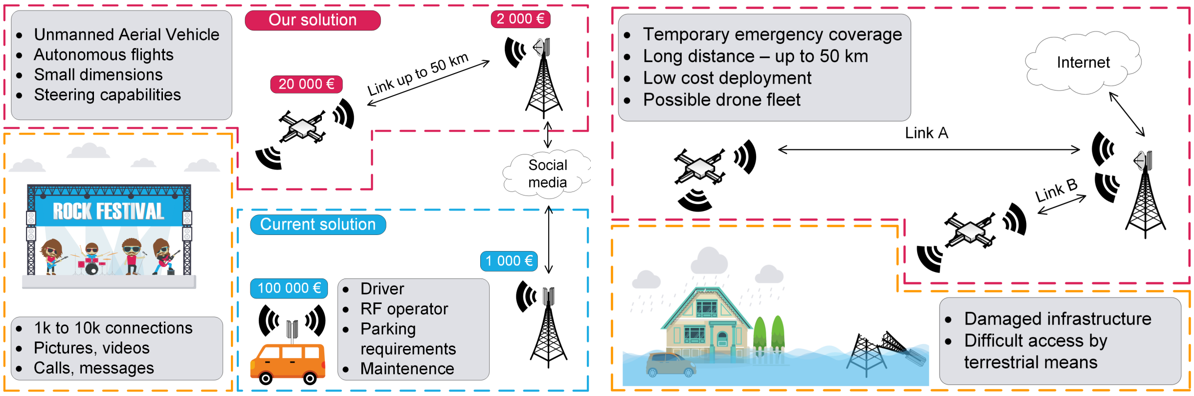


(a) Service on demand – mass event. (b) Disaster recovery.

Fig. 1. UAV base station: operating scenarios.

A. *Related Work*

The motivation for our research is strongly supported by the research community. The authors in [29] studied the coverage provided by low-altitude platforms for use in urban and rural disaster-affected areas. In [30], the authors proposed a statistical propagation model for the air-to-ground path loss between an LAP and a terrestrial terminal. Solutions with balloons are typically not very fast and flexible due to their slower deployment, lower mobility, and larger dimensions. Some prior research investigated opportunities for drone deployment in different scenarios. The authors of [31] focused on analyzing urban utilization of skyscraper drone BSs. This study modeled such a system, which is relatively close to the results collected in our study.

Overall, aerial BSs using UAVs with propellers, specifically, quadcopters, hexacopters, or octocopters, were also considered by other researchers. The recent work in [32] describes flying cell towers using UAVs with propellers with a GreenCell LTE BS that extends an existing cellular network or creates a new one. Furthermore, CyPhy company develops a tethered drone powered from the ground, which allows extension of currently limited flight times, but at the cost of lower mobility and more complex deployment. The proposed drones were developed for various purposes, one of them being communications [33]. The industrial giant Nokia has also developed a compact LTE solution that employs drones for public safety [34].

The work in [35] presents an innovative approach for enabling emergency communications in the field based on a combination of aerial and terrestrial mobile stations. The project aims to considerably improve disaster recovery and crisis management. A similar concept is described in [36]. In parallel with prototyping, many researchers are working with aerial access points from a simulation perspective. The conventional aspects of capacity, coverage, and interference are discussed in [37, 38].

The overall benefits brought by utilizing aerial access points for cellular network enhancement are discussed in [39]. The work in [40] sheds some light on interference and propagation impact of cellular BSs. The authors of [41] developed an analytical model to evaluate drone-to-ground communications. In general, many telecommunication developers and researchers have the same goal: to bring network coverage to remote areas by employing an aerial vehicle. A drone can reach the designated area promptly while delivering connectivity to locations not accessible by conventional ground vehicles.

B. *Main Contributions*

In this study, we consider two types of scenarios shown in Fig. 1: (i) *a public event* (or on-demand connectivity) and (ii) *a Public Protection and Disaster Relief* (PPDR) situation [7, 42]. The first type of layout is usually known in advance and could be planned efficiently. Here, the advantage of the proposed solution is the cost of deployment. The second scenario can correspond to a natural disaster, which is unpredictable and requires an immediate response.

In this paper, we discuss our concept of an aerial BS, where backhaul (BH) link connectivity is implemented via microwave communication between the BS and the drone. The main contributions of our paper are as follows:

1. **Concept design.** We propose a new design for an aerial vehicle controlled via the TCP/IP protocol stack (IP layer). The introduced solution is capable of carrying network equipment for a BH link. This UAV was specially designed, constructed, and tested.

2. **Easy-to-deploy LTE BS solution.** The UAV-based eNodeB is flexible and can be deployed quickly. LTE relays are usually transported on trucks, which are slow and can potentially be stopped by damaged terrain and/or poor road infrastructure. The proposed solution can completely replace current alternatives due to its lower cost demands and significantly reduced reaction times in case of an unexpected situation, e.g., PPDR.

3. **Steering algorithm and mechanism.** The drone is a highly mobile aerial vehicle that cannot be fixed to any solid object. Its movement, whether intentional or not, can be random and not very precise. For this reason, we developed a steering algorithm that compensates for drone movement and maintains radio signal stability at high levels.

4. **Early-stage measurements.** We conducted initial connectivity and signal strength measurements with the utilized equipment and compared our results with the free-space propagation model.

II. Proposed System Architecture

Before continuing with the actual steering mechanism description, it is important to construct an initial setup for the UAV and the ground station. This initial composition will further facilitate the configuration of actual devices.

In this section, we describe the complete architecture of our developed testbed. It includes a description of the working UAV prototype together with the networking equipment and ground station. The overall setup of our proposed system is shown in Fig. 2. It includes the BH link, which handles two data streams: (i) one stream transmits user data and information (red link) and (ii) another carries telemetry information and provides drone control (blue link). Those links are established via a routing device located on the UAV side. The aerial vehicle is equipped with 5 GHz antennas to establish a BH link between the UAV and the ground station. The utilization of higher frequencies may also be considered [43].

