A NOVEL RANGE-FREE LOCALIZATION SCHEME FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

This paper present a low-cost yet effective localization scheme for the wireless sensor networks. There are many studies in the literature of locating the sensors in the wireless sensor networks. Most of them require either installing extra hardware or having a certain amount of sensor nodes with known positions. The localization scheme we propose in this paper is range-free, i.e., not requiring extra hardware devices, and meanwhile it only needs two anchor nodes with known position. Firstly, we install the first anchor node at the lower left corner (Sink X) and the other anchor node at the lower right corner (Sink Y). Then we calculate the minimum hop counts for each unknown node to both Sink X and Sink Y. According to the minimum hop count pair to Sink X and Sink Y of each node, we can virtually divide the monitored region into zones. We then estimate the coordinate of each sensor depending on its located zone. Finally, we adjust the location estimation of each sensor according to its relative position in the zone. We simulate our proposed scheme and the well-known DV-Hop method. The simulation results show that our proposed scheme is superior to the DV-Hop method under both low density and high density sensor deployments.

KEYWORDS

Wireless Sensor Networks, Localization Scheme, Range-Free Localization, Zone-Based Method

1. INTRODUCTION

Wireless sensor networks (WSNs) have gained worldwide attention in recent years. A WSN consists of spatially distributed autonomous sensors to cooperatively monitor a deployed region for its physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, and pollutants.

Due to the recent advance of Micro-ElectroMechanical Systems (MEMS) technology, the manufacturing of small and low-cost sensors has become technically and economically feasible. A sensor node can sense, measure, and gather information from the environment and, based on some local decision process, it can transmit the sensed data to the sinks (or base stations) via a wireless medium [1].

Since the transmission power of a wireless radio is proportional to distance squared or even higher order in the presence of obstacles, multi-hop routing will be usually considered for sending collected data to the sink instead of direct communication [20].

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Most of the routing algorithms for WSN require the position information of sensor nodes [12,15]. However, for some hazardous sensing environment, it is hard to deploy the sensor nodes to the locations as required. Thus, for the environments which are hard to plan the location of sensors in advance, we can use localization techniques to estimate the positions of the sensors. Probably, the simplest and available localization technique is to install GPS for each sensor in the sensor networks. However, although the cost of GPS receiver is getting down, it is still too costly to install too many GPS receivers in a sensor network.

In this paper, we propose a low-cost yet effective localization scheme for WSNs. We only need two sensors with known position. The performance of our proposed scheme is compared with the DV-Hop method to show its superiority.

The rest of this paper is organized as follows. The related works of localization algorithms of WSNs are reviewed in section II. The broadcast protocol used to divide the deployed region into zones is presented in section III. The method to estimate the positions of the sensor nodes is presented in section IV. In section V, we simulate our proposed localization scheme and the DV-Hop method, and evaluate their performance. In the last section we conclude the paper.

2. RELATED WORK

Research interest in WSN localization has recently increased greatly [1,7,19,20]. Localization technologies of WSN can be divided into two categories: *range-based method* and *range-free method* [9,10,18,19]. The range-based method is to position the sensor nodes by additional devices, such as, timers, signal strength receivers, directional antennas, and antenna arrays. In contrast, range-free is not required for additional hardware, instead of using the properties of wireless sensor network and designate algorithms to obtain the location information.

Range-based localization relies on the availability of point-to-point distance or angle information. The distance/angle can be obtained by measuring Time-of-Arrival (ToA), Time- Difference-of-Arrival (TDoA), Received-Signal-Strength-Indicator (RSSI), and Angle-of-Arrival (AoA), etc. The range-based localization may produce fine-grained resolution, but have strict requirements on signal measurements and time synchronization.

ToA [6] measures the signal arrival times and calculates distances based on transmission times and speeds. GPS is the most popular ToA-based localization system. By precisely synchronizing with a satellite's clock, GPS computes node position based on signal propagation time.

