Detecting the source of an RF signal with a transceiver-equipped UAV

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***Abstract*—Wireless UAV networks are characterized by dynamic reconfigurable infrastructure nodes. One of the critical tasks of a UAV in a wireless UAV network is localizing and moving towards the network users. This paper proposes simple control algorithms to localize and move towards the source of an RF signal with a transceiver-mounted UAV. Existing work on using UAV motion to detect the source of an RF signal is reviewed, and improvements to existing methods are proposed to overcome practical limitations of UAV platforms. We then present an experimental framework where a real quadrotor is equipped with a software-defined radio, and used to detect the source of an RF signal. Test results show that leveraging the motion of the UAV is indeed an effective method to detect the source of a RF signal. In all of our testflights, the UAV is successfully able to detect and move towards the source of the RF signal.**

***Index Terms*—UAV, software-defined radios, flying base stations, localization and tracking**

I. Introduction

The decreasing cost of small autonomous flying platforms has made the perspective of flying wireless infrastructure a new reality. One common application scenario is the following: in cases of natural disasters (earthquakes, floods), one can expect cellular networks to be damaged or saturated by emergency calls. In this work, we envision a system of Unmanned Aerial vehicles (UAVs) equipped with wireless transceivers (or Wi-UAVs) to act as flying base stations that will offer emergency connectivity to victims.

Compared to classical wireless communications, UAV-based communications have some very attractive features. Whereas classical communications is characterized by a static infrastructure, Wi-UAV networks are composed of dynamic access points that can react to channel conditions. The network no longer needs to suffer from wireless channel uncertainties, but by reacting to current channel conditions, the Wi-UAV network can reduce channel uncertainties to arbitrarily low values. This turns the whole problem of wireless communications around: the question is no longer how we can live with the communication channel uncertainty, but how we can eliminate this uncertainty. From a control theory perspective, the question is no longer how wireless communications can help to solve the control problem, but rather how control algorithms can be adapted to meet communication objectives. Wi-UAV communications offer new perspectives to problems that have been around for decades in wireless communications: precise localization of RF transmitters in complex environments, network deployment optimization in environments with varying densities of users, large-area deployment of low-power sensor nodes.

There are three main technical challenges that must be solved to make Wi-UAV networks a reality:

1) The UAVs must be able to localize the users (possibly without user cooperation),
2) the Wi-UAVs must be able to establish a high-speed backhaul link with each other,
3) the location of the different Wi-UAVs must be optimized as a function of radio link parameters, rather than simple geographical coverage.

This paper addresses the first challenge: how can a Wi-UAV detect and track the location of a user? Having precise geographical coordinates is not only important to optimize the SNR between user and UAV, it also provides the Wi-UAV fleet operator with video footage of the user environment (which is of crucial importance in the case of natural disaster scenarios).

Related work: UAV-based communication has recently started gaining more attention in literature, and many challenges must be addressed before they become a reality [1]. Most work on UAV-based wireless networks has focused on how to provide capacity improvement for cellular network users or sensor networks [2][3][4]. Regarding RF source localization with a UAV, the major problem of RF localization in conventional cellular networks has always been the uncertainty that plagued the localization metrics, mostly due to multipath fading [5]. Several papers have investigated the use of unmanned *ground* vehicles to track the source of an RF signal. In [6], a land-mobile robot uses a rotating antenna to detect the direction of the source of an RF signal, which will inspire the algorithms proposed for flying platforms in later work. In [7] a land-mobile robot follows the RSS gradient until it reaches the source of the RF signal. This method suffers heavily from multipath propagation and shadowing effects, and results in long travel times to reach the RF source. The authors in [8] propose an algorithm that uses channel second-order statistics to detect the bearing of the RF source. Only simulation results are presented in this paper, and it is uncertain if real-life wireless channels would exhibit such stable channel statistics. In [9],[10] the rotational movement of an antenna on a monoblade UAV is used to estimate the bearing of the RF source and track the position of this RF source. It is shown, both theoretically and experimentally, that the UAV is able to find the RF source even under the presence of obstacles (such as buildings). This concept was extended to a quad-rotor platform in [11], where a control algorithm was proposed to have the quad-rotor continuously rotate while translating in order to move while providing bearing estimates of the RF source. This is of course unpractical in real scenarios, and is one of the problems we will overcome in this paper.

