Determining Times of Arrival of Transponder Signals in a Sensor Network using GPS Time Synchronization

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Abstract: In this paper, obtaining time of arrival (TOA) measurements in a sensor network is investigated. Differentiating these TOA measurements provides the Time Difference of Arrival (TDOA) measurements between sensor pairs. An approach is proposed to estimate the TOA at a single sensor in a semi-passive scenario. The theoretical investigation is supported by field trials. This experimental analysis pursues two main goals. First, experimental results demonstrate the feasibility of determining the TOA of transponder messages. Second, the quality of TDOA measurements strongly depends on the synchronization accuracy. Here, sensors are synchronized using GPS where an accuracy in the nanosecond range is achieved.

1 Introduction

Localization of emitters in a network of several distributed sensors using various types of measurements is a widely investigated topic [Tor1984, HF08, KMK10]. In this paper, the focus is on Time Difference of Arrival (TDOA) measurements [CH1994]. A minimum of two sensors is needed for gaining TDOA measurements [FRM07, MK08, Kau09]. Each sensor receives the signal from the emitter and measures the Time of Arrival (TOA) of the arriving message. TOA measurements may be gained in three ways: first, active where the time of emission is known. Secondly, passive, here, the emitter, the emitting time and the structure of the signal are unknown. An overview on the time delay estimation in active and passive systems is given in [Q1981]. Thirdly, a semi-cooperative method, where the emitter and the time of emission are not known, but there exist knowledge about the structure of the signal. In the following, the analysis is on this semi-passive type of obtaining TOA and TDOA measurements. An example for signals with known structures is the Automatic Dependent Surveillance-Broadcast (ADS-B) encountered in aviation. ADS-B data which can be recorded by the sensors provide information on the location of the emitting aircraft. This information can be validated using the TDOA measurements for localizing the emitter.

There are strong demands on the time synchronization and the data communication between the sensor nodes in order to get TDOA measurements of high quality. Usually, TDOAs are obtained by correlating the signals of two different sensor nodes [KC1976]. Therefore, the complete signal must be transmitted to a central station or the common

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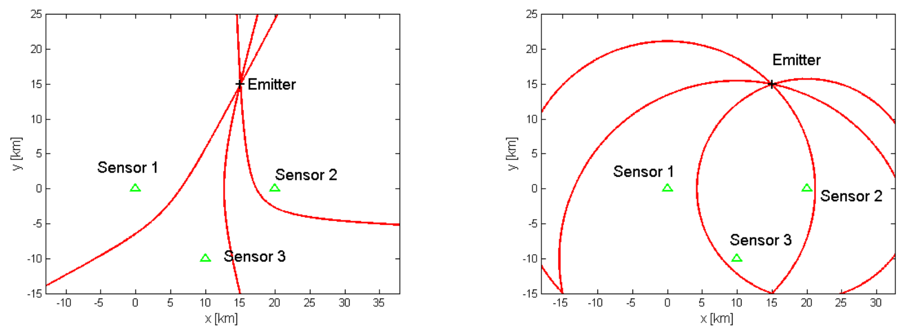
reference sensor which implies high communication requirements in the sensor network. The contribution of this paper is to propose an approach which drastically reduces the communication demands. Each sensor has little intelligence to determine the TOA of the incoming signal. Only this TOA with a short information for the signal identification has to be transmitted in the network to the master station. At the master station, using these informations the TDOA measurements can be generated and used to localize the emitting source.

This paper presents an alternative approach for gaining TDOA measurements using TOA measurements of a sensor network. Field trials support the feasibility of this approach. The experimental analysis shows the ability of determining the TOA at a single sensor. The synchronization is done using the Global Positioning System (GPS) which presents sufficient accuracy in the nanosecond range.

2 Scenario description



(a) (b)

Figure 1: (a) TDOA and (b) TOA scenario with hyperbolae and circles respectively as possible emitter locations

An unknown emitter $\mathbf{e} = (\mathbf{x}^T, \dot{\mathbf{x}}^T)^T$ sends a signal which several stationary sensors $\mathbf{s}^{(i)} = \mathbf{x}^{(i)}$, $i = 1, \dots M$, receive. The TOA consists on the emitting time t_0 and the time the signal needs to propagate the distance between emitter and sensor i:

$$\text{TOA} = t_0 + \frac{||\mathbf{x} - \mathbf{x}^{(i)}||}{c}, \tag{1}$$

where c is the speed of light.

