A Directionality based Location Discovery Scheme for Wireless Sensor Networks

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ABSTRACT

A sensor network is a large ad hoc network of densely distributed sensors that are equipped with low power wireless transceivers. Such networks can be applied for cooperative signal detection, monitoring, and tracking, and are especially useful for applications in remote or hazardous locations. This paper addresses the problem of location discovery at the sensor nodes, which is one of the central design challenges in sensor networks. We present a new method by which a sensor node can determine its location by listening to wireless transmissions from three or more 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 the performance of the proposed method obtained from computer simulations.

Categories and Subject Descriptors

B.8.2 [**Hardware**]: Performance Analysis and Design Aids; I.1.4 [**Symbolic and Algebraic Manipulations**]: Applications; D.2.2 [**Software Engineering**]: Desgin Tools and Techniques

General Terms

Algorithms, Design, Performance

Keywords

Sensor networks, localization, directional antennas, triangulation.

1. INTRODUCTION

Recent advances in embedded systems and wireless technology have made it possible to design small and inexpensive smart sensors that are also capable of wireless communication. A collection of a large number of such wireless sensors can be networked to coordinate amongst themselves and perform the much larger task of distributed microsensing [5, 9, 4, 8]. Networking of sensor information can improve sensing accuracy by providing a multi-dimensional view of an event (for instance, by combining the information on temperature, acoustic data, images, etc). In addition, networked sensors can be adapted to focus attention to critical events and locations, either automatically when triggered by other sensors, or due to inputs from an external user. Moreover, networked sensors have a high tolerance to node failures. Such large scale, dynamically changing, and robust *sensor networks* will be useful for continuous unmanned surveillance and are particularly advantageous in hostile physical environments such as remote geographical regions, toxic locations, and in situations where it is difficult to obtain microlevel local information. Applications include detection of a fire or chemical leak in manufacturing plants, intrusion detection in a large establishment, detection of machine malfunction in factories, and target tracking in a tactical environment.

The detection of a target signal or an event is usually also associated with the issue of determining its location. Consequently, it is necessary for the nodes in a sensor network to know their own physical locations. In a network of a large number of densely distributed sensor nodes, location information can also be utilized by many network functions for applying localized algorithms, which can substantially reduce the complexity and processing requirements. Examples of such localized network function include location-aided routing, collaborative signal processing, and optimization of communication tasks in the network [11, 13, 10, 7].

However, location discovery in sensor networks poses significant design challenges. Because of constraints in size, form factor, and cost of construction of sensor nodes, it is impractical to use traditional GPS receivers at the sensor nodes. Moreover, sensor networks may be deployed in regions where satellite signals may not be available. Hence a significant amount of work has been reported in recent years on algorithms that enable wireless nodes in a large ad hoc network to determine their locations without using GPS-like infrastructure [3, 16, 2, 14, 15, 17]. These algorithms aim to enable low cost, low complexity, small sensor nodes to be randomly deployed in a given target area and automatically determine their positions with respect to some reference point.

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In this work, we present a localization technique by which the sensor nodes determine their position with respect to a set of 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. In section 2 we discuss some of the main issues related to localization in sensor networks. The network model assumed for this work is described in section 3. We present our proposed technique in section 4. Performance of the proposed method, obtained from computer simulations, are presented in section 5. Conclusions are presented in section 6.

2. LOCATION DISCOVERY IN SENSOR NETWORKS

Several issues make the location discovery problem in sensor nodes particularly challenging. Firstly, constraints in size and construction cost preclude the use of complex hardware at the sensor nodes. Secondly, a sensor network may consist of a fairly dense collection of sensor nodes, which implies that the estimated locations should be fairly accurate so that the corresponding relative positions of the nodes match the actual network topology. Thirdly, limited transmission range of the sensor nodes prevents them to be in direct communication with the beacon nodes, which may be few and located at the periphery of the network area. Moreover, the sensor nodes have to conserve battery power, requiring all functions to adhere to a minimum power consumption policy.