Contributions: In this paper, we propose the following contributions:

- we extend existing control algorithm that use rotation-based methods to account for non-continuous rotations, and we propose a new bearing estimation algorithm based on UAV rotation;
- we develop an experimental platform that integrates a quadrotor UAV and a software-defined radio;
- we perform a series of experiments that show that the extended control algorithm works in all of our testflight, and we compare the new bearing estimtion algorithm with an existing one. We show that, contrary to expectations, the new control algorithm does not perform significantly better than existing ones.

One important note we want to make is about the difficulty of performing realistic simulations for UAV-based wireless networks. Besides the well-known variability of multipath wireless channels, UAV are subject to many slight attitude changes, mostly due to maneuvering and to meteorological conditions. These slight attitude changes will affect the orientation of the on-board antennas, changing the received amplitude of the radio signal. This could be reproduced in simulations by using geometry-based channel models [12], however, to the best of the authors knowledge, no experimentally validated geometry-based channel model exist for ground-to-air and air-to-air wireless channels. Geometry-based wireless channel models are traditionally measured and validated with channel sounders [13], but a channel sounder is heavy, bulky hardware that can hardly be mounted on a small flying platform. Therefore, this paper adopts an experimental-based approach by validating our techniques and algorithms on an experimental platform.

II. Wi-UAV control algorithms

A. Rotation-based control algorithm

In this control algorithm, the UAV is mounted with a directional antenna. When the UAV performs a full rotation, the received signal strenght (RSS) of the signal changes according to the radiation pattern, as was demonstrated in [11]. By taking the orientation corresponding to the peak of the RSS over one rotation (assuming the antenna is mounted with its main lobe along the UAV's front direction), a bearing estimate of the RF transmitter is obtained. It was shown in [9] that such a bearing estimation provides the following estimate:

$$\psi_k = (1 - \sigma_k)(\theta_k + n_k) + \sigma_k w_k \tag{1}$$

where k indicates the k-th estimation, ψ_k is the estimated angle, θ_k is the true angle towards the transmitter, n_k is an i.i.d. Gaussian-distributed additive noise, w_k is a noise term uniformly distributed over $[0, 2\pi[$, and $\sigma_k \in \{0, 1\}$ an i.i.d. Sequence of Bernouilli random variables with parameter $p \in [0, 1]$. The event $\sigma_k = 1$ corresponds to the case where an outlier measurement is obtained (e.g. due to a strong multipath reflection), and the event $\sigma_k = 0$ correspond to the case where the measurement is close to the true angle (with some additive Gaussian noise).

In the rotation-based control algorithm, the UAV performs a full rotation, thereby making an estimate of the transmitter's bearing ψ_k, and then moves in that direction for a distance h. It was shown in [9] that, even with correlated outlier measurements in (1), the UAV is guaranteed to eventually converge towards the true location of the RF source. However, experiments in [9][11] were only performed for continuously-rotating UAVs, so this guarantee could not be proven experimentally for larger values of h. We will show in Section III that this rotation-based control algorithms also works for UAVs only performing occasional rotations.

