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# Angle-of-arrival localization based on antenna arrays for wireless sensor networks ☆

Paweł Kułakowski [a,*], Javier Vales-Alonso [b], Esteban Egea-López [b], Wiesław Ludwin [a], Joan García-Haro [b]

[a] Department of Telecommunications, AGH University of Science and Technology, Poland
[b] Department of Information Technologies and Communications, Polytechnic University of Cartagena, Spain

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ABSTRACT

Among the large number of contributions concerning the localization techniques for wireless sensor networks (WSNs), there is still no simple, energy and cost efficient solution suitable in outdoor scenarios. In this paper, a technique based on antenna arrays and angle-of-arrival (AoA) measurements is carefully discussed. While the AoA algorithms are rarely considered for WSNs due to the large dimensions of directional antennas, some system configurations are investigated that can be easily incorporated in pocket-size wireless devices.

A heuristic weighting function that enables decreasing the location errors is introduced. Also, the detailed performance analysis of the presented system is provided. The localization accuracy is validated through realistic Monte-Carlo simulations that take into account the specificity of propagation conditions in WSNs as well as the radio noise effects. Finally, trade-offs between the accuracy, localization time and the number of anchors in a network are addressed.



## 1. Introduction

Wireless sensor networks (WSNs) attract the attention of telecommunication world incessantly from at least 10 years. They promise multiple possible applications, e.g. monitoring an environment in dangerous regions, controlling traffic in streets, controlling an inventory in storehouses, tracking patients in hospitals or monitoring enemy forces in a battlefield. In most of these applications, data gathered by sensors should be associated with sensor positions and it is worthless without information about the place of its origin. Thus, it is crucial that sensors know their positions with the aid of a localization algorithm.

Despite the huge research effort, there is still no well-accepted approach on how to solve the localization issue, especially for outdoor sensor networks. Because of large number of sensor nodes and their desirable low cost, it is not feasible to mount a GPS receiver at each node. There have been a large number of localization techniques proposed so far [1–4], but there is no consensus on the existence of a simple, accurate, decentralized and energy efficient solution suitable for WSNs. The expensive ultra-wideband (UWB) techniques [5] give a very decent localization accuracy, but only in indoor environments, where the distances between the sensors are very limited. The similar weakness concerns the systems based on the transmission of acoustic waves [6,7]. Moreover, the acoustic transmission requires an additional hardware that increases the system cost. A

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* Corresponding author. Tel.: +48 12 617 3937.
*E-mail address:* kulakowski@kt.agh.edu.pl (P. Kułakowski).

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good accuracy could be obtained with the algorithms based on the time-of-arrival calculations, but the simple sensor transceivers are not able to perform such exact measurements. Finally, there is a group of thoroughly investigated and promising techniques based on the received signal strength (RSS) levels. However, it was shown that they cannot guarantee the appropriate precision [8,9], also because of the difficulties with matching the channel model parameters with the real propagation conditions [10].

Also, the real WSN deployments, test-beds and measurements confirm the doubts concerning the localization techniques. Good results are reported for the indoor networks [7,11], especially when the sensors are deployed in a single room, however with the aid of additional UWB or acoustic hardware. For the outdoor scenarios, the measurements are either very limited [12], the accuracy is not satisfactory [10] or the localization issue is neglected and left unsolved [13,14]. Clearly, the problem lacks a proper solution.

Localization in WSNs can be also performed using angle-of-arrival (AoA) measurements. In this work, the idea of the AoA localization system where some sensor nodes are equipped with directional antennas is developed and carefully analyzed. Having in mind the requirements and objectives of outdoor WSNs, the focus is on a simple solution that could be incorporated into small wireless sensors, while still being accurate enough for WSN applications.

The contribution of the paper is as follows. First, an AoA localization system concept suitable for small-size sensor nodes is described. Then, the detailed performance analysis is presented showing that the system is very promising even in adverse propagation conditions. Also, to refine a well-known least-squares algorithm, a new heuristic weighting function is proposed. It enables combining the information from all the anchors more effectively and reducing the location errors. The algorithm is validated by Monte-Carlo simulations using sensor parameters typical for MICAz motes [15] and a realistic propagation model [16,17]. To the best of authors knowledge, it is the first paper where the influence of Signal-to-Noise Ratio on the AoA localization accuracy is taken into account in the simulations. Finally, the trade-offs between the accuracy, localization time and number of anchors are exemplified, analyzed and discussed.

The rest of the paper is organized as follows. In Section 2, we address the related work in the area of AoA localization schemes. The specific technique analyzed in this paper is described in Section 3 and then, its accuracy is validated in Section 4. In Section 5 the AoA technique is compared to other proposals and finally, in Section 6, some conclusions are given and scope of future research is outlined.

## 2. Related work

While the angle-of-arrival localization is a well-known technique and thoroughly described in the open literature, there are not many papers dealing with AoA schemes appropriate for wireless sensor networks and their specific objectives, requirements and applications.

In Refs. [18,19], AoA schemes are described where sensor nodes are forwarding their bearings with respect to anchors, i.e. nodes which are assumed to know their own coordinates and orientations. Unfortunately, these methods require a strong cooperation between neighbor nodes, and they are prone to error accumulations. In Ref. [20], anchor nodes with adaptive antennas are used to communicate with sensors located in different parts of a network. A similar concept in Ref. [21] assumes a single anchor in the center of a network sending an angle bearing. The other nodes calculate their coordinates with the aid of the bearing and some extra information from their neighbors. However, both these solutions also need some RSS data. The idea of anchor nodes with sector antennas was also presented in Ref. [22]. There, the position of a sensor node is determined as an intersection of antenna sectors of different anchor nodes. More precise algorithms assume that sensors can receive exact AoA information from anchors [23,24]. This can be accomplished if the anchors have directional antennas rotating with a constant angular speed. The sensors can estimate the AoA of the signal registering the time when the rotating beacon has the strongest power. However, in Ref. [23], the anchors with unrealistic radiation patterns are analyzed, the radio noise is not taken into consideration and the calculations are possible only for three anchors. In Ref. [24], the rotating antennas are too large for tiny anchor nodes. Finally, a common idea of a lighthouse was adapted to wireless sensor localization in Ref. [25], but it suffers the same frailty of unfeasibility and additionally requires the optical communication between the anchor and the sensors. Generally, the main challenge of the AoA localization schemes for WSNs is the difficulty in achieving good accuracy while keeping the system simple and feasible to implement in pocket-size devices.

## 3. Algorithm details

Taking into account the difficulties mentioned above, a solution is sought that could combine the simplicity and localization accuracy suitable for the applications of outdoor WSNs. It is proposed that each anchor in the considered network be equipped with an array of four antennas ($\lambda/2$ dipoles) arranged in a square with a diagonal equal to $\lambda/2$ (6.25 cm for the 2.4 GHz band). By changing the direction of maximum radiation of the antenna array, a rotating beacon is created. In order to do that, the phases of the signals at all four antennas are adjusted to have four radio waves interfering constructively at a specific direction, according to the well-known scanning phased array (beamforming) technique [26]. The obtained radiation pattern has a maximum directivity between 6.8 dBi and 8.1 dBi (depending on the required azimuth of the beacon) and the half-power beamwidth between 63° and 75°. Despite such a large beamwidth, the localization errors of the algorithm, pre-