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Research Article

Accuracy of Radio Signal Source Localization by Unmanned Aerial Vehicle (UAV) in Dispersive Channel and Increasing Received Signal Strength Indicator (RSSI) Number

Jaroslaw MICHALAK
Military University of Technology, Warsaw, Poland
jaroslaw.michalak@wat.edu.pl

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Abstract

The article attempts to assess the usefulness of simple UAVs (COTS in principle) for supporting radio communication networks operating in a dispersive two-dimensional space. Comparative results of the accuracy of several methods of locating the position of a ground radio signal source (Min-Max, Least-Squares and Linear Regression) in the conditions of an increasing number of received signal level measurements (RSSI) are presented. It is estimated that, by increasing the number of recorded RSSI in the conditions of the Raileigh channel, one can count on doubling the original accuracy of source localization.

Keywords: UAV, Rayleigh, Location, Kalman.

Introduction

For many years, we have been observing an ever-increasing intensity of development of UAV applications in almost all areas of human life, including military applications (e.g. (Sładkowski, A., & Kamiński, W., (2021)), (Shakhatreh, H., Sawalmeh, A.H., Al-Fuqaha, A.I., Dou, Z., Almaita, E.K., Khalil, I.M., Othman, N.S., Khreishah, A., & Guizani, M., (2018)), (Elmeseiry, N., Alshaer, N., & Ismail, T., (2021)). The development of artificial intelligence algorithms opens up areas of autonomous work in accordance with the planned mission and the ability to independently respond to changing external conditions (e.g. (Sai, S., Garg, A., Jhawar, K., Chamola, V., & Sikdar, B., (2023))). Although the article deals with the analysis of the mission of a single UAV, it is also worth noting the development of UAV systems, including Ad-Hoc UAV systems ((Miller, J.A., Minear, P.D., Niessner, A.F., DeLullo, A.M., Geiger, B.R., Long, L.N., & Horn, J.F., (2005)), (Bhatia, T.K., Gilhotra, S., Bhandari, S.S., & Suden, R., (2024))). The dynamics of COTS applications on both the civilian and military markets deserve special attention, e.g. in the area of intelligence, surveillance, and reconnaissance (ISR) ((Kim, S.J., & Sheikh, N.J., (2022)), (Gargalakos, M., (2021)), (Stodola, P., Kozubek, J., & Drozd, J., (2018)), (Ma'sum, M.A., Arrofi, M.K., Jati, G., Arifin, F., Kurniawan, M.N., Mursanto, P., & Jatmiko, W., (2013))). COTS applications ensure mass availability and relatively low price of devices. These are most often small-sized solutions with simple antenna systems. Battery power and

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popularly used brushless motors emit few interference signals, which is crucial for ISR applications due to the sensitivity of radio receivers. ((Gabriel, D. L., Meyer, J., & Du Plessis, F., (2011)), (Pandey, M. K., Tripathi, A., & Dwivedi, B., (2015)), (Sun, Z., Zhong, L., Cheng, X., & Guo, J., (2023)), (Araar, O., Mimouni, M. Z., Fellah, K., & Osmani, H., (2017)), (Zulkipli, A. H., Raj, T., Hashim, F. H., & Huddin, A. B., (2016))).

Related Works

The topic of locating the radio signal source discussed in this study assumes a two-dimensional scenario and is a continuation of the work (Michalak J., (2023))), where we are talking about localization based on the estimation of the distance from the radio signal source (e.g. (Sivasakthiselvan, S., Nagarajan, V., (2020)), (Azmi, N.A., Samsul, S., Yamada, Y., Yakub, M.F.M., Ismail, M.I.M., Dziyauddin, R.A., (2018))). It can be expected that increasing the number of measurement points will result in increased source locating accuracy.

A description of the use of UAVs in localization tasks can be found e.g. in (Goswami, S., (2013)), (Karimi, H.A. (Ed.), (2013)), (Zekavat, S.A., Buehrer, R.M. (Ed), (2012)), (Liu, Y., Yang, Z., (2011)), (Poisel, R.A., (2012)) and (Zafari, F. , Gkelias, A. , Leung, K.K., (2019)), and a description of RSSI-based methods e.g. in (Uluscan, S., Filik, T., (2016)), (Saeed, N. , Nam, H., Al-Naffouri, T.Y. , Alouini, M.S., (2019)), (Bohidar, S., Behera, S., Tripathy, C.R., (2015)), (Duy, Q., De, P., (2016)). These methods do not offer high precision results, but their simplicity (cheap and energy-efficient) means that they enjoy constant interest. In (Azmi, N.A., Samsul, S., Yamada, Y., Yakub, M.F.M., Ismail, M.I.M., Dziyauddin, R.A., (2018)), the authors compared the complexity and quality of the Min-Max, Multilateration, Maximum-Likelihood (ML) and ROC-RSSI localization algorithms, indicating that the simplest and least accurate of the evaluated algorithms was the Min-Max algorithm, while the most complicated but at the same time the most accurate was the ML algorithm. Application descriptions of the compared localization methods can be found e.g. in ((Rattanalert, B., Jindamaneepon, W., Sengchuai, K., (2015)), (Robles, J.J., Pola, J.S., Lehnert, R., (2012)), (Xie, S., Hu, Y., Wang, Y., (2014)), (Guo, Z., Xin, L. , Zhen, X., Han, L, (2015)) and (Liu, L., Ma, H., (2014))).

