Beacons with Rotating Beams in AoA Localization Technique for WSN

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ABSTRACT

Despite the fact that localization techniques for wireless sensor networks (WSN) were intensively studied during the last five years, there is no consensus on the existence of simple, accurate, decentralized and energy efficient technique suitable for WSN. In this paper, it is shown that an angle-of-arrival technique can fill this gap. The proposed algorithm is based on anchor nodes equipped with antenna arrays and generating the rotating beams. The sensor nodes can learn their coordinates receiving the signals from at least two anchors in 2-dimensional space. Signals from additional anchors are used to enhance the localization accuracy using a standard least-squares approach. The accuracy of the presented algorithm is verified by Monte-Carlo simulations using sensors' parameters typical for MICAz nodes. The analysed model takes into account the signal distortions caused by the noise of the receiver what is rather novel approach in simulations of WSN localization techniques.

KEYWORDS

Wireless sensor networks, localization techniques, smart antennas, antenna theory, channel modelling.

INTRODUCTION

Wireless sensor networks (WSN) attract the attention of telecommunication world incessantly from at least ten years. They promise multiple possible applications: monitoring an environment in the dangerous or inaccessible regions, controlling a traffic in streets, controlling domestic appliances or an inventory in storehouses, tracking patients in hospitals or monitoring enemy forces in a battlefield.

A data gathered by sensors in a WSN must be delivered with an information about the location where the data is gathered. Thus, it is crucial that sensors have a knowledge about their positions.

There are several groups of techniques that enable sensors to estimate their positions. Those that are widely described in literature are: time-of-arrival, receive signal strength (RSS), acoustic and wideband techniques. All of them have weaknesses that make them difficult to apply in sensor networks. They are very

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inaccurate (RSS), impossible to realize with simple sensors' transceivers (time-of-arrival) or they need to make sensors' hardware very complicated (acoustic or wideband).

A localization dilemma in WSN could be solved using angle-of-arrival (AoA) techniques. Some interesting solutions are proposed in [1] and [2], where the described localization process is based on anchors (nodes that know their positions) using antennas with multiple sectors. However, another idea would be more worthwhile: is it possible that sensors estimate not only sectors, but even angles-of-arrival from anchors?

In this paper, an angle-of-arrival localization algorithm for WSN is proposed. It is assumed that all anchors in WSN are equipped with antenna arrays and are able to shape their radiation patterns. The anchors are transmitting beacons using directional antenna beams. The beams are rotating with a constant angular speed. Just before starting to transmit the rotating beam, each anchor sends a very short omni-directional pulse. The sensors can estimate the angle of arrival of the signal calculating the time difference between the pulse and the moment when the rotating beam has the strongest power. The accuracy of the presented algorithm is verified by Monte-Carlo simulations using sensors' parameters typical for MICAz nodes [5].

The fundamental concept of this method is not totally novel. It was described in [3], but without any solid assessment of its accuracy. It is also the basis of VOR (VHS Omni-directional Range) – a system used in aircraft navigation. However, to the best of the author's knowledge, there is no sound validation of the precision of this method for wireless sensor networks.

The main contribution of the research presented in this paper is as follows:
- the performance of the localization algorithm for beacons equipped with realistic four element antenna arrays is investigated,
- the influence of the Gaussian noise on the localization accuracy is analysed,
- the methods of cancelling the noise effects using time averaging and metrics of confidence are shown.

**ALGORITHM DETAILS**

The considered WSN consists of anchors and sensors. Anchors are only a small fraction of the network, but they perfectly know their positions – they are programmed or they have GPS receivers on boards. Learning the sensors' locations is the goal of the localization algorithm.

All the anchors are equipped with arrays of 4 antennas (\(\lambda/2\) dipoles) arranged in a square with a diagonal equal to \(\lambda/2\), as it is presented in Fig. 1. The anchors are transmitting the beacons with rotating radiation patterns. The rotation is realized by changing the direction of maximum radiation of the antenna array. The signals transmitted from dipoles have equal and constant amplitudes, but their phases are continuously adjusted. The signals emitted by dipoles are interfering constructively on the chosen direction [4]. In Fig. 1, it is shown how the phases of the signals should be chosen. The obtained radiation pattern has maximal directivity between 6.8 dB and 8.1 dB (depending on the direction of maximum radiation) and the half-power beamwidth between 63° and 75°.
Fig. 1. An array of 4 antennas in an anchor. Phases of signals emitted by the antennas required to obtain the direction of maximum radiation = $\alpha$ are also shown.

