From Theory to Practice: Implementations issues for Techniques based on AoA and TDoA

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ABSTRACT

This paper presents a bridge between theory and hardware implementations of radio direction finding (RDF) techniques particularly Angle of Arrival (AoA) and radiolocalization technique namely Time Difference of Arrival (TDoA) in non-collaborative scenarios. It presents aspects that must be considered in the system design and performance tests, including antenna array features in AoA. Minimum required distance between target node (TN) and reference nodes (RN), sampling frequency, etc., in TDoA. Furthermore, the paper presents a method to calculate the experimental estimation range value in TDoA algorithms.

Keywords

Radio Direction Finding, Angle of Arrival, Time Difference of Arrival, Antenna Array, Reference Node, Target Node, Global Positioning System (GPS).

1. INTRODUCTION

Radio Direction Finding (RDF) techniques have been employed since II World War to locate enemy ships through their radio communications [1].

Over time, those algorithms have improved their performance. Goals as reaching smaller antenna arrays and better resolution have been achieved. Nowadays the radiolocalization algorithms employs hybrid information to estimate the position, aiming to mitigate the limitations of pure techniques.

Commonly, the applications fields of these techniques have been Sonar, Radar and others. Because of recent applications as cognitive radio and ITU's recommendations about spectrum management [2], the use of this technology has been extended to fulfill spectrum monitoring tasks. However, commercial devices are expensive, specially for developing countries. For this reason, the development of low-cost prototypes and systems for developing countries was proposed on The Spectrum Monitoring Manual [2], ITU k.83 [3] and k.91 (unpublished).

When practical implementations are required, the real problems emerge, not only because theoretical developments do not consider many aspects of the real world but also because there are many hardware issues that increase the complexity for a real deployment.

This paper pretends to show the main aspects that must be considered in a Radio Direction Finding implementation, based on Angle of Arrival (AoA) and a classical radiolocalization technique based on Time Difference of Arrival (TDoA). The recommendations are based in experimental works develop by research group GIDATI at Pontificia Bolivariana University (UPB).

The document is organized as follows: section II includes all aspects to consider in a AoA implementation, specially related to antenna arrays features. The recommendations to implement a TDoA algorithm in hardware are presented in section III. Finally the conclusions are shown in section V.

2. AOA ALGORITHMS

2.1 Overview

The general AoA estimator scheme [4], [5] is represented in Fig. 1. It shows D incident signals on a linear array with M-elements from angles θ_N. The received signals $x_m(k)$ are given by (1), where $\overline{A} = [\overline{a}(\theta_1) \quad \overline{a}(\theta_2) \quad ... \quad \overline{a}(\theta_D)]$ is the $M \times D$ matrix of steering vectors, which depends directly on the type of antenna array. $\overline{s} = [\overline{S_1}(k) \quad \overline{S_2}(k) \quad ... \quad \overline{S_D}(k)]^T$ is the vector of incident complex monochromatic signals at time k, and $\overline{n}(k)$ is the $1 \times D$ noise vector at each array element M with zero mean and covariance matrix $\overline{R}_{nn} = \sigma^2 \overline{I}$ [6].

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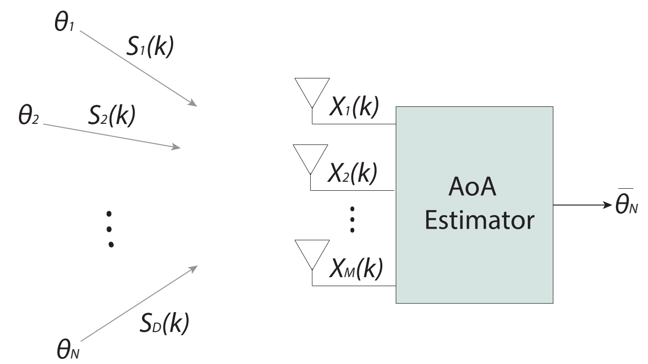

Figure 1: General scheme of AoA system [6]

$$\overline{x}(k) = \overline{A} \cdot \overline{s}(k) + \overline{n}(k) \quad (1)$$

The signal of interest $x_m(k)$ contains useful information and noise, with covariance matrix given by: $\overline{R}_{xx} = \overline{A}\overline{R}_{ss}\overline{A}^H + \overline{R}_{ss}$.

2.2 Suggestions for hardware implementation

Specific algorithms to calculate the angle of arrival were described in [6].