B. Improvement of RSS-based bearing estimation

One of the major drawbacks of the rotation-based control algorithm is the large amount of outliers in the bearing estimation that is obtained by using the maximum RSS over a single rotation. Figure 4 shows the the measured RSS when the UAV is performing a full rotation. The distortions of the radiation pattern can clearly be observed, and are due to multipath propagation, UAV drift during a single rotation, software lags between the threads controlling the UAV and the radio, etc. When using the maximum RSS over a single rotation to estimate the transmitter's bearing, these distortions generate a large portion of outlier measurements. Previous works [9][11] had the UAV continuously performing bearing estimations, so a single outlier measurement would quickly be detected and corrected. In contrast, our control algorithm has the UAV perform a single rotation and then move for some distance. In this case, a single outlier measurement would send the UAV in the wrong direction, significantly increasing the time required to reach the destination.

In order to improve the bearing estimation, we do not use the maximum RSS over a single rotation, but perform a correlation over the RSS measured over a single rotation and the radiation pattern measured in an anechoic chamber. We will investigate in Section III how this affects the number of outliers in the bearing estimation algorithm, thereby guaranteeing shorter times required to reach the transmitter. The final flow chart of the control algorithm is shown in Figure 1.

III. Experimental results

A. Experimental setup

Our experimental setup consist of a developer-oriented DJI Matrice-100 quadrotor, which is controlled autonomously by an on-board Raspberry Pi 3. The DJI Matrice-100 can be

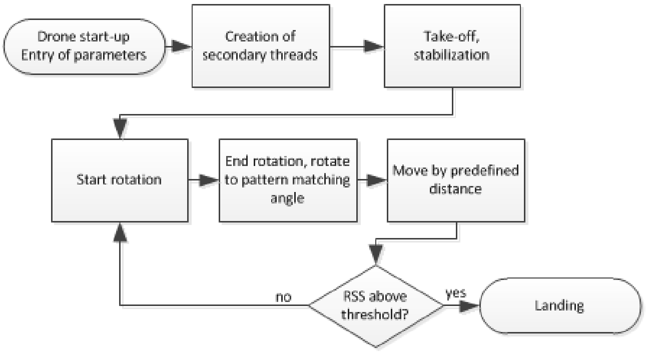

Fig. 1. Flow chart of the control algorithm.

controlled through a serial port, which also provides access to internal navigation information. An operator can bypass the autonomous flight mode with the remote control at all times. The UAV is mounted with a USRP-B205-mini-I software-defined radio (SDR), which allows to transmit and receive from 200 MHz to 6 GHz with a bandwidth of 20 MHz. The SDR is also controlled by the Raspberry Pi 3. The RF source is an embedded USRP-E310, which transmits a constant pilot tone at 900 MHz. In order to detect and track the RF source, the quadrotor is equipped with a directional log-periodic receive antenna. The radiation pattern was measured in an anaechoic chamber with and without the quadrotor, as shown in Figure 2. Without the quadrotor, the antenna's half-power beamwidth is about 120°. With the quadrotor, this half-power beamwidth reduces to 90°, making the antenna more directional. A picture of the testbed is shown in Figure 3.

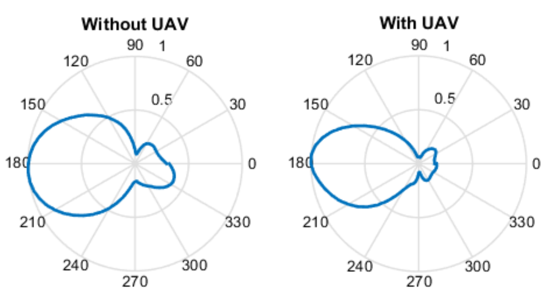

Fig. 2. Antenna's radiation pattern, without and with the quadrotor.

The major challenge of this setup is the software integration of the DJI software development kit (SDK) with the USRP Hardware Driver (UHD) development environment. Both of these are open-source and accessible online [14][15], but must be integrated into a single development environment. Fortunately, UHD provides extended *cmake* functions that allows to integrate third-party SDKs into the UHD framework. The software is composed of four threads that run in parallel: the main thread that controls the drone movement, a second thread that receives the USRP data and computes the mean RSS periodically, a third thread for logging all the measured data, and a fourth high-priority thread that allows an operator to override the autonomous control in case of emergency. The control thread will query the latest measured RSS value to the USRP thread to match a given yaw with a given RSS value.

