Selective Iterative Multilateration for Hop Count-Based Localization in Wireless Sensor Networks

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Abstract

Iterative multilateration techniques have been proposed to improve position estimates in localization schemes for sensor networks. However, these techniques are hampered by problems such as propagation of errors, which results in inferior estimates, and high communication overheads leading to poor scalability. In view of this, a novel Selective Iterative Multilateration (SIM) algorithm is described in this paper to improve the accuracy of location estimation in hop count-based localization schemes without incurring unnecessary overhead costs. New anchor nodes are selected judiciously such that their initial position estimates are sufficiently accurate. Also, such new anchor nodes are prevented from appearing in the same regions so that unnecessary overhead is kept to a minimum.

1. Introduction

Location information is a vital aspect of many wireless sensor network (WSN) applications like environmental monitoring, target tracking and inventory control. In these applications, it is often necessary to orientate the sensor nodes with respect to a global coordinate system so that geographically meaningful data can be reported. This global coordinate system is defined by anchor nodes whose global positions are known priori.

In some environments, deploying more than a handful of anchors is not always feasible due to high deployment costs. Equipping nodes with GPS may be too costly, or GPS is not available (e.g. underwater, indoor environments, etc.), and anchors have to be manually calibrated, thus incurring high deployment costs. Hence, the number of anchors is preferred to be kept as low as possible.

However, localization schemes often result in poor estimation when the number of anchors is low. While refinement techniques based on iterative multilateration [12] have been proposed, they introduce a new set of problems, including poor scalability, error propagation and poor convergence.

In view of these problems, we propose a simple yet novel Selective Iterative Multilateration (SIM) algorithm that allows any hop count-based localization scheme, even in networks with a low number of anchors, to achieve more accurate location estimation, without yielding to the adverse effects of error propagation. At the same time, SIM keeps communication overheads low and thus is a practical solution even for large networks.

The structure of the paper is organized as follows. Section II reviews background and related work. Section III presents the Selective Iterative Multilateration (SIM) algorithm. Section IV presents and analyzes the simulation results, and finally, Section V concludes the paper and discusses possible future work.

2. Background and Related Work

A WSN is a group of wireless nodes or embedded devices that sense, acquire and sometimes perform in-network data analysis. Sensor nodes are small in size, have limited power and are inexpensive. Many WSN applications have been proposed, such as habitat monitoring, battlefield surveillance, environmental monitoring, smart spaces, inventory control, target tracking and so forth.

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Many sensor network applications require location information in order to report data that is geographically meaningful. Location information is also essential for middleware services such as data aggregation0 and geographic routing (e.g. GPSR[2] and LAR[3]). In general, localization schemes operate by estimating either the distances from each node to the anchors, or the angles from node to node. A computation methodology, such as triangulation, is then employed to compute an estimate for the node's location.

Localization schemes can be categorized into range-based (fine-grained) and range-free (coarse-grained). In range-based localization, specialized hardware is used to obtain point-to-point distance estimates or angle estimates to compute location. In range-free localization, no such hardware is required and instead, only connectivity information is utilized.

Range-based localization protocols use a variety of techniques, including Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) and Received Signal Strength Indicator (RSSI).

In ToA and TDoA technologies, signal propagation time is used to extract range information. An example of a localization scheme that employs TDoA is AHLos[12][13]. Systems using such technologies require expensive and energy-consuming electronics that may not be suitable for low-power sensor network devices.

AoA techniques allow nodes to estimate relative angles between neighbors for location computation. Niculescu and Nath proposed a scheme that utilizes AoA technology[5]. Again, AoA demands additional hardware that may not be cost effective for large scale sensor networks.

RSSI technology has been proposed in schemes such as RADAR[4] and DV-Distance[5], where either theoretical or empirical models are used to translate signal strength into distance estimates. Such models are often impeded by physical-layer problems inherent in RF systems, such as erratic signal propagation, multi-path fading and background interference. These problems make the use of RSSI technology unreliable for localization in sensor networks.