The article attempts to assess the degree of improvement in location accuracy as a function of the growing amount of data (RSSI) collected by the UAV, which performs the task of supporting the communication network. Chapter 3 presents the network structure with a description of the UAV mission; Chapter 4 describes the channel model; and then Chapters 5 and 6 characterize the compared localization methods and present the results of simulation studies.

Network Structure and UAV Mission

From the point of view of assessing location accuracy, the structure of the network itself is not decisive, but the method of collecting measurement data by the UAV is. Based on previous work, a network structure was assumed as shown in Fig. 1, and a variable UAV route marked with a dashed line. The parameterization and range of variability of flight parameters affecting the mission effectiveness are presented in Table 1.

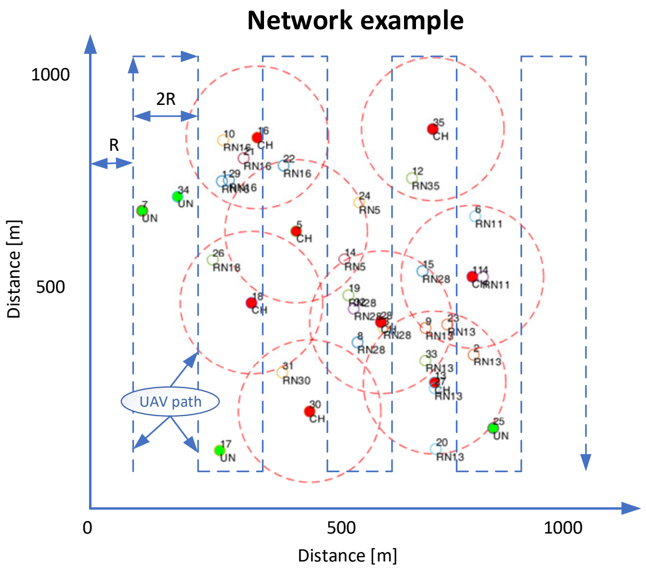

Fig. 1. An example of the network structure. RN - Regular Node, CH - Cluster Head (red), UAV - Unmanned Aerial Vehicle (blue line), UN - Unknown Node (green, the localized node). Source: Own.

For the purposes of the experiment, the UAV, not knowing the location of individual nodes, but only the operating area of the entire network, performs a mission of flying around the area along a route ensuring full connectivity (Michalak J., (2021)), (Michalak J., Nowosielski L., (2019)). From the point of view of assessing the precision of the locating process, it does not matter which node it concerns, however, the scenario assumes that these are nodes that are communicationally disconnected from the rest of the network and require support (reporting such a need via radio, in Fig. 1, these are UN nodes marked in green). The full scope of assumptions related to the implementation of the location is presented graphically in Fig. 2.

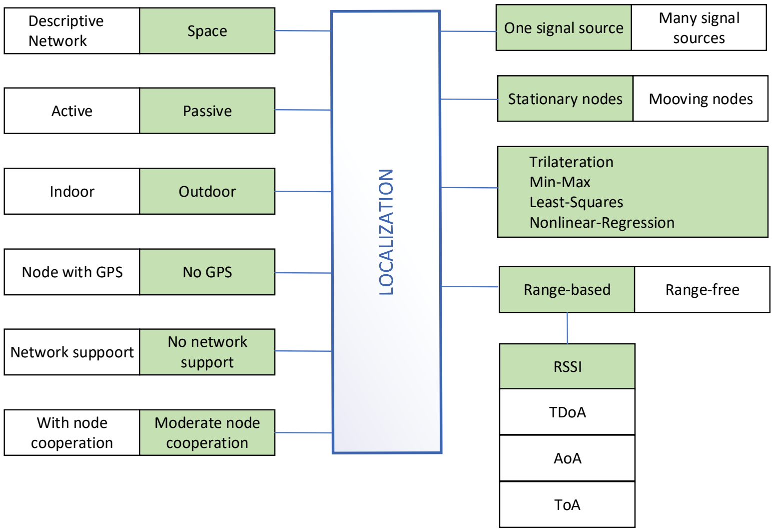

Fig. 2. Simulation assumptions. Source: Own.

