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Opportunistic RSS-based localisation using SDR and ADS-B system

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Abstract

Nowadays, a growing increase in air traffic and regulatory directions are leading to using transponders compatible with ADS-B Mode S technology. This scenario means an increase in signal availability that provides helpful information for the location process. Like GNSS, aircraft send their position through Top and Bottom interfaces. This work proposes an SDR receiver and an opportunistic localisation method based on RSSI measurements combined with communication channel estimation. The results demonstrate an improvement in distance estimation through a set of techniques based on statistical analysis, outlier filtering and classification of received messages. The performance analysis of the proposed solution includes an analysis of the impact of Sampling Frequency and yields an error lower than 0.8 Km using a 2-minute processing window.

1 Introduction

According to EUROCONTROL forecasts for 2023-2028, after the drastic drop in the number of air routes in the years 2020-2022 due to COVID-19, a full recovery (2023) and a further increase is foreseen for the next few years. New programs and regulations have been proposed to deal with this increase in air traffic. In Europe specifically, the SESAR (Single European Sky ATM Research) program and its evolutions (i.e., SESAR 3 Joint Undertaking) stand out, comprising the development of the most advanced technological solutions to manage conventional aircraft, drones, air taxis and vehicles flying at higher altitudes. From a regulatory point of view, European directives set the performance and interoperability requirements for Single European Sky Surveillance [1], which in this case focus on the use of operational secondary surveillance radar transponders compatible with ADS-B (Automatic Dependent Surveillance Broadcast) extended spontaneous signals. Annex II of Implementing Regulation (EU) No. 1207/2011 sets Mode S level 2 as the minimum operating capability of a surveillance secondary radar (SSR) transponder.
The future scenario is clear: more congested airspace, efficient location and surveillance technologies and increased onboard communication capabilities. In particular, ADS-B technology plays a fundamental role in tracking and localising other devices capable of receiving the emitted signal. This localisation method is opportunistic because it uses RF signals and information available in the ether but is not initially designed for the receiver's localisation purpose. The algorithms proposed in this scenario are primarily based on Multilateration from measurements of the time difference (TDOA) [2], Time of Arrival (TOA) or distance determination from models where Received Signal Strength (RSS) [3, 4] is related to the distance between transmitter and receiver. The constant evolution of Software Defined Radio (SDR) makes it the preferred radio communications system for implementing RF receivers cost-effectively, flexibly, and rapidly deployable. Platforms such as USRP from Ettus Research and ADALM-PLUTO from Analog Devices Inc. have been used to implement ADS-B receivers. Although the most widely used HW for ADS-B is the RTL-SDR [2](used in *Flightradar24*, *OpenSky Network*, and *FlightAware*), it has limitations in terms of bandwidths that impact the functionality of the receiver.
This work addresses the challenge of determining receiver position from the opportune decoding of ADS-B signals using SDR. The multilateration process uses the distance determined from the RSS-based measurements of the received signal. An RSS-distance model is generated experimentally from extended periods of measurements in the field. Furthermore, an evaluation of the impact of the receiver bandwidth on the distance estimation process, localisation process and performance of the ADS-B receiver is performed. For this reason, Section 2 describes the methodology followed in implementing the receiver and the localisation process. Also, Section 3 presents the experimental activities carried out to validate the reception of ADS-B signals and the channel model obtained. Section 4 describes the results obtained, and Section 5 concludes this article.

2 Methodology and problem formulation

The idea of determining the spatial coordinates of an object using information from the received ADS-B signal is addressed in three fundamental steps. The first step is to use power measurements of the received signal to generate a model to determine the distance between the transmitter (aircraft) and the receiver. The next phase consists of solving a system of equations, one equation for each aircraft available in a given time window, using Multilateration algorithms. The third fundamental aspect is constructing an

SDR-based receiver to detect, decode and measure ADS-B messages.

RSS Channel Model

The most widespread model used to describe radio signal propagation is the Log-Normal Shadowing model, a generalisation of the Friis free space equation. Equation (1) shows the simplicity of the model, where $RSSI_0$ is a constant term which takes into account the transmission power of the airborne transponder, d is the distance between the transmitter and receiver, β is the path loss exponent, and η is a zero-mean Gaussian random variable.

$$RSSI(dBm) = RSSI_O(dBm) - 10\beta log(d) + \eta \tag{1}$$

$$\hat{d} = 10^{\frac{RSSI_O(dBm) - RSSI(dBm)}{10\beta}} \tag{2}$$

$$RSSI(dBm) = \frac{1}{N}\sum_{n=1}^{N} RSSI_{n,t} \tag{3}$$

The channel model assumes that the noise has a Gaussian distribution. When a variable has a Gaussian distribution, its mean value equals its averaged value. However, in practical conditions, where some outliers may exist, it is better to use the mean value because it is more robust to outliers. In Equation (2), the value of $\hat{d}$ is estimated from the mean RSSI measured on a set of messages from the same airborne in a given time window.