In reality, TOA measurements are noisy. The measurement noise is modeled as white Gaussian with standard deviation σ_{TOA}:

$$\text{TOA} = t_0 + \frac{||\mathbf{x} - \mathbf{x}^{(i)}||}{c} + v, \quad v \sim \mathcal{N}(0, \sigma_{\text{TOA}}^2). \tag{2}$$

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Differentiating two TOAs eliminates the unknown time of emission and delivers a TDOA measurement. A single twodimensional TDOA measurement defines a hyperbola of possible target locations while a single TOA measurement describes a circle of possible target locations when the time of emission can be eliminated, see Fig. 1.

3 Determination of TOAs

In the following, the determination of TOAs is accomplished using ADS-B signals. For these signals, frequency, modulation and structure are known [ICAO07, RTCA].

3.1 Structure of ADS-B signals

Messages from ADS-B transponders are transmitted at 1090 MHz using pulse position modulation (ppm) as modulation method.

Signals are recorded by an ADC with sampling rate f_s. Therefore, all signals are time discrete and quantized. The discrete time is defined as

$$t = \frac{n}{f_s}, \tag{3}$$

where n is the sample index.

3.2 Correlation with the preamble

Each ADS-B message starts with the same preamble to indicate the arrival of a new message. To determine the first edge of the message the signal is correlated with the simulated ideal preamble shown in Fig. 2(a).

Over the interval of $[0; 8\,\mu s[$ the ideal preamble can be described [1] by

$$p(t) = 2\left[\mathrm{rect}(\frac{t-\tau_0}{T}) + \mathrm{rect}(\frac{t-\tau_1}{T}) + \mathrm{rect}(\frac{t-\tau_2}{T}) + \mathrm{rect}(\frac{t-\tau_3}{T})\right] - 1 \tag{4}$$

with

$$T = 0.5\,\mu s,\ \tau_0 = 0.25\,\mu s,\ \tau_1 = 1.25\,\mu s,\ \tau_2 = 3.75\,\mu s,\ \tau_3 = 4.75\,\mu s,$$

where T is the pulse duration and the τ_i, $i = 0, \ldots, 3$, are the displacements of the pulse in t-direction.

The discrete correlation function $r(n)$ is defined as

[1] For the definition of the rect function see [LUE02]

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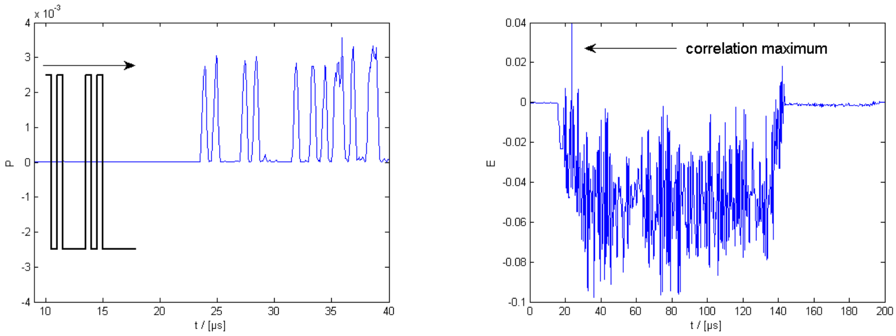
$$r(n) = \sum_{m=-\infty}^{\infty} s(m)p(n+m), \tag{5}$$

where s denotes the discrete time signal segment and p the simulated preamble respectively. Fig. 2(a) depicts the correlation.



(a) (b)

Figure 2: (a) Simulated preamble and signal segment and (b) correlation function of signal and preamble

In fig. 2(b), the resulting correlation function is shown.

The argument at the maximum of the correlation function, $\arg\max_n r(n)$, gives the required sample number. Division by the sampling rate f_s yields the time in seconds where the preamble of the ADS-B message begins relative to the start of the recorded signal. As defined in [RTCA], the message starts $8\,\mu s$ after the begin of the preamble. Therefore, the time τ of the first edge of the signal is defined as

$$\tau = \frac{\arg\max_n r(n)}{f_s} + 8\,\mu s. \tag{6}$$

3.3 Timestamp generation

To determine a more precise timestamp for the beginning of the message and to decode the messages bit string, the signal is shifted samplewise over a simulated 1 Mbit/s synchronization clock. Since an approximate sample index of the start of the message is given by $\arg\max_n r(n) + f_s * 8\,\mu s$, only a shift by a small number of samples is needed to identify the exact message start. Let n_{start} denote the number of samples the signal needs to be shifted to best match the clock. The TOA timestamp of the message is then defined as