The impracticality, especially in terms of monetary and energy costs, associated with using range-based localization schemes in sensor networks, has made range-free schemes a much more viable alternative. This is especially so because many sensor network applications do not demand a very high degree of precision in its localization requirements. Range-free localization schemes rely only on connectivity information among nodes to estimate positions, rather than rely on expensive hardware.

Range-free localization schemes can be further divided into subcategories. In proximity-based protocols like the centroid scheme[10] and Approximate Point In Triangulation (APIT)[11], a reasonable location estimate of a sensor node can be deduced if it falls within the transmission range of enough anchor. For hopcount based protocols such as DV-Hop[5][6], Amorphous[7] and Density-aware Hop count Localization (DHL)[8][9], the location of a sensor node is estimated by keeping track of the number of hops to anchors such that a node need not be in direct transmission range of the anchors. Two of the hopcount-based localization schemes, namely DV-Hop and DHL, will be used to demonstrate the effectiveness of SIM. These two schemes are described in further detail below.

2.1 DV-Hop

DV-Hop[5][6] adopts a distance vector mechanism for localization. Each anchor floods the entire network with its global position. While this information is being propagated, each node keeps track of the minimum number of hops to each anchor. Through this distance vector approach, all nodes (including other anchors) obtain the least number of hops to every anchor.

This hop count is translated into a distance metric by multiplying the number of hops with the average hop distance. This average hop distance (or distance per hop) is estimated using the anchor-to-anchor paths. Once a node acquires distance estimates to three or more anchors, triangulation (or multilateration) is used to compute a location estimate.

2.2 Density-aware Hopcount Localization (DHL)

A drawback of DV-Hop is that localization errors escalate when network topologies are highly irregular, i.e. when the actual distance per hop varies greatly among pairs of nodes. DHL[8][9] has been proposed to address this shortcoming, in which localization accuracy improves over DV-Hop, especially when node distribution is non-uniform.

Instead of simply incrementing the hop count along the path from anchor to node, DHL adds up the range ratios along the path. The range ratio is the effective percentage of a transmission range covered by a single hop, and is a function of the number of neighbors around a node. The distance estimate from anchor to node is simply obtained by multiplying the sum of range ratios and the transmission range. Similar to DV-Hop, DHL uses triangulation to obtain the location estimate.

2.3 Related Work

The initial estimates in hopcount-based localization can be fine-tuned using an additional refinement technique known as iterative multilateration[12]. In iterative multilateration, nodes that have successfully estimated their positions can act as new anchors. These new anchor nodes then propagate their own estimated location.

In the iterative multilateration technique of the Ad Hoc Localization System[12][13] (AHLoS), each node calculates an initial estimate of its location based on geometric constraints, and updates the estimate iteratively. However, this iterative technique can be used only when the proportion of anchors is high. Moreover, errors introduced by nodes can easily be propagated throughout the network.

Saverese et. al[16] proposed an iterative refinement procedure, in which each node's initial position is gradually adjusted by using the measured ranges between its neighboring nodes. However, the technique imposes a large amount of computational overhead on the network, and assumes that nodes are equipped with RSSI capability.

Iterative multilateration is also utilized in other localization algorithms[14][15], but too many iterations in these algorithms inhibit scalability. In general, common problems that exist in many existing iterative multilateration techniques include: propagation of large errors, excessive overhead, lack of scalability and the inability to converge. These problems have led to a need to find a simple yet effective iterative multilateration technique that can both improve location estimation and prevent excessive communications overhead.

3. Selective Iterative Multilateration

3.1 Overview

Nagpal et. al.[7] analyzed theoretically the expected error of hop count-based localization, and have concluded that the error of a node does indeed depend on the position of the node relative to the anchors. It is also highly desirable for anchors to be placed along the perimeter of the network for higher accuracy.

Performance results for both DV-Hop[5][6] and DHL[8][9] have shown that large errors often gather around the edges of the network (see Figure 1) when anchors are placed at the four corners of the terrain. Localization accuracy is often highest in the center of the network, i.e. the centroid position bounded by the anchor nodes. Based on this observation, nodes in the center of the network are good candidates for acting as new anchors. However, too many new anchors in a certain area may be redundant and not cost effective, because of excessive overhead. Hence, it is more appropriate to selectively introduce new anchors so that such redundancy is reduced.