MLAT problem solution

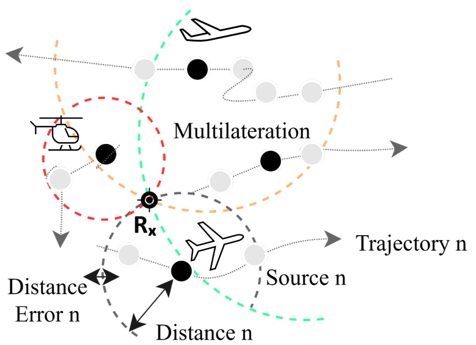

Figure 1. ADS-B scenario and multilateration process.

The localization process using multilateration is based on the solution of a system of equations where the solution corresponds to the receiver coordinate. In our case, the estimated distance between the transmitter and receiver is determined based on a model relating to the RSSI measured at the receiver. The application of a statistical model leads to errors in distance estimation. These errors in distance estimation lead to the use of optimization methods in selecting the correct solution.

Given the n reference points $P1(X_1,Y_1,Z_1)$, $P2(X_2,Y_2,Z_2),...Pn(X_n,Y_n,Z_n)$ and the range measurements $d_1,d_2,...,d_n$. The solution of the coordinates (x,y,z) using n points is equivalent to solving a quadratic system of equations with $n-th$ expression:

$$(x - X_n)^2 + (y - Y_n)^2 + (y - Y_n)^2 = d_n^2 \tag{4}$$

Manipulating (4) we can write:

$$\begin{aligned} &(x^2 + y^2 + z^2) - (2xx_n + 2yy_n + 2zz_n) \\ &= d_n^2 - (x_n^2 + y_n^2 + z_n^2) \end{aligned} \tag{5}$$

Equation (5) allows to compose a linear system equation with the form $\mathbf{A}x = \mathbf{b}$. Applying Least Squares (LS) methods with the constraint $x \in \{(X_0, X_1, X_2, X_3)^T \in R^4 / X_0 = X_1^2 + X_2^2 + X_3^2\}$ and using pseudo-inversion functionalities in MATLAB the solution can be written as follows: $\hat{x} = (A^T A)^{-1} A^T b$. However, solutions offered by this method depend only on the matrix $\mathbf{A}$ and the vector $\mathbf{b}$, which depends only on the coordinate values received in the ADS-B messages that are opportunely decoded by the receiver. Finally, the selected solution is the one that minimises the sum of squared distance error.

3 SDR-based ADS-B receiver

There are two types of ADS-B downlink signals (centred at 1090 MHz) in mode S, the short response (56 bits) and the extended response (112 bits), which correspond to the short and long interrogations of the secondary surveillance radar (SSR). The bit duration is 1 microsecond and uses Pulse-Position Modulation (PPM). All Mode S responses start with a fixed preamble of 8 symbols (duration 8 microseconds) and continue with a long or short bit sequence (payload). Civil Aeronautics ADS-B messages after the 8-microsecond preamble continue with the binary sequence 10001, corresponding to the Downlink Format (DF) field. The next three bits correspond to the Transponder Capability field, followed by the ICAO code, which identifies the aircraft and is 24 bits long. The short messages continue sequentially with the 24-bit Parity/Interrogator (PI) field, completing the 56 bits. However, before concluding with the PI, the long messages contain a block message (ME) that contains information concerning the aircraft's position, altitude, speed, heading and status. In particular, the extended messages are very useful in the localisation process described before. This way, a stream of information regarding the aircraft's position/speed/altitude is available. Since the distance estimation method uses power-averaged values, a more accurate value will depend on analysing a significant number of messages from the same aircraft. It is essential to detect as many messages as possible to reduce the analysis time window. Theoretically, the frequency of extended position and velocity messages is 2 Hz, and the total number of messages (on average) exceeds six messages per second. The received data is split into In-phase and Quadrature digital components (I&Q) when using SDR platforms with Zero-IF architectures as Front-End. Although the frequency is centred at 1090 MHz, frequency shifts may be experienced due to errors in the SDR device's local oscillator (LO) [5], the airborne transponder or the Doppler effect introduced by the speed difference between transmitter and receiver. Therefore, the first blocks of our receiver are dedicated to the correct centring of the band, the elimination of the DC component and the filtering of the signal to increase the Signal to Noise Ratio (SNR).