$$\tau_{start} = \tau + \frac{n_{start}}{f_s}. \tag{7}$$

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4 Field experiments

The goal of our trials is to determine the accuracy of gaining TOA measurements, the precision of timetamp generation for incoming ADS-B messages. Previous unpublished analysis concerning the accuracy of GPS time synchronization of the employed sensors have shown that synchronization between a sensor pair with mean $\mu \approx 9$ ns and standard deviation $\sigma \approx 8$ ns is achievable. In the synchronization trials, signals were fed directly into the sensors without using antennas of any kind.

Two different measurement trials are performend. In the first measurement setup, two sensors share one RF antenna to determine the error which results from GPS time synchronization and our timestamp generation without having to deal with different (maybe unknown) signal propagation delay.

In a second trial, each sensor is equipped with an own RF antenna. These second experiments are performed in order to show that our results are not constrained by the factor that both sensors share one reception antenna.

4.1 Sensors share one RF antenna (A)

Measurement setup A

Two sensors, each equipped with a GPS antenna for time synchronization and position determination, are connected through a power splitter to one RF antenna (see fig. 3(a)). Both sensors simultaneously start the signal reception of ADS-B signals at 1090 MHz center frequency. The output of the sensors is a time discrete, quantized baseband signal and a corresponding timestamp for the first captured sample. This timestamp is generated using a GPS synchronized clock.

In three session, a set of 100 measurement pairs $(m_{(1,j)}, m_{(2,j)}) \in M_A$, where $m_{(i,j)}$ denotes the $j-$th measurement from sensor i, is recorded. Each measurement most likely contains multiple ADS-B messages which are selected. The messages are decoded and checked for errors by calculating the ADS-B checksum. Messages with errors are discarded. For the remaining ones a time of arrival timestamp is calculated using the methods described in section 3.

Subsequently, messages extracted from $m_{(1,j)}$ are compared to messages from $m_{(2,j)}$ $\forall j = 1..100$ in order to identify the corresponding ones. For corresponding pairs of ADS-B messages, the difference of their timestamps, the TDOA measurement, is calculated. Due to the fact that sensors share one RF antenna, they receive the signal at the same position and the same time. Therefore, the TDOA in an ideal system without errors should be zero. Non-zero values could be caused by synchronization errors or inaccurate determination of the TOA measurements.

The time resolution of the timestamps strongly depends on the sample rate f_s. For our trials, a sample rate $f_s = 10$ MS/s is used, therefore only a time resolution of 100 ns is

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possible. Better time resolution and more robust message decoding is achieved by interpolating the signals before determining the exact timestamp.

Experimental Results A

Fig. 3(b) shows the time differences between corresponding messages from sensor one and sensor two calculated using the original data without interpolation. From the set M_A, 1521 pairs of messages from both sensors are decoded correctly with $\mu = 4.5108$ ns, $\sigma = 41.7658$ ns and a maximum time difference of 163 ns. The sample rate $f_s = 10$ MS/s only gives us time resolution of 100 ns between two samples, this quite good result already indicates a good time synchronization and reliable timestamp generation.