Thus, the main objectives of iterative multilateration are: (1) to select new anchors that have a high probability of having a good initial estimate, (2) to spread out the new anchors such that redundancy is reduced, and most importantly (3) to obtain a better estimation throughout the network using the new anchors. These objectives are what the SIM algorithm will set out to achieve.

3.2 Main Algorithm

After the initial flooding stage of the hop count localization algorithm, each node performs triangulation to obtain an initial location estimate. Selective Iterative Multilateration (SIM) then proceeds as follows.

First, we let the nodes that "think" they are near the network center broadcast a message to surrounding nodes. We define a candidate node as a node that finds its location estimate within one hop from the centroid of the anchors. The centroid position of N number of anchors is given by the following formula:

$$(X_{Centroid}, Y_{Centroid}) = \left(\frac{X_1 + ... + X_N}{N}, \frac{Y_1 + ... + Y_N}{N} \right)$$

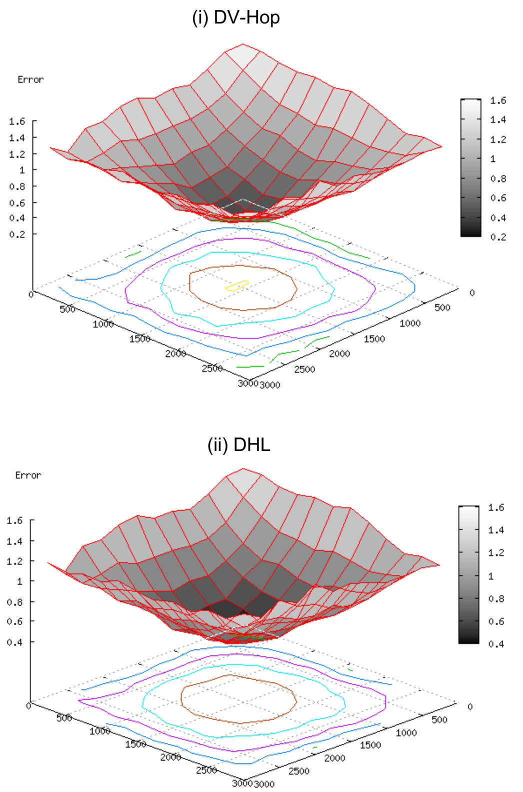

Figure 1. Geographic error distribution for DV-Hop and DHL

Hence, a node with an initial estimate (X_{est}, Y_{est}) is a candidate node if and only if the following condition is satisfied:

$$\sqrt{(X_{est} - X_{Centroid})^2 + (Y_{est} - Y_{Centroid})^2} \leq R$$

where R is the transmission range of each node.

During the refinement stage, each candidate node starts to broadcast a CENTER message to its immediate neighbors, indicating that its estimate lies within one hop from the centroid of the anchor nodes. At the same time, each candidate node keeps a counter, $CENTER_{rcvd}$, of the number of CENTER messages it receives from its neighbors.

Next, we compute a metric for each node that is used as a basis for selecting the new anchor. Each node is assumed to know its number of neighbors. Each candidate node computes the proportion P of neighbors whose estimates also lie within one hop from the centroid of the anchors. However, to minimize the occurrence of more than one node having the same value of P, we append a small random number r to the value of P, as follows:

$$P = \frac{CENTER_{rcvd}}{N_{ngbr}} + r$$

In other words, if there is more than one candidate node with the highest P value, the above has an effect of choosing one of these nodes randomly as the new anchor.

Finally, we propagate a node's P value around the network center, in order to establish a single node as the new anchor. Each candidate node broadcasts a tuple consisting of {*ID*(*Candidate Node*), *P*}. Every node stores and broadcasts the highest known P value and its corresponding candidate node. This propagation can be restricted to a certain hop limit so that unnecessary communication overhead is reduced. After a stipulated time of inactivity, if a candidate node realizes that no other node has a higher P value, it declares itself as the new anchor, and begins to flood the network with its estimated position.