AHLos [17], a TDoA based scheme, requires base stations to transmit both ultrasound and RF signals simultaneously. The RF signal is used for synchronization purposes. A sensor first measures the difference of the arrival times between the two signals, then determines the range to the base station. Finally, multilateration is applied to combine range estimates and generate location data.

RSSI computes distance based on transmitted and received power levels, and a radio propagation model. RSSI is mainly used with RF signals, but the range estimation can be inaccurate due to multipath fading in outdoor environments [17].

AoA-based methods [16] first measure the angle at which a signal arrives at a base station or a sensor, then estimates the position using triangulation. The calculation is quite simple, but AoA techniques require special antenna and may not perform well due to omni-directional multipath reflections. Further, the signals can be difficult to measure accurately if a sensor is surrounded by

scattering objects. In [11] the authors proposed a prototype navigation system for autonomous vehicles, which estimates AoA by means of a set of optical sources and a rotating optical sensor. The system is not suitable for out-door sensor networks due to its cost and complexity. [12] first transforms TDoA measurements into AoA information, then applies triangulation for location estimates. It requires three base stations with synchronized rotating directional antennae.

Range-free localization requires no measurement on distance or angle among nodes. It can be further divided into two categories: local techniques and hop-counting techniques [9].

For the local techniques, a node with unknown coordinate collects the position information of its neighbor beacon nodes with known coordinate to estimate its own coordinate. A simple centroid algorithm is proposed in [3], in which each sensor estimates its position as the centroid of the locations of the neighboring beacons. The computation error can be reduced by a density adaptive algorithm if beacons are well-positioned [4]. However, this is unfeasible for ad hoc deployment. Later, He et al. proposed the APIT method [5], which divides the environment into triangular regions between beacon nodes. Each sensor determines its relative position with the triangles, and estimates its own location as the center of gravity of the intersection of all the triangles that the node may reside in. However, APIT requires long-range beacon stations, which requires expensive high-power transmitters.

Hop-counting technique was first proposed by D. Niculescu and B. Nath in [14]. They called it DV-Hop method in their paper. In DV-Hop method, each unknown node asks its neighbor beacon nodes to provide their estimated hop sizes and then tries to get the smallest hop count to its neighbor beacon nodes by the designated routing protocol. Each unknown node estimates the distances to its neighbor beacon nodes by the hop counts to them and the hop size of the closest beacon node. Then, the unknown nodes can apply trilateration to estimate their position by the estimated distances to three suitable neighbor beacon nodes. The algorithm is stated as follows.

DV-Hop Algorithm :

Step 1: Each beacon node broadcasts a beacon packet flooding throughout the network containing the node location with a hop-count value initialized to one. Each receiving node maintains the minimum hop-count value per beacon node of all packets it receives. Packets with higher hop-count values to a particular beacon node are defined as invalid information and will be ignored. Then those valid packets are flooded outward with hop-count values incremented by one at every intermediate hop. Through this mechanism, all nodes in the network get the minimal hop-count to every beacon node.

Step 2: Once a beacon node gets hop-count value to other beacon node, it estimates an average size for one hop, which is then flooded to the entire network. After receiving hop-size, unknown nodes multiply the hop-size by the hop-count value to derive the physical distance to the beacon node. The average hop-size is estimated by beacon node i using the following formula:

$$HOP\_SIZE_i = \frac{\sum \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}}{\sum h_{i,j}} ; i \neq j$$

where (X_i, Y_i), (X_j, Y_j) are coordinates of beacon node i and beacon node j, $h_{i,j}$ is the hop counts between node i and node j. Each beacon node broadcasts its *hop-size* to network using controlled flooding.

Step 3: Unknown nodes receive *hop-size* information, and save the first one. At the same time, they transmit the *hop-size* to their neighbor nodes. This scheme could assure that the most nodes receive the *hop-size* from beacon node who has the least hops between them.

