Measurement based performance evaluation of drone self-localization using AoA of cellular signals

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***Abstract*—This paper focus on drone self-localization based on received signals from stationary base stations with known locations without having access to global navigation satellite system (GNSS) signals. In the considered method, the drone first estimates the angle of arrival (AoA) based on the downlink signal strength measurements by rotating non-isotropic antenna. Once AoA is estimated from several base stations, the drone can be localized on a 2D plane by using the least squares method. This method was selected due to its simplicity and thus ease of implementation in low cost drones. To better understand the achievable performance of the studied AoA estimation method, we performed several measurements using a prototype system to characterize the antenna rotation and AoA estimation errors. The error models were then plugged into simulator to analyze the achievable performance in typical macro cellular setting. Our measurement results indicate, that the AoA could be estimated with 6.02° accuracy in case of a hovering drone. Our simulation results indicate, that in typical macro cellular setup with line-of-sight propagation, the median localization error was less than 45 m for a hovering drone.**

***Index Terms*—Angle-of-arrival estimation, drones, self-localization**

I. Introduction

To localize aeronautical systems, such as drones, the Global Navigation Satellite Systems (GNSS) are widely used and they can provide very good location accuracy. GNSS systems, however, have their limitations. For instance, the localization can fail if the GNSS receiver can't see enough satellites due to some obstructions, like that of hills and buildings. In addition to this, GNSS systems are vulnerable by spoofing and jamming attacks which can cause satellite-based localization to fail [1].

For maintaining localization even in GNSS denied conditions, alternative means should be implemented in the drone. One option is to utilize a dedicated ground based navigation system, but such systems are too costly to be deployed to support low-cost drone operations. Another option is to use signals of opportunity [2] for the localization. That is, to use signals with known transmitter locations for estimating the receiver location. Examples of such signal sources include TV transmitters, radio transmitters and cellular base stations. Different features of the signal can be utilized for the localization including Time-of-Arrival (ToA) [2], Received Signal Strength Indication (RSSI) and Angle of Arrival (AoA) [3].

In this paper, we focus on the use of cellular system generated signals. Base stations periodically transmit synchronisation signals, downlink pilot signals, and other control information that could be utilized by the drone for localizing itself. Long Term Evolution (LTE) and New Radio (NR) use timing advance estimation to determine and compensate for the propagation time between the receiver and transmitter. This could be utilized as a proxy for the distance. Unfortunately, the granularity of those measurements is poor. For LTE it would provide the distance with 78.12 m steps ranging from 0 to 100.15 km. Hence ToA approach would lead to very coarse localization. Cellular modems provide Radio Signal Strength Indication (RSSI) which too could be utilized for distance measurements. Base station antennas are typically down tilted and thus an aerial user is likely to be in one of the sidelobes of the antenna which results in rapidly fluctuating RSSI as the drone moves. This imposes a challenge for RSSI based localization scheme. Angle of arrival measurement are more robust as they do not directly depend on the RSSI value. Accurate AoA measurements could be done using an antenna array with steerable beam. In this paper, we adopt cheaper option and use simple range finding antenna instead.

Many AoA estimation based self-localization algorithms have been proposed in the literature including the triangulation [4]–[6] method, the maximum likelihood (ML) estimator [7], and the pseudo-linear estimation method [8]. In this paper, we adapt the well-known least squares (LS) method, which is simple to implement and fast to compute, but suffers from bias. We selected this method for its simplicity such that it could be easily computed with the on-board unit of the drone.

The rest of this paper is organized as follows: Section II describes the system considered in this paper; Section III discuss AoA estimation using non-isotropic steerable antenna. Section IV reviews the least squares method for localization; Section IV discuss the AoA estimation error accuracy based on experimental results and simulation; Section V uses propagation simulations to predict how the AoA estimation errors would map to location error in a typical macro cellular environment; finally Section VI concludes the paper.

II. System Description

We consider a drone equipped with non-isotropic two antenna elements that receive the downlink pilot signal from multiple base stations. The signal from the two antennas is combined in the analog domain and connected to a single

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RF frontend. The antenna beam is steered mechanically by rotating the antenna.