Fig. 3. Picture of the experimental testbed showing the quadrotor mounted with the log-periodic antenna. The USRP and the Raspberry Pi 3 are hidden below the external battery.

B. Rotation-based bearing estimation

The first experiment aims at determining how to estimate the bearing of the RF transmitter using the UAV rotations. Two UAV bearing estimation algorithms will be compared. The first one uses the UAV yaw corresponding to the maximum RSS (over a full UAV rotation) as the direction of the transmitter. The second algorithm correlates the RSS/yaw profile with the radiation pattern measured in the anechoic chamber. The measurements were conducted in an indoor sports hall. The RF transmitter was placed on one side of the hall, and the UAV was flown at nine different locations in the hall. At each location, the UAV would perform a full rotation to record RSS and yaw values.

Figure 4 shows the RSS/yaw profile for nine different measurement locations, with the red line indicating the true direction of the RF transmitter. A few observations can be made based on Figure 4. First, the presence of multiple noise sources will degrade the shape of the theoretical radiation pattern from Figure 2. Among these noise sources, multipath is certainly an important one, but drone translation during a single rotation and drone pitch also play a role. Second, despite the multiple noise sources, the overall shape of the radiation pattern can still be observed. This means that, even under sever multipath, matching the RSS/yaw profile with the radiation pattern should provide us with a fairly good bearing estimation. The angle estimated with the pattern matching and the maximum RSS algorithm are also shown in Figure 4. The amount of measurements do not allow to make quantitative conclusions at this stage, but it is fair to say that both algorithms seem to work reasonably well even in the presence of strong multipath.