Step 4: Each unknown node chooses three beacon nodes that are close to it than others. Compute the distance to the beacon nodes based on hop-length and hops to the beacon nodes. Then, use trilateration to estimate the location of the unknown node.

There are many follow-up studies of DV-Hop method. In [2], the authors proposed the DV-Loc method that shows how Voronoi diagrams can be used efficiently to scale a DV-Hop algorithm while maintaining and/or reducing further DV-Hop's localization error. The main idea of DV-Loc is to use the Voronoi diagram to limit the scope of the flooding in a DV-Hop localization system. DV-Loc is a scalable solution that uses the Voronoi cell of a node to limit the region that is flooded when computing its position in order to reduce its localization error.

In [18], the authors proposed a range-free localization algorithm using expected hop progress to predict the location of any sensor in a WSN. The algorithm was based on an analysis of hop progress in a WSN with randomly deployed sensors and arbitrary node density. By deriving the expected hop progress from a network model for WSNs in terms of network parameters, the distance between any pair of sensors can be computed.

Traditionally, hop-counts between any pair of nodes can only take on integer value regardless of relative positions of nodes in the hop. In [10], the authors argued that by partitioning a node's one-hop neighbor set into three disjoint subsets according to their hop-count values, the integer hop-count can be transformed into a real number accordingly. The transformed real number hop-count is then a more accurate representation of a node's relative position than an integer-valued hop-count. In the paper, the author presented an algorithm termed HCQ (hop-count quantization) to perform such transformation.

3. THE ZONE-BASED LOCALIZATION SCHEME

Most wireless sensor networks are distributed with random deployed sensors which have multi-forwarding capability. Flooding is one of the major mechanisms for sending message between sinks and sensor nodes. Flooding is a simple and effective mechanism that guarantees we can reach the target node if the network is connective. In this paper, we use flooding mechanism as our initial routing step to acquire the zone coordinate for each sensor.

3.1. Localization Scheme

In our localization scheme, named *Flooding Mechanism Localization Method* (FMLM), we first install two sink nodes at the lower left corner (Sink X) and the lower right corner (Sink Y) of the monitored area. We assume that (1) all the sensors are homogeneous, (2) they are randomly deployed, and (3) the network is connective.

FMLM consists of three major steps: compute the minimum hop counts, divide the monitored region into zones, and estimate the represented coordinate for each zone.

Step 1: Compute the minimum hop counts

Firstly, we let both Sink X and Sink Y broadcast a Hop-Counting packet (HC packet in short),

respectively, to their neighbor sensors. The HC packet contains two fields: minimum hop count to the source node (initial value is 1) and the source node ID (Sink X or Sink Y).

Each sensor records two current minimum hop counts, which are both initiated to infinite, to Sink X and Sink Y. Once a sensor receives a HC packet, it checks the hop count field in HC packet. If the value is smaller than its current minimum hop count, then it updates its current minimum hop count, and increments hop count value of HC packet by one. Meanwhile, it forwards the HC packet to all its neighbor sensors. Otherwise, the sensor discards the incoming HC packets which have higher hop count values.