In our approach, we make the following main assumptions;

- All the transmitters are stationary with known locations.
- All the transmitters transmit orthogonal downlink pilots.
- Drone is flying high enough such that it has unobstructed line-of-sight to the base station transmitters.
- The downlink signals of the transmitters have high signal-to-noise ratio (SNR) at the drone receiver.

The drone estimates the angle of arrival of the downlink signal transmitted by a base station by measuring its pilot power from different physical angles φ by mechanically rotating its antenna array while it is hovering (See Section IV). This could be done either by rotating the drone or having the antenna attached to a gimbal. Once the angles of arrival have been estimated, the location is estimated using the standard least squares method (See Section V) which allows the drone location to be calculated using a fast to execute matrix inverse procedure. Figure 1 shows the general system architecture of the localization.

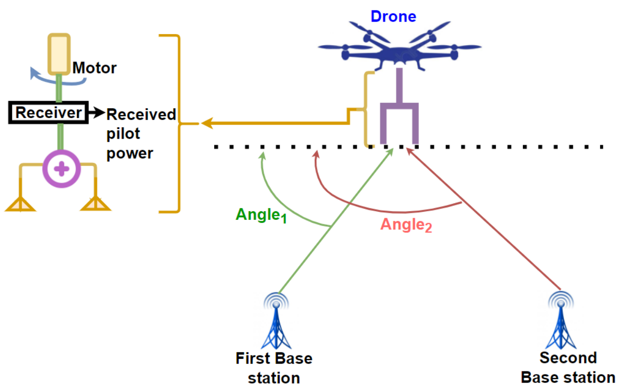

Fig. 1: General schematic diagram of the drone localization

III. Angle of Arrival Estimation Algorithm

Consider the drone's antenna gain $G_{rx}(\theta, \psi)$ where θ is the azimuth angle and ψ is the elevation angle for the arriving signal. Assume that the azimuth angle 0 radians corresponds to magnetic North. Let φ denote the angle that the drone antenna array is facing away from the magnetic north. A known emitter is located in the direction θ from the magnetic pole. In the line-of-sight (LoS) conditions, the Frii's equation states that

$$P_{rx}(\varphi) = G_{rx}(\theta - \varphi, \psi) \left(\frac{\lambda}{4\pi d}\right)^2 G_{tx}(\theta, \psi) P_{tx} \tag{1}$$

where λ is the wavelength, d is the distance between the drone and the signal source, G_{tx} is the transmitter antenna gain and P_{tx} is the transmitted power. It is notable that base station antennas are typically tilted down and a high flying drone is likely to be in some of the sidelobes of the downwards pointing vertical beam. This means that the antenna gain $G_{tx}(\theta, \psi)$ has high variability in the elevation angle which makes it difficult to use the received signal strength (RSS) as a proxy for the distance. We can nevertheless use the power for estimating the Angle-of-arrival (AoA).

The drone measures the power $P_{rx}(\varphi_k)$ in several known angles, $\{\varphi_k, k \in \mathcal{K}\}$ and then seeks to find the angle θ that maximizes the convolution between the power and given antenna pattern:

$$\theta = \mathsf{argmax}_{-\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}} \sum_k G_{rx}(\theta - \varphi_k, \psi) P_{rx}(\varphi_k)$$

which could be efficiently implemented using Fast Fourier Transform (FFT). The unknown transmit power and antenna patter $G_{tx}(\theta, \psi)P_{tx}$ simply scales the magnitude of the result, but as long as the signal-to-noise ratio at the receiver is high, they have no impact on the estimated azimuth angle θ.