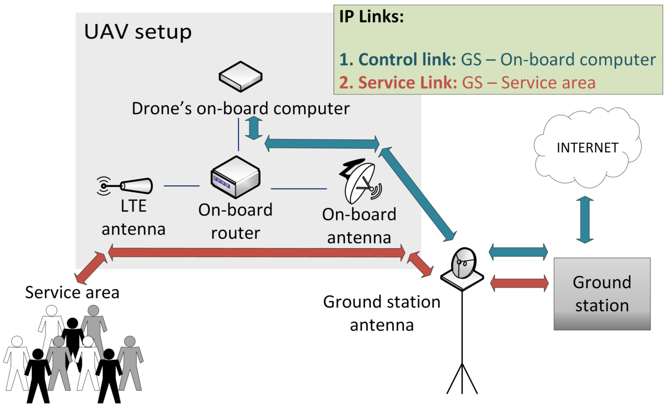


Fig. 2. Configuration of the backhaul link and sub-links allocated within (control link and service link).

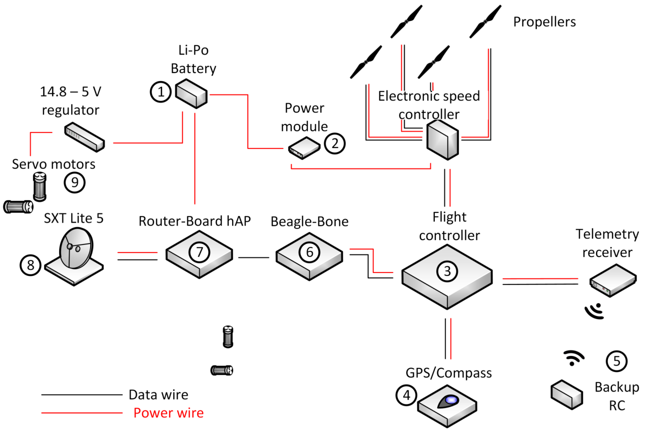
A crucial feature of the utilized UAV in our proposed test scenario is represented by a case where the UAV must move to a desired position and remain static by maintaining a connection to the ground station through a BH link. Therefore, the ground station can exchange data packets with users and telemetry packets with the UAV, as well as control the UAV in real time. To enhance the functionality of this link, a steering system is designed that autonomously tracks both antennas (detailed in Section III) in the UAV and the ground station. This system allows the UAV to be controlled over longer distances.

The following subsection discusses the hardware selected for the aerial vehicle and the ground station, along with a clarification of the relevant components.

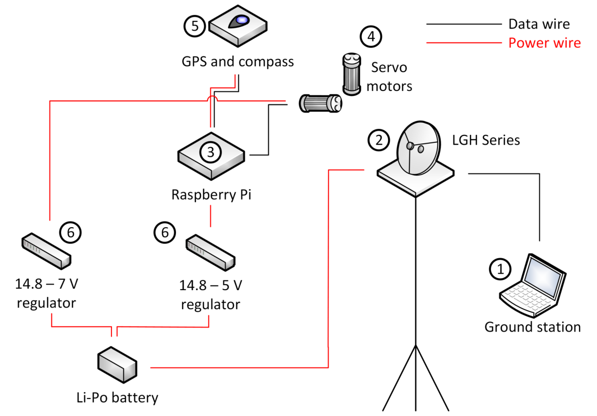
A. UAV Prototype

Our UAV prototype has been designed similar to one completed by the authors in a prior robotic system project [44]. The key difference is that our current idea refers to an aerial vehicle instead of a terrestrial vehicle, thus resulting in different hardware requirements.

A diagram with the relevant hardware integrated into the UAV is detailed in Fig. 3(a). The primary equipment used in the UAV prototype is listed in Table. 1.



(a) UAV.



(b) Ground station.

Fig. 3. Interconnection between the UAV and the ground station.

B. Ground Station Configuration

The ground station includes a computer and an antenna providing the BH link. In our testbed, the computer is connected to the UAV via the BH link to control the drone and deliver connectivity. Fig. 3(b) shows the hardware used in the ground station. Since the tests in this project were carried out in the field, an extra battery was added to power the hardware on the ground station side. The primary hardware used in our ground station is listed in Table 2.

In what follows, we describe our autonomous steering system that enables bidirectional operation of the BH link.

III. Automatic Antenna Steering System

A. General Description

One of the solutions to extend coverage with the BH link and maintain signal quality at an appropriate level is the use of high gain and directional antennas at both sides of the link. The radiation pattern of such antennas is very narrow, and even a small misalignment may result in significant signal-to-noise ratio reduction. This gives rise to the requirement that both antennas are continuously pointed at each other. Hence, steering must be

Table 1. Main components of the UAV (refer to Fig. 3(a)).

Element	Description
① Li-Po battery	Power supply for the UAV. Provides 14.8 V and has a capacity of 30,000 mAh.
② Power module	DC-DC voltage regulator from 14.8 V to 5 V with maximum provided current of 3 A.
③ Flight controller	Module managing the rotation of each motor to control the trajectory of the UAV based on its position, axis state (roll, yaw, pitch), and commands issued by the operator from the ground station.
④ GPS and compass	Module providing the position and heading of the UAV.
⑤ Telemetry receiver and backup RC	Radio controller acting as a backup in case the BH link fails.
⑥ Beagle Bone	Microcomputer that provides a bridge between the IP layer and the flight controller.
⑦ On-board router	Device routing data and telemetry packets to the BH link.
⑧ On-board antenna	Antenna mounted on the UAV providing the BH link to the ground station. The antenna gain is 16 dBi and it communicates over the Mikrotik Nv2 protocol at 5.5 GHz.
⑨ Servo motors	Electronic devices providing steering to the on-board antenna. The supported torque is 5.1 kg/cm.

Table 2. Main components of the ground station (refer to Fig. 3(b)).

Element	Description
① Terminal	Computer controlling the UAV and handling the network in real time.
② Ground station antenna	Antenna communicating with the on-board antenna of the UAV to provide the BH link. The device gain is 24.5 dBi. The antenna communicates over the MikroTik Nv2 protocol in the 5.5 GHz band.
③ Raspberry Pi	Board controlling the servo motors.
④ Servo motors	Electronic devices used to steer to the ground station antenna. Supported torque is 5.1 kg/cm.
⑤ GPS and compass	Hardware module obtaining the coordinates and heading of the ground station antenna.
⑥ Voltage regulators	DC-DC regulators converting voltage from 14.8 V to 5 and 7 V to power the Raspberry Pi and servo motors, respectively.

implemented in our system. The elevation and azimuth for both devices must be obtained to accurately track the antennas.

