

# Directionality based Location Discovery Scheme using Beacon Nodes with Transmission Capabilities throughout Sensor Network

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## Abstract

*In this paper, we propose a range-free localization scheme for wireless sensor networks (WSNs) using four beacon nodes (BNs) equipped with a directional antenna with special transmission capabilities for sending wireless beacon signals throughout the sensor network. Each beacon node rotates with a constant angular speed and broadcasts its angular bearings. A sensor node can determine its location by listening to wireless transmissions from the four fixed beacon nodes. The proposed method is based on an angle-of-arrival estimation technique that does not increase the complexity or cost of construction of the sensor nodes. We present error analysis and the best positions of beacon nodes in the proposed method. Numerical results, obtained by simulating of several scenarios, show that the algorithm can reach a good level of convergence.*

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

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## 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]. In such networks, hundreds if not thousands of miniature sensor nodes are randomly deployed in a sensing field to detect specific events. Once an event is detected, the sensors forward the sensed information to a remote sink, which processes the information in accordance with the requirements of the specific application. 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. For example, in [2], each sensor node utilizes the location information of its neighbors to test for the satisfaction of a local coverage condition. In addition, many scalable and energy-efficient forwarding and routing schemes based on the positioning information of the local nodes have been proposed [3]. Each node knows its own location and that of its neighbors and a location service system [4] is used to obtain the position of the destination node such that an appropriate forwarding path can be derived.

The global positioning system (GPS) [5] 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 [6–22]. 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 [23–31]. 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.

In this work, we present a localization technique by which the sensor nodes determine their positions 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 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. System Model

In this section we describe the details of the system model to which we apply our localization technique.

### 2.1. Network Model

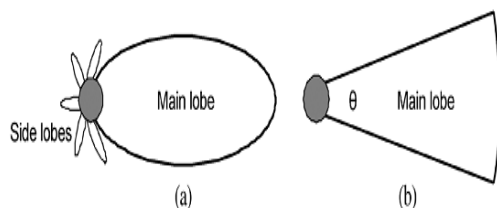
We assume the network consists of a large number of sensor nodes (SNs), which are located in random but fixed locations. Each SN has a processor, memory, and hardware that allow limited signal processing. The SNs have limited transmission range. Hence, they rely on store-and-forward multi-hop packet transmission for communication.

### 2.2. Beacon Signal Generation

We assume the presence of four beacon nodes equipped with a directional antenna with special transmission capabilities for sending wireless beacon signals throughout the sensor network. In contrast to omnidirectional antennas which emit and receive energy equally in all directions, a directional antenna radiates and receives more energy in one particular direction than in others. As shown in Figure 1(a), a directional antenna has a main lobe (or beam) in the direction of maximum radiation or reception and several side lobes. Based on the side lobe suppression methods, the side lobes can be suppressed by measuring the relative signal strengths [30]. Similar to [20], the localization scheme developed in this study ignores these side lobes and approximates the antenna pattern as a conical section with an apex angle (i.e., beam width) of [see Figure 1(b)]. The beacon signals are designed to enable any sensor node to determine its angular bearings with respect to the beacon nodes. For this purpose, we assume that each

beacon node, whose directional beam width is  $\theta$  ( $0 < \theta < \frac{\pi}{2}$ ), anticlockwisely rotates with a constant angular speed of  $\omega$  radians/s, initial and end value of 0. without the loss of generalization, we assume a circle network area, with four beacon nodes denoted by B1, B2,

B3, and B4 of which the coordinates are  $(-\frac{l}{2}, 0)$ ,  $(0, -\frac{l}{2})$ ,  $(\frac{l}{2}, 0)$ ,  $(0, \frac{l}{2})$  placed in the network as shown in Figure 2. The transmissions from different beacon nodes must be distinguishable, which may be achieved by using unique RF carrier frequencies for each beacon. It may also be implemented by using different signature sequences or codes on the same carrier frequency.



(a) Actual pattern (b) Approximated pattern.

