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A New Localization Method for WSNs Based on DOA

Qin-li An[1], Jian-feng Chen[2] and Zhong-hai Yin[3]

[1]*College of Marine, Northwestern Polytechnical University, Xi'an, 710072, China*
College of Science, Air Force Engineering University, Xi'an, 710051, China
[2]*College of Marine, Northwestern Polytechnical University, Xi'an, 710072, China*
[3]*College of Science, Air Force Engineering University, Xi'an, 710051, China*

an_qinli@126.com[1]

Abstract

This article proposes a new localization method for wireless sensor networks (WSNs) in which four beacon nodes (BNs) are equipped with a directional antenna with special transmission capabilities for sending wireless beacon signals throughout the sensor network. Each beacon node's directional antenna rotates and broadcasts its angular bearings. Using trigonometry, the proposed method is based on angle-of-arrival estimation technique that does not increase the system cost of the sensor nodes or decrease the positioning accuracy. We present the performance of the proposed method obtained from error analysis and computer simulations.

Keywords: *wireless sensor networks, localization, beacon node, directional antenna, trigonometry*

1. Introduction

Recent advancements in the wireless communications and hardware technology field have facilitated the development of wireless sensor networks (WSNs) for a wide variety of real-world applications, including environmental monitoring, disaster relief, site security, medical diagnostics, battlefield surveillance, and so on [1]. The literature contains numerous studies addressing many different aspects of WSNs, *e.g.*, addressing, coverage, data aggregation, deployment, routing, and so forth. In many cases, the solutions proposed in these studies require the locations of the individual sensors to be accurately known.

The global positioning system (GPS) [2] is one of the most well-known and widely used localization techniques since it has a remarkable accuracy. However, fitting every sensor in a large-scale WSN with a GPS receiver is prohibitively expensive, and thus many more cost-effective localization mechanisms have been proposed. For example, with the time-of-arrival (TOA), time-difference-of-arrival (TDOA), angle-of-arrival (AOA), and received signal strength indicator (RSSI) methods, the node positions are determined by range-based schemes in accordance with distance or angle information [3–19]. These types of localization methods provide a reasonably high level of accuracy, but require each sensor node to be equipped with additional hardware for ranging purposes, and therefore increase the system cost. Conversely, range-free schemes provide a coarser positioning accuracy, but avoid the requirement for specific hardware support [20–26]. To improve the positioning accuracy of range-free schemes while preserving a low implementation cost, such mechanisms typically require a large number of static anchor nodes, specific node deployments, or the use of local node communication schemes.

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In this work, we present a localization technique by which the sensor nodes determine their position with respect to four fixed beacon nodes that are capable of covering the entire network area by powerful directional wireless transmissions. Even though our technique requires costly implementation of the beacon nodes, we show that the sensor nodes do not need additional hardware complexity. This paper is organized as follows. The network model assumed for this work is described in Section 2. We present our proposed technique in Section 3. The error analysis of the proposed method is presented in Section 4. The best positions of beacon nodes are given in Section 5. Performance of the proposed method, obtained from computer simulations are presented in Section 6. Conclusions are presented in Section 7.

2. Network Model

We assume the network consists of a large number of sensor nodes (SNs). Each SN has a processor, memory, and hardware that allow limited signal processing. Without the loss of generalization, we assume a square network area, with four beacon nodes denoted by B1, B2, B3, and B4 of which the coordinates are

$$\left(-\frac{l}{2},0\right)_{,}\left(0,-\frac{l}{2}\right)_{,}\left(\frac{l}{2},0\right)_{,}\left(0,\frac{l}{2}\right)$$

placed in the network as shown in Figure 1.

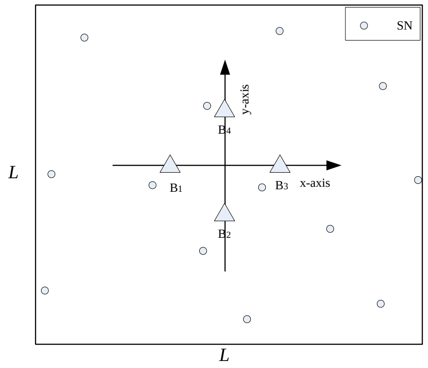

Figure 1. The Coordinates of BNs in the Sensor Network

3. Localization Principle

Each beacon node’s directional antenna rotates with a constant angular speed and broadcasts its angular bearings. A sensor node determines its location through listening to wireless transmissions from the four fixed beacon nodes.