IV. Positioning Algorithm

We seek to estimate the 2D location (x, y) based on AoA location and the height z based on altimeter or downwards placed laser range finder. The drone is able to make angle of arrival estimates $\theta_k, \in \mathcal{K}$ from $\in \mathcal{K} = 1, 2, \ldots, K$ known transmitters located in 2D plane in coordinates (x_k, y_k). In the absence of AoA estimation errors and drone location uncertainty, we would have

$$\tan\theta_k = \frac{y - y_k}{x - x_k}, \quad \forall k \in \mathcal{K} \tag{2}$$

We assume that the estimated angle is Gaussian distributed around the true value $\hat{\theta}_k \sim \mathcal{N}(\theta_k, \sigma^2_{\theta_k})$. It follows that

$$\mathbb{P}\mathsf{r}\left\{\tan\hat{\theta}_k \leq t\right\} = \Phi\left(\frac{\arctan(t) - \theta}{\sigma_{\theta_k}}\right) \tag{3}$$

where $\Phi(x)$ is the cdf of the standard normal distribution. It is notable that $\tan\hat{\theta}_k$ does not have well defined moments, since $\tan(z) \to \infty$ as $|z| \to \frac{\pi}{2}$. However, it is easy to derive that

$$\mathsf{median}\{\tan\hat{\theta}_k\} = \tan\left(\theta_k + \Phi^{-1}\left(\frac{1}{2}\right)\sigma_{\theta_k}\right) = \tan\theta_k \tag{4}$$

Hence, if we can obtain multiple measurements for the single AoA angle $\hat{\theta}_k(t)$, we have

$$\tau_k = \tan\theta_k = \frac{y - y_k}{x - x_k} \tag{5}$$

where $\tau_k \triangleq \mathsf{median}\{\tan\hat{\theta}_k\}$. Given AoA measurements from K different base stations, we can then localize the drone by solving the least squares (LS) problem

$$\min_{(x,y)\in\mathbb{R}^2} \sum_{k\in\mathcal{K}} e_k^2$$

where

$$e_k = (x - x_k)\tau_k - (y - y_k)$$

We can write the error in vector form as

$$\boldsymbol{e} = \boldsymbol{G}\boldsymbol{p}_0 - \boldsymbol{h} \tag{6}$$

where $\boldsymbol{p}_0 = (x, y)^T$ denotes the location of the drone,

$$\boldsymbol{G} = \begin{bmatrix} \boldsymbol{\tau} & -\mathbf{1} \end{bmatrix}$$

and $\boldsymbol{\tau} = (\tau_k, k \in \mathcal{K})$ is a vector containing the medians of the measured tangents of the AoA angles, $\mathbf{1}$ is a vector consisted of all ones, and $\boldsymbol{h} = (h_k, k \in \mathcal{K})$, $h_k = \boldsymbol{g}_k^T \boldsymbol{p}_k$. The vector $\boldsymbol{g}_k^T$ denotes the k^{th} row of of the matrix $\boldsymbol{G}$ and $\boldsymbol{p}_k = (x_k, y_k)^T$ is a vector of the base station locations. The resulting location estimate is then given by

$$\hat{p}_0 = (\boldsymbol{G}^T \boldsymbol{G})^{-1} \boldsymbol{G}^T \boldsymbol{h} \tag{7}$$

V. AoA Estimation Error

In this section, we investigate the performances of the AoA estimation algorithm with the help of both measurement and simulation based on different technical parameters. The sensor used for obtaining the orientation of the receiver antenna is an Inertial Measurement Unit (IMU) Adafruit BNO055 absolute orientation sensor by Bosch [9]. The sensor gives a 3-axis orientation output utilizing a sensor fusion algorithm, which combines measurements from accelerometer, gyroscope and magnetometer. The receiver antenna is mounted on a rotating system that rotates using an arduino-controlled servo. The rotation is programmed such that each step is controlled using the pulse width modulation (PWM) limits of the servo starting from 0° to 180°. Taking this into account the servo motor rotation is bound to have an error. In one full rotation, the measured error had a standard deviation of 0.8°. A summary of the most important technical parameters used for all measurements is given in table I.

TABLE I: System configuration parameters

Parameters	Values
Number of antennas	2
Types of antenna	Uniform Linear Antenna (ULA)
Inter element spacing	0.5λ
Frequencies	3.0 GHz and 3.03 GHz
Number of base stations (BSs)	2
Signal generator output	20dB
True AoA (degree)	90° and 120°

A. Measurement evaluation

In this subsection, we discuss the AoA estimation errors obtained in calibration and outdoor measurements. Before the measurements were conducted, the BNO055 was fixed on the rotating system, keeping the magnetic north as a reference the accelerometer, gyroscope and magnetometer were calibrated. The calibrated values for the accelerometer and gyroscope were stored in the system and preloaded when the system initialized for all the measurements conducted. The magnetometer, however, calibrates each time upon initialization of the system and since it can be affected by soft or hard metal and how the earth's magnetic field changes at different locations the sensor is susceptible to errors in determining the orientation. Hence, we compare an ideal and the sensor angle in the outdoor measurement. In the ideal case, we assume the receiver antenna is rotating from 0° to 180° only taking into account servo motor error.