Channel Model

Radio channel models for UAVs have been developed for several years along with the growing popularity of their use in reconnaissance and telecommunications. An extensive classification and description of ground-air channel models for various scenarios can be found, for example, in (Yan, C., Fu, L., Zhang, J. and Wang, J., (2019)) and (Khawaja, W.A., Guvenc, I., Matolak, D.W., Fiebig, U., and Schneckenburger, N, (2018)). In general, propagation models of low-flying UAVs of popular use (flight altitude approximately 100 m above ground level (AGL), usually a maximum of 120 m AGL, maximum speeds usually up to approximately 160 km/h) do not fit into the set of aviation models. The frequencies used for control and data transmission are the most frequently unlicensed 2.4GHz and 5.8GHz bands. I'm not talking about the frequencies used by additional on-board devices, which may vary depending on the application. It should also be remembered that depending on the phase of the mission (take-off, landing, flight at full height), the channel model may differ, but in this article the take-off and landing phase are excluded from the mission implementation time. Many studies assume the use of the Rice or Rayleigh channel model, which has its justification in (Khawaja, W.A., Guvenc, I., Matolak, D.W., Fiebig, U., and Schneckenburger, N, (2018)), (Diang Y., Xiao Y., Xie J., Zhang T., (2017)) and (Djuknic, G.M., Freidenfelds, J., & Okunev, Y., (1997)), and an omnidirectional antenna (SISO communication), which is characteristic in small COTS drones. It is also worth remembering about the Dopper frequency shift if the UAV movement is relatively fast (usually it can be neglected for slowly flying UAVs) (Fig. 3)) and about the changing nature of the mentioned phenomena (non-stationary channel). Research on the effectiveness of ground station location using a UAV that collects a large number of RSSI level measurements in the Rice Channel was published in (Michalak J., (2023)). It presents a comparative evaluation of several localization algorithms in terms of their potential to increase localization accuracy as a function of an increasing amount of measurement data. The effectiveness of the Kalman filtration was also assessed (effective mainly with a small number of measurement data). Research indicates approximately a 10% improvement in location accuracy. In this paper, a similar evaluation is performed for the case of a Rayleigh channel, typical of an urban environment and low-flying UAV. The channel model was parameterized based on COST207 recommendations (Fallini M., (1988)) for typical urban (TU) case parameters (non hilly) area. These are the following values:

Relative time vector [μs]: [-3, 0, -2, -6, -8, -10],

Average relative power vector [dB]: [0, 0.2, 0.6, 1.6, 2.4, 5.0].

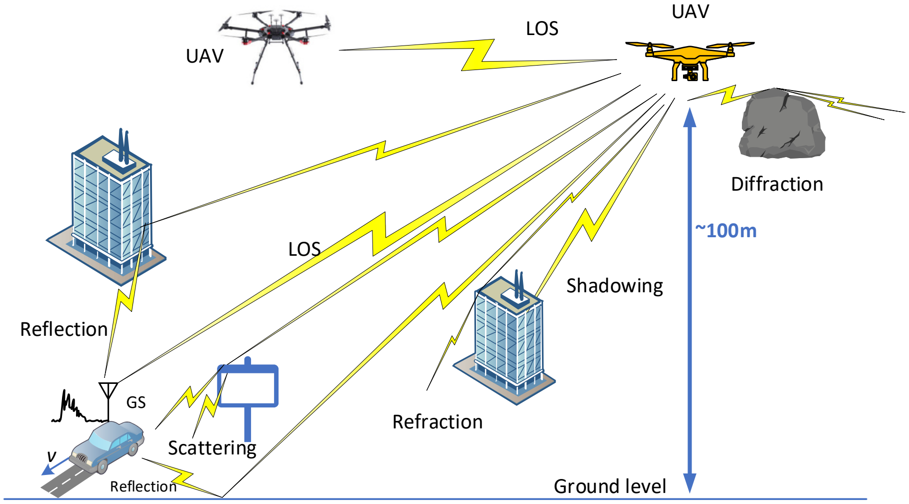

Fig. 3. Propagation phenomena. Source: Own.