Once the corresponding angles are determined, the horizontal and vertical inclination of both antennas can be adjusted so that they precisely point at each other. To achieve this, four servo motors were installed to provide mechanical rotation according to these calculated values. As we are considering short-to-medium distances for our prototype, we proceed with a flat-Earth approximation. This decreases the computational complexity but introduces a potential error factor. However, this error factor is negligible at such short distances. Fig. 4 shows the general scheme of our scenario and defines this problem.

To tackle the steering system, it is important to consider the parameters required to compute the elevation and azimuth angles, as explained in [45]. The final angles to steer the antennas can be obtained from the longitude, latitude, altitude, and heading of the UAV in the Earth-fixed coordinates. As we are adding another antenna to the UAV, one must consider the corresponding parameters for both antennas. The important parameters in our system are listed in Table 3.

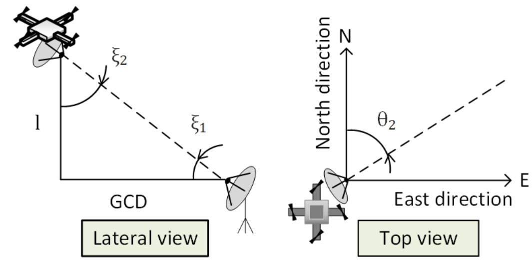


Fig. 4. Computation of elevation and azimuth for the UAV antenna and the ground station antenna (GSA).

Table 3. Main parameters of the antenna steering system.

	Notation	Description
Input parameters	ϕ_1	Altitude of the UAV
	λ_1	Longitude of the UAV
	ϕ_2	Latitude of the GSA
	λ_2	Longitude of the GSA
	l	Relative altitude of the UAV
	h	Altitude of the GSA
Output parameters	ξ_1	Elevation angle of the GSA
	θ_1	Bearing angle of the GSA
	ξ_2	Elevation angle of the UAV antenna
	θ_2	Bearing angle of the UAV antenna

The calculations required to obtain the final angles for the elevation and azimuth are performed as follows. The elevation angles for the ground station and the UAV are defined as

$$tan(\xi_1) = \frac{l - \sum_{i=1}^{n} h_i}{GCD}, \xi_1 = arctan\Big(\frac{l - \sum_{i=1}^{n} h_i}{GCD}\Big). \quad (1)$$

Here, GCD refers to the great-circle distance between the coordinates of the UAV and the GSA. This value can be computed using the Haversine expression:

$$d = Rc, \quad (2)$$

where R refers to the radius of the Earth, while c and a are computed as follows:

$$c = 2atan2\Big(\sqrt{a}, \sqrt{1-a}\Big), \quad (3)$$

where

$$a = sin^2\Big(\frac{\phi_2 - \phi_1}{2}\Big) + cos(\phi_1)cos(\phi_2)sin^2\Big(\frac{\lambda_2 - \lambda_1}{2}\Big). \quad (4)$$

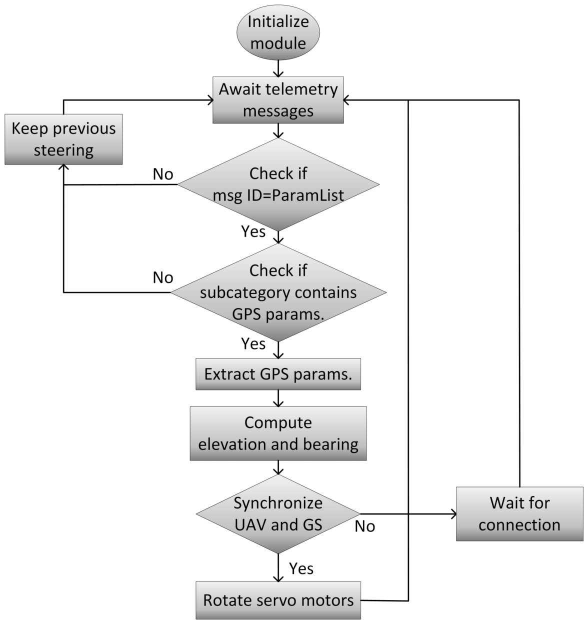


Fig. 5. Algorithm for autonomous steering between the UAV and GSA.

At this point, the elevation angle of the UAV's on-board antenna is obtained directly from the following:

$$\xi_2 = 180 - 90 - \xi_1. \tag{5}$$

The bearing angle θ of two GPS coordinate points expressed in latitude [radians] and longitude [radians] can be computed from

$$\begin{aligned}\theta = atan2\Big(&sin(\lambda_2-\lambda_1)cos(\phi_2), cos(\phi_1)sin(\phi_2)\\ &- sin(\phi_1)cos(\phi_2)cos(\lambda_2-\lambda_1)\Big).\end{aligned} \tag{6}$$

This procedure is required for obtaining the bearing angle for both antennas. The antennas must be rotated by the angle computed above with respect to the North cardinal point. With this procedure, the four angles required to point the antennas are obtained. Note that the input parameters stated above must be known continuously at both sides of the link to compute the final elevation and bearing angles. As a result, communication must be established between the UAV and the GSA during initial synchronization. This transmission is allocated over the telemetry link.

The process described above is entirely autonomous and is executed in a loop, as explained in [46]. The implemented algorithm is executed repeatedly to continuously steer both antennas. A flowchart of the algorithm used to point both antennas is shown in Fig. 5.

B. Potential Sources of Errors

Once the autonomous steering system has been implemented, potential sources of errors that might affect the accuracy of the steering algorithm can be analyzed. This study may be considered as a base for future improvements in the real-world system. It is important to remember that the implemented prototype is to be operated over short-to-medium distances (of below 1 km). Hence, only errors that become significant over long-distance communication might affect the accuracy of the steering system. The relevant sources of errors are sorted according to their expected impact:

- Geodesic calculations – Should the system be operated over longer distances, the calculations performed above are to be performed according to a geodesic model that takes into account the curvature of the Earth.
- GPS and compass inaccuracies – As explained in [47], GPS systems are susceptible to failure or may give inaccurate results due to surrounding obstacles, such as mountains, vegetation, or human-made structures.
- Altitude inaccuracies – The UAV is responsible for managing information regarding its altitude using a barometric sensor that reads air pressure continuously. Errors due to these readings should also be considered.
- Servo motor and mechanical structure errors – Inaccuracies in the structure used to track antennas must be considered and reduced as much as possible.
- Yaw and pitch correction – Whenever the UAV moves, it necessarily nods in the direction it is moving to, thus causing a misalignment in the UAV antenna.