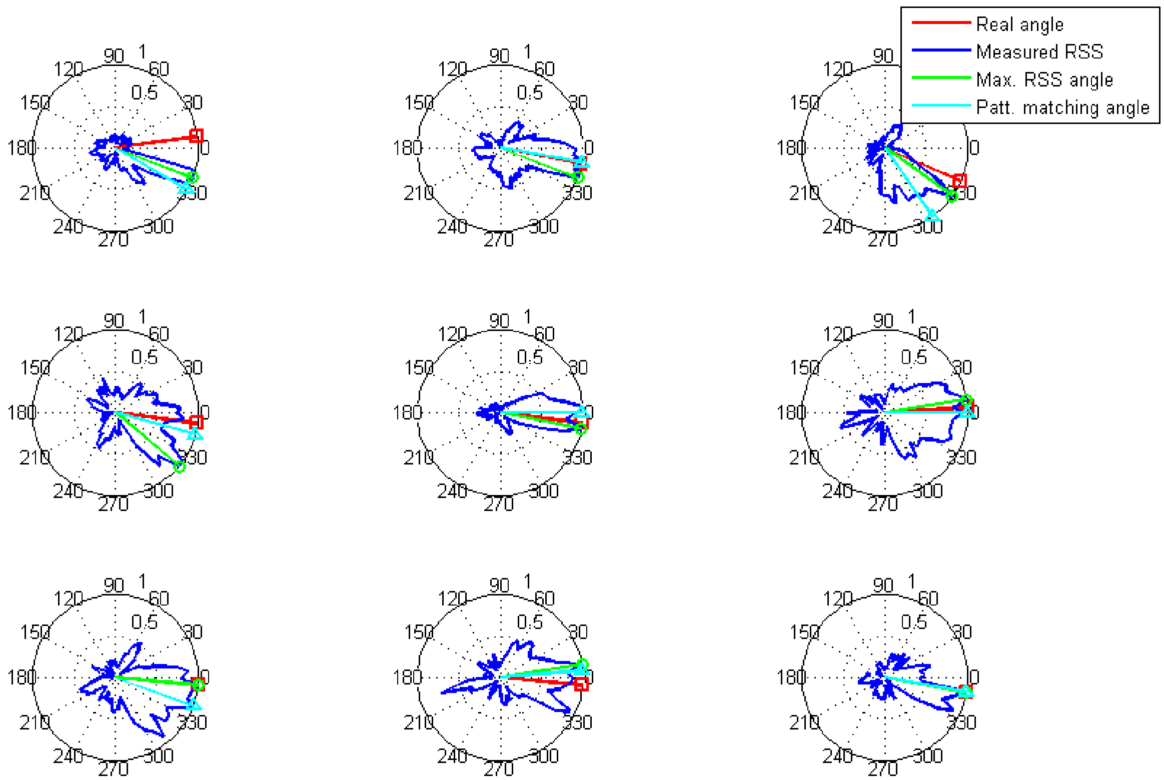

Fig. 4. Measured RSS versus yaw, for nine different indoor locations. The red line indicates the real transmitter bearing.

C. Rotation-based control algorithm

The control algorithm described in Section II was implemented on our hardware testbed. A total of twelve testflights were performed, with the UAV taking of from different locations around the transmitter. The distance between the transmitter and the UAV takeoff position was between 13 and 41 m. The tesflights were performed on a parking lot, with buildings on one side of the parking lot (as shown in the satellite image in Figure 5). In all of our testflights the UAV was able to reach the transmitter (as shown in Figure 5 for flights 5 to 12), showing the robustness of the proposed control algorithm. The number of rotations performed by the UAV was between 2 and 7, with a travel distance of between 5 to 10 m between two succesive rotations. The UAV was performing pattern matching between the measured RSS and the theoretical radiation pattern to determine the bearing of the transmitter. Figure 6 shows an example of a testflight with four rotations. The UAV performs a first rotation as soon as it takes off, and subsequently performs a rotation roughly every 10 m. Once the UAV reaches the transmitter, the operator takes back control and lands the UAV. Figure 7 shows the measured RSS at each rotation. The overall shape of the radiation pattern can be clearly identified, and both the maximum-RSS and the pattern matching algorithms provide bearing estimates that are close to the true bearing. The pattern matching bearing was chosen as the direction that would be taken by the UAV.

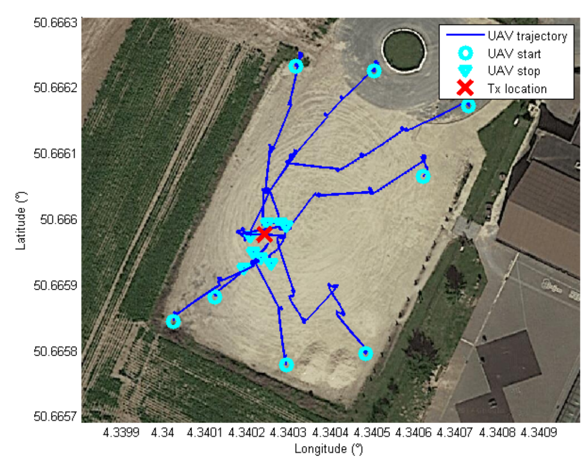

Fig. 5. Testflights 5 to 12. The UAV is able to reach the destination in all testflights.

Over all twelve testflight, a total of 51 rotations were performed. These rotations have been post-processed to determine

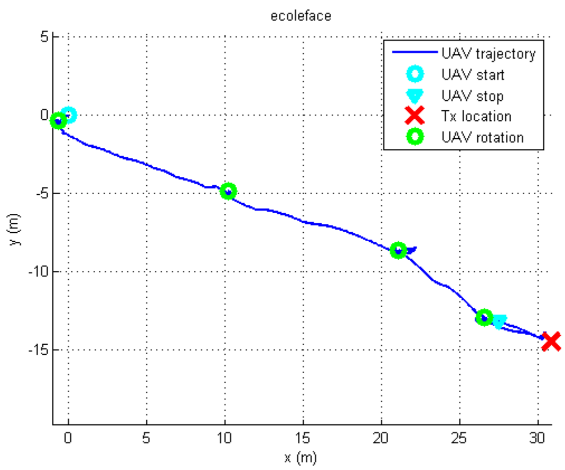

Fig. 6. Test flight with four rotations. It can be seen that the UAV flies almost straight towards the transmitter.