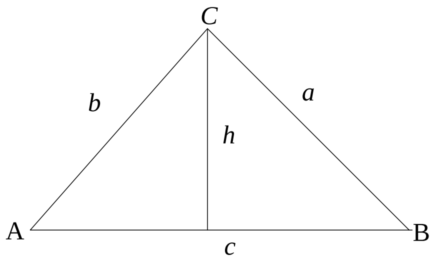

Figure 2. The Model of Trigonometry

From Figure 2, using trigonometry we get

$$S_{\Delta ABC} = \frac{1}{2}ab\sin C = \frac{1}{2}ch\,, \quad \frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin C}{c}$$

then

$$a = \frac{\sin A}{\sin C}\times c\,, \quad b = \frac{\sin B}{\sin C}\times c$$

We have

$$h = \frac{\sin A \sin B}{\sin C}\times c \tag{1}$$

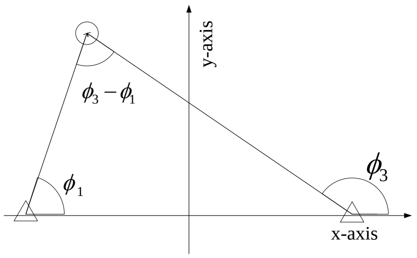

Figure 3(a). Sensor Node is above x-axis

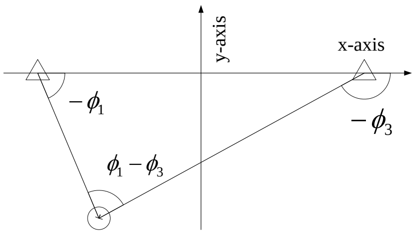

Figure 3(b). Sensor Node is below x-axis

From Figure 3, using (1) the sensor node's ordinate (i.e., y -coordinate) value is

$$\frac{\sin\phi_1 \sin\phi_3}{\sin(\phi_3-\phi_1)}\times l$$

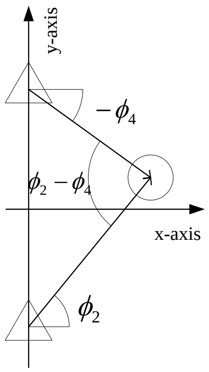

Figure 4(a). Sensor Node is on the Right of y-axis

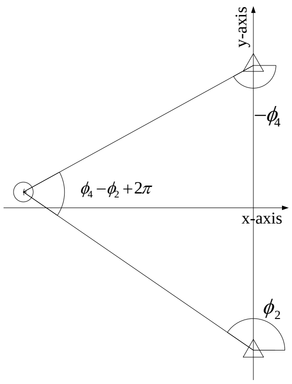

Figure 4(b). Sensor Node is on the Left of y-axis.

From Figure 4, using (1) the sensor node's abscissa(*i.e.*, x-coordinate) value is

$$\frac{\cos\phi_2\cos\phi_4}{\sin(\phi_2-\phi_4)}\times l$$

Considering denominators are zero, the coordinate formulas of the sensor node are

$$y=\begin{cases}0, & \sin(\phi_3-\phi_1)=0;\\ \dfrac{\sin\phi_1\sin\phi_3}{\sin(\phi_3-\phi_1)}\times l, & \textit{otherwise}.\end{cases} \tag{2}$$

$$x=\begin{cases}0, & \sin(\phi_2-\phi_4)=0;\\ \dfrac{\cos\phi_2\cos\phi_4}{\sin(\phi_2-\phi_4)}\times l, & \textit{otherwise}.\end{cases} \tag{3}$$

4. Error Analysis

Assumed that the error of $\phi_i\,(i=1,\cdots,4)$ follows uniform distribution that parameter values are $-\dfrac{\Delta\varphi}{2}$ and $\dfrac{\Delta\varphi}{2}$, *i.e.*,

$$\delta\phi_i \sim U(-\frac{\Delta\varphi}{2},\frac{\Delta\varphi}{2})(i=1,\cdots,4)$$