It is assumed that deploying the sensor nodes according to a chosen location pattern is prohibitive. Hence, sensor nodes must determine their locations with respect to some fixed beacon nodes using wireless or infrared signals and possibly engaging in cooperative computations. Existing location discovery techniques typically use distance or angle measurements from a fixed set of reference points and apply multilateration or triangulation techniques to solve for the unknown location. The distance or angle estimates may be obtained from:

- **Received signal strength (RSSI) measurements:** where knowledge of the transmitter power, the path loss model, and the power of the received signal are used to determine the distance of the receiver from the transmitter. A sensor node estimates the distances from three of more beacon nodes to compute its location. The major drawback of this method is that multipath reflections, non line-of-sight conditions, and other shadowing effects might lead to erroneous distance estimates. Techniques using a combination of RSSI and other measurements may lead to reliable location estimates, as proposed in [2, 3, 15]. However, nonuniform propagation environments make RSSI methods unreliable and inaccurate.

- **Time-of-arrival and time-difference-of-arrival (ToA, TDoA) measurements:** which may be used to estimate the distance from a set of reference points by measuring the propagation times (or differences thereof) of the signals. However, due to the high propagation speed of wireless signals, a small measurement error causes a large error in the distance estimate. Hence, when a dense network is involved, such as a sensor network, localization techniques using ToA or TDoA measurements need to use a signal that has a smaller propagation speed than wireless, such as ultrasound [16]. Though this gives fairly accurate results, it requires additional hardware at the sensor nodes to receive the ultrasound signals.

- **Angle of arrival (AoA) measurements:** where special antenna configurations are used to estimate the angle of arrival of the received signal from a beacon node. This concept is used in the VOR/VORTAC system for aircraft navigation, where the VORTAC stations act as beacon nodes, which transmit special omnidirectional signals that allow a receiver to determine its bearings with respect to the stations [1]. A prototype navigation system described in [12] is also based on a similar concept but it uses a set of optical sources and a rotating optical sensor for obtaining the angular measurements. The main drawback of this technique for terrestrial systems is the possibility of error in estimating the directions caused by multipath reflections. To the best of our knowledge, the possibility of applying this method to sensor networks has not been reported yet.

Several existing localization systems employ application specific improvements to these basic techniques. The RADAR system [2] is designed for indoor localization, which uses extensive RF signal strength measurements that are performed offline to design signal strength maps. These maps are used during localization to estimate the distance from signal strength measurements. In the Cricket location support system [14], which is also designed for indoor environments, fixed beacons broadcast local geographical information to the listener nodes to increase the accuracy of distance estimation from ultrasound signals. The BAT system [17] uses an array of ultrasound receivers for processing received signals from a user of unknown location.

Our work is motivated by the intention of keeping the hardware required for location discovery at the sensor nodes to a minimum. Localization techniques based on signal strength measurements are prone to inaccuracies. ToA or TDoA based techniques cannot be applied to wireless signals alone to achieve the desired level of accuracy. Ultrasound signals require additional hardware. Hence, we explore the possibility of using *direction estimates* for localization. According to our scheme, each sensor node estimates its bearing (direction) with respect to three or more beacon nodes by analyzing the wireless beacon signals received from them. These angular bearings and the known locations of beacon nodes are used for determining the location of the sensor node using a standard triangulation technique.

3. SYSTEM MODEL

In this section we describe the details of the system model to which we apply our localization technique. The proposed technique is quite general, and may be applied in a number of application contexts other than that considered here. However, in this work we focus on a sensor network.

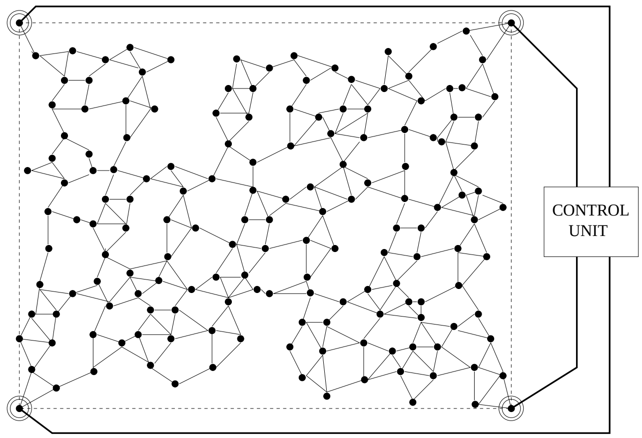

Figure 1: An example of a sensor network that includes 4 gateway nodes.

