Distributed Direction-based Localization in Wireless Sensor Networks

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Abstract

Localization is an important issue in wireless sensor networks (WSNs). Several applications in WSNs can tolerate the diverse levels of accuracy in geographic information such as physical location. Besides, direction information is sufficient for numerous applications in WSNs. Thus, the paper develops a direction-based localization scheme, DLS, in which a node can be aware of its relative direction to a sink rather than its physical absolute location without requiring additional equipments. DLS not only takes the spatial locality property into account, but also exploits the anchor deployment strategy to benefit sensor direction learning. Additionally, DLS can more precisely position sensors around the boundaries with the aid of the dual-direction coordinate system. Experimental results validate the practicability of DLS and show that DLS is able to achieve well accurate direction estimates.

1. Introduction

A *wireless sensor network* (WSN) is a network within which a large number of sensor nodes are arbitrarily deployed. Currently, WSNs are applied in various applications, including military, agriculture, transportation, rescue missions, etc. [2]. Physical location, for such applications, is an important attribute which presents the pertinent information for reducing the number of packets flooding the network for route discovery, identifying the location of the tracking object, assisting in delivering packets to the fields of interest, and providing sensor deployment for mitigating coverage overlap.

Recently, localization has become an attractive research issue. The majority of the existing localization schemes are generally classified into *range-based* and *range-free*, depending on the use of absolute distance (range) or angle estimates. (GPS) is a wide-area system, but it is extremely expensive when applied to certain applications [5]. Other solutions to sensor localization, including RSSI, AoA, and ToA/TDoA are unsuitable for WSNs owing to hardware costs and energy constraints, in addition to environmental conditions such as fading, shadowing, and obstacles [1, 4]. The range-free localization scheme, which requires a small percentage of location-aware nodes, has been developed for sensor positioning [3]. Much previous work confirm that in comparison with the range-based scheme, the range-free one is most likely to suffice for sensor positioning due to its cost-effectiveness [3].

Most of existing localization schemes focus on the precise sensor location. However, such information is not essential for some applications of WSNs, and in terms of efficiency, acquiring the direction of a sensor node requires less effort than identifying its physical location. In WSNs, several applications can tolerate diverse levels of imprecision in location information, depending on their requirements [6]. For example, the fire detection can be realized with the approximate geographic information (e.g., direction and distance), which identifies the area of the event via the relatively coarse-grained coordinates. The approximate information is obviously sufficient for disaster detection and tracking. We, thus, reasonably conclude that the approximate geographic information such as direction of sensor nodes accompanied with hop count information is favorable for numerous applications.

This paper presents a novel distributed direction-based localization scheme, DLS, for a sensor to estimate its relative direction to a sink without GPS-support. Node direction is represented in the form of the *Gray code*. DLS is mainly motivated by the idea called *spatial locality property*. Additionally, DLS has two major components, *anchor deployment strategy* and *dual-direction coordinate system*, to assist in improving estimation accuracy. Overall, DLS has three significant advantages: (1) DLS achieves well ac-

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curate direction estimations. (2) DLS is cost-effective due to lack of additional facilities (e.g., GPS receiver). (3) DLS does not require complicated computation for sensor direction estimating.

The rest of this paper is organized as follows. Section 2 formulates the localization problem, and mentions the basic concept of DLS. Section 3 then provides a greedy localization method. Next, a novel direction-based localization scheme, DLS, is described in detail in Section 4. Meanwhile, the experimental results are given in Section 5. Finally, Section 6 concludes the paper and presents future research directions

2. Preliminaries

This section first describes the localization problem and assumptions of the system model, and then gives the basic idea of the proposed solution.

2.1. Problem Description

Basically, localization in WSNs can be regarded as a sensor coordinate estimating problem. Unlike much research on sensor positioning, we attempt to estimate sensor direction instead of the physical location (i.e., 2-D coordinate). Such direction represents the geographic information for a node relative to the sink. A node without the priori direction, called the *unknown node*, estimates its direction based on packets received.

Consider a square network, in which the sink is placed at the center. The previous research mentions that placing the location-known nodes effectively enables accurate location estimations [3]. We also place a small fraction of nodes, called *anchors*, with priori knowledge of directions either via digital compasses or manual presetting at the radio range from the sink on each boundary. The radio ranges of the sink, anchors, and unknown nodes are assumed to be identical.