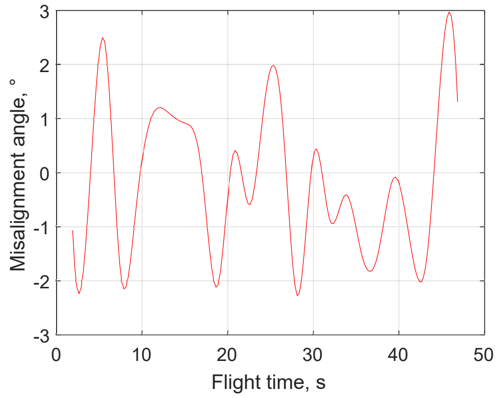
Most of the noted errors may lead to antenna misalignment and cause overall degradation of the link quality. This effect is analyzed using simulation results in the following subsection. Weather may also affect the operation of our system. In particular, weather conditions such as rain may become a serious source of attenuation at frequencies of above 5 GHz. However, we can rely on existing measurements to predict this impact. For example, in [48] the authors found that rain constitutes 0.2 to 3.7 dB/km of attenuation for a similar frequency for rainfall rates ranging from 5 (light rain) to 132 (heavy rain) mm/h. Water vapor does not significantly contribute to attenuation at this frequency [49]. Watery snow conditions have slightly stronger attenuation ranging up to 15 dB/km [50].

Given our equipment, we may conclude that the effect of rain may be neglected in the desired operating scenario. Going further, we plan to investigate the impact of wind on the steering system, whenever the corresponding weather conditions will be met in a live deployment.

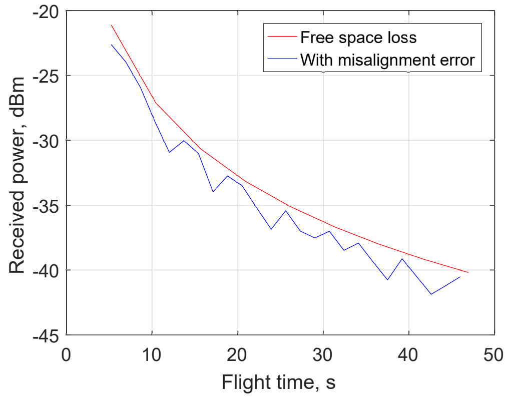
C. Simulating Misalignment Errors

To complement the above considerations, we prepared a dedicated simulation script to observe and characterize the impact of one of the main sources of errors in our algorithm: steering misalignment. Other types of errors, such as inaccuracies produced by the compass or altitude barometer that are inherent to these devices are difficult to characterize, since their relative effect lays within the absolute value of the measurement results. A scenario with a drone following a predefined trajectory was created to simulate the impact of misalignment errors.

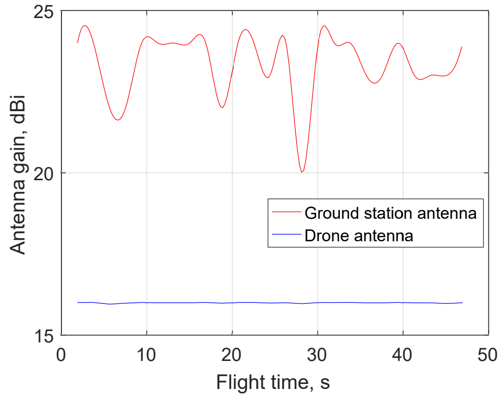
First, 10 reference points were selected for the trajectory, where the drone followed a straight line from point $[50, 15]$ to point $[500, 150]$. The altitude was maintained at 10 ± 0.5 meters. The movement speed was set to 10 m/s so that the simulation results closely correspond to our experimental scenario. In



(a) Azimuth plane antenna misalignment.



(b) Received power.



(c) Antenna gain.

Fig. 6. Simulated antenna misalignment impact.

the simulations, we assigned a misalignment error of 5^o in both planes. Hence, two randomly chosen sets of values distributed between -2.5 and 2.5 were generated. An example for errors in the azimuth plane is shown in Fig. 6(a). This misalignment angle is expected to appear due to weather conditions or mobility problems. The resulting received power data is shown in Fig. 6(b). Note that the received power decreases because the drone moves farther away from the ground station during the simulations. It is clear that such a small angular fluctuation does not have a significant effect on propagation.

Table 4. Antenna parameters

Parameter	GSA	UAV antenna
Manufacturer	MikroTik	MikroTik
Model	LGH 5	SXT Lite 5
Protocol	Nv2	Nv2
Transmit power	20 dBm	20 dBm
Maximum gain	24 dB	16 dB
Beamwidth	7° × 7°	25° × 25°
Frequency	5150 – 5875 MHz	4920 – 5920 MHz
Bandwidth	40 MHz	40 MHz

Furthermore, the antenna gains on both sides of the link were calculated from the radiation patterns for each antenna (described in Table 4) for the generated misalignment angles (see Fig. 6(c)). Note that the antenna gain is not the maximum gain of the antenna, but rather the value corresponding to the misalignment angle for the antenna pattern. This confirms that the practical impact of the ground station (more directivity and reduced effect due to wind) is much higher than that of the drone antenna due to the beamwidth of the main lobe. Hence, this confirms that the hardware selected for our experimental setup was appropriate.

D. Comparison with Existing Solutions

In the following lines, the steering algorithm proposed in this study is compared with two other solutions to demonstrate and confirm its efficiency. A similar steering solution between two terrestrial robotic systems was proposed in [51]. The authors used a direction of arrival algorithm, which requires that an array of antennas continuously reads the phases of the received signals to compute the steering angle. In this way, a linear array of antennas can be used to obtain the steering angle in one direction (either azimuth or elevation), while a two-dimensional array can be used to obtain both the azimuth and the elevation steering angles simultaneously. In our system, we utilize our own algorithm to obtain both steering angles, which avoids the need for more than two antenna elements in the overall system.