For hardware implementation a simplification on the model must be done. The covariance matrix must be calculated as follows [6]:

$$\hat{R}_{xx} \approx \frac{1}{K} \sum_{k=1}^{K} \overline{x}(k)\overline{x}^H(k) \quad (2)$$

The AoA algorithms works under triangulation principle and use multiple antenna elements at a reference node (RN) to determine the incident angle of an arriving signal [7]. However, in order to determine the location of a source in a two dimensional space, is sufficient with two RN [7]; even with one single node can be estimated the direction of arrival. In this case there are two possible angles of arrival, and prior information is necessary to discard the reflected lobe present in the pseudospectrum [8]. If there are two RN, both perform the same process and compare the obtained position. The common value is the real angle, while the other values can be ignored. Fig. 2 illustrated the case when there are two RN to locate a source using AoA techniques.

A key feature in AoA techniques is the antenna array factor, because it contains all the angular information required for the angle estimation [8]. Based on the above, selection of the antenna array is critical to guarantee a good system performance. Some aspects must be considered about it, like the number of elements, the distance between them, operation frequency, and position of the array.

As the number of antenna elements increases the resolution and accuracy of the estimation algorithms improves. However the computational load increased because calculations become more complicated [10], [11]. A bigger distance between antenna elements will produce better resolution on the algorithms. However, the required distance between the elements must be calculated carefully to avoid the appearance of grating lobes. A grating lobe, is a lobe of the same height as the main lobe and it appears when $d > \lambda/2$, where d is the distance between antenna array elements [12].

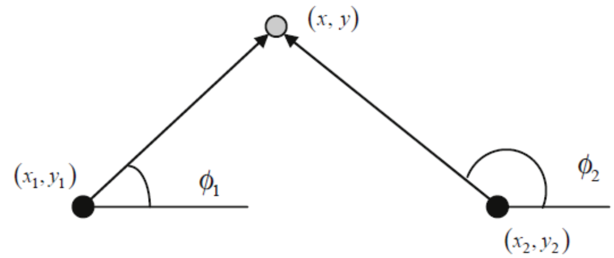

Figure 2: AoA Postioning with two Reference Nodes [9]

The array position will impact the design, because the array manifold vector depends on the reference coordinate system used [12]. Finally, the operation frequency affects the distance between antenna elements and hence the resolution and the possible appearance of grating lobes.

3. TDOA ALGORITHMS

This section presents some aspects to consider in implementations of TDoA systems.

3.1 Overview

TDoA is a positioning technique based on trilateration principle and it can be employed when there is no synchronization between the target node (TN) and the reference nodes (RN), but there is synchronization between RN [7]. For this reason, TDoA methods are employed in noncollaborative radiolocation scenarios.

Time Difference of Arrival (TDoA) isa technique based on the idea that the position of the unknown source can be determined by examining the difference in time at which the signal arrives at multiple reference points. Each TDoA measurement constrains the location of the source to be on a hyperboloid with a constant range difference between the two reference points, as shown in Fig. 3. For two-dimensional position estimation three reference nodes are required, and for 3D estimation four or more RN must be used [13].

The target node position can be estimated using an hyperbolic equations system, denoted by (3), where (x, y) are the unknown target node coordinates, (x_i, y_i) are the known reference nodes coordinates, and r_i is the range estimation [14].

$$(x - x_i)^2 + (y - y_i)^2 = r_i^2, (i = 1, ..., N) \quad (3)$$

The procedure to estimate the position using a TDoA algorithm requires first to choose one of the RN as a primary node; usually this node is the closest to the TN, hence is the one that receives first the emitted signal and in this paper we denote it RN_1. Then, the time difference of arrival must be calculated with respect to RN_1, obtaining $N - 1$ non-redundant TDoA for source location [15].

3.2 Suggestions for hardware implementation

The TDoA systems must be calibrated to compensate the constant offset induced by devices processing time. It can be

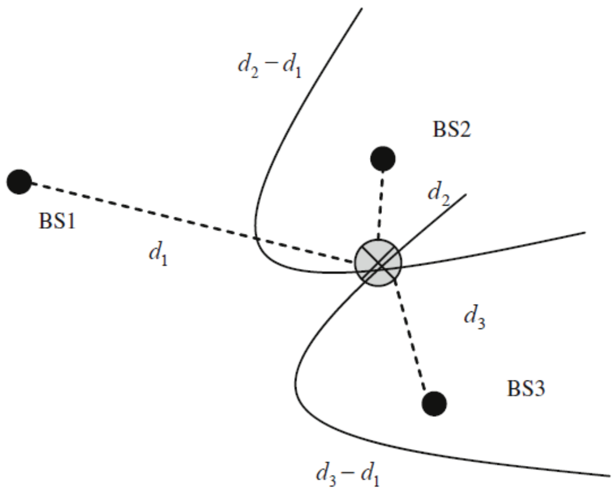

Figure 3: TDoA Positioning with three Reference Nodes [9]

achieved through a proceeding that includes the transmission of an AWGN signal, because it is uncorrelated in two different time instances. The signal is received by the RNs which are located in the same place. The time difference of arrival corresponds to processing delay because all of the RNs share the same coordinates.