Suppose the network is virtually partitioned into numerous distinct regions. Each region is labelled as a unique direction code. Let the number of directions $N_{dir} = 2^n$, where n is a positive integer. All direction codes represented in the form of the Gray code are arranged counterclockwise and numbered in order. By means of the Gray code representation, a node can easily identify whether a received packet comes from one of its adjacent regions.

In the paper, we assume the perfect spherical radio propagation, and the receiver is able to measure the accurate signal strength in spite of attenuation of radio signal. Moreover, the connected network, within which each node has at least one neighbor, is required in DLS because the isolated node is unable to receive any packet during packet dissemination.

2.2. Basic Concept

DLS is a one-step process and performed after sensor deployment. In DLS, packet dissemination is the main operation that the packet is originated from the sink. During packet dissemination, a node will receive many packets, and determine its direction according to these messages. An unknown node is most likely to obtain the correct direction if its neighbors have the accurate estimates. Additionally, because the packet is sent from the sink, exact direction estimate at the node closed to the sink obviously achieves high accuracy in direction estimating.

Figure. 1 depicts the basic concept of DLS with $N_{dir} = 4$. The sink is located at the center, and all unknown nodes are arbitrarily deployed. Each region is represented by its own direction code, counterclockwise indexed by 00, 01, 11, and 10. All anchors lie on each boundary, which is defined as the virtual borderline between two distinct regions, whose direction codes differ only in one bit.

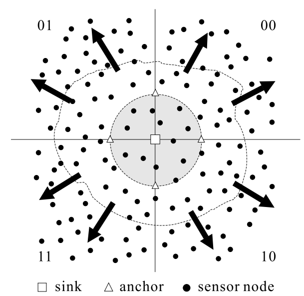

Figure 1. Basic concept of DLS.

After sensor deployment, the sink originates a *Locating_Request* packet (LREQ) to its neighbors. When receiving an LREQ packet, a node waits for a period of time to receive more LREQ packets. Once the waiting time expires, the node immediately determines its direction according to the information involved in all LREQ packets received. In case the direction changes, the node issues an LREQ packet, comprising its direction and hops from the sink to itself outward. Obviously, DLS enables nodes to correct their estimates with the aid of more beneficial LREQ packets. Such procedure runs iteratively and terminates when the directions of all unknown nodes are determined and never changed.

3. Greedy Localization Scheme (GLS)

Since the packets a node receives significantly result in different levels of error in direction, we, thus, made numerous experiments to observe the impacts of the packets received at a node. Figure. 2 shows the result, in which each neighbor of a node locates in one of *same*, *adjacent*, and

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other directions. The network is a $500m \times 500m$ square region with N_{dir}=4. For a node located in direction 00, the packets from directions 00 and 11 are respectively notated as same and other, whereas the packet from either direction 01 or 10 is represented by adjacent.

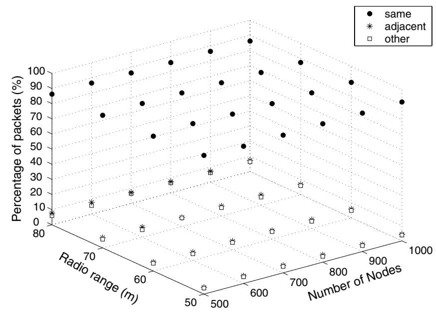

Figure 2. Experimental results for the impacts of the packets at a node.

We formulate the following spatial locality property based on the above experimental results.

Property 1 *Spatial locality describes the phenomenon that most of the packets received at a node are likely to be derived from its neighbors located in the same direction.* □

Inspired by the spatial locality property, we design a greedy scheme named GLS for sensor direction estimating. The central idea of GLS is that each unknown node estimates its direction only according to the received LREQ packets. Thus, each node has to maintain a neighbor table called NRB_i, which is the set of entries composed of node id, direction code, and hops corresponding to all neighbors of node i.

Improving the estimated accuracies of nodes closed to the sink is likely to benefit node localization. Thus, in GLS, we set all anchors within the radio range of the sink. The numbers of anchors and directions are identical. Anchors are evenly distributed in each direction region.