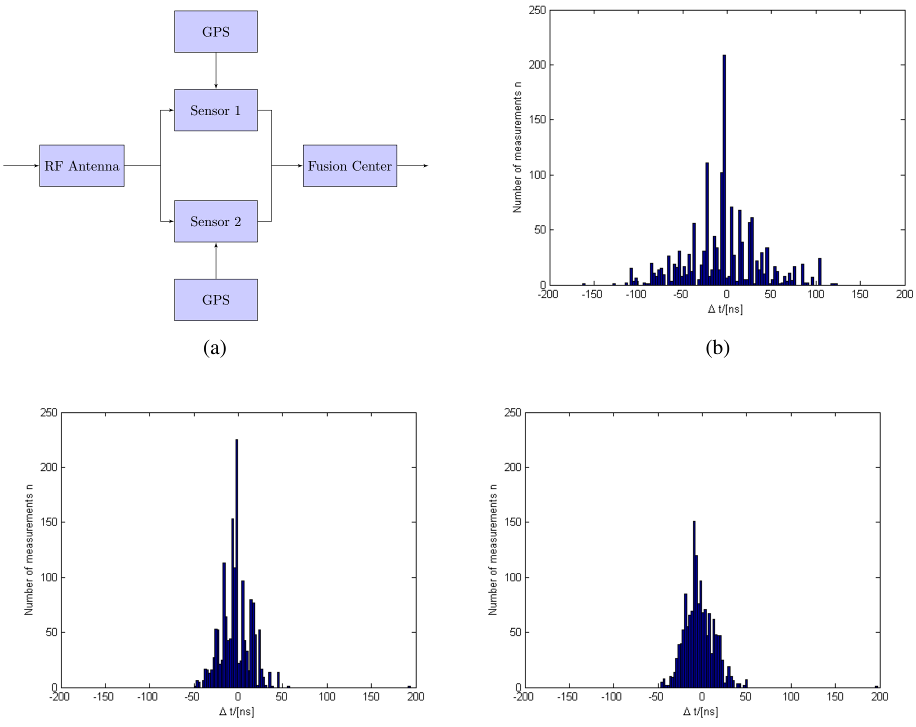

Figure 3: (a) Measurement setup A, results with (b) no interpolation, (c) interpolation by factor 10 and (d) interpolation by factor 100.

By signal interpolation with factor 10, 1561 messages from both sensors are decoded correctly with $\mu = -2.8386$ ns and $\sigma = 17.1384$ ns, as shown in fig 3(c). As depicted in fig. 3(d), further interpolation does not much improve the results. $\mu = -3.3105$ ns and $\sigma = 16.8774$ ns for 1504 messages is achieved. Nonetheless, if the signals are recorded at $f_s = 10$ MS/s, interpolation by factor 100 is needed in a sensor network with multiple sensors at different positions for accurate TDOA localization. Since the sensors in our trials use the same RF antenna, the resulting error between the two sensors is due to GPS time synchronization and timestamp generation inaccuracy.

4.2 Sensors equipped with own RF antennas (B)

Measurement setup B

In addition to our trials with one RF antenna as described in section 4.1, a second set consisting of 50 measurements $(m_{(1,j)}, m_{(2,j)}) \in M_B$ is recorded using one RF antenna for each sensor. In this setup, both sensors are completely independent and do not share any sort of hardware (see fig. 4(a)).

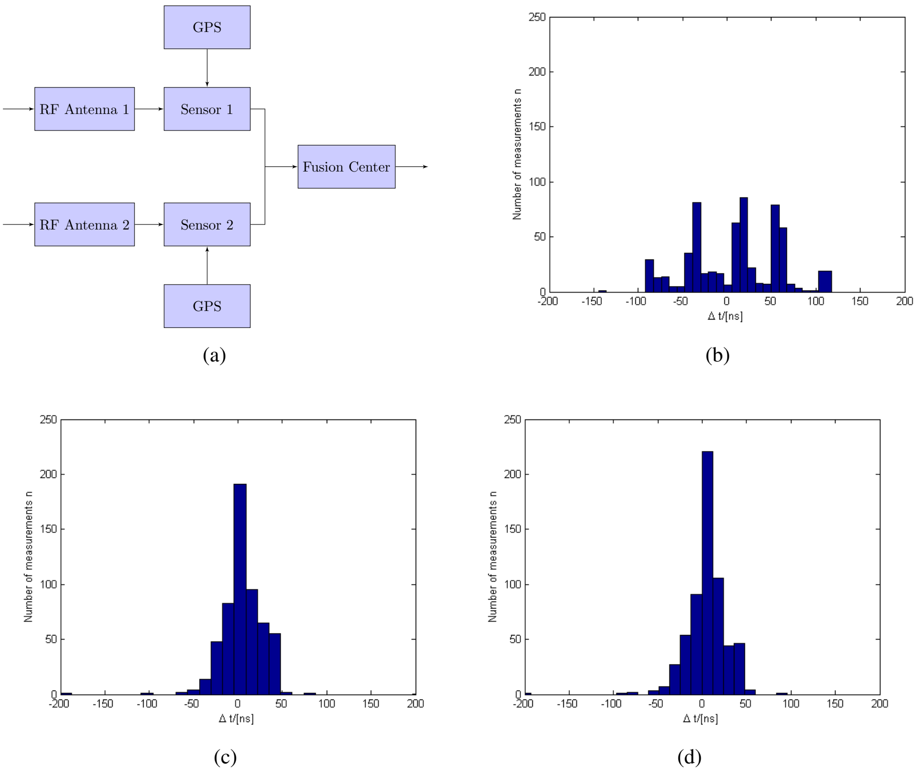

Figure 4: (a) Measurement setup B, results with (b) no interpolation, (c) interpolation by factor 10 and (d) interpolation by factor 100.