Then

$$|\delta y|=|\frac{\partial y}{\partial\phi_1}\delta\phi_1+\frac{\partial y}{\partial\phi_3}\delta\phi_3|\le\left|\frac{\partial y}{\partial\phi_1}\right||\delta\phi_1|+\left|\frac{\partial y}{\partial\phi_3}\right||\delta\phi_3|$$

$$\le l\times\frac{(\sin^2\phi_3)\dfrac{\Delta\varphi}{2}+(\sin^2\phi_1)\dfrac{\Delta\varphi}{2}}{\sin^2(\phi_3-\phi_1)}=\frac{(\sin^2\phi_3)+(\sin^2\phi_1)}{\sin^2(\phi_3-\phi_1)}\times l\times\frac{\Delta\varphi}{2}$$

$$|\delta x|=|\frac{\partial x}{\partial\phi_2}\delta\phi_2+\frac{\partial x}{\partial\phi_4}\delta\phi_4|\le\left|\frac{\partial x}{\partial\phi_2}\right||\delta\phi_2|+\left|\frac{\partial x}{\partial\phi_4}\right||\delta\phi_4|$$

$$\le l\times\frac{(\cos^2\phi_4)\dfrac{\Delta\varphi}{2}+(\cos^2\phi_2)\dfrac{\Delta\varphi}{2}}{\sin^2(\phi_2-\phi_4)}=\frac{(\cos^2\phi_4)+(\cos^2\phi_2)}{\sin^2(\phi_2-\phi_4)}\times l\times\frac{\Delta\varphi}{2}$$

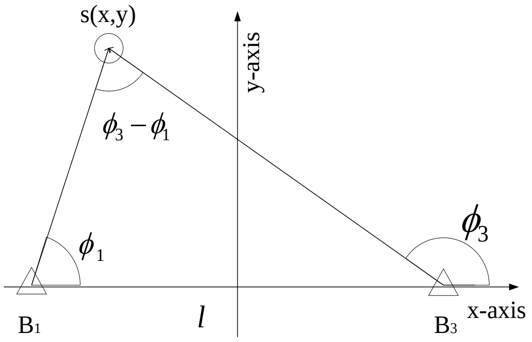

Figure 5. Error Analysis of the Sensor Node's Ordinate

From Figure 5, using (1) the error of the sensor node's ordinate is

$$|\delta y| \le \frac{(\sin^2\phi_3)+(\sin^2\phi_1)}{\sin^2(\phi_3-\phi_1)} \times l \times \frac{\Delta\varphi}{2} = \frac{(x+\frac{l}{2})^2+y^2+(x-\frac{l}{2})^2+y^2}{l^2} \times l \times \frac{\Delta\varphi}{2}$$

$$= (\frac{x^2+y^2}{l}+\frac{l}{4}) \times \Delta\varphi \tag{4}$$

Analogously, the error of the sensor node's abscissa is

$$|\delta x| \le (\frac{x^2+y^2}{l}+\frac{l}{4}) \times \Delta\varphi \tag{5}$$

5. The best positions of beacon nodes

Using (4)(5), let

$$\Delta y = \Delta x = (\frac{x^2+y^2}{l}+\frac{l}{4}) \times \Delta\varphi$$

Considering the minimum mean error of localization, then

$$error_{ordinate} = \Delta\varphi \int_{-\frac{L}{2}}^{\frac{L}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} (\frac{x^2+y^2}{l}+\frac{l}{4}) dxdy \ = \Delta\varphi(\frac{L^4}{6l}+\frac{lL^2}{4})$$

Let $\frac{d(error_{ordinate})}{l}=0$, we have

$$l = \frac{\sqrt{6}}{3}L$$

i.e., the coodinates of B_2 and B_4 are

$$(0,-\frac{\sqrt{6}L}{6}),(0,\frac{\sqrt{6}L}{6})$$

Analogously, the coodinates of B_1 and B_3 are

$$(-\frac{\sqrt{6}L}{6},0),(\frac{\sqrt{6}L}{6},0)$$

6. Simulation Results

In this section we present some results obtained from computer simulations demonstrating the performance of the proposed technique. We assume a network area similar to that depicted in Figure 1 with $L = 2$ and $l = \frac{\sqrt{6}}{3} L = \frac{2\sqrt{6}}{3}$. The coordinates of sensor nodes is given as

$$\{(x, y) \mid x, y = -\frac{L}{2} : 0.1 : \frac{L}{2} = -1 : 0.1 : 1\}.$$

We evaluate the errors in location discovery using the proposed technique under different parameters as

$$\Delta\varphi = \frac{pi}{180} \times k (k = 1, 3, 6)$$

Considering the error of $\phi_i (i = 1, \cdots, 4)$, rewriting formulas (2)(3), we adopt the coordinate formulas of the sensor node for simulation as

$$y = \begin{cases} 0, & |\sin(\phi_3 - \phi_1)| < \sin(\frac{\Delta\varphi}{2}); \\ \frac{\sin\phi_1 \sin\phi_3}{\sin(\phi_3 - \phi_1)}, & otherwise. \end{cases}$$

$$x = \begin{cases} 0, & |\sin(\phi_2 - \phi_4)| < \sin(\frac{\Delta\varphi}{2}); \\ \frac{\cos\phi_2 \cos\phi_4}{\sin(\phi_2 - \phi_4)} \times l, & otherwise. \end{cases}$$