The anchors are transmitting their beacons in turn, not simultaneously. Each beacon is started by sending the anchor position and, after that, a strong short omnidirectional pulse. Then, the rotating beacon is emitted with constant angular speed $\omega$, which is known to all the sensors. The sensors are trying to register the moment when the power of the beacon is the strongest. A difference in time between receiving the initial pulse and the maximum of the beacon power ($\Delta t$) multiplied by the angular speed of the beacon ($\omega$) can be interpreted as the angle of arrival of the signal:

$$\alpha = \Delta t \cdot \omega.$$

(1)

When the angle $\alpha_i$ (from $i$-th anchor) is known, it can be used to write a simple linear equation that binds the coordinates of the anchor and the sensor:

$$X - x_i = (Y - y_i) \cdot \tan \alpha_i,$$

(2)

where $[X \ Y]$ and $[x_i \ y_i]$ are the coordinates of the sensor and the $i$-th anchor, respectively. If the angles of arrival from two or more anchors are known, the sensor position can be estimated using a standard least-squares approach. The appropriate system of linear equations can be written as:

$$A \cdot c = b,$$

(3)

where:

$$A = \begin{bmatrix}
1 & -\tan \alpha_1 \\
1 & -\tan \alpha_2 \\
\vdots & \vdots \\
1 & -\tan \alpha_n
\end{bmatrix}, \quad c = [X \ Y] \quad \text{and} \quad b = \begin{bmatrix}
x_1 - y_1 \tan \alpha_1 \\
x_2 - y_2 \tan \alpha_2 \\
\vdots \\
x_n - y_n \tan \alpha_n
\end{bmatrix}.$$
The estimated vector with coordinates can be calculated as:

$$\hat{c} = (A^T A)^{-1} A^T b.$$  \hspace{1cm} (4)

In the current form, the AoA localization algorithm is vulnerable to the radio noise, which can effect in errors when sensors are registering the moment of the strongest beacon's power. Some additional simple refinements can be done to make this algorithm more resilient and enhance its accuracy. First, the angular speed $\omega$ of rotating beacons needn't to be large, so the sensors can sample the beacons many times to take the average value and cancel out the noise. Second, each sensor can define a metric of confidence for every beacon. Each metric should be proportional to the received power of the respective beacon. The metrics can be taken into account in least-squares approach as weighted coefficients:

$$\tilde{A} \cdot c = \tilde{b},$$  \hspace{1cm} (5)

where:

$$\tilde{A} = \begin{bmatrix}
m_1 - m_1 tg\alpha_1 \\
m_2 - m_2 tg\alpha_2 \\
\vdots \\
m_n - m_n tg\alpha_n
\end{bmatrix}, \quad \tilde{b} = \begin{bmatrix}
m_1x_1 - m_1y_1 tg\alpha_1 \\
m_2x_2 - m_2y_2 tg\alpha_2 \\
\vdots \\
m_nx_n - m_ny_n tg\alpha_n
\end{bmatrix}$$

and $m_i$ is the maximal power received from $i$-th anchor.

**SIMULATION PARAMETERS**

The AoA localization algorithm was implemented in C++ and Monte-Carlo simulations were performed to analyse its accuracy. All the nodes of the WSN (the anchors and the sensors) were located randomly in an area of 50 m x 50 m. Each anchor had an array of four antennas and emitted rotation beacons with a resolution of 1°. The parameters of wireless nodes were based on MICAz motes working in 2.4 GHz frequency band [5]. The transmission power of anchors was equal to 0 dBm. As the sensitivity of MICAz motes is equal to -95 dBm and SNR required for used O-QPSK modulation is 5 dB [6], the power of the radio noise at the receiver's antennas was assessed as -100 dBm. The path loss was calculated according to a propagation model for the rural environment provided by COST 2100 SIG A. The model was based on WSN measurements performed at University of Bologna (CNIT) [7]:

$$\text{Path Loss [dB]} = 40 + 29.9 \log(d) + s,$$  \hspace{1cm} (6)

where $d$ is the distance in meters between a transmitter and a receiver and $s$ is a log-normal shadow fading with a standard deviation of 3.5 dB.