Each node in GLS has three states: *Idle* state, *Learning* state, and *Sending* state. All nodes are initially in the *Idle* states. When a node, i, receives an LREQ packet from node j, with direction code c and hops k, it enters the *Leanring* state for direction estimating. Node i also updates the direction code to c if node j exists in NBR_i. Otherwise, node i adds a tuple (j, c, k) to NBR_i.

Node i then calculates the number of entries for each direction, and sets its estimate as the direction with the maximum value among all directions. The method, in which a node determines its direction by only one received LREQ packet is called the *one-message decision technique*. Subsequently, node i enters the *Sending* state if its direction changes, while returns to the *Idle* state in case its direction remains unchanged. Once entering the *Sending* state, node i immediately sends an LREQ packet, comprising its direction estimate to all of its neighbors, and then enters the *Idle* state.

4. Direction-based Localization Scheme (DLS)

GLS, a straightforward and cost-effective method, is simple and easy to implement, though some problems may cause estimation inaccuracy during packet dissemination. This work, thus, refines GLS and then proposes an elegant direction-based localization scheme, DLS, for making all unknown nodes aware of their directions in a fully distributed manner.

4.1. Anchor Deployment Strategy

The interesting and helpful idea of the anchor placement in GLS has inspired this investigation to design a refined localization scheme. To reduce the estimated errors during packet propagation, we develop a novel technique, anchor deployment strategy, in which all anchors are located on each boundary with the characteristic of manual placement.

Figure. 3 shows an example, in which N_{dir} is 8. We focus on two regions whose direction codes are 000 and 001. The direction codes of anchors A_1, A_2, and A_3 are 100, 000, and 001, respectively. A node with which the sink can directly communicate obviously locates within one of areas I, II, III, and IV. Due to the assumption that the sink and all anchors have the same radio range, a node within area I, II, III, or IV is able to receive the packets originating from at least two anchors.

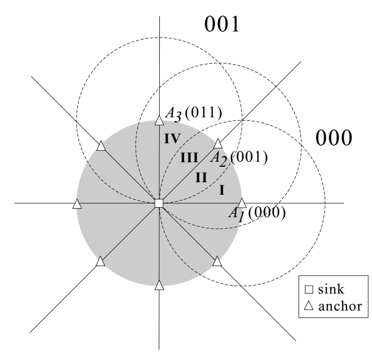

Figure 3. Anchor deployment strategy. All nodes in the shaded region are neighbors of the sink.

The unknown node within the shaded region determines its direction by means of the measurements of RSSI corre-

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sponding to the LREQ packets from all anchors within its radio range. Here, we give the following property for code assignment of a node.

Property 2 *If c_1 and c_2 are the direction codes of the two closest anchors to node i, and the anchor with code c_2 locates in the counterclockwise direction of that with code c_1, then the direction code of node i is assigned as c_1.* □

Based on Property 2, unknown nodes within areas I, II, III, and IV, consequently identify their direction codes as 000, 000, 001, and 001, respectively.

4.2. Dual-direction Coordinate System

The anchor deployment strategy significantly guarantees accurate estimates for nodes near the sink, but erroneous estimates may frequently occur for the nodes close to boundaries, especially for the scenario of high-density sensor deployment around boundaries. Thus, we introduce an additional direction code to efficiently identify the node within the *boundary error region*. The boundary error region is the area, within which a node is able to receive packets from adjacent regions.

To clearly distinguish between the two direction codes, we regard the direction code mentioned before as the *primary direction code* to indicates the node direction, while the additional code is called the *auxiliary direction code*. The direction codes respectively form the *primary-direction* and *auxiliary-direction* coordinate systems. The auxiliary-direction coordinate system originates from the rotation with angle $\alpha = \frac{\pi}{N_{dir}}$ of the primary-direction one. The approach to auxiliary-direction code assignment resembles the generation of the primary-direction code. As shown in Figure. 4, a system involving the primary-direction and auxiliary-direction coordinate systems is named the *dual-direction coordinate system*. Such coding system is demonstrated in Figure. 5.