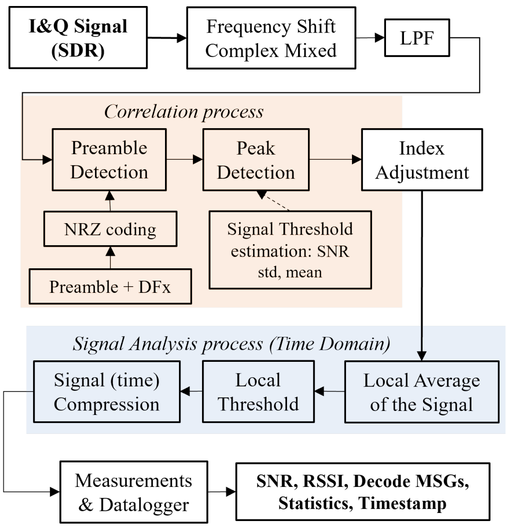

Figure 2. SDR-based ADS-B receiver.

The receiver processes the baseband samples to detect preambles that indicate the start of an ADS-B message. The correlation process uses pre-coded NRZ sequences to obtain a higher sensitivity in preamble detection. The detection of a "peak" indicating the presence of an ADS-B message is based on local metrics, where the (temporal) signal segment to be analysed is statistically evaluated. Figure 2 indicates the blocks working in the frequency domain with a pink colour. Once the preambles are identified, their position in the time domain is determined, and false positives are discharged. Having identified the positions of the messages in the time domain, a signal analysis is performed to validate the results obtained in the frequency domain. The validation also confirms that the preamble's "high" pulses are within 3dB of the reference power. After the correct validation of the messages, the time slots without signal presence are removed and passed to the parser block (*MSGs Decode*), which is responsible for decoding the information. At the end, the data is stored in a structure that includes the following fields: RSSI (before filtering and after filtering), decoded message information (Speed, Position, Altitude), internal buffer index, timestamp, SNR and the identification of the aircraft through the ICAO code.

4 Results

The experimental tests were conducted outdoors at the University of L'Aquila (Italy). The SDR platform was the USRP X310 (UXB160 daughterboard) configured with 36 dB of RF gain centred to 1090 MHz. The first experimental activities aimed to analyse the performance of the ADS-B receiver, and for this reason, captures were performed at different sampling rates.

Table 1. ADS-B-based SDR receiver performance.

Parameters	2 MSps	4 MSps	10 MSps	20 MSps	50 MSps	100 MSps
No.Airbornes detected [U]	6	7	7	7	9	9
No.Messages passed CRC [U]	957	1192	1315	1862	2934	3382
% position messages	36.57	35.82	35.51	35.66	36.37	36.56
Max. distance [Km]	182.57	200.43	202.61	208.33	210.41	210.57

Table 1 demonstrates the impact of using a higher-performing receiver. An increase in sampling frequency impacts the number of correctly detected messages (passing the CRC), the sensitivity of the receiver and hence, the ability to detect aircraft at a greater distance. This process is also influenced by geography and atmospheric conditions. The data in Table 1 corresponds to an acquisition window of 120 seconds (2 min). The messages are lower than expected (6 x number of aircraft x 120s) since they are not visible to the receiver during the whole interval.

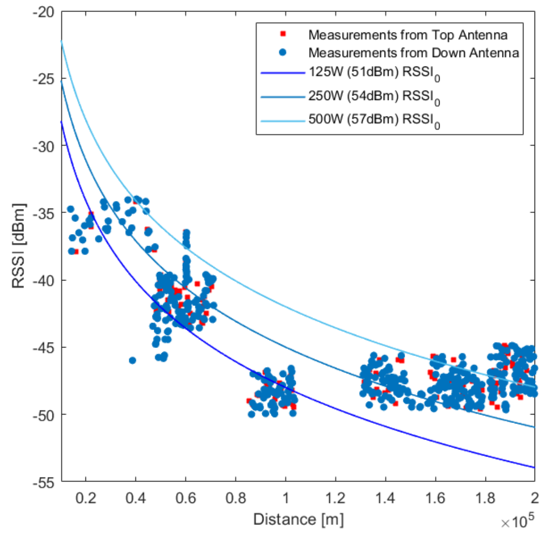

Figure 3. RSSI - distance model. Three different curves corresponding to aircraft transponder power values: 500, 250 y 125 W.