It is possible to easily extend the above algorithm to accommodate more than one elected anchor. This may be done when there is more than one area in the network with the lowest errors. This happens when there are more anchors. However, for simplicity and ease of interpretation of results, the simulations as described in the next section involve only one new elected anchor.

4. Simulation Results

4.1 Experimental Setup

To evaluate and analyze the performance of SIM, we conducted simulations using GloMoSim[17], a simulation environment for network systems. Three basic scenarios were tested. Scenarios A and B describe a non-uniform network, i.e. the node density varies widely throughout the network. The nodes are randomly placed in the network, but are constrained by a ratio of average node densities in nine different regions of equal area as depicted in Figure 2. For example, the number of nodes in the top left region of Scenario A would be a third that of the center region. Scenario A describes a network topology where the node distribution is skewed towards the center, and scenario B describes a topology where the node distribution is sparse in the center. Scenario C uses a network where the nodes are randomly placed with a uniform distribution.

Scenarios A and B were simulated using 1000 nodes with an average number of neighbors (henceforth referred to as connectivity) of 23.4 and 21.0 respectively. For Scenario A, the connectivity in the most sparse and dense regions is 12 and 37 respectively. As for Scenario B, the corresponding connectivity values are 8 and 27. Scenario C was simulated using a range of connectivity – from 8 through 24, in increments of 2. In all scenarios, an anchor is placed at each of the four corners of the square terrain. Two hop count-based localization schemes, namely DV-Hop[5][6] and DHL[8], are used to gauge the effectiveness of SIM.

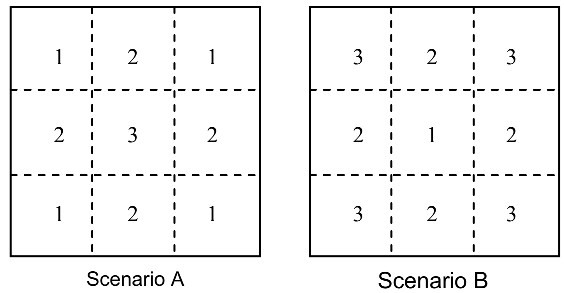

Figure 2. Ratio of node densities for Scenarios A and B

4.2 Position Accuracy Comparison

First, we measure the position accuracy of SIM when it is employed in hop count-based localization schemes. Figure 3 illustrates the position accuracy when SIM is applied to DV-Hop and DHL in the three different scenarios. In this case, 1000 nodes are deployed in all three scenarios. The error δ_P of a node, with actual position (X, Y) and estimated position (x, y) and transmission range R, is computed using:

$$\delta_P = \frac{\sqrt{(X-x)^2 + (Y-y)^2}}{R} \times 100\%$$

Figure 3 describes the percentage of nodes in the network with errors at or below the corresponding cumulative error amount. In the case of Scenario A, where node density is higher in the center, SIM improves both DV-Hop and DHL only slightly. However, for Scenario B, where the nodes are sparser in the center, SIM provides a much better improvement for both DV-Hop and DHL. This is because there is a higher concentration of nodes at the corners of the network in this scenario than in Scenario A. Hence, there are more nodes in Scenario B that experience higher error (see Figure 1) and could benefit more from SIM than in the case of Scenario A. For Scenario C, the improvement gained from SIM is between that for Scenario A and B. Hence, it could be inferred that although SIM enhances the