With the aid of the auxiliary direction code, a node within the boundary error region is able to be identified in the vicinity of the exact boundary although obtaining the incorrect estimate. Overall, the main goal of the dual-direction coordinate system is to improve DLS to identify the realistic locations of the unknown nodes with the same direction code, but around the different boundaries. The system is probably beneficial for several applications such as battlefields and disaster areas, which require the high accuracy in geographic information.

4.3. DLS Operation

The one-message decision technique in GLS probably leads to faulty estimations especially in case involving numerous neighbors located near the node. Successively received LREQ packets seem to be considered in direction estimation since meaningful information (such as, direction codes or hops) may be carried in these packets. In DLS, we take a reasonable duration into account to gather more LREQ packets for the enhancement of direction estimation. Thus, besides of the states in GLS, DLS requires a new state, *Waiting* state, to wait for a period of time for collecting more packets once a node receives an LREQ packet.

Figure. 6 shows the state transition diagram in DLS. In DLS, when receiving an LREQ packet, a node in the *Idle* state enters the *Waiting* state. Upon the expiration of the waiting time, the node enters the *Learning* state. In the *Learning* state, a node sets its direction as the direction with the maximum value among all directions. Once determining the direction, a node enters either the *Sending* or the *Idle*

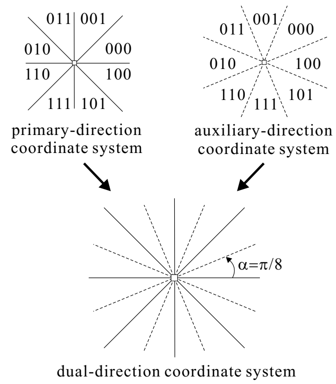

Figure 4. Dual-direction coordinate system with 8 directions.

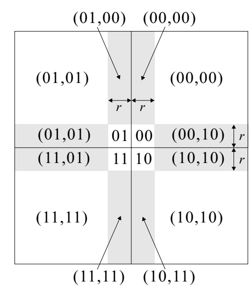

Figure 5. Coding system with 4 directions, where r is the radio range of a sensor node. All unknown nodes in the boundary error regions (namely, shaded regions) have two direction codes represented in the form (primary-direction code, auxiliary-direction code).

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state according to the variation of its direction. The main events resulting in state transitions in both the *Learning* and the *Sending* states are similar to those in GLS.

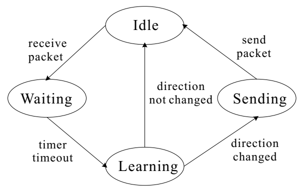

Figure 6. State transition diagram in DLS.

5. Performance Evaluations

In the paper, we conduct numerous simulations to evaluate the proposed localization schemes in terms of different node numbers and radio ranges.

5.1. Experimental Setup

Simulations are performed on a network, which is a square region sized $500m \times 500m$. Various numbers of directions such as 4, 8, and 16 are considered. The sink is placed at the center of the network. Meanwhile, all unknown nodes are randomly scattered in the network with a uniform distribution. Experiments differs from node numbers with 500, 600, 700, 800, 900, and 1000. All nodes have the same radio range, ranging from $50m$ to $80m$ with a step of $10m$. The results are averaged over 30 simulation runs. The metrics evaluated in the simulation are the radio range and number of nodes.

5.2. Simulation Results

To verify the efficiency of different anchor deployment strategies, we first observe the results for the scenario where anchors are randomly deployed throughout the whole network and located only within the radio range of the sink. Figures. 7 and 8 respectively illustrate the estimated accuracies for different numbers of nodes and radio ranges. Compared with the manner of random deployment, GLS obviously produces more accurate estimates because the unknown nodes within the radio range of the sink always obtain the correct directions regardless of the number of nodes and radio range. Figures. 7 and 8 also clearly demonstrates the effectiveness of the anchor deployment method, in which all anchors are placed near the sink.

In Figure. 9, totally 438 nodes are identified the accurate directions. Namely, DLS in this case achieves an estimate accuracy of approximately 88%.

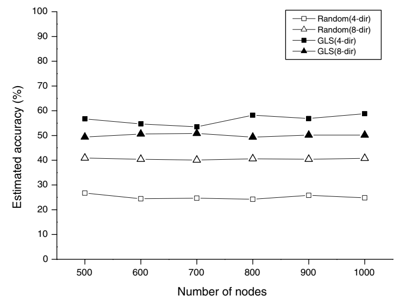

Figure 7. Estimated accuracy vs. number of nodes.