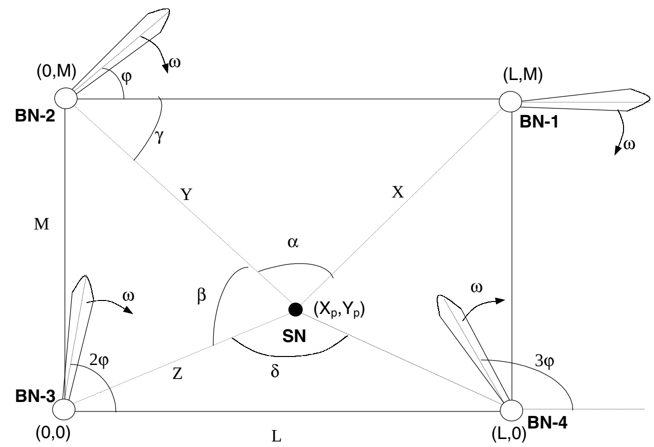

Figure 2: The model of rotating directional beacon signals from 4 beacon nodes: BN-1, BN-2, BN-3, and BN-4, located on the corners of the sensor network area. The figure shows a test sensor node SN with its angular bearings with respect to the four beacon nodes.

3.1 Network Model

We assume a sensor network model as depicted in Figure 1. The network consists of a large number of *sensor nodes* (SN), which are located in random but fixed locations, and a central processing and control unit. The sensors take periodic observations to detect the existence of a target signal in its vicinity (such as temperature, contamination level, physical movements, etc.), and transmit a locally processed information to the *control unit* (CU) when necessary. Each SN has a processor, memory, and hardware that allow limited signal processing, data compression, and wireless networking operations. The SNs have limited transmission range. Hence, they rely on store-and-forward multi-hop packet transmission for communication. All nodes maintain multihop routes to one of several gateway nodes in the network, which have wired links to the CU. The CU is responsible for taking the final decision on the existence of a target signal and determining the its location based on the observations sent by the sensors and other geographical information. To achieve scalability, the sensor network may be designed such that the SNs cooperate and combine their observations locally before sending any message through the network to the CU. It must be noted that the actual functioning of the networking operations is not a direct concern in this work. We describe the network model for the reader to visualize the application scenario where the localization principle is applied.

3.2 Beacon signal generation

We assume the presence of at least three fixed wireless transmission stations or *beacon nodes* in the network. These nodes are equipped with special transmission capabilities for sending wireless beacon signals throughout the sensor network. 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 signal consists of a continuous RF carrier signal on a narrow directional beam that rotates with a constant angular speed of ω degrees/s. The locations of the beacon nodes can be arbitrary. For illustration, we assume a rectangular network area, with four beacon nodes denoted by BN-1, BN-2, BN-3, and BN-4 placed in the four corners of the network and co-located with the gateway nodes, 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. There is a constant angular separation of ϕ degrees between the directional beams from the four beacon nodes BN-1, BN-2, BN-3, and BN-4, (see Figure 2) where ϕ can be any value. Since all beacons nodes are wired and controlled by the central controller, it is possible to achieve phase synchronization and maintain identical angular speeds in all of them, which is a requirement for the functioning of the proposed localization principle. A rotating directional beam may be implemented by a directional antenna that is mechanically rotated as done in a radar system, or it could be generated by an electronically steerable smart antenna [6]. We assume that the transmission range is sufficient for the beacon signals to be received by all sensor nodes in the network. Consequently, each sensor node will receive periodic bursts of the four beacon signals, all with the same period of $360/\omega$ seconds. However, periodic bursts from different beacons will be staggered in time by amounts that depend on the location of the sensor node.