For all scenarios considered below, the Monte-Carlo simulations were performed 100 times and the average values were calculated. The results of AoA localization accuracy are presented using two quantities. The first one is a position error $P$ defined as:

$$P = \frac{\text{RMSE}}{R},$$  \hspace{1cm} (7)

where RMSE is an average root mean square error of the sensors' positions and $R$ is an average distance between sensors. The second one is a localization inefficiency defined as a percentage of the sensors which were not localized correctly. In this
paper, it is assumed that a sensor is not localized if the error of its estimated position is greater than $2R$. Such sensors are not included into the statistics when $P$ is calculated. The localization inefficiency can be associated with network coverage of the localization algorithm [8]. The sum of these two quantities is always equal to 100%.

**SIMULATION RESULTS**

In Fig. 2÷5, the initial results of the AoA localization algorithm are introduced. For each measured value of the position error, the respective localization inefficiency is also given (the percentage values written in the figures).

The influence of the radio noise and the effect of refinements (time averaging and metrics of confidence) is illustrated in Fig. 2. Obviously, when metrics of confidence are applied, the position error is smaller – the average difference is about 0.2. The effect of time averaging is smaller for a large number of samples – e.g. increasing the number of samples from 20 to 50 has nearly no effect. The AoA localization without metrics of confidence and with single samples results in $P = 0.82$ and the localization inefficiency is larger than 10%. When the metrics are used and the measured power is sampled e.g. 10 times, $P$ equals to 0.46 and the localization inefficiency decreases to 2%. It should be stressed that if the radio noise was neglected (as it is common in localization simulations), the position error would be limited only by finite resolution of rotation beacons. In the considered case, the position error would be equal to 0.06.
Fig. 2. The position error of the AoA localization algorithm as a function of a number of samples in time averaging. Two cases are depicted: with metrics of confidence (blue crosses) and without the metrics (red boxes). The percentage values give the localization inefficiency.

In the next figures (Fig. 3÷5), time averaging (10 samples) and metrics of confidence are always present. The position error as a function of average distance $R$ between sensors is documented in Fig. 3. Despite the fact that $P$ is calculated as RMSE divided by $R$, position error increases with $R$. It is the consequence of decreasing SNR when the anchors and the sensors are further from each other. The same effect is shown in Fig. 4, where the position error decreases as anchors' transmission power increases. This relation is almost linear.
Fig. 4. Almost linear relation between anchors' transmission power and the position error.

Figure 5 gives the position error as a function of the number of the anchors in the network. When there is only 2% of anchors (in these simulations, there were 2 anchors and 115 sensors), the position error is about 0.8 and there are more than 20% of the sensors that are not localized. The position error decreases quickly when a few anchors are added. Increasing the percentage of anchors from 10% to 20% is rather not worthwhile.

![Figure 5](image)

Fig. 5. The position error is decreasing when new anchors are added to the network.

CONCLUSIONS

Angle-of-arrival localization techniques seem to be well suited for wireless sensor networks. They are rather simple: they don't require nor complicated calculations neither any additional hardware for sensors. They work in a decentralized manner. Also, it is not needed to have a large percentage of anchors in the network.

In this paper, a simple AoA localization algorithm was presented and a few refinements were described that can increase its accuracy. The initial simulation results of this algorithm were provided. The simulations were made with real sensors' parameters from the MICAz motes' specification. The propagation model was based on radio channel measurements performed strictly for sensor networks. In order to precisely assess the localization accuracy of the AoA algorithm, the radio noise was also taken into account. The obtained results show a very good accuracy and a network coverage of the analysed algorithm and prove its large potential in future applications of wireless sensor networks.
REFERENCES


[6] 802.15.4 IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs).
