Flying Rebots: First Results on an Autonomous UAV-Based LTE Relay using OpenAirInterface

Rajeev Gangula, Omid Esrafilian, David Gesbert, Cedric Roux, Florian Kaltenberger, and Raymond Knopp
Communication Systems Department, Eurecom, France
Email: {gangula, esrafili, gesbert, cedric.roux, kaltenberger, knopp}@eurecom.fr

***Abstract*—In this paper we introduce the design of the "Rebot" (Relaying Robot) for future wireless networks. The Rebot concept is first of its kind in providing enhanced end-to-end LTE connectivity to ground users from a fixed base station via a flying relay which is enabled with an autonomous placement algorithm. The Rebot that we have built is a customized integrated UAV relay and its communication layer is based on OpenAirInterface. The ground user carries an off-the-shelf commercial LTE mobile terminal. We also present a placement algorithm that updates the UAV position in real time based on user location and wireless channel conditions so as to maximize the throughput at all times. The experimental results show throughput gains by using this UAV relay and also illustrate the learning/tracking behavior of the Rebot.**

I. Introduction

A flying radio access network (FRAN) provides wireless connectivity to ground users by aerial base stations (BSs) that are mounted on unmanned aerial vehicles (UAVs) or balloons. Recently, significant effort has been invested in the design of FRANs in both academia and industry. The motivation for such networks arises from the use cases like, fast and dynamic network deployment during an emergency or temporary crowded events, providing connectivity in areas lacking network infrastructure, etc.

Depending on the application, FRANs may use High Altitude Platforms (HAPs) or Low Altitude Platforms (LAPs) to deploy the aerial BSs. Several substantive projects have looked into the aspects of providing broadband wireless access using HAPs [1], [2]. Well known examples from industry are, project loon from Google where balloons are used as a HAP [3], and Facebook's project [4] where long-endurance solar plane is used as a HAP. Typical altitude of these platforms are between 18 and 25 kilometers. Moreover, project loon claims to provide LTE connectivity to the users on the ground with connection speeds of up to 10 Mbps using their balloon relay network [3]. The advantages of using HAPs include wider coverage area, longer endurance and hence long time connectivity, which makes them suitable for applications such as providing connectivity in rural and remote areas where network infrastructure is not available.

On the other hand, FRANs based on LAPs, such as small commercial UAVs are in general faster to deploy and configure, and have lower implementation cost than the HAPs. This makes them suitable for applications like on-demand wireless services, providing temporary connectivity in unpredicted events, etc. Moreover, since UAVs fly at low-altitude they can contribute in maintaining short range (line-of-sight) LOS links to ground users which can lead to significant increase in the throughputs.

Few works have considered using micro UAVs to deploy or carry aerial BSs to provide LTE connectivity. In [5], Nokia Bell Labs demonstrated an UAV based delivery of a Nokia's small cell to a desired location [5]. The carried small cell is self powered and has a wireless backhaul. However, in this scenario UAV is only used as a means to carry the small cell to a stationary landing spot, akin to UAV based goods delivery systems. In a blog post by Nokia [6], telecommunications operator EE and Nokia have used an UAV-mounted tiny BS to provide LTE services in rural areas of Scotland. They used a satellite based backhaul link which connects the UAV-mounted BS to the core network of EE. Operator AT&T used an UAV that carries a small BS which also provides LTE services [7]. However, the UAV-mounted BS is tethered to the ground by a fiber optic and power cable. Again, a satellite based backhaul solution was used. Finally, the ABSOLUTE project consortium has designed and analyzed a hybrid system architecture based on LTE and satellite based connectivity using Helikite platforms [8].

To the best of our knowledge, most prior work designing the UAV based FRANs hinges on the simplifying assumption that the UAV serves as a carrier and the BS as a communication payload, and their functionalities are mostly kept decoupled. However, a joint design of robotic and communication capabilities would substantially enhance the overall performance of FRANs, affecting the communication throughput by the optimal placement or trajectory design [9]–[16]. Towards this end, in this paper we introduce the concept of **Rebot**: The Rebot not only functions as a LTE relay between the ground user and a fixed BS, but also acts as an autonomous robot by positioning itself based on suitable radio measurements, so as to maximize the throughput offered to the ground user. Note that the first results revealed in this paper consider the case of a single ground user, while an extension to many users is currently ongoing and will be published elsewhere. Key ingredients of this work are:

- The design of an UAV mounted LTE relay which provides end-to-end LTE connectivity between a ground user and the core network.
- The relay solution that is embedded on the UAV is based

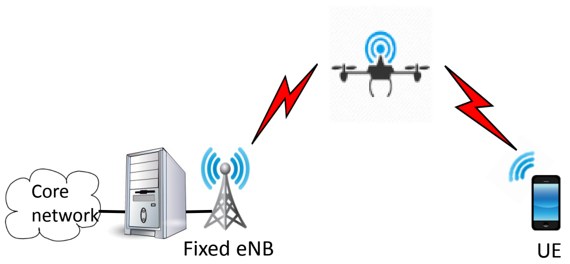

Figure 1: UAV-based LTE relaying system.

on OpenAirInterface (OAI) BS or eNB[1] [17], which is an open-source software.

- The interaction between the UAV's flight controller and a placement algorithm which exploits the radio channel measurements (provided by OAI eNB's) to autonomously place the UAV-relay so as to maximize the throughput of the user.

II. System Design

We consider the design of an UAV that acts as a relay between the user and a fixed eNB as shown in Figure 1. The UAV is used to boost the LTE connectivity to the user. The equipment, tools and the software used for designing this system are described next.

A. UAV Design

Since the experiment requires the interaction between the UAV or drone and the embedded OAI eNB, we needed a fully customized drone to enable us sending control commands to the drone and reading drone information like instantaneous drone location. For this, we have designed a customized drone by considering the required flight time and maximum payload. To build the drone, we have used an off-the-shelf Quad-Rotor carbon body frame with diameter of 60 cm, DJI propulsion system and PIXHAWK 2 flight controller which is an open-source flight controller and allows us to manipulate the drone by the output of the autonomous placement algorithm which is based on the radio measurements obtained from OAI eNBs. Note that the overall weight of the drone without considering the communication parts is about 2 Kg. To control and fly the drone manually (in emergency cases) we use a Futaba T8J radio controller (RC) which is an 8 channel radio controller and works in 2.4 GHz frequency ISM band. Different parts of the drone are shown in Figure 2.

B. OAI eNBs

There are in total two OAI eNBs used in this setup, one used as a fixed eNB on the ground and another is mounted on the UAV which is used as a relay. The OAI's eNB software is compliant with 3GPP LTE standards, and runs on a commodity x86 based Linux computing equipment. Details regarding the OAI software can be found at [17]. Both eNBs are configured to run in TDD mode in LTE frequency band 38 where EURECOM has the license to transmit. The UAV to ground user link and the backhaul link between UAV and the fixed eNB use orthogonal 5 MHz bandwidth channels within band 38. We use USRP platform [18] along with a custom designed power amplifier by EURECOM as the RF front end. The maximum transmission power of the eNB is 23 dBm.

[1]In this paper we use several acronyms from 3GPP-LTE terminology without explicitly stating them.

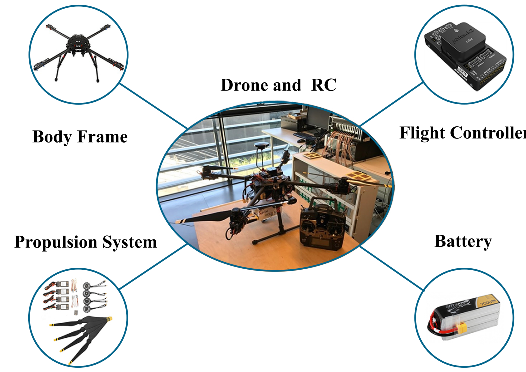

Figure 2: Custom-built UAV.

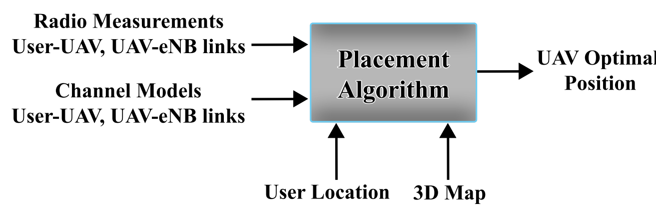

Figure 3: UAV placement algorithm.