Step 2: Divide the monitored region into zones

After finishing the flooding of HC packets by Step 1, each sensor should have two hop count values (say X_{hop} and Y_{hop}) to Sink X and Sink Y respectively. For those sensors that have the same (X_{hop},Y_{hop}) pair, they are actually located in the same *zone*, and we denoted the zone as zone(X_{hop},Y_{hop}). Figure 1 is a scenario of dividing the monitored region into zones, in which the color irregular arcs are added for easy visualization. Each node have its own (X_{hop},Y_{hop}) pair. For example, X_{hop} of node A is 3 and Y_{hop} is 8. Therefore, we say node A is in zone(3,8). Similarly Node B is in zone(6,5), and Node C is in zone(5,7).
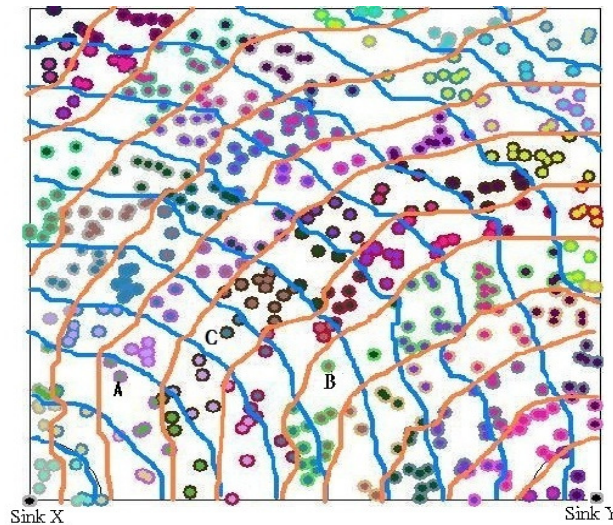

Figure 1: A scenario of 300 sensors with communication range 20 meters dividing a monitored region (200x200 m^2) into zones. The color irregular arcs are added for easy visualization.

Step 3: Estimate the represented coordinate of each zone
Although we have the hop counts of each sensor and therefore we know which zone the sensor belongs to, it is still not sufficient for us to decide the location of the given sensor. As in Figure 1, since the distance of each hop is not necessary the same, the strip width corresponding to a hop is not equal. In subsection B, we will analyze the range of the distance to the sinks for a given sensor node with minimum hop counts, and further give the estimated distance to the sinks. In this subsection, we assume that we already have the estimated distances to Sink X and Sink Y of each node.

Suppose the coordinates of Sink X and Sink Y are (0,0) and (*w*,0) respectively, where *w* is the width of the monitored region. We assume that the distance from an unknown sensor S to Sink X is d_x, and to Sink Y is d_y. Then the coordinate (*x*,*y*) of the sensor *S* can be obtained by the following equations:

$$\begin{cases} (x-0)^2 + (y-0)^2 = d_x{}^2 \\ (x-w)^2 + (y-0)^2 = d_y{}^2 \end{cases}$$

Thus, $x = \dfrac{d_x{}^2 - d_y{}^2 + w^2}{2w}$ and $y - \sqrt{d_x{}^2 - x^2}$

Therefore, the coordinate of the unknown sensor S is:

$$\left(\frac{d_x{}^2 - d_y{}^2 + w^2}{2w} \ , \ \sqrt{d_x{}^2 - \left(\frac{d_x{}^2 - d_y{}^2 + w^2}{2w}\right)^2} \right)$$

3.2. Estimate the distances between sensors and the sinks

The location of zones in the monitored region is related to the communication range and the density of the sensors in the region. For the case of high density, each sensor has a certain amount of sensors within its communication range. Therefore, for Sink X (or Sink Y) it is highly possible that there are sensors located at the rim of its communication range. For the extreme case shown in Figure 2, there always exist sensor nodes at the rim of the communication range of each hop from the sink. Therefore, suppose the communication range is CR, it is easy to see that the maximum distance of a sensor with hop count n to the sink is $n \times CR$.
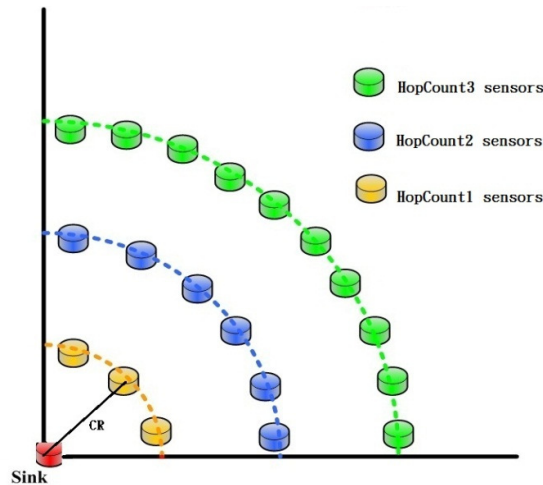

Figure 2: A scenario of maximum distance to the sink: sensor nodes are located at the rims of communication range. Thus, the maximum distance of sensors to the sink with hop count n is $n \times CR$, where CR is the communication range.