4. LOCALIZATION PRINCIPLE

The localization principle is based on a sensor node noting the times when it receives the different beacon signals, and evaluating its angular bearings and location with respect to the beacon nodes by triangulation. Denote the times at which an SN receives the beacons signals from BN-1, BN-2, BN-3, and BN-4 by t_1, t_2, t_3, and t_4, respectively. Since the sensor nodes have no time synchronization with the beacon nodes, the absolute values of these times bear no useful information. However, the time difference of arrivals can be

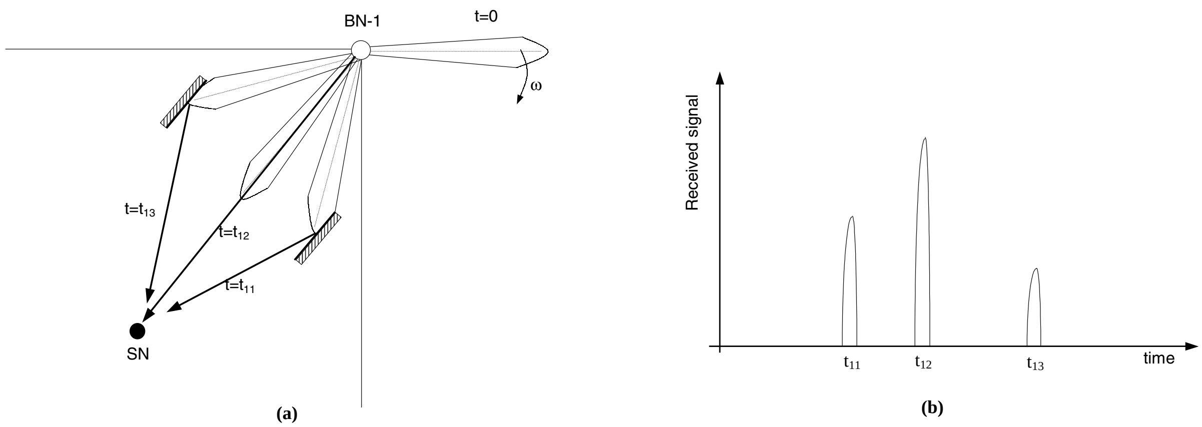

Figure 3: (a) An example of multipath reflections, and (b) corresponding signal received at SN from BN-1.

translated to angular values as follows:

$$\begin{aligned} \alpha &= \phi - \omega\tau_1 \\ \beta &= \phi - \omega\tau_2 \\ \delta &= \phi - \omega\tau_3 \end{aligned} \quad (1)$$

where $\tau_1 = t_2 - t_1$, $\tau_2 = t_3 - t_2$, and $\tau_3 = t_4 - t_3$. Any two angles chosen from α, β, and δ can then be used to solve for the location of the SN using trigonometry. For instance, using the values of α and β, we get:

$$\begin{aligned} \gamma &= arctan\left[\frac{cos(\beta) - Ssin(\alpha)}{Scos(\alpha) - sin(\beta)}\right] \\ Y &= L\frac{sin(\gamma - \alpha)}{sin(\alpha)} \end{aligned} \quad (2)$$

where

$$S = \frac{L\ sin(\beta)}{M\ sin(\alpha)}. \quad (3)$$

With these, the location of SN is given by:

$$\begin{aligned} X_p &= Y cos(\gamma) \\ Y_p &= M - Y sin(\gamma) \end{aligned} \quad (4)$$

Causes of errors: There are some concerns with the above location discovery technique, which we describe with the help of an illustration of a typical signal received by an SN from a beacon node, shown in Figure 3. The illustration depicts a scenario in which SN receives three multipath reflected signals from BN-1. The direct (line-of-sight) signal is received at t_{12} when the center of the rotating beam is aligned with the direction of SN from BN-1, whereas two reflected signals are received at t_{11} and t_{13} when the rotating beams are aligned with two reflecting objects in the network. This illustration indicates the following two concerns in determining the effectiveness of the proposed localization technique:

1. *Non-zero beam width of the directional beam:* a directional beam from a wireless antenna has a finite beam width, no matter how small, which will make it difficult for the SN to estimate the exact time at which the center of the directional beam passes through it. This could be a major concern for estimating the angles of arrival of the beacon signals and lead to an error in location discovery using this technique. We suggest that this error could be minimized if the SN determines the center of the burst by estimating the time at which the received signal strength reaches a maximum. The effectiveness of this scheme will obviously depend on the transmitting antenna pattern and the accuracy of signal strength measurement at the receiver. However, it is expected to be unaffected by propagation path losses and shadowing as long as the propagation conditions are static.