The choice of UAV's eNB configuration has a direct impact on the design of the UAV. Higher bandwidth configurations requires generally higher computing power which will limit the flying time of the UAV. Hence, there is an interesting trade off between complexity, throughput, weight and the power consumption of the eNB solution that is mounted on the UAV.

C. Autonomous Placement

The autonomous placement software allows the UAV to position itself to maximize the throughput to the ground user. This requires communication between the placement algorithm and the flight controller. The optimal UAV position is updated according to the instantaneous user location and then is sent to the UAV flight controller by the placement algorithm. The block-diagram of the autonomous placement algorithm is depicted in Figure 3.

Generally, these algorithms depends on wireless channel parameters that vary slowly with time such as pathloss or shadowing. In some scenarios, the wireless channel parameters are estimated beforehand in an offline fashion and then given to the algorithm, whereas in some others the UAV has to learn them on the fly by making radio measurements. Our system design allows us to implement both types of algorithms.

The placement algorithm can be implemented in an on-board computer along with OAI eNB/relay on the UAV or at a ground station. If the algorithm is computed at a ground station, the new coordinate is sent to the UAV by using the backhaul link between the fixed eNB and the UAV. Learning wireless channel parameters on the fly by making radio measurements is a computationally expensive task. In such scenarios, it is therefore favorable to implement the algorithm at a ground station where computing cost and power consumption is not an issue as opposed to on the UAV.

For the experiment presented in this work we use a placement algorithm which has access to the channel parameters that are estimated beforehand in an offline fashion. The algorithm is described in the next section.

III. UAV PLACEMENT

The autonomous placement algorithm relies on the fact that information regarding the 3D map of the environment, and the wireless channel parameters is known in advance. The 3D map can be obtained from either photogrammetry or radio (including recently UAV-aided) based reconstruction approaches [19], [20], while the wireless channel parameters needs to be estimated. The channel model and the method for estimating the parameters involved are explained next.

A. Parameter estimation

We use the same channel model for both UAV-eNB and UAV-user links. Classically, the channel gain in dB between a transmitter and a receiver that are separated by a distance d is given by [21]

$$\gamma = \beta_s - 10\alpha_s \log_{10} d + \xi_s, \tag{1}$$

where α_s is the path loss exponent, β_s is the average channel gain at a reference point, and ξ_s models the shadowing effect which is considered as a Gaussian random variable $\mathcal{N}(0, \sigma_s^2)$. The subscript s emphasizes the strong dependence of the propagation parameters on the (line-of-sight) LOS or (non-line-of-sight) NLOS nature of the channel [22]. Depending on the transmitter and receiver locations, the radio link can either be of LOS or NLOS i.e., $s \in \{\mathrm{LOS}, \mathrm{NLOS}\}$. Once we have access to the pathloss measurements labeled with the distance d and nature of the channel s, the parameters α_s and β_s can be estimated using maximum likelihood estimation (MLE). See [22] for more details. The estimated parameters along with the 3D map are then used in the placement algorithm.

B. Placement Algorithm

The aim of the UAV placement algorithm is to find the optimal UAV position that maximizes the downlink throughput of the ground user. However, the throughput in a LTE system depends not only on the channel gains but also on many parameters such as scheduling, modulation and coding, etc., which makes the problem intractable. Therefore, we resort to an approximation where we try to find an UAV position that maximizes the minimum of the average channel gains of the UAV-user and UAV-eNB links. This serves as a good approximation as we use a decode-and-forward type of relay protocol on the UAV, and the transmission powers of the UAV and the fixed eNB are kept same in our system. Note that the placement algorithm depends on the channel gains which are defined according to (1), hence, we consider channel parameters that vary slowly with time. This assumption is justifiable as the time scale of UAV mobility is much larger than the fast fading channel variations. Before presenting the details of the algorithm, we introduce some notations.