The other extreme case occurs while the density of sensor nodes in the region is low and there are very few neighbours for each sensor node, yet the network remains connective. As in Figure 3, sensor nodes are located two by two close to the communication range boundary. The first node in each group is within the communication range of the second node of its previous group, but just outside the communication range of the first node of its previous group. Meanwhile the second node in each group is just outside the communication range of the second node of its previous group.

For example, in Figure 3, node C is within the communication range of node B, but just outside the communication range of node A. Node D is just outside the communication range of node B. Thus, the minimum distance of sensors with hop count n is $\lfloor n/2 \rfloor \times CR + \epsilon$, where ϵ is a very small value. For example, the hop count of node C is 4 and the distance to the Sink is $2 \times CR + \epsilon$, and the hop count of node D is 5 and the distance is $2 \times CR + \epsilon'$, where ϵ' is a very small value larger than ϵ. If the two nodes of each group are very close to each other yet still satisfies the conditions just mentioned, then we can ignore the small value ϵ and say the minimum distance of sensors with hop count n is $\lfloor n/2 \rfloor \times CR$.
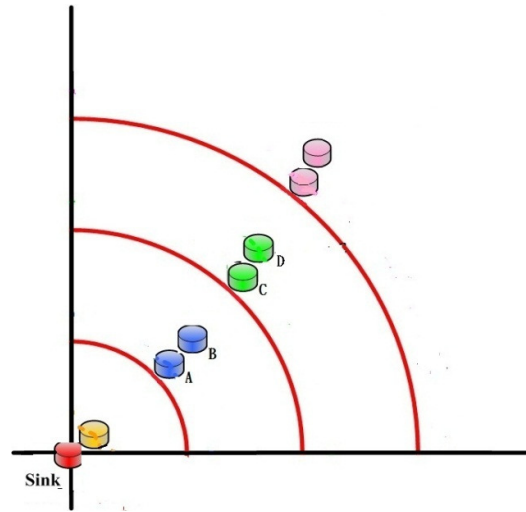

Figure 3: A scenario of minimum distance to the sink: sensor nodes are located two by two close to the communication range boundary.

From the above analysis, we know that any sensor with hop count n, its distance to the sink is between $\lfloor n/2 \rfloor \times CR$ and $n \times CR$ (ϵ is ignored). Therefore, suppose a sensor S with minimum hop count pair (m, n) to Sink X and Sink Y, we can use the following formula to set the distances d_x and d_y of sensor S to Sink X and Sink Y, respectively:

$$d_x = \left\{ \lfloor m/2 \rfloor + \left[(m - \lfloor m/2 \rfloor) * \alpha_1 \right] \right\} * CR$$
$$d_y = \left\{ \lfloor n/2 \rfloor + \left[(n - \lfloor n/2 \rfloor) * \alpha_2 \right] \right\} * CR$$

where $\alpha_1 (\alpha_2)$ is a parameter between 0 and 1. In Section V, we show that the value of $\alpha_1 (\alpha_2)$ is related to the communication range and the density of the sensors in the monitored region, and we will suggest suitable values of $\alpha_1 (\alpha_2)$ for different conditions of a WSN.

4. THE COORDINATE MODIFICATION METHOD

In Section III, we present a localization scheme to estimate the position of a sensor based on which zone the sensor located. We call the coordinates of sensors obtained by this scheme the *FMLM coordinates*. However, for those sensors in the same zone, i.e., with the same hop count pair to Sink X and Sink Y, their estimated FMLM coordinates are the same. Trivially, the

estimation error grows as the area of each individual zone become larger. In this section we propose an adjustment algorithm, called the *Coordinate Modification Method* (CMM), to improve the estimation error. The basic idea of the algorithm is to determine the possible location of a sensor in the zone, and adjust the coordinate of the given sensor depending on the FMLM coordinates of its closer neighbor zones.