The study of the typology of the messages made it possible to verify both the correct functioning of the receiver and the theoretical nominal frequency described in previous sections. In particular, the messages received according to their typology were distributed as follows: approximately 4 % corresponded to identification messages (TC: 1-4); 35 – 36 % corresponded to messages with position information[1] (TC: 9-18); approximately 37 % of the messages indicated the speed (TC: 19) and 22 % of the messages indicated airborne status information. Figure 3 shows one of the strategies followed to minimise the errors in calculating the distance from formula (2). In this work, we use three models that respond to the three possible values of authorised power in commercial transponders: 500, 250, and 125 W. In addition, Figure 3 identifies with different colours the

[1] All measurement campaigns conducted confirm that the altitude value is obtained from barometric sensors

measurements taken from the top or bottom interface of the antennas of each detected aircraft. Specifically, the filtering strategies performed to increase the accuracy in the localisation process focus on excluding spurious measurements from the same reflected signals. In many cases, messages from the opposite antenna interface of the same aircraft are detected and decoded. This undesired effect is solved by classifying and sorting based on the timing difference between messages. In addition, highly attenuated measurements that are affected by the geometry of the dipole radiation pattern are excluded.

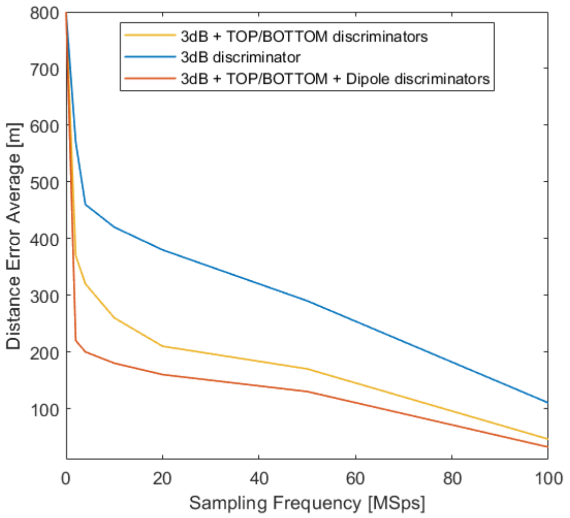

Figure 4. Impact of applied techniques and sampling frequency on distance error.

Figure 4 shows the final results and the impact of the techniques applied to mitigate errors in the distance calculation process. In all cases, we start with a time window of 2 minutes where the statistical methods for eliminating spurious values are applied. The blue curve represents the results obtained from analysing/applying a dedicated model depending on the aircraft classification and, therefore, the type of transponder used. In the second case (yellow curve), the transmission interface identification process is added, thus eliminating values coming from the second antenna, further increasing the accuracy of the measurements. The last case includes all the techniques described above and tries to identify (offline) the outliers caused by the toroidal radiation pattern of the dipole antenna.

5 Conclusions and future directions

This paper presents an SDR-based solution for cooperative localisation using ADS-B Mode S signals. The methodological approach based on experimentation to describe the channel can be extended to other application fields, exploiting the SDR paradigm's modularity and flexibility. From the point of view of the results in terms of errors in the localisation domain, it constitutes a starting point for future solutions closer to a real-time approach.

Regarding the power analysis, some outliers are registered and must be filtered out before the distance calculation. In most cases, messages with a very distant RSSI are caused by reflection processes occurring at the non-visible antenna interface of the airborne antenna. The solution proposed in this work consists of a time-based filtering analysis. Both aircraft interfaces (Top/Bottom) transmit messages in alternate mode every 0.5 seconds, with a maximum error of 0.1 seconds. This feature allows us to correctly group the information from each interface and promptly discard the values that introduce a significant error. Another element that has been detected and is proposed to be addressed in future work is the error introduced by the antenna radiation pattern itself, which can be attenuated by using gain masks depending on the aircraft's orientation.
The proposed techniques to improve the localisation process by timely identification of the phenomena affecting the ADS-B signals are excellent, showing a considerable improvement in the results (8.6 Km) found in the literature [4]. Maintaining distance errors in the model, on average, less than 800 metres, is a remarkable result in the context addressed. This result improves previous work that aims to mitigate the error in distance calculation based on a power model [3].

6 Acknowledgements

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