The downlink channel gains for the UAV-user and eNB-UAV links are denoted by γ_u and γ_e, respectively. The user's coordinate is denoted by $\mathbf{x_u}$ while that of the fixed eNB is denoted by $\mathbf{x_e}$. We assume that the UAV can fly over a selective search area in 3D which is denoted by $\mathcal{C}$. The altitude of this search area is restricted to be in between h_{min} and h_{max} with the value of h_{min} is greater than the heights of all the bildings where the experiment is conducted. In practice, the search area $\mathcal{C}$ is discretized. The UAV placement algorithm then solves

$$\max_{\mathbf{x_d} \in \mathcal{C}} \min \left\{ \mathrm{E}\left[\gamma_u\right], \mathrm{E}\left[\gamma_e\right] \right\}, \tag{2}$$

where $\mathbf{x_d}$ represents the coordinate of the UAV and the expectation is taken over the shadowing coefficient which is of zero mean. From now on we use the optimal UAV position in the sense of (2). While the ground eNB's coordinates are fixed, the coordinates of the user and the UAV are obtained using GPS receivers which are embedded in both devices. The placement algorithm solves (2) using the 3D map which contains the information regarding LOS/NLOS nature of the channels, and the coordinates $\mathbf{x_u}, \mathbf{x_e}$ and $\mathbf{x_d}$.

IV. EXPERIMENTAL RESULTS

We have conducted our experiments in EURECOM's premises. The ground user has a commercial Moto G(3rd gen) mobile handset. The fixed eNB's antenna is mounted on a mast situated on the top of a building block, while the user is located on the ground. Both the fixed eNB and the UAV are equipped with a single vertically polarized dipole antenna. The user is typically obstructed by the building, hence, always in NLOS with respect to the fixed eNB. The experimental setup is shown in Figures 4 and 5. When using the UAV relay, its position is obtained using the UAV placement algorithm described in Section III. For applying the algorithm, we first need to estimate the wireless channel parameters based on the measurements that are collected in the environment where the experiment is conducted.

Since the pathloss parameters have strong dependence on the LOS or NLOS nature of the channel, we make measurements in both scenarios. Figures 6 and 7 show the channel gains as a function of the distance between the transmitter and the receiver in LOS and NLOS scenarios, respectively. The channel gains are obtained from the measured Reference Signal Received Power (RSRP) values. The corresponding best-fit path loss parameters can be obtained as described in Section III-A, and they are given in Table I. Note that the channel model presented here does not correspond to a general

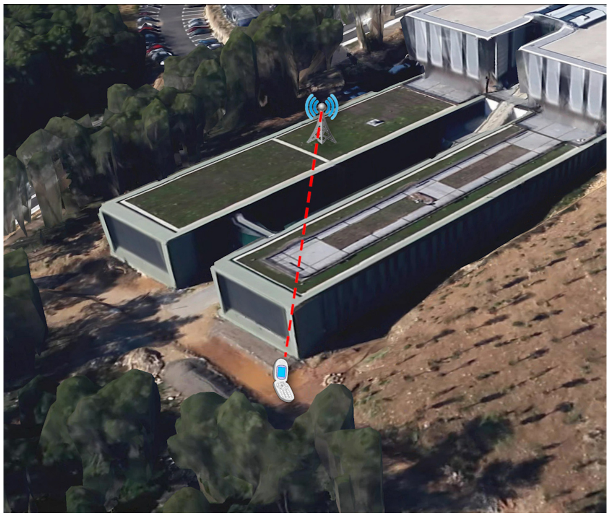

Figure 4: Outdoor experiment setup with only fixed eNB.

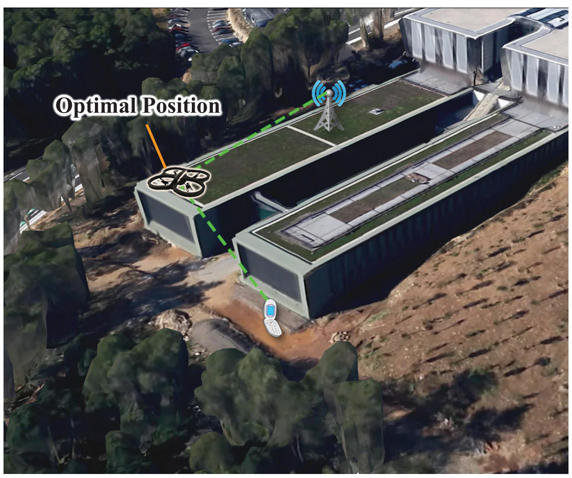

Figure 5: Outdoor experiment setup with UAV relay.

wireless channel and it is highly dependent on our system setup. To get accurate wireless channel models, in addition to the distance one needs to take into account the height of the transmitter, its antenna orientation and gain, etc. The model presented here can only be used in this specific scenario. Study of general channel models for UAVs is itself an interesting problem [23], which is beyond the scope of this paper.