Another solution for the tracking problem at hand is to use high resolution video cameras combined with an image processing algorithm to detect and track the target, as was considered in [46]. However, this method requires direct line-of-sight (LOS) to detect the target with high resolution images produced by the camera. Therefore, this solution is not preferred when considering scenarios where LOS can be blocked by surrounding objects. To the best of our knowledge, no other group has published any research on the automatic steering capabilities of the GSA and the aerial vehicle. We thus believe that our novel solution can be considered as a starting point for future implementations and improvements that target UAV-aided communication systems.

IV. Numerical Results

For a number of applications, high throughput becomes one of the primary metrics of interest [52–54]. To deliver high data rates to remote areas, it is necessary to use highly directional antennas with relatively large transmit power. However, antenna beam misalignment will produce additional losses, which can affect the link quality. In this section, we study the impact of antenna misalignment depending on their radiation pattern. To analyze this appropriately, the radiation patterns from each antenna must be obtained. The GSA patterns were acquired from the manufacturer's website[1]. However, the manufacturer did not provide patterns for the UAV antenna[2], and it was necessary to approximate the radiation pattern from the antenna parameters. The maximum gain and beamwidth were taken into account, while a Chebyshev filter was used to approximate the final model. We assumed the elevation and azimuth patterns to be equal.

According to the parameters provided in Table 4, one can see that the drone's main antenna lobe is wider than that of the GSA, which makes this antenna less sensitive to beam misalignment. From the radiation patterns, we can analytically obtain 3D plots for the misalignment losses, which also corroborate this claim. The theoretical plots are shown in Fig. 7 and 8, and these figures represent losses produced by misalignment in the vertical and horizontal planes, depending on the radiation pattern for each antenna. Higher losses will be produced due to misalignment for an antenna with higher directionality.

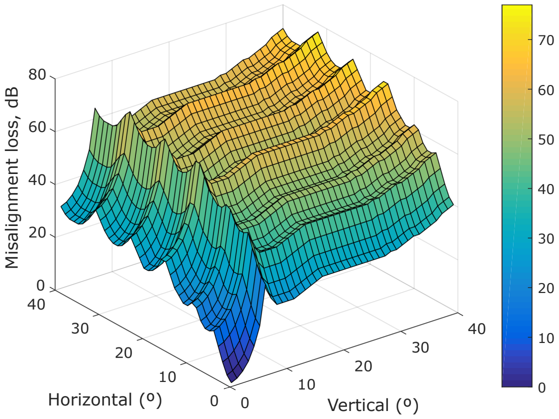


Fig. 7. Misalignment losses for the ground station antenna.

V. Experimental Results

It is useful to model the propagation channel to further analyze the misalignment effect. Then, the system will compare the measured values with the results given by the model, and the tracking setup will be adjusted according to this difference. This section reports experimental measurements that may serve as a reference point for propagation modeling.

The UAV and the ground station are shown in Fig. 9. The antenna is located below the mainframe (including the battery) to lower the side effects of the UAV. Hence, a simplified prototype was used to conduct the initial measurements and evaluate the

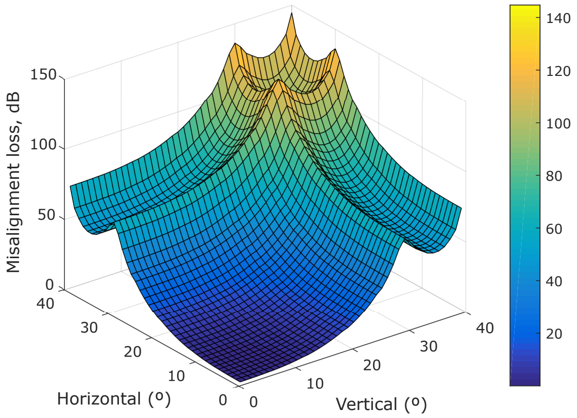


Fig. 8. Misalignment losses for the drone antenna.

capabilities of the selected hardware. The experiment was conducted in a suburban area under a LOS scenario over distances ranging from 0 to 550 m. The ground station antenna was fixed at one meter above ground and the drone was kept at approximately 3 m above ground. Measurements were gathered while mindful of the Fresnel zone to illustrate the propagation behavior of the signal.

Fig. 9. Equipment for propagation measurements.

According to theory, the central part of the signal energy propagates in the first Fresnel zone [55]. This zone is an ellipsoid around the ideal direct ray. As an approximation, signal loss during propagation is considered to be free-space loss (FSL) if the first Fresnel zone is free from obstacles. However, propagation can also be assumed to follow FSL when there are obstacles within 60 % of the radius of the first Fresnel zone.

We obtained the path loss (PL) while gathering our measure-

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[1] See "LHG 5 datasheet" by MikroTik, 2018: `https://i.mt.lv/routerboard/files/LHG-170927115805.eps`

[2] See "SXT 5 datasheet" by MikroTik, 2018: `https://i.mt.lv/routerboard/files/sxt_5-150206095451.eps`

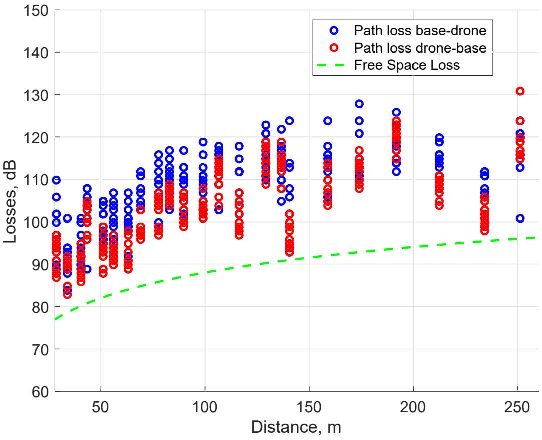


Fig. 10. Measured and analyzed path loss.

ments, as shown in Fig. 10. The considered values were acquired at various distances and were compared to FSL [56]. During measurements, a simple script was executed at both sides of the link to read the received power.