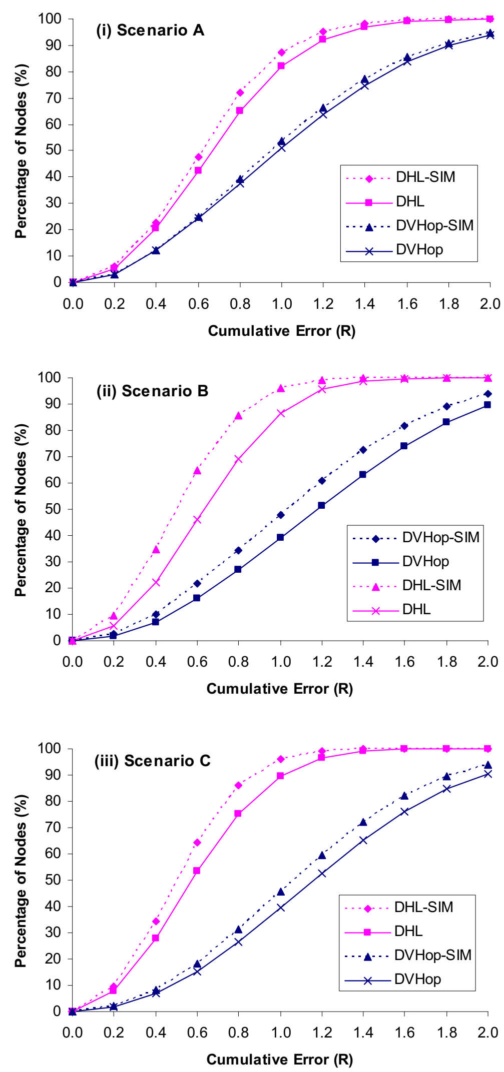

Figure 3. Cumulative position error for all scenarios

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localization accuracy of networks with various node distribution, the gains in accuracy are highest when the node density is higher at the corners than at the center of the network.

SIM improves the localization accuracy of DV-Hop and DHL in Scenario A by an average of 3.1% and 7.8% respectively. For Scenario B, SIM improves the accuracy of DV-Hop and DHL by an average of 11.4% and 20.1% respectively.

Next, we extended Scenario C by varying the connectivity of the network and computing the position error (see Figure 4). SIM improves the accuracy of DV-Hop by 7.4% and DHL by 13.0% on average. SIM makes an improvement for every single trial (30 trials for each node density). Hence, it can be seen that SIM performs consistently well in terms of accuracy improvement in both uniform and non-uniform networks, fulfilling its main objective of providing better accuracy to hop count-based localization schemes.

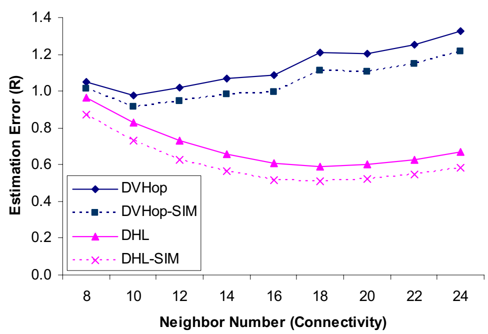

Figure 4. Estimation error with varying connectivity

4.3 Elected New Anchor Node Accuracy

Next, we shall study the accuracy of the elected anchor's estimated position. Figure 5 shows the error of the elected anchor node as compared to the average error (before refinement) of all nodes in the network under Scenario C with varying connectivity. It is clear that the elected anchor node has an error which is significantly lower (by more than 35%) than all the other nodes in the network. In other words, the new anchor is well elected such that its low error does not adversely affect the accuracy of the entire network when its estimate is propagated.

Figure 5 also compares the error of the elected node when it is in the center of the network (i.e. within one hop from the centroid of the anchors) and when it is outside of the center. As expected, the latter results in a higher estimation error for the elected node, as these anchor nodes are actually situated outside the center but have estimated positions inside the center. However, it has been shown in Figure 6 (Scenario C) that as connectivity increases, the probability of an elected anchor landing inside the center increases to about 80%. Furthermore, whether the elected node lands inside or outside of the center, its position error is almost always far lower than the average error of all nodes.