B. Antenna calibration measurement

Based on the specifications presented in table I, we first made calibration of our setup in an anechoic chamber for incoming signals from two base stations located in different positions. With respect to the orientation of the receiver, the first BS and the second BS are located at 90° and 120° respectively. We performed multiple measurements to evaluate the consistency of the received signal from the two base stations. These measurements were also performed with steps for the rotation at 2° and 5°, it was seen that the changes did not affect the angle estimation, hence a 10° step was chosen for time efficiency.

Figure 2 shows the received power of the measurements, from which the measured mean angle estimation for BS_1 and BS_2 is 88.5° and 117.5° respectively, and the measured angular errors in BS_1 and BS_2 remains less than 0.5°.

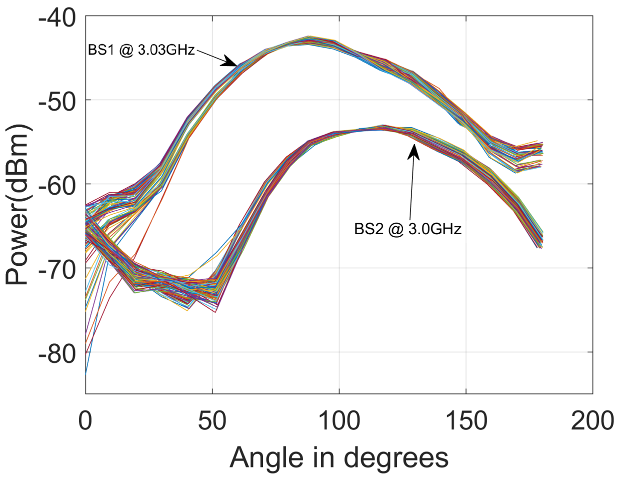

Fig. 2: Received power from two base stations

C. Outdoor measurement

In order to evaluate the effects of ground reflections and wind pressure on drone location estimation, we considered two cases, in one the drone is stationary on a shelf and in the other it is hovering under the same wind pressure.

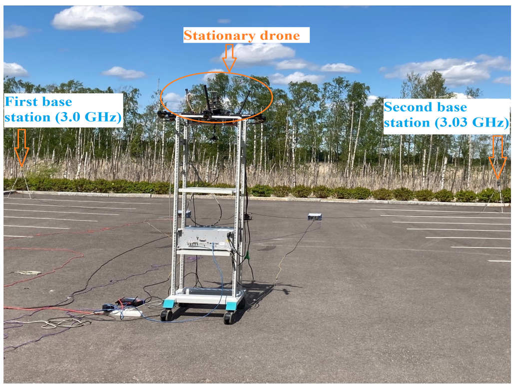

Fig. 3: Outdoor measurement setup without hovering the drone

In both scenarios, the antenna receivers are fixed at the bottom of the drone body. To validate the performance of the angle estimation algorithm while the drone is hovering, we first conducted consecutive and multiple measurements by fixing the drone on the ground, as shown in Figure 3. In each measurement, the received power from the BSs is disturbed by the ground reflection and our algorithm was not able to compensate for it and this affects the angle and location estimations.