2. *Multiple signals generated by multipath reflections:* the idea of estimating the angular bearings with respect to beacon nodes using rotating directional beams relies on the fact that the propagation environment is ideal. However, as shown in Figure 3, reflections from surrounding objects can cause the beacon signal to be received at the SN even when the beam is not directed towards it. The number of reflections received, their times of arrival, and intensities will be randomly distributed and possibly different for each beacon. However, we maintain that if the directional antennas have a sufficiently small beam width, then the multipath reflected signals will create bursts of RF signals similar to the direct signal received at the SN. The SN can consider each burst that exceeds a certain threshold to be a possible direct signal and calculate its location based on all possible sets of bursts received from three specific beacon nodes. This will obviously lead to a number of solutions, of which only one is correct (the one that corresponds to the direct signals) and the others being errors caused by multipath reflections. The SN may determine the right solution by cross-checking with the set of solutions obtained from signals received from *another* set of beacon nodes. For instance, if an SN receives three random bursts from each of BN-1, BN-2, BN-3, and BN-4, then by using the bursts from BN-1, BN-2, and BN-3, it will have a solution set of $3^3 = 27$ locations. It will have another set of 27 locations when it uses the beacons received from BN-2,

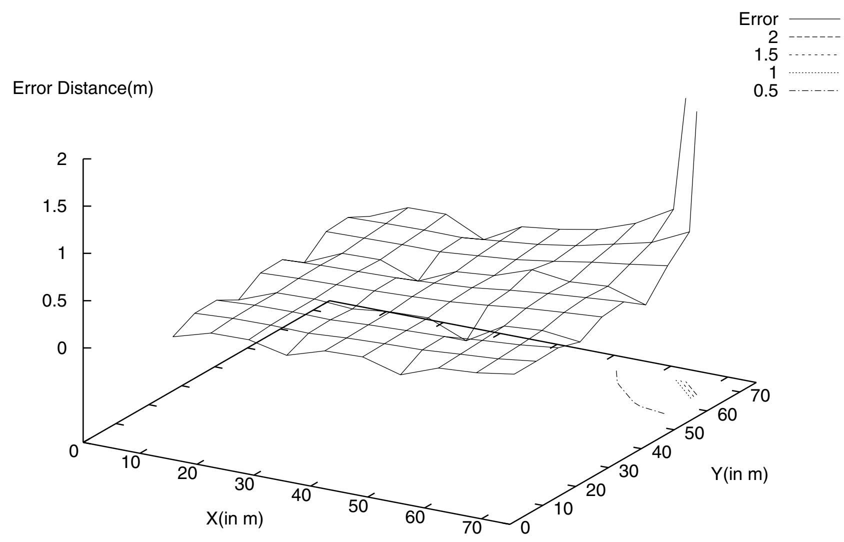

Figure 4: Distribution of error in location discovery using ideal directional transmissions from BN-1, BN-2, and BN-3, which are located at (0,75), (0,0), and (75,0), respectively.

BN-3, and BN-4. Assuming that the multipath reflections are random and the SN always receives the direct beams, the two sets of solutions are likely to have only one point in common - one that corresponds to the correct location. In case multiple solutions are common between the two sets, the SN can consider a third set of beacon nodes for finding another solution set for comparison, such as BN-1, BN-3, and BN-4. Since the localization principle requires the angular directions of any three beacon nodes, it is possible to obtain multiple sets of solutions as long as the number of beacon nodes exceeds three.

5. 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 L=M=75m. We evaluate the errors in location discovery using the proposed technique under different parameters.

We first obtain the best case error performance of the proposed localization technique by evaluating the errors in location estimates derived assuming "ideal" directional beams from the beacon nodes, i.e. assuming the beam width to be zero. The location errors obtained at sensor nodes located at different points in the network based on the beacons received from BN-1, BN-2, and BN-3, are depicted in Figure 4. In this figure, BN-1 is located in the corner that is farthest from the front (i.e. at coordinates (0,75)), with BN-2, BN-3, and BN-4 placed in the other corners counterclockwise from BN-1 (i.e., at (0,0), (75,0), and (75,75), respectively). These results basically indicate the effect of finite precision errors that are introduced during the conversion from time differences to angular separations and the subsequent trigonometric calculations. As expected, the errors increase as we move further away from the beacon nodes whose signals are used for the computation, i.e. diagonally away from BN-2. An analytical treatment of the uncertainty of the estimated location due to errors in the angular estimates is given in [12].