Table 4 summarizes the values used within the power budget when both antennas were set to operate at 5500 MHz. The PL was calculated with the equation below using given values of P_{tx}, P_{rx}, G_{tx}, and G_{rx} as

$$PL(dB) = P_{tx}(dBm) - P_{rx}(dBm) + G_{tx}(dB) + G_{rx}(dB). \tag{7}$$

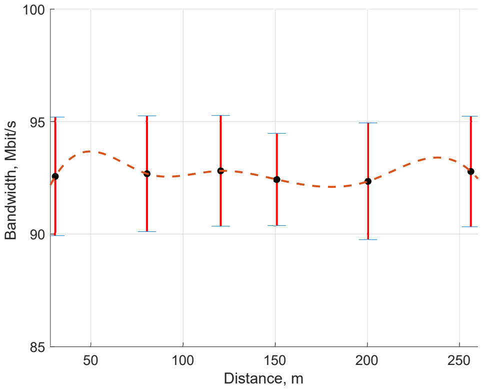
We obtained a free-space model for our scenario based on the above results. As a first approach, measurements were compared with FSL, which can be approximated as recommended by 3GPP [57]. Since the measurements were performed in non-ideal scenarios, the obtained losses were considerably higher than those predicted from the FSL model. However, the PL follows the trend that would be observed in an ideal scenario.

$$L_{FSL}(dB) = 32.45 + 20log_{10}\Big(d(km)\Big) + 20log_{10}\Big(f(MHz)\Big). \tag{8}$$

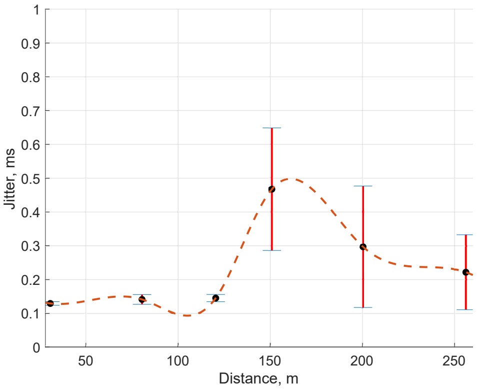
Finally, we evaluated the link quality as a function of distance. A network connection was delimited by two hosts running iPerfv3, with the drone acting as a server and the ground station acting as a client. The evaluation was completed based on the following set of metrics (see Fig. 11):

- Jitter – variation in the delay between received packets. Measured based on iPerf UDP tests.
- Packet losses were also measured with iPerf UDP tests (<1%, if not, multiple retransmissions).
- Throughput was measured with iPerf via TCP tests under saturated conditions.

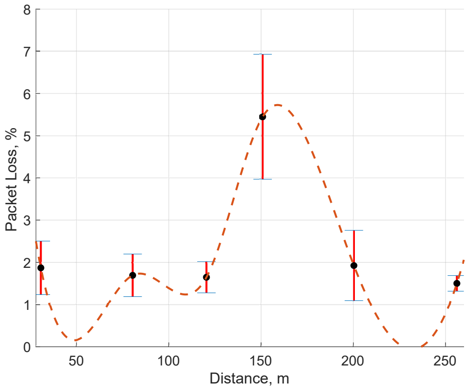
Overall, the measurements represent the mean and the 95% confidence interval for all plots (see Fig. 11). As one can see from the plots, the bandwidth delivered with our designed system is insensitive to communication distance in this scenario. In contrast, packet losses and jitter are more significantly affected by the environmental conditions, even though they still satisfy the target application requirements. Interestingly, while gathering measurements at around 120 meters, a truck was passing between the transmitter and the receiver. Its presence affected packet loss and jitter but had almost no impact on bandwidth.



(a) Bandwidth.



(b) Jitter.



(c) Packet loss.

Fig. 11. Prototype-based measurements.

To this end, Fig. 11(c) reveals that the link budget of a wireless connection allows throughput to be maintained with even further increased data losses due to an Ethernet limitation of 100 Mbit/s. Overall, we show that our developed framework may deliver high throughput and low latency communication in mission-critical and on-demand scenarios.

VI. Conclusions and Lessons Learned

In this paper, we developed a prototype of an aerial base station. This system has been discussed at length in the past, but was never thoroughly investigated in the field trials due to a number of challenges. We presented a working prototype of the UAV base station, which may carry a microwave antenna and a steering beam alignment mechanism that keeps the antenna pointed toward the ground station. The steering mechanism operation is the most challenging and crucial component in our solution. Since our measurements were collected for link lengths ranging up to 550 m, and the microwave connection used an IEEE 802.11a/n-like protocol, the resulting accuracy was sufficient as a starting point. In the future, we plan to employ millimeter-wave equipment, which will require a more precise steering system.

We also presented our initial measurements, which were gathered with the constructed prototype. The results were collected in an outdoor scenario and were further compared with the theoretical free-space model. The trend in the measured losses is similar to theoretical expectations, but losses shift to higher values due to realistic weather conditions. In a future study, we plan to utilize gas-powered UAVs in a subsequent phase of our development. This should allow us to test not only the backhaul link itself, but also the downlink from the UAV to potential ground stations. One could subsequently determine the equipment requirements and develop a full-scale proof-of-concept system.

REFERENCES

[1] VNI Cisco, "Global mobile data traffic forecast 2016–2021." White Paper, 2017.

[2] G. Wang, G. Feng, S. Qin, and R. Wen, "Efficient traffic engineering for 5G core and backhaul networks," *Journal of Communications and Networks*, vol. 19, no. 1, pp. 80–92, 2017.

[3] W. Guo, C. Devine, and S. Wang, "Performance analysis of micro unmanned airborne communication relays for cellular networks," in *Proc. of the 9th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, pp. 658–663, IEEE, 2014.

[4] B. Sanou, "ICT Facts & Figures-The world in 2015," 2015.

[5] N. Headley, "Telkom focuses on urban areas in network push," *BusinessLIVE*, [online]. Available: https://www.businesslive.co.za/bd/companies/telecoms-and-technology/2018-01-22-telkom-focuses-on-urban-areas-in-network-push/, 2018.

[6] A. Izaddoost and S. S. Heydari, "Risk-adaptive strategic network protection in disaster scenarios," *Journal of Communications and Networks*, vol. 19, no. 5, pp. 509–520, 2017.