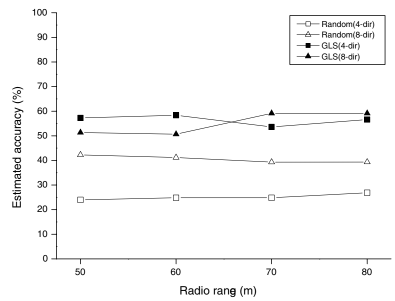

Figure 8. Estimated accuracy vs. radio range.

Figures. 10 and 11 show the simulation results of the estimated accuracy with different node numbers and radio ranges for various N_{dir}. The estimated accuracies generated by DLS are better than those obtained by GLS. For N_{dir}=4, 8, and 16, approximately 83%, 68%, and 57% nodes suffer no less in accuracy, respectively. DLS outperforms GLS for N_{dir}=4 about 36%, for N_{dir}=8 about 28%, and for N_{dir}=16 about 22%. Because of the usage of the anchor deployment strategy, all neighbors of the sink can exactly determine their directions, and further enhance the performance. A notable trend is that the estimated accuracies degrade in both GLS and DLS with increasing N_{dir} owing to a significant increase in the size of the boundary region.

In Figure. 10, GLS causes the marked variation in accuracy with the limited range between 30% and 50%. The result is probably due to the approach that anchors are randomly deployed. Unknown nodes within the region without placing any anchor most likely generate erroneous estimates because our anchor deployment strategy becomes invalid. In DLS, better estimated accuracy is obtained with larger

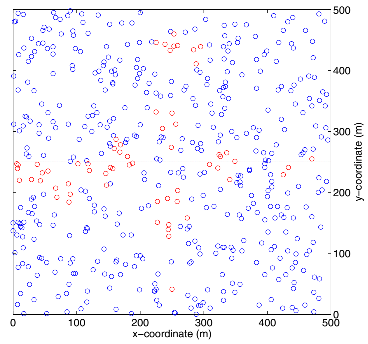

Figure 9. Example of the estimated result for 500 nodes scattered in the network with 4 directions. The blue and red nodes represent the accurate and erroneous estimates, respectively.

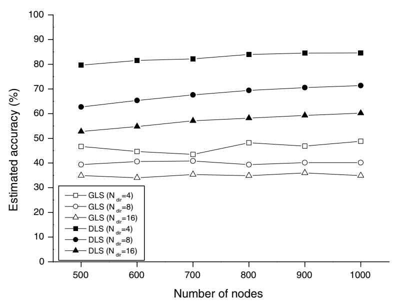

Figure 10. Estimated accuracy vs. number of nodes for GLS and DLS.

number of nodes since more node deployment leads to more accurate and faulty nodes. Besides, all nodes are randomly placed in each direction, and consequently the estimated accuracy does not vary significantly.

Figure. 11 focuses on the accuracy in terms of different radio ranges. Intuitively, the number of packets received at a node increases with increasing radio range. Such packets may enhance the estimate in accordance with the information attached. Therefore, the total estimated accuracies also increase with large radio ranges.

6. Conclusions

To our best knowledge, the paper is the first investigation to the localization problem based on sensor direction. DLS not only considers the spatial locality property,

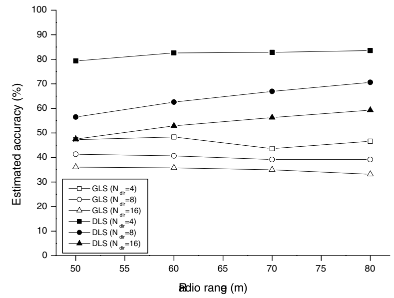

Figure 11. Estimated accuracy vs. radio range for GLS and DLS.

but also invokes the anchor deployment strategy for direction estimating. Experimental results demonstrate that DLS achieves reasonably accurate direction estimates. Future studies can investigate solutions such as the Bayesian inference method and efficient anchor deployment techniques for improving accuracy of estimates. Moreover, a novel addressing scheme is being developed based on this research, which will be used to design an efficient routing protocol for WSNs.

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