The estimated parameters are then fed to the algorithm which predicts the optimal location for the UAV. In Figure 8, we compare the downlink throughput of the user in scenarios shown in Figures 4 and 5, respectively. The downlink throughput is measured using the iperf application, which generates UDP traffic from the core network to the user. If the user

Parameter	LoS	NLoS
α	2.34	3.75
β	-58	-51.2

Table I: Pathloss parameters.

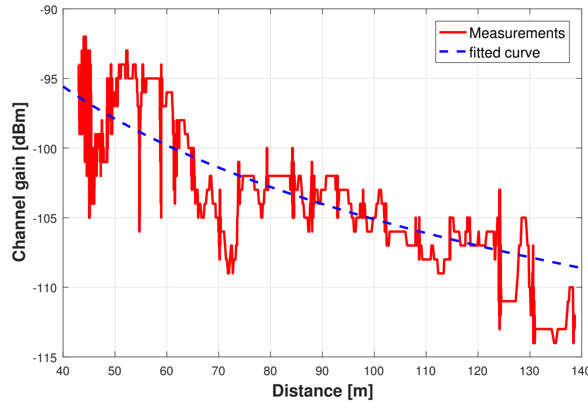

Figure 6: Channel measurements for LOS scenario.

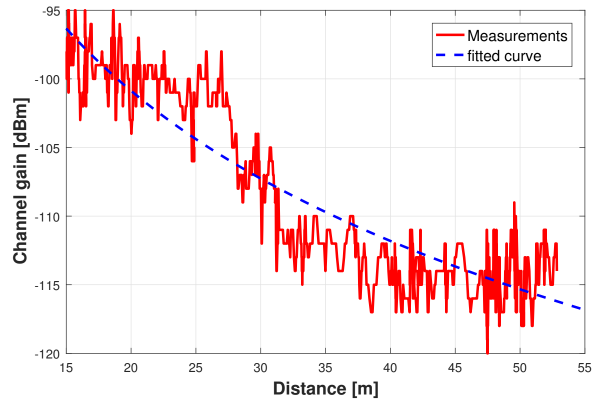

Figure 7: Channel measurements for NLOS scenario.

moves to a new location, the position of the UAV is updated according to the placement algorithm. This is demonstrated in our recent demo [24].

V. Conclusions and Future Work

In this work, we have illustrated the design of a custom-built UAV relay based on OAI, and then presented experimental results related to throughput improvement offered to a ground

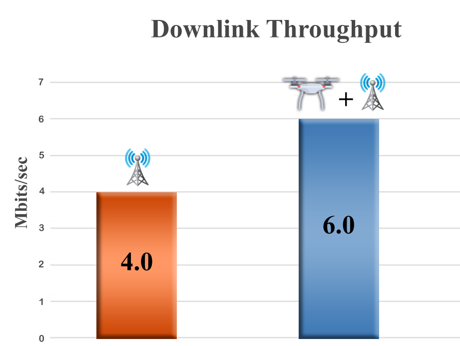

Figure 8: Instance of throughput comparison at a given user location.

user by using this relay. Although, these are initial results based on a single user and single UAV scenario, we believe that this experiment is an initial step towards building more advanced UAV-based LTE relay networks. We have used an autonomous placement algorithm which updates the UAV position in real time based on the user location, 3D map of the environment and a wireless channel model. The output of the placement algorithm often results in an UAV position where it has LOS links to the user and the fixed eNB.

While experimenting with this UAV relay prototype, we have faced some interesting issues both in the system design and algorithm development, which we intend to address in our future works. They are presented below.

A. Design improvement

In the current prototype we have used a vertically polarized dipole antenna for the UAV relay. However, the choice of the antenna and how to optimally mount it on the UAV is not considered in the design. It is well known that the radiation pattern and the polarization losses depends on the orientation of the antenna, and also a conducting surface near the antenna (carbon frame in the case of UAV) might change its radiation pattern. Knowing the antenna pattern and the possible polarization losses is essential in coming up with channel models based on the measurements done by this UAV.

B. Channel models

Although the UAV placement algorithm used in this paper can be adapted to any channel model, further work is needed to analyze the UAV-user and UAV-eNB links. The channel measurements and the model fitting should take into account the impact of UAV height, its antenna orientation with respect to the receiver or transmitter i.e., UAV yaw angle etc., for example as done in [25].