[7] A. Ometov, E. Sopin, I. Gudkova, S. Andreev, Y. V. Gaidamaka, and Y. Koucheryavy, "Modeling Unreliable Operation of mmWave-Based Data Sessions in Mission-Critical PPDR Services," *IEEE Access*, vol. 5, pp. 20536–20544, 2017.

[8] W. Müller, H. Marques, L. Pereira, J. Rodriguez, F. Brouwer, B. Bouwers, I. Politis, A. Lykourgiotis, A. Ladas, O. Adigun, *et al.*, "Secure and interoperable communication infrastructures for PPDR organisations," in *SPIE Defense+ Security*, International Society for Optics and Photonics, 2016.

[9] J. Y. Ryu, W. Choi, D. I. Kim, and R. Schober, "Beamforming for cooperative retransmission via user relaying in multiple-antenna cellular systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, pp. 854–869, 2015.

[10] W. Xing, F. Liu, C. Wang, M. Xiao, and P. Wang, "Multi-source network-coded D2D cooperative content distribution systems," *Journal of Communications and Networks*, vol. 20, no. 1, pp. 69–84, 2018.

[11] M. Bakhouya, J. Gaber, and P. Lorenz, "An adaptive approach for information dissemination in vehicular ad hoc networks," *Journal of Network and Computer Applications*, vol. 34, no. 6, pp. 1971–1978, 2011.

[12] H. Moustafa and H. Labiod, "Multicast routing in mobile ad hoc networks," *Telecommunication Systems*, vol. 25, no. 1-2, pp. 65–88, 2004.

[13] M. Deruyck, J. Wyckmans, L. Martens, and W. Joseph, "Emergency ad-hoc networks by using drone mounted base stations for a disaster scenario," in *Proc. of 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pp. 1–7, IEEE, 2016.

[14] L. Rabieekenari, K. Sayrafian, and J. S. Baras, "Autonomous relocation strategies for cells on wheels in environments with prohibited areas," in *Proc. of IEEE International Conference on Communications (ICC)*, pp. 1–6, IEEE, 2017.

[15] ICS Industries PTY LTD, "Cell on Wheels: Engineered for All Environments," [online]. Available: http://www.icsindustries.com.au/downloads/brochures?download=37:cell-on-wheels, 2017.

[16] D. Chambers, "LTE relay introduced as a popular choice for those with spectrum assets," *ThinkSmallCell*, [online]. Available: https://www.thinksmallcell.com/Technology/lte-relay-introduced-as-a-popular-choice-for-those-with-spectrum-assets.html, 2017.

[17] A. Orsino, A. Ometov, G. Fodor, D. Moltchanov, L. Militano, S. Andreev, O. N. Yilmaz, T. Tirronen, J. Torsner, G. Araniti, *et al.*, "Effects of Heterogeneous Mobility on D2D- and Drone-Assisted Mission-Critical MTC in 5G," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 79–87, 2017.

[18] D. Solomitckii, M. Gapeyenko, V. Semkin, S. Andreev, and Y. Koucheryavy, "Technologies for Efficient Amateur Drone Detection in 5G Millimeter-Wave Cellular Infrastructure," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 43–50, 2018.

[19] Z. Kaleem and M. H. Rehmani, "Amateur Drone Monitoring: State-of-the-Art Architectures, Key Enabling Technologies, and Future Research Directions," *IEEE Wireless Communications*, vol. 25, no. 2, pp. 150–159, 2018.

[20] X. Shi, C. Yang, W. Xie, C. Liang, Z. Shi, and J. Chen, "Anti-drone system with multiple surveillance technologies: Architecture, implementation, and challenges," *IEEE Communications Magazine*, vol. 56, no. 4, pp. 68–74, 2018.

[21] I. Guvenc, F. Koohifar, S. Singh, M. L. Sichitiu, and D. Matolak, "Detection, tracking, and interdiction for amateur drones," *IEEE Communications Magazine*, vol. 56, no. 4, pp. 75–81, 2018.

[22] FAA, "Federal Aviation Administration," [online]. Available: https://www.faa.gov/, 2018.

[23] J. Nakajima, Y. Ohta, H. Miyajima, M. Tokunaga, Y. Sugita, H. Omote, H. Hayashi, and T. Fujii, "A Balloon-Based Wireless Relay System for Disaster Response," in *Proc. of 82nd Vehicular Technology Conference (VTC Fall)*, pp. 1–6, IEEE, 2015.

[24] L. Nagpal and K. Samdani, "Project Loon: Innovating the connectivity worldwide," in *Proc. of 2nd IEEE International Conference on Recent Trends in Electronics, Information Communication Technology (RTEICT)*, pp. 1778–1784, May 2017.

[25] EE Press Office, "EE pioneers 'Air mast' technology for rural mobile coverage and disaster recovery," [online]. Available: http://newsroom.ee.co.uk/ee-pioneers-air-mast-technology-for-rural-mobile-coverage-and-disaster-recovery/, 2018.

[26] R. Ghanavi, E. Kalantari, M. Sabbaghian, H. Yanikomeroglu, and A. Yongacoglu, "Efficient 3D Aerial Base Station Placement Considering Users Mobility by Reinforcement Learning," *arXiv preprint arXiv:1801.07472*, 2018.

[27] A. Al-Hourani, S. Chandrasekharan, S. Kandeepan, and A. Jamalipour, "Aerial platforms for public safety networks and performance optimization," in *Wireless Public Safety Networks 3*, pp. 133–153, Elsevier, 2017.

[28] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, "3-D placement of an unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage," *IEEE Wireless Communications Letters*, vol. 6, no. 4, pp. 434–437, 2017.

[29] J. Sae, S. F. Yunas, and J. Lempiainen, "Coverage aspects of temporary LAP network," in *Proc. of 12th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, pp. 1–4, IEEE, 2016.

[30] A. Al-Hourani, S. Kandeepan, and A. Jamalipour, "Modeling air-to-ground path loss for low altitude platforms in urban environments," in *Proc. of Global Communications Conference (GLOBECOM)*, pp. 2898–2904, IEEE, 2014.

[31] I. Bor-Yaliniz, S. S. Szyszkowicz, and H. Yanikomeroglu, "Environment-Aware Drone-Base-Station Placements in Modern Metropolitans," *IEEE Wireless Communications Letters*, vol. 7, no. 3, pp. 372–375, 2017.