We next consider a more realistic antenna pattern having a finite beam width. Here, we assume that the directional antenna pattern is confined within a small angular span of θ degrees, as shown in Figure 5. We also assume that the characteristics of the transmitting antenna is such that the pattern peaks at the center. Hence, a receiver can determine when the center of the beam is pointing towards it by measuring the time at which the received signal reaches a maximum. However, we note that there is always a possibility of error in estimating the center point, which will be proportional to the beam width θ. To assess how the beam width affects the location estimation process, we evaluate the maximum possible error in the location estimate when the center of a beam is estimated to lie *anywhere* within the antenna beam received at SN. The maximum error will correspond to either the leading edges or the trailing edges of the rotating beams observed at SN. An exhaustive search of all combinations was performed to evaluate the maximum errors in the location estimates obtained at different points on the diagonal line from BN-2. These are plotted in Figure 6 for two different values of θ, along with the minimum error values (those obtained with $\theta = 0$ degrees) at different SN locations on the diagonal from BN-2. This diagonal represents the path along which the location error is found to increase monotonically with distance, caused by increasing finite precision errors as well as increasing values of the antenna beam widths. Results show that localization errors remain small for all locations that are within three-fourth of the diagonal distance from BN-2. However, when a sensor node is located beyond that, considerably high errors

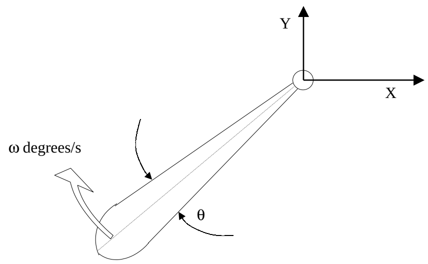

Figure 5: Directional antenna pattern.

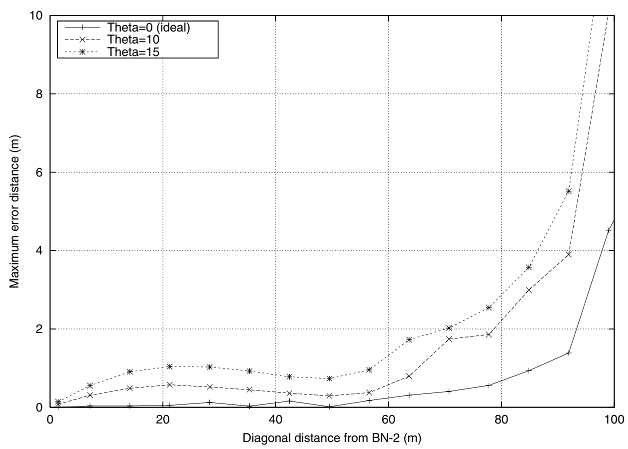

Figure 6: Error in location discovery versus diagonal distance from BN-2.

are possible. Hence, if an SN in a network of dimensions 75 m square computes its location based on the beacon signals received from the three *closest* beacon nodes, then the maximum error can be limited within 2 m, when the beam width of the beacons is 15 degrees or lower.

The above results were obtained assuming ideal propagation characteristics, i.e. when multipath reflections are not present. To evaluate the performance of the proposed localization technique in the presence of multiple reflections, we simulate a situation where the direct signal from each beacon node is accompanied by two reflected signals. We assume that the multipath reflected signals suffer reflection losses, causing their amplitudes to be randomly distributed. We model the amplitudes by a Rayleigh distributed random variable. The reflectors are assumed to be uniformly distributed throughout the network. Hence, we use a uniform random distribution for the time differences of reception of the reflected signals at the SN with respect to the direct signal, which is always assumed to be present. This results in 27 different location estimates at an SN from the signals received from a set of three beacon nodes, taking one signal burst from each beacon node to calculate each location. The solution sets using the beacon signals from BN-1, BN-2, and BN-3 in one case, and BN-2, BN-3, and BN-4 in the other, are plotted in Figure 7. The results show that the two sets have only one common solution, which matches