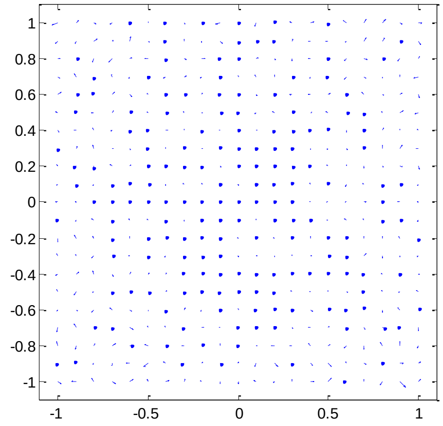

Figure 6. Error of the Sensor Node's Ordinate for $\Delta\varphi = \frac{\pi}{180}$

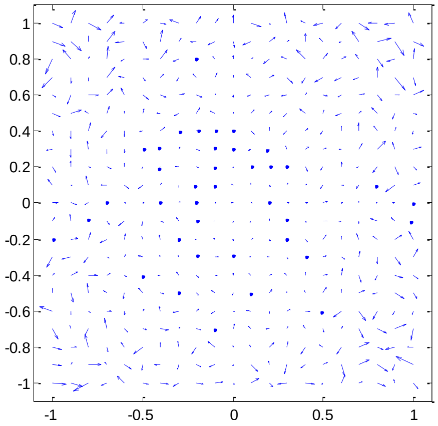

Figure 7. Error of the Sensor Node's Ordinate for $\Delta\varphi = \frac{\pi}{180} \times 3$

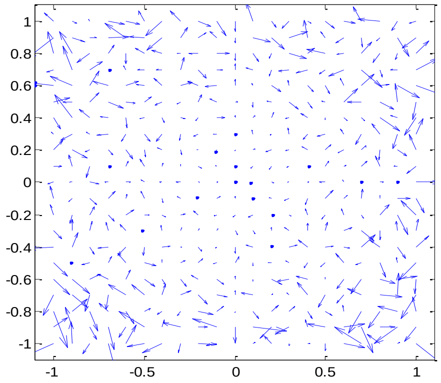

Figure 8. Error of the Sensor Node's Ordinate for $\Delta\varphi = \frac{\pi}{180} \times 6$

Figure 6, Figure 7, Figure 8 shows the variation of the localization error in the network area, when $\Delta\varphi = \frac{pi}{180} \times k (k = 1,3,6)$ respectively. Note that the arrow tails are real coordinates of sensor nodes in the network area, while the arrow heads are computed coordinates. The results show that the localization errors increase as the distance between sensor node and origin is increased and the error of angular bearing is increased. This result is to be expected as the error analysis above.

7. Conclusions

This article has proposed an accurate, range-free, and simple localization scheme for wireless sensor networks. Although the proposed approach requires the beacon nodes to be equipped with a directional antenna, the sensor nodes have no specific hardware requirements and can be implemented using simple omnidirectional antennas. The performance of the proposed localization scheme has been analysed and evaluated by performing a series of numerical simulations using MATLAB. Overall, the error analysis and simulation results have shown that the localization performance of the proposed localization scheme depend upon the distance from origin to sensor node and the angular bearing error.

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Authors

Qinli An was born in 1975 and received the bachelor degree in Applied Maths from National University of Defense Technology in China, master degree in Applied Maths from Air Force Engineering University in China and a Ph.D. student from Northwestern Polytechnical University in Communication and Information Engineering. He is a lecturer in Air Force Engineering University. His current research interests are mobile ad hoc networks with directional antenna and wireless sensor networks. E-mail: an_qinli@126.com

Jianfeng Chen was born in 1972 and received the bachelor degree, master degree and doctor degree in Communication and Information Engineering from Northwestern Polytechnical University in China. He is a Professor in Northwestern Polytechnical University. His current research interests are Acoustic array processing, Speech processing, Wireless Sensor Network and Modern spectral analysis. He is currently IEEE Senior member, IEEE Signal Processing Society Member, Pattern Recognition Society Member, International Communication Society member and member of IEEE Xi’an Section Executive Committee.

Zhonghai Yin received the doctor degree in School of Telecommunications Engineering of Xidian University in China. He is a Professor in in Air Force Engineering University. His current research interests are Modern spectral analysis, mobile ad hoc networks with directional antenna and wireless sensor networks.