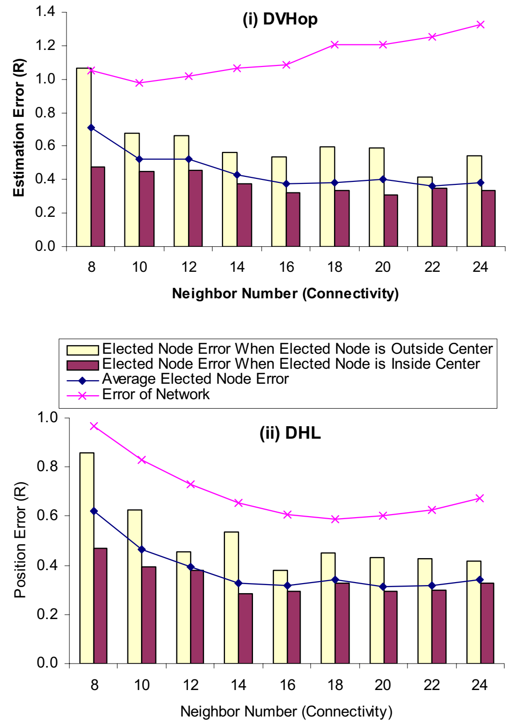

Figure 5. Error of elected anchor compared with all other nodes for (i) DV-Hop and (ii) DHL

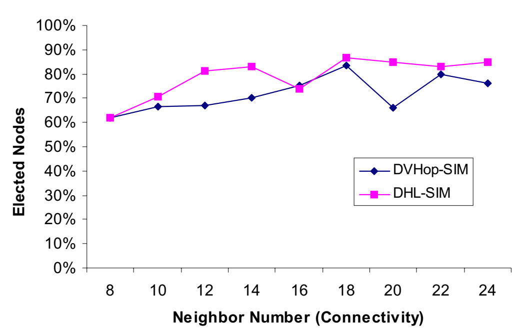

Figure 6. Percentage of elected anchors in center of network

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It can be concluded that the elected node has a far lower position error than the average node in the network. Thus, the problem of propagation of large errors resulting from iterative multilateration is averted in SIM.

4.4 Overhead Comparison

In other iterative multilateration techniques (e.g. in [12][14][15]), no consideration has been given to the fact that too many new anchor nodes in a particular region may be excessive without producing justifiable gains in accuracy. In SIM, only one new anchor node is elected within a region bounded by anchor nodes. Hence, much unnecessary overhead is reduced. Figure 7 illustrates the additional packet overhead required by SIM for Scenario C, which averages about a reasonable 27% over the original hop count-based schemes. 25% of this packet overhead is attributed to the propagation of the elected node's estimated location. This figure is similar to a scenario where an extra anchor node is added to the network. Control overhead for electing the new anchor makes up only about 2% of the total packet overhead. Compared to other iterative multilateration solutions which appoint new anchors indiscriminately, the additional communication overhead in SIM is small. Hence, SIM can easily scale to large networks without depleting the valuable energy resources of the sensor nodes.

5. Conclusions and Future Work

In this paper, we have described a Selective Iterative Multilateration (SIM) method that is simple to implement, yet enhances position estimates in hop count-based localization schemes without excessive communications overhead. Simulations have shown that SIM is able to consistently improve localization accuracy in both DV-Hop and DHL while keeping communications overhead low. Furthermore, nodes elected to be new anchors have low position errors, hence preventing the propagation of large errors.

Our ongoing and future work include studying the relationship between hop count and distance error and how this could be used to further improve accuracy in hop count-based localization schemes, as well as looking into the feasibility of energy-aware iterative multilateration techniques in hop count-based localization schemes.

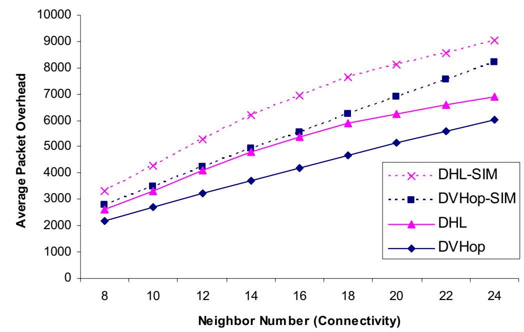

Figure 7. Average packet overhead with varying connectivity

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