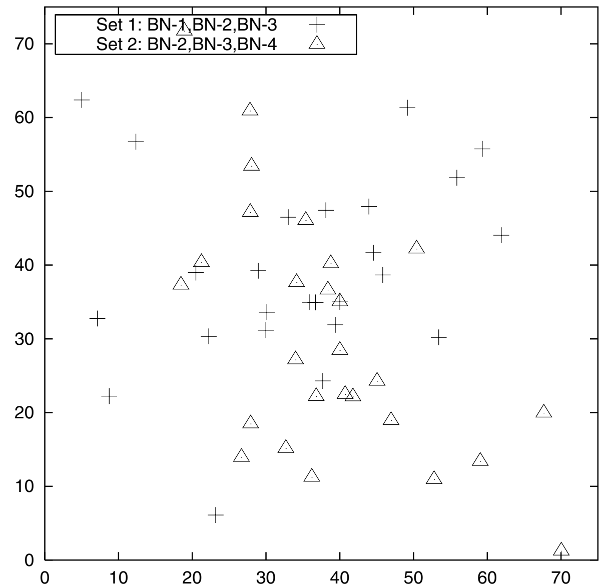

Figure 7: Location estimates obtained from beacon signals received from two different sets of beacon nodes at a sensor node located at (40,35).

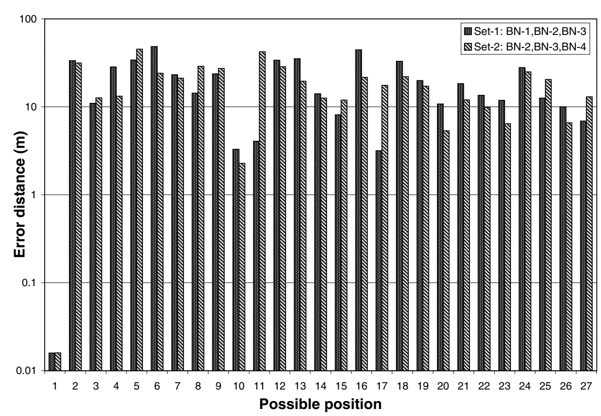

Figure 8: Errors in location discovery in the two sets depicted in Figure 7.

with the actual location of the SN. The error distances from the true location (40,35) to all the solutions from both sets are shown in Figure 8. This figure shows that all solutions have significant error margins, except the ones that give the correct location. This will be true whenever the multipath signals received from the same beacon node are distinguishable at the sensor node. Though we considered only two multipath reflections for each beacon signal, the same policy for determining the correct location estimate can be applied when more reflections are present. However, the amount of computations and the difficulty of resolving the multiplicity of the solutions increase exponentially with the number of multipath reflections received, which is a drawback of this scheme.

6. CONCLUSIONS

We present a technique by which sensor nodes equipped with low powered transceivers can determine their positions in a sensor network by obtaining angular bearings relative to a set of fixed beacon nodes. Each beacon node enables the direction estimation process by continuously transmitting a unique RF signal on a narrow directional beam that is rotated at a constant angular speed. At least three beacon nodes are required for the localization technique to work in an ideal case, with additional beacon nodes needed for resolving errors from multipath reflections. We present performance evaluations of the proposed scheme using results obtained from computer simulations.

The proposed localization scheme exhibits excellent accuracy and requires very little additional complexity at the sensor nodes. The main source of error is due to the beam width of the directional beacon signals. However, the location error has been found to be small for beam widths within 15 degrees. Since each sensor node performs its own location discovery from the received set of beacons, the performance of this method is not affected by the density or number of sensor nodes in the network. An additional advantage of the proposed scheme is that since it is based on angular estimates, its performance does not depend on the absolute dimensions of the network area. This will make the scheme useful for localization within a small area, whose dimensions might fall below the resolution of a GPS. The major cost of implementing the scheme lies with constructing the antennas for transmitting a rotating directional beam from the beacon nodes.

7. ACKNOWLEDGMENT

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