Figure 1. Directional Antenna Pattern

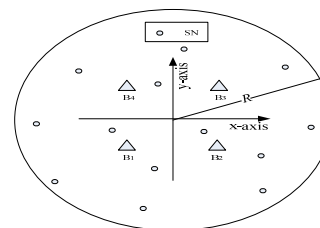


Figure 2. The Coordinates of BNs in the Sensor Network

### 3. Localization Principle

Assume that the WSN contains  $S = \{s_i | i = 1, \dots, n\}$  sensor nodes and  $B = \{B_i | i = 1, 2, 3, 4\}$  beacon nodes. Each beacon node transmits one beacon message sequentially from its antenna every beacon distance as it rotates through the sensor network. Note that the beacon distance is the distance between two successive beacon message.

The beacon messages have the form (angular bearing, flag), where the angular bearing field contains the beacon node's angular bearing  $\varphi (-\pi \leq \varphi < \pi)$  and the flag field indicates beacon node index. Each sensor node  $S_i$  maintains four beacon lists, i.e.  $B_i = \{\varphi_p | p = 1, \dots, N_i\} (i = 1, 2, 3, 4)$  to store angular bearing information received from the beacon nodes within the WSN, where  $N_i$  denote the number of received beacon messages whose flag is  $i$ , respectively. When sensor node  $S_i$  receives a beacon message, if the flag is  $i$ , then inserts the contents of the angular bearing field into  $B_i$  respectively (the negative angular bearing add  $2\pi$  if the first angular bearing is positive).

Based on the antenna configuration and the proposed trajectory, the statistical mean can be exploited for angular bearing estimations. node  $S_i$  determines its angular bearing  $\phi_i (i = 1, \dots, 4)$  by estimating the mean of  $B_i (i = 1, 2, 3, 4)$  respectively, i.e.,

$$\phi_i = \frac{1}{N_i} \sum_{p=1}^{N_i} \varphi_i (i = 1, \dots, 4)$$

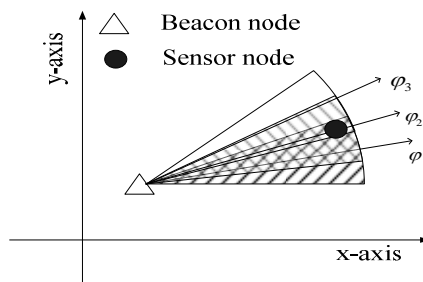


Figure 3. An Example of Angular Bearing Estimation

Figure 3 presents an illustrative example of the proposed scheme. As shown, a beacon node anticlockwisely rotates with a constant angular speed of  $\omega$  radians/s. The sensor node receives three beacon messages  $\varphi_1, \varphi_2, \varphi_3$  from the beacon node. The sensor node computes the mean of  $\{\varphi_1, \varphi_2, \varphi_3\}$  as its angular bearing. Thus the sensor node determines its angular bearing with respect to the beacon node.

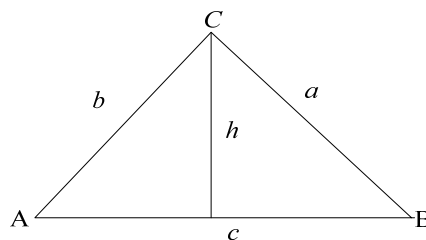


Figure 4. The Model of Trigonometry

From Figure 4, The formula is given using trigonometry as follows:

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

We have:

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

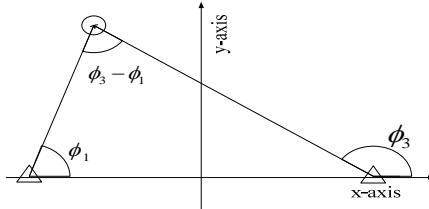


Figure 5. Sensor Node is above the x-axis

From Figure 5, using formula (1) the sensor node's ordinate (i.e.,  $y$  -coordinate) value is:

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

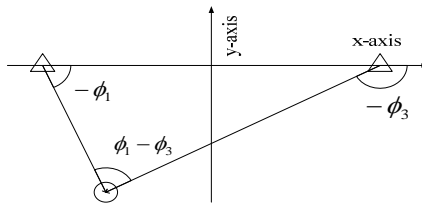


Figure 6. Sensor Node is below the x-axis

From Figure 6, using formula (1) the sensor node's ordinate value is:

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

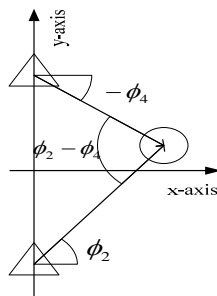


Figure 7. Sensor Node is on the Right of the y-axis

From Figure 7, using formula (1) the sensor node's abscissa(i.e.,  $x$  -coordinate) value is

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

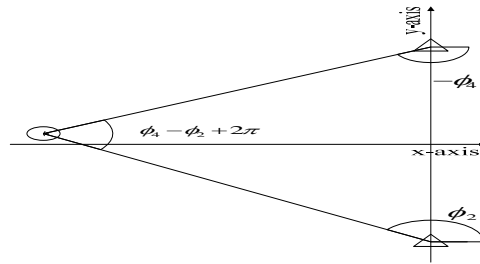


Figure 8. Sensor Node is on the Left of the y-axis

From Figure 8, using formula (1) the sensor node's abscissa value is:

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

From the discussion above, we find that the sensor node's ordinate value and abscissa value are respectively.

$$\frac{\sin \phi_1 \sin \phi_3}{\sin(\phi_3 - \phi_1)} \times l \tag{2}$$

$$\frac{\cos \phi_2 \cos \phi_4}{\sin(\phi_2 - \phi_4)} \times l \tag{3}$$

Considering denominators are zero, the coordinate's formulas of the sensor node are given as follows:

$$y = \begin{cases} 0, & \sin(\phi_3 - \phi_1) = 0; \\ \frac{\sin \phi_1 \sin \phi_3}{\sin(\phi_3 - \phi_1)} \times l, & \text{otherwise} \end{cases}$$

$$x = \begin{cases} 0, & \sin(\phi_2 - \phi_4) = 0; \\ \frac{\cos \phi_2 \cos \phi_4}{\sin(\phi_2 - \phi_4)} \times l, & \text{otherwise} \end{cases}$$

**4. Error Analysis**

Let  $\Delta\varphi = \omega \times \text{beacon distance}$ , then the error of  $\phi_i$  follows uniform distribution that

parameter values are  $-\frac{\Delta\varphi}{2}$  and  $\frac{\Delta\varphi}{2}$ , i.e.,

$$\delta\phi_i \sim U\left(-\frac{\Delta\varphi}{2}, \frac{\Delta\varphi}{2}\right)$$

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

Then,  $\leq \left| \frac{\partial y}{\partial \phi_1} \right| |\delta\phi_1| + \left| \frac{\partial y}{\partial \phi_3} \right| |\delta\phi_3|$

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

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

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

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

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

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

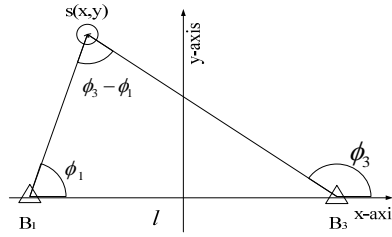


Figure 9. Error Analysis of the Sensor Node's Ordinate

From Figure 9, using formula(1) the error of the sensor node's ordinate is:

$$\begin{aligned} \delta y &\leq \frac{(\sin^2 \phi_3) + (\sin^2 \phi_1)}{\sin^2(\phi_3 - \phi_1)} \times l \times \frac{\Delta \varphi}{2} \\ &= \frac{(x + \frac{l}{2})^2 + y^2 + (x - \frac{l}{2})^2 + y^2}{l^2} \times l \times \frac{\Delta \varphi}{2} \\ &= (\frac{x^2 + y^2}{l} + \frac{l}{4}) \times \Delta \varphi \quad (4) \end{aligned}$$

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

$$\delta x \leq (\frac{x^2 + y^2}{l} + \frac{l}{4}) \times \Delta \varphi \quad (5)$$

From the analysis above, we find that the errors of the sensor node's ordinate (abscissa) increase in accordance with the square of the distance from origin and the product of angular speed  $\omega$  and beacon distance.