The TDoA algorithms require r_i values to estimate the position, but in practice these values cannot be calculated directly, because the target node coordinates are unknown. To face this problem the relation between distance and time must be considered, aiming to express r_i in terms of distance through speed of light [9]. This relation can be expressed as follows:

$$r_{i,1} = r_i - r_1 \tag{4}$$

$$r_{i,1} = ct_i - ct_1 \tag{5}$$

$$r_{i,1} = c(t_i - t_1)r_{i,1} = c\triangle t_{i,1} \tag{6}$$

TDoA or $\triangle t_{i,1}$ can be estimated by two methods [16]:

- Subtracting the ToA (Time of Arrival) from the two RNs.
- Correlating two versions of the signal at the two RNs.

The first is unfeasible in non-collaborative scenarios. The second method is known as Generalized Cross-Correlation (GCC) [16]. Through correlation functions is possible to obtain the time lag between the received signals in each RN. Nevertheless it can be achieve only when all RN share the same clock source, otherwise the estimation is unreachable. Typically GPS clock source is used to synchronize the RN, due to the separation among the receivers. However, it is necessary but not sufficient, for this reason a known signal reference and a PPS signal in every reference node are required, aiming to assure that the receive signal begin in the same time in all RN. According to the above, the order to begin the capture of the finite number of samples in the sensor must come from a central element who plays the role of the "*network's brain*". The brain can be a different element in the network or one of the sensors can assume this role, it depends of the sensors intelligence. In addition, the RN and the brain must share the same clock source, but tipically the brain is not connected to a GPS, that's why a NTP server is recommended to avoid inconsistencies.

In order to prove the system performance is essential to consider the minimum distance required between the TN and the RN, aiming to have a good time resolution. The speed signal propagation corresponds to speed of light, hence the distance must be enough to capture at least one signal period (T_s). If more samples are taken, the results will be better. Another option is to have a very high sampling frequency; however most of the low cost devices have a limitation in this aspect. To face this issue an interpolation factor can be used to increase the number of samples without having a very high sampling frequency.

Having into account, $T_s = 1/f_s$, then the minimum required distance is given by (7). Additionally, must be consider the devices processing time which impacts the total time that must be considered. That is why a system calibration is necessary in this kind of systems.

$$d \geq \frac{c}{f_s} \tag{7}$$

Moreover, the reference nodes can not have the same distance respect to the target node, because there would not exist any difference between times of arrival, making unfeasible the estimation.

To prove the system, ITU recommends to guarantee that the received signal corresponds to the interest signal. There are two ways to know that: measure the SNR level and demodulate the signal.

There is not a standard SNR value, hence the first option may not be suitable in some cases. The second option assure that the system captures the signal of interest being more used in practice.

In summary, there are many error sources in a TDoA system, including insufficient SNR, measurement noise, non-line of sight propagation, multipath propagation, synchronization errors [17]. However, according to our experience, the most critical aspect is the synchronization and many authors agree with this, as shown in [18], [17] and [19]. All of these aspects must be considered in all platforms, low and high cost system. However, embedded systems like USRP can reduce the system cost, and they can be a good alternative to fulfill spectrum sensing activities in developing countries, because exist a balance between accuracy and cost.

4. CONCLUSION

This work presents a connection between theoretical and experimental works, aiming to provide a base to develop prototypes and systems able to estimate a source position based on Radio Direction Finding techniques specifically AoA and radiolocalization technique namely TDoA.

In the case of AoA, the recommendations are focus in the antenna array. The distance between the antenna elements must be lower than $\lambda/2$ to avoid the grating lobes presence. According to the relationship between λ and frequency f, the array size increases when f decreases. Furthermore the array position impacts the array factor, then it is important to know the reference system and array geometry.

In the other hand, the aspects that must be considered in TDoA implementations are related to the performance tests to ensure a good algorithm resolution. The main feature to take into account is the synchronization between reference nodes, which is mandatory. It can be achieve using an external clock source, like a GPS. Furthermore a NTP server, a reference signal and a PPS signal are required. In order to prove the system, the minimum required distance between RN and TN must be greater than c/f_s, with the purpose to capture one signal period at least, even more samples are taken the result will be better. It can achieve using an interpolation factor. A system calibration is recommended to compensate the constant offset induced by devices processing time.

In addition, a method to calculate the experimental estimation range value is presented. It is based on cross correlation functions and the relation between distance and time, knowing that the signal speed propagation is given by speed of light.

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