[32] K. Namuduri, "When Disaster Strikes, Flying Cell Towers Could Aid Search and Rescue," *IEEE Spectrum*, May 2017.

[33] CyPhy Works, Inc., "The Future of High-Powered Commercial Drones," [online]. Available: https://www.cyphyworks.com/products/parc/, 2017.

[34] Nokia, "Nokia compact LTE," [online]. Available: https://networks.nokia.com/solutions/compact-lte-solutions, 2018.

[35] K. Gomez, S. Kandeepan, M. M. Vidal, V. Boussemart, R. Ramos, R. Hermenier, T. Rasheed, L. Goratti, L. Reynaud, D. Grace, *et al.*, "Aerial base

stations with opportunistic links for next generation emergency communications," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 31–39, 2016.

[36] R. Singh, M. Thompson, S. A. Mathews, O. Agbogidi, K. Bhadane, and K. Namuduri, "Aerial Base Stations for Enabling Cellular Communications during Emergency Situation," in *Proc. of International Conference on Vision, Image and Signal Processing (ICVISP)*, pp. 103–108, IEEE, 2017.

[37] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Drone small cells in the clouds: Design, deployment and performance analysis," in *Proc. of Global Communications Conference (GLOBECOM)*, pp. 1–6, IEEE, 2015.

[38] D. G. Cileo, N. Sharma, and M. Magarini, "Coverage, capacity and interference analysis for an aerial base station in different environments," in *Proc. of International Symposium on Wireless Communication Systems (ISWCS)*, pp. 281–286, IEEE, 2017.

[39] S. Mignardi and R. Verdone, "On the Performance Improvement of a Cellular Network Supported by an Unmanned Aerial Base Station," in *Proc. of 29th International Teletraffic Congress (ITC 29)*, vol. 2, pp. 7–12, IEEE, 2017.

[40] B. Van der Bergh, A. Chiumento, and S. Pollin, "LTE in the sky: trading off propagation benefits with interference costs for aerial nodes," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 44–50, 2016.

[41] R. Kovalchukov *et al.*, "Analyzing Effects of Directionality and Random Heights in Drone-based mmWave Communication," *IEEE Transactions on Vehicular Technology*, [Early Access] 2018.

[42] J. Rajamäki, "Kinetic Controlled Flying of Micro Air Vehicles (MAV) for Public Protection and Disaster Relief (PPDR)," in *Proc. of the 10th International Proc. of Conference on Circuits, Systems, Signal and Telecommunications (CSST '16)*, pp. 47–52, WSEAS Press, 2016.

[43] J. Kim and A. F. Molisch, "Fast millimeter-wave beam training with receive beamforming," *Journal of Communications and Networks*, vol. 16, no. 5, pp. 512–522, 2014.

[44] B.-C. Min, E. T. Matson, and J.-W. Jung, "Active antenna tracking system with directional antennas for enhancing wireless communication capabilities of a networked robotic system," *Journal of Field Robotics*, vol. 33, no. 3, pp. 391–406, 2016.

[45] W. Tan, K. Liu, and J. Liao, "Study of S-band antenna tracking algorithm based on FPGA," in *Proc. of International Conference on Ubiquitous Wireless Broadband (ICUWB)*, pp. 1–4, IEEE, 2016.

[46] M. Ilamathi and K. Abirami, "Automatic target tracker for main battle tank," in *Proc. of International Conference on Communications and Signal Processing (ICCSP)*, pp. 318–321, IEEE, 2015.

[47] E. Choi and S. Chang, "A consumer tracking estimator for vehicles in GPS-free environments," *IEEE Transactions on Consumer Electronics*, vol. 63, no. 4, pp. 450–458, 2017.

[48] U. Kesavan, M. R. Islam, K. Abdullah, and A. Tharek, "Rain attenuation prediction for higher frequencies in microwave communication using frequency scaling technique," in *International Conference on Computer and Communication Engineering (ICCCE)*, pp. 217–219, IEEE, 2014.

[49] S. Sun, G. R. MacCartney, and T. S. Rappaport, "A novel millimeter-wave channel simulator and applications for 5G wireless communications," in *Proc. of International Conference on Communications (ICC)*, pp. 1–7, IEEE, 2017.

[50] J.A. Vander Star, M.M. Kharadly, "Measurements of copolar attenuation through the bright band at 4 and 7 GHz," in *Annales des Télécommunications*, vol. 36, pp. 48–53, Springer, 1981.

[51] B.-C. Min, E. T. Matson, and B. Khaday, "Design of a networked robotic system capable of enhancing wireless communication capabilities," in *Safety, Security, and Rescue Robotics (SSRR), 2013 IEEE International Symposium on*, pp. 1–8, IEEE, 2013.

[52] G.-J. M. Kruijff, F. Pirri, M. Gianni, P. Papadakis, M. Pizzoli, A. Sinha, V. Tretyakov, T. Linder, E. Pianese, S. Corrao, *et al.*, "Rescue robots at earthquake-hit Mirandola, Italy: A field report," in *Proc. of IEEE International Symposium on Safety, Security, and Rescue robotics (SSRR)*, pp. 1–8, IEEE, 2012.

[53] G. Zhou, C. Li, and P. Cheng, "Unmanned aerial vehicle (UAV) real-time video registration for forest fire monitoring," in *Proc. of IEEE International Geoscience and Remote Sensing Symposium, IGARSS'05.*, vol. 3, pp. 1803–1806, IEEE, 2005.

[54] A. Miller, P. Babenko, M. Hu, and M. Shah, "Person tracking in UAV video," in *Proc. of Multimodal Technologies for Perception of Humans*, pp. 215–220, Springer, 2008.

[55] H. D. Hristov, *Fresnal Zones in Wireless Links, Zone Plate Lenses and Antennas*. Norwood, MA, USA: Artech House, Inc., 1st ed., 2000.

[56] J. A. Shaw, "Radiometry and the Friis transmission equation," *American Journal of Physics*, vol. 81, no. 1, pp. 33–37, 2013.

[57] 3GPP, "Channel model for frequency spectrum above 6 GHz," tech. rep., Technical Specification Group Radio Access Network, 2016.

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