### 5. The Best Positions of Beacon Nodes

Using formulas (4)(5) by polar coordinates, let:

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

Considering the minimum mean error of localization, then:

$$\begin{aligned} error_{ordinate} &= \Delta \varphi \int_{-\pi}^{\pi} \int_0^R (\frac{r^2}{l} + \frac{l}{4}) r dr d\theta = \Delta \varphi \int_{-\pi}^{\pi} \int_0^R \frac{r^3}{l} + \frac{lr}{4} dr d\theta = \Delta \varphi \int_{-\pi}^{\pi} \frac{R^4}{4l} + \frac{lR^2}{8} d\theta \\ &= \pi \Delta \varphi (\frac{R^4}{2l} + \frac{lR^2}{4}) \end{aligned}$$

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

$$l = \sqrt{2} R$$

i.e. the coordinates of B2 and B4 are:

$$(0, -\frac{\sqrt{2} R}{2}), (0, \frac{\sqrt{2} R}{2})$$

Analogously, the coordinates of B1 and B3 are:

$$\left(-\frac{\sqrt{2}R}{2}, 0\right), \left(\frac{\sqrt{2}R}{2}, 0\right)$$

### 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 2 with  $R=1$ . From a set of  $n$  nodes, each node is independently randomly placed according to two-dimensional uniform distribution in a circular area (disk) of radius  $R$ . Let  $l = \sqrt{2}R$ . We evaluate the errors in location discovery using the proposed technique under different parameters as:

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

Considering the error of  $\phi_i (i = 1, \dots, 4)$ , we adopt the coordinate's formulas of the sensor node for simulation as:

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

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

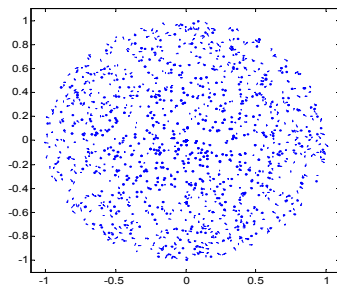


Figure 10. Error of the Sensor Node's Coordinates for  $\Delta\varphi = \frac{\pi}{180}$

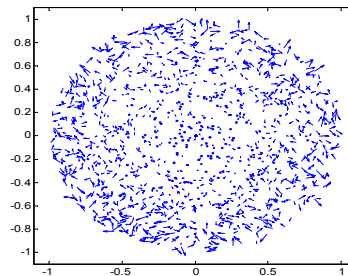


Figure 11. Error of the Sensor Node's Coordinates for  $\Delta\varphi = \frac{\pi}{180} \times 3$

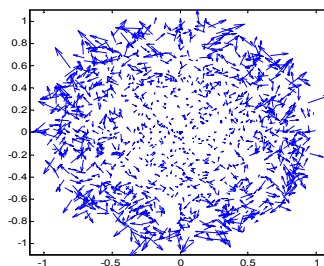


Figure 12. Error of the Sensor Node's Coordinates for  $\Delta\varphi = \frac{\pi}{180} \times 6$

Figure 10, Figure 11, Figure 12 shows the variation of the localization error in the

network area, when  $\Delta \varphi = \frac{\pi^i}{180} \times k$  ( $k = 1, 3, 6$ ) 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 beacon nodes is increased and the error of angular bearing is increased. This result is to be expected as the error analysis above.

## 7. Conclusion

This paper has proposed an accurate, distributed, range-free, scalable, and simple localization scheme for wireless sensor networks. In the proposed approach, beacon nodes are fitted with a directional antenna and transmit beacon messages as they rotate through the sensor network. The beacon messages are received by the sensor nodes, which then apply the statistical mean to compute their coordinates based upon the advertised angular bearings of the beacon nodes. Although the proposed approach requires the beacon nodes to be fitted 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 is dependent upon the distance between sensor node and beacon nodes, the angular bearing error.

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