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The RF antennas and sensors are separated by a distance of approximately 1 meter. Depending on the position of the emitter, the signal propagation delay between the antennas may vary. In free space, signals propagate at speed of light $c \approx 3 * 10^8$ m/s. With a distance of 1 meter between the antennas, the delay may differ between 0 ns and $\frac{1 \text{ m}}{3*10^8 \text{ m/s}} \approx 3.3$ ns.

Experimental Results B

Fig. 4 shows the results of this trial. Without signal interpolation, 596 messages are decoded with a time difference between timestamps of $\mu = 6.4597$ ns and $\sigma = 50.0302$ ns. By interpolating the signal by factor 10, 564 messages are decoded with $\mu = 5.2447$ ns and $\sigma = 26.9964$ ns. With further interpolation, the timestamp generation accuracy is given by $\mu = 4.9967$ ns and $\sigma = 25.8131$ ns.

5 Conclusions

In this paper, determining TOAs of transponder messages in a sensor network has been analyzed. Experimental results demonstrate the feasibility of obtaining TOA measurements at a single sensor in a semi-passive scenario.

The benefit of this method is a drastic reduction of communication requirements. The amount of data that needs to be transmitted to a reference sensor or a central station significantly decreases since only a timestamp and a message ID or the whole message (only 112 bit for ADS-B messages) is required for TDOA calculation.

In two different measurement setups, it is shown that an accuracy in the nanosecond range can be achieved. A not marginal part of this error is most likely due to synchronization errors using GPS.

References

[CH1994] Y. T. Chan and K. C. Ho. A Simple and Efficient Estimator for Hyperbolic Location *IEEE Trans. on Signal Processing*, 42(8): 1905–1915, August 1994.

[FRM07] F. Fletcher, B. Ristic and D. Mušicki. Recursive Esitmation of Emitter Location using TDOA measurements from two UAVs. *10th International Conference on Information Fusion*, Fusion 2007 Quebec, QC, Canada, July 2007.

[HF08] X. Hu and M. L. Fowler. Sensor selection for multiple sensor emitter location systems. *IEEE Aerospace Conference '08*, Big Sky, Nevada, March 2008.

[ICAO07] ICAO Annex 10. Aeronautical Telecommunications. Volume IV: Surveillance and Collision Avoidance Systems Fourth Edition, Montréal: ICAO 2007, ISBN 9789291949526, 2007.

ISBN 978-3-88579-286-4

[Kau09] R. Kaune. Gaussian Mixture (GM) Passive Localization using Time Difference of Arrival (TDOA). *Informatik 2009-Workshop Sensor Data Fusion: Trends, Solutions, Applications*: 2375–2381, 2009.

[KMK10] R. Kaune, D. Mušicki, W. Koch. On passive emitter tracking. chapter in *Sensor Fusion* edited by C. Thomas, publisher: sciyo, ISBN 978-953-307-101-5, August 2010, pp. 293-318, www.intechweb.org.

[KC1976] C. H. Knapp and G. C. Carter. The Generalized Correlation Method for Estimation of Time Delay. *IEEE Trans. on Acoustics, Speech, and Signal Processing*, 24(4): 320–327, August 1976.

[MK08] D. Mušicki and W. Koch. Geolocation using TDOA and FDOA Measurements. *11th International Conference on Information Fusion*, Cologne, Germany, June 30 2008-July 3 2008.

[LUE02] J.R. Ohm and H.D. Lüke. *Signalübertragung*. Springer, 2002.

[Q1981] A. H. Quazi. An Overview on the Time Delay Estimate in Active and Passive Systems for Target Loaclization. *IEEE Trans. on Acoustic, Speech, and Signal Processing*, 29(3): 527–533, June 1981.

[RTCA] RTCA Inc. *Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance Broadcast (ADS-B) and Traffic Information Services Broadcast (TIS-B)*, Working Paper 1090-WP30-18 as DRAFT Version 4.2 of DO-282B. RTCA, Inc., 20xx

[Tor1984] D. J. Torrieri. Statistical Theory of Passive Location Systems *IEEE Trans. on Aerospace and Electronic Systems*, 20(2): 183–198, March 1984.

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