Location Methods

The article carried out comparative studies of such RSSI-based localization methods as:

1. Min-Max – based on the use of RSSI of received radio signals at various measurement points and then analyzing the differences in their strengths. Each RSSI value is converted into the distance from the signal source d_i (for a given channel model). Then, for each d_i (where i is a reference to the UAV position number), squares are determined describing the circles of the estimated ranges, assuming that the source position is in the center of the common area limited by the values $x_{min}, x_{max}, y_{min}, y_{max}$.The center of the common area (x, y) is defined as:

$$x = \frac{(x_{min} + x_{max})}{2} \tag{1}$$

$$y = \frac{(y_{min} + y_{max})}{2} \tag{2}$$

2. Least-Squares – using the least squares method to estimate the position of the transmitter.

If the coordinates of the localized node are marked as (x, y), and the estimated distances of this node d_i from the Reference Nodes (x_i, y_i), $1 \le i \le n$, where n is the number of Reference Nodes (UAV measurement points), then we can write (Liu, Y., Yang, Z., (2011)):

$$d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2}, \tag{3}$$

where:

$$\begin{aligned} d_1^2 &= (x_1 - x)^2 + (y_1 - y)^2\ , \\ d_2^2 &= (x_2 - x)^2 + (y_2 - y)^2\ , \\ &\dots \\ d_3^2 &= (x_n - x)^2 + (y_n - y)^2\ , \end{aligned} \tag{4}$$

3. Nonlinear-Regression - using advanced non-linear regression techniques consisting in fitting a series of results (RSSI) to a predefined curve to estimate the location of the transmitter. Unlike other (less complicated) methods, this technique takes into account non-linear relationships between signal strength and distance. To determine the estimate of the radio signal source location, the MATLAB Nonlinear Regression function was used, giving the model function in the form modelfun = @ (b, X) (abs (b (1) -X (:, 1)). ^2 + abs(b(2) - X(:, 2)). ^ (1/2) and the starting point of searching for the optimal solution (position of the target station) in the centre of the monitored plane.

The tests were carried out in NLOS channel conditions and the effectiveness of Kalman filtration was additionally assessed. The results may be an interesting comparison with those presented in (Michalak J., (2023)), where the research assumed the Rice propagation model, typical for some UAV use scenarios. In (Michalak J., (2023)), you can also find a detailed description of the operation of individual location methods.

The research assumed a slow UAV speed and ignored the frequency shift resulting from the Doppler effect. Assuming the use of appropriate correction systems in practice, these considerations do not lose their generality.

It should be realized that due to the movement of the UAV in three-dimensional space and external factors such as wind or radio interference (e.g. GPS signal interference), precise determination of the position of the ground station may in practice be burdened with additional error.

Simulation Results

The simulation tests were carried out using MATLAB R2023b software (version 23.2.0.2459199) under the conditions presented in .

Table ***1*** and repeated in 30 different implementations of the radio channel to provide conditions for statistical evaluation of the result.

Table 1. UAV flight conditions

Parameter	Value
Channel type	FSPL, Rayleigh
Noise Variance	1
Number of UAV	1
Number of measures	Depending on the track and the turning radius R of the UAV, average approx. 50, 70 or 250
Tracking Base [m]	From 200 to 425 for FSPL Channel; 10m for Rayleigh Channel
Turning radius R of the UAV [m]	100, 150, 200, 250

FSPL Channel

The initial verification of the model was performed in the FSPL (Free Space Path Loss) channel for variable number of reference points (RP) without additional filtering of the measured signal. For the case of RP 3, for each of the above-mentioned location methods, the targeting base (TB) was changed from 200 to 425 m to the extent allowed by the simulation scenario. The results confirm the correctness of the model, giving the location accuracy at the level of 10^{-10} m, except for the Min-Max method, the assumptions of which disqualify it for use in the conditions of the tested scenario (Michalak J., (2023)).

The position error was calculated from the relationship:

$$Est.Pos.Error = \frac{\sum_{i=1}^{n} \sqrt{(x-\hat{x}_i)^2 + (y-\hat{y}_i)^2}}{n}, \tag{5}$$

where n – number of repetitions (in the model n=30).