Figure 4 compares the angle of arrival estimation of the consecutive measurements from the two base stations. From

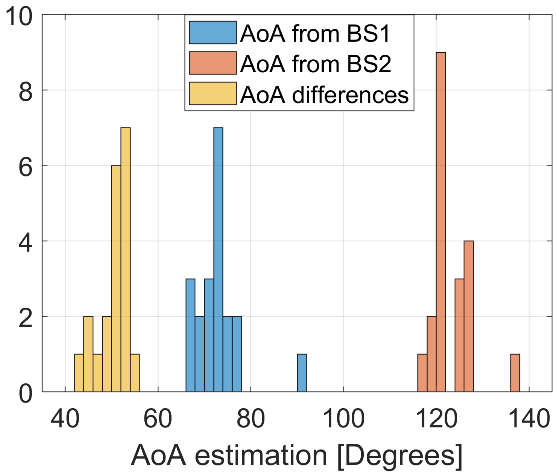

Fig. 4: AoA estimation without flying the drone

the histogram, 95% of the estimated AoA from BS_1 fall between 65° and 77°, resulting in a mean estimated AoA of 71.5°. On the other hand, 95% of the estimated AoA from BS_2 varies in the range of 120° to 126°, with a mean estimate of 122.5°. Based on the absolute angle difference of the angle estimates from both base stations, 70% fall between 50°and 54°, on an average. Using the difference of the AoA, the standard deviation (Std) is calculated and used for stationary drone simulation.

After performing multiple ground measurements, we flew the drone in the same area as shown in Figure 5. Table II presents all the measured parameters of the drone while it hovers.

TABLE II: Drone hovering measurement observations

Drone flying measurement Parameters	Values
Distance between the BSs (m)	15
Ground distance between the BS and drone (m)	21
Angle between the BSs (degree)	44°
Height of the BS (m)	1.2
Height of the flying drone (m)	3.0
Back and forth drone movement (m)	0.5
Up and down drone movement (m)	0.3
Wind speed (m/s)	2
Wind gust (m/s)	4

Due to the additional variation caused by the wind while the drone hovers, the received power values vary in each

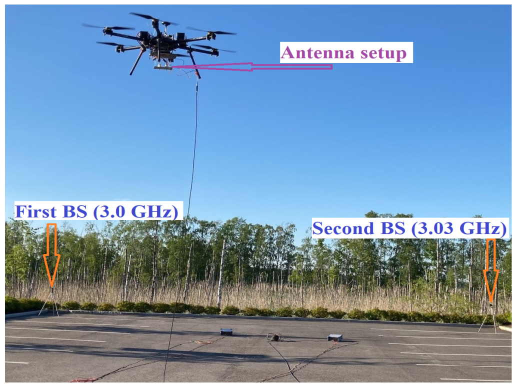

Fig. 5: Outdoor measurement setup with hovering the drone

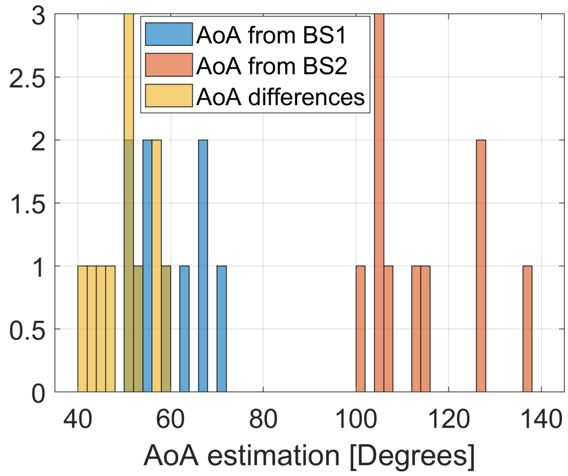

Fig. 6: AoA estimation while the drone hovers

measurement and this has a significant effect on the angle estimation.

Figure 6 displays the histogram distribution of AoA estimation for all the consecutive measurements. From the histogram, 80% of the estimated angles from BS_1 varies from 100° to 136°, giving a mean angle close to 109°. In BS_2, 60% of the estimated angle varies in the range of 60° to 92°, with a mean angle of 64°. Likewise, 45% of the absolute angle difference of the estimated angles falls from 50° to 60°. Then, the location of the hovering drone is simulated using the standard deviation (Std) of the difference of the AoAs.

TABLE III: AoA from the outdoor measurements (Degrees)

	Drone is hovering		Drone is stationary	
	Mean	Std	Mean	Std
AoA from BS_1	61	12.5	72.5	5.3
AoA from BS_2	112	13	122.6	4.2
Difference of the AoAs	50.3	6.02	50	3.2

VI. Numerical evaluation of the self-localization accuracy

In this section, we evaluate by simulation, the achievable location accuracy in a typical hexagonal macro cellular. The inter-site distance between the base stations is considered to be 500 m. The considered base station locations are marked with asterix in Figure 7.