VI. Acknowledgments

This work has been performed within the framework of the PERFUME project which is supported by the European Research Council under the European Union's Horizon 2020 research and innovation program (Agreement no. 670896).

References

[1] J. Thornton, D. Grace, T. K. C. Spillard, and T. Tozer, "Broadband communications from a high-altitude platform: the European HeliNet programme," *Electronics & Communication Engineering Journal*, vol. 13, June 2001.

[2] D. Grace, M. H. Capstick, M. Mohorcic, J. Horwath, M. B. Pallavicini, and M. Fitch, "Integrating users into the wider broadband network via high altitude platforms," *IEEE Wireless Communications*, vol. 12, no. 5, pp. 98–105, Oct 2005.

[3] Project Loon, https://x.company/loon/.

[4] Facebook Aquila, https://en.wikipedia.org/wiki/Facebook_Aquila.

[5] Nokia Bell Labs, "Drone Deployment of a Nokia Bell Labs F Cell," https://youtu.be/LVoYdwS4xok, 2016.

[6] Nokia and EE, "Pushing the limits of technology with drones," https://www.nokia.com/en_int/blog/nokia-ee-pushing-limits-technology-drones, 2016.

[7] AT&T, "AT&T's Cell on Wings (COW) in Action," https://youtu.be/WEIplszMzoI, 2017.

[8] S. Chandrasekharan, K. Gomez, A. Al-Hourani, S. Kandeepan, T. Rasheed, L. Goratti, L. Reynaud, D. Grace, I. Bucaille, T. Wirth, and S. Allsopp, "Designing and implementing future aerial communication networks," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 26–34, May 2016.

[9] J. Chen and D. Gesbert, "Optimal positioning of flying relays for wireless networks: A LOS map approach," in *IEEE International Conference on Communications (ICC)*, 2017.

[10] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP Altitude for Maximum Coverage," *IEEE Wireless Communications Letters*, 2014.

[11] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Drone Small Cells in the Clouds: Design, Deployment and Performance Analysis," in *IEEE Global Communications Conference (GLOBECOM)*, 2015.

[12] ——, "Optimal transport theory for power-efficient deployment of unmanned aerial vehicles," in *IEEE International Conference on Communications (ICC)*, 2016.

[13] 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*, 2017.

[14] Y. Zeng, R. Zhang, and T. J. Lim, "Throughput Maximization for UAV-Enabled Mobile Relaying Systems," *IEEE Transactions on Communications*, vol. 64, no. 12, pp. 4983–4996, Dec 2016.

[15] R. Gangula, P. de Kerrert, O. Esrafilian, and D. Gesbert, "Trajectory Optimization for Mobile Access Point," in *Asilomar Conference on Signals and Systems*, 2017.

[16] A. T. Klesh, P. T. Kabamba, and A. R. Girard, "Path planning for cooperative time-optimal information collection," in *American Control Conference*, June 2008.

[17] OpenAirInterface, www.openairinterface.org.

[18] https://www.ettus.com.

[19] A. T. Irish, J. T. Isaacs, F. Quitin, J. P. Hespanha, and U. Madhow, "Probabilistic 3D mapping based on GNSS SNR measurements," in *IEEE International Conference on Acoustics, Speech and Signal Processing*, May 2014.

[20] O. Esrafilian and D. Gesbert, "3D City Map Reconstruction from UAV-Based Radio Measurements," in *IEEE Global Communications Conference*, Dec 2017.

[21] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[22] J. Chen, U. Yatnalli, and D. Gesbert, "Learning radio maps for UAV-aided wireless networks: A segmented regression approach," in *IEEE International Conference on Communications*, May 2017.

[23] W. Khawaja, I. Guvenc, D. Matolak, U. C. Fiebig, and N. Schneckenberger, "A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles," *arXiv*, Jan 2018. [Online]. Available: http://arxiv.org/abs/1801.01656v1

[24] EURECOM, "Autonomous Aerial Cellular Relaying Robots," https://youtu.be/GI_lOsg_qmQ, 2017.

[25] E. Yanmaz, R. Kuschnig, and C. Bettstetter, "Channel measurements over 802.11a-based UAV-to-ground links," in *IEEE GLOBECOM Workshops*, Dec 2011.