A similar verification was performed assuming a variable number of RPs (from 50 to 200, naturally without the Trilateration method, which assumes the use of 3 RPs) and a constant TB = 10m (Fig. 4 and Fig. 5). The correctness of the algorithm and the low usefulness of the Min_Max method were confirmed (Michalak J., (2023))

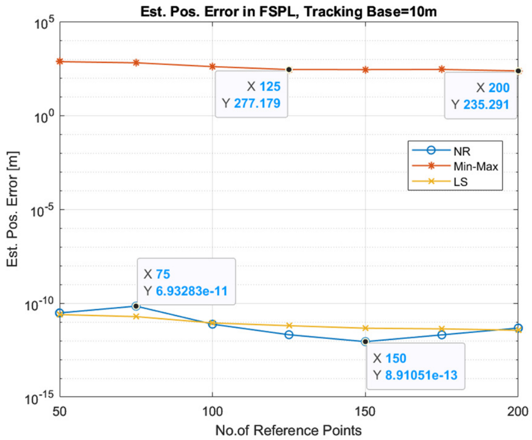

Fig. 4. Position error in the FSPL condition

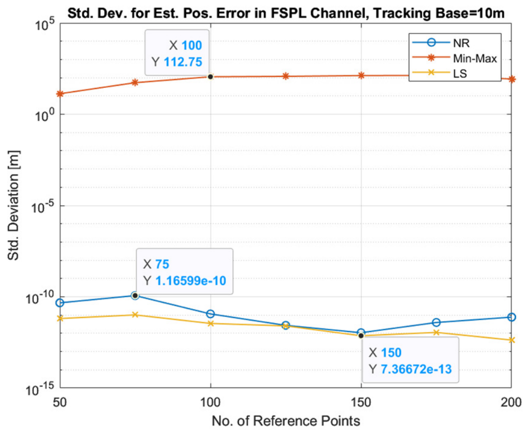

Fig. 5. Standard deviation of the position error in the FSPL condition

Rayleigh Channel

The results of assessing the accuracy of locating a ground station in the Rayleigh channel for a fixed TB value and a variable number of RPs are presented in Fig. 6 and Fig. 7. The channel parameters have been defined in **Error! Reference source not found.**. It is worth noting that the model does not use additional techniques to combat the effects of multipath, such as the MIMO technique or the RAKE receiver. Therefore, only the positive effect of increasing the number of RPs is assessed.

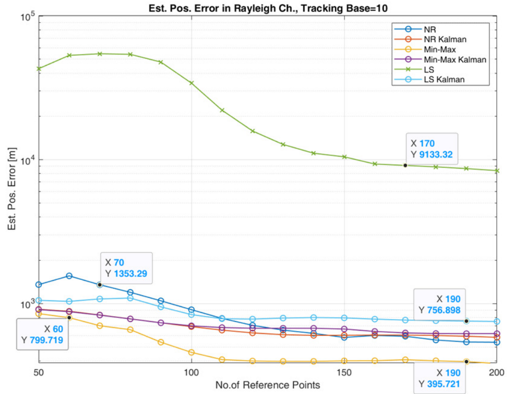

Fig. 6. Position error in the Rayleigh channel for an increasing number of the RP

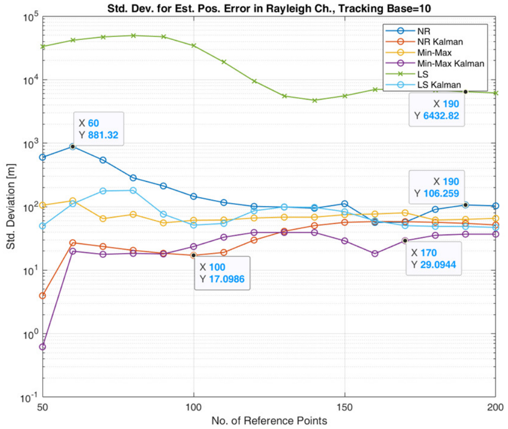

Fig. 7. Standard deviation of the position error in the Rayleigh channel for an increasing number of RP

The presented analysis of the effects of increasing the number of RPs indicates that a significant increase in locating accuracy occurs after accumulating just over 100 RPs. At the same time, we can count on an approximately 2-fold reduction in the initial error (although in absolute numbers, under the assumed scenario conditions, the error remains at an unacceptable level). It is, in the best case, approximately 20% of the side dimension of the flight square. This results, among other things, from the assumed UAV flight scenario. In order to reduce the mentioned error, an iterative approach is often used, which consists in repeated estimation of the position as a function of the simultaneous approach (reduction of the distance) to the signal source. However, this remains outside the scope of the analysis presented here. It can also be noted that the use of Kalman filtration in the case of the Rayleigh channel does not bring any significant benefits, except in the case of Least Squares.

Conclusions

Based on the conducted comparative simulation tests based on RSSI of the Min-Max, Least-Squares and Nonlinear Regression methods for locating the source of the terrestrial radio signal in the Rayleigh channel, it can be proven that increasing the number of RSSI measurements carried out by the UAV has the potential to double the accuracy of the result. Kalman filtration does not always introduce significant gains. The proposed channel parameterization is typical for low-flying UAVs in NLOS propagation conditions.

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