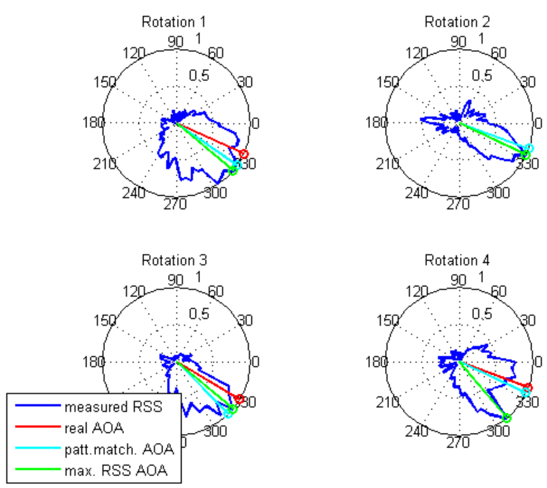

Fig. 7. Measured RSS at each rotation. The bearing of the transmitter can easily be deduced.

the performance of the maximum-RSS and the pattern matching bearing algorithm. The cumulative distribution function of the bearing estimation error is shown in Figure 8 for both bearing estimation algorithms. Contrary to our expectations, the improvement of the pattern matching algorithm over the maximum-RSS algorithm is only marginal, both in RMSE of non-outlier measurements and outlier percentage. If we set the threshold for outliers at $45°$, the percentage of outliers is 5.9% for both the pattern matching and the maximum-RSS algorithms. The RMSE of the non-outlier measurements is $13.7°$ for the pattern matching, and $15.3°$ for the maximum RSS algorithm, showing no significant difference between both techniques. A detailed analysis of the log files for high outlier measurements show that these are due to particular high wind speeds. When wind speeds are high, the UAV needs to adjust its roll and pitch angles to maintain its trajectory, thereby

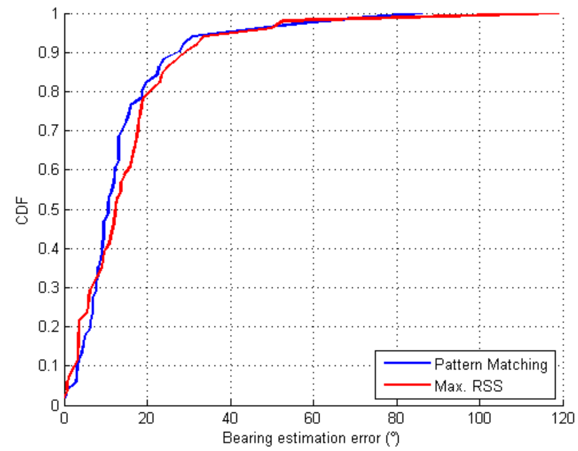

Fig. 8. CDF of the bearing estimation error.

changing the radiation pattern of the antenna in the horizontal plane and degrading the performance of the bearing estimation.

IV. Conclusion

This paper investigated the use of a transceiver-equipped UAV to detect and navigate towards the source of an RF signal. To that end, we built an experimental testbed consisting of a quadrotor UAV, mounted with a SDR and a directional antenna. We showed that existing rotation-based algorithms can be extended to non-continuously rotating platforms. Our experiments indicated that using a pattern matching algorithm to detect the bearing of the transmitter does not show significant advantages over using a (simpler) maximum RSS algorithm.

Acknowledgments

The authors acknowledge the financial support of the David and Alice Van Buuren fund. They would also like to thank UCLouvain's WELCOME lab for granting access to their anechoic chamber, funded by the FNRS.

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