In the simulation, we first compute the the down link pilot power from the considered base stations using (1). We then calculate the exact AoA and a gaussian distributed AoA error using the values given in Table III for a hovering drone. After obtaining noisy AoA estimate, we calculate the drone location using the LS method described in Section IV. The estimated position of the drone after simulation is given in Figure 7. Figure 8 shows the Cumulative Probability Density (CDF) of the location error for both stationary and hovering drone. From the CDF plot, we can observe that for 50% of the measurements, the drone localization error increases by 25 meters when the drone hovers compared to perfectly stationary drone.

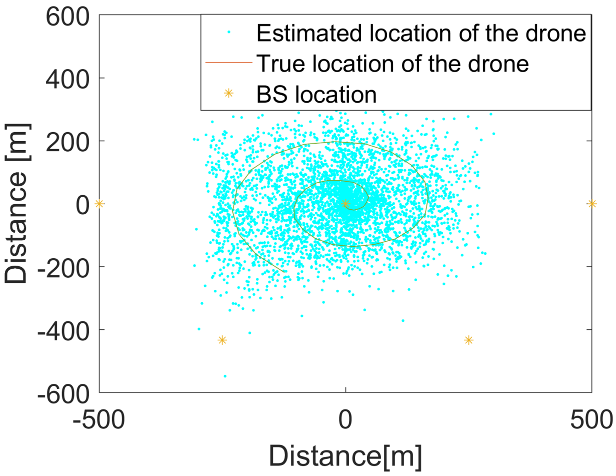

Fig. 7: Simulation of drone position estimation

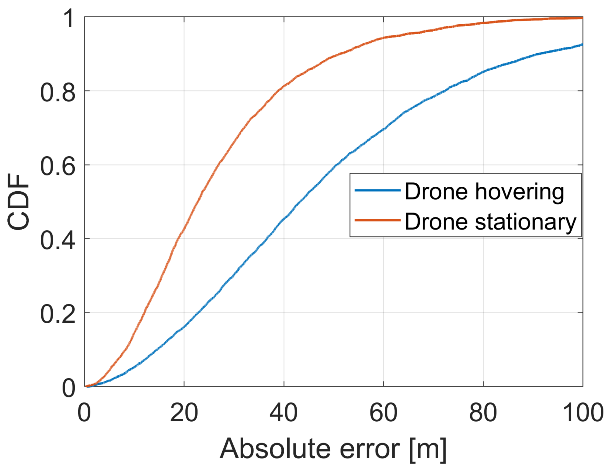

Fig. 8: Simulation of drone location error

VII. Conclusion

This paper evaluated the performance of a simple method for the drone to estimate its location based on the received signal from the known location of base stations. The method used in the paper is based on the well-known radio direction finding scheme where an non-isotropic antenna is rotated in order to estimate the angle of arrival for the received signal. We build and calibrated a prototype antenna system and studied its performance both in the laboratory setting and stationary deployment. The system had two sources for angular errors:1) receiver noise and 2) the limited accuracy of the rotating system for the antenna. When hovering drone was used to perform the AoA measurement, the drone controllers ability to keep the drone stationary introduced additional errors. Especially strong gusts of wind cause sudden moves to the drone location as well as yaw rotation, which in turn affected the measurements from the rotating system for the antenna. Since the distances used in the measurement were short, even the small movements of the drone had significant impact on the drone location. Based on the measurements, we evaluated the AoA estimation error statistics that we then utilized in simulation to evaluate what would be localization accuracy in typical dense cellular setup. The result indicated that median error of 45 meters could be achieved with this simple system. The accuracy of the system could be improved by using better antenna, more accurate gimbal, compensating for the drone movement based on dead reckoning and using more accurate but computationally heavier algorithm for mapping the angles to position.

VIII. Acknowledgement

The authors would like to acknowledge partial financial support from the Academy of Finland project ULTRA (decision n:o 328215) and Business Finland project MULTICO (n:o 6598/31/2019).

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