In the monitored region, except for the boundary zones, each zone has eight neighbor zones. In the following, we discuss how to determine which neighbor zones are closer to a given sensor in a zone, and how to adjust its coordinate.

The Coordinate Modification Method (CMM)

Step 1: Each sensor use *half communication range* to broadcast a packet which contains its ID, its hop count pair to Sink X and Sink Y, and its FMLM coordinate. (Note: According to our simulation results in [8], broadcasting by half communication range is better than by full communication range, especially for the sensors in boundary zones.) Figure 4 shows a scenario after the broadcasting step.

Step 2: For each sensor receives packets from its neighbor nodes, it adjusts its coordinate according to following step.

a. Extract the FMLM coordinates from the received packets. Ignore the duplicate coordinates from the same zone, and consider the extracted coordinates as a set of points. Compute the centroid of the set of points, i.e., take the arithmetical mean of all the coordinates.
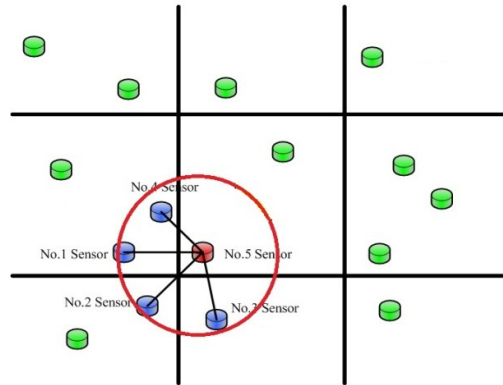

Figure 4: The blue sensors are within half communication range of No.5 Sensor. It indicates that No. 5 Sensor is near its southwest neighbor zones.

b. Suppose the centroid coordinate is (x_c, y_c) and the FMLM coordinate of the sensor to be adjusted is (x_s, y_s), then the adjusted coordinate is set to the center of the two coordinate, i.e., $(\frac{x_c + x_s}{2}, \frac{y_c + y_s}{2})$.

In next section we will compare the error rate of the coordinates obtained by the FMLM and the CMM.

5. SIMULATION RESULTS AND ANALYSIS

In this section, simulation results are presented and analyzed. We simulated the DV-Hop and our proposed methods (FMLM and CMM) to evaluate the localization performance which includes the location error and the error range. The comparison variables are number of sensors,

communication ranges, and number of anchor nodes. The experiment region is a square area with the fixed size of 200×200 m^2.

The radio communication range of sensor nodes (*CR*) is set from 20 to 60 meters. The number of sensors varies from 300 to 1000. The rate of anchor nodes for the DV-Hop method is set to 20% because the performance is reduced significantly while using less than 20% anchor nodes [8,14]. More simulations of anchor node ratio can be found in [8].

The parameters *Location Error* and *Error Range* are defined as follows.

$$Location\ Error = \sqrt{(X_{real} - X_{est})^2 + (Y_{real} - Y_{est})^2}$$

$$Error\ Range = \frac{Location\ Error}{CR}$$

where (X_{real}, Y_{real}) and (X_{est}, Y_{est}) are the real coordinate and the estimated coordinate, respectively, of the given sensor.

Table 1 shows the α values of best performance for different combinations of sensor densities (i.e., number of sensors over the area of experiment region) and communication ranges. As shown in the table, the best α values are between 0.6 and 0.75 except for the cases of communication range is equal to 20 and with low sensor densities. Note that most of the best performance results occur while α is equal to 0.7.

Table 1. The best performance α values for different sensor densities (i.e., *number of sensors / area of monitored region*) and communication ranges

Density (Number of Sensors) Communication Range (meters)	0.0075 (300)	0.01 (400)	0.0125 (500)	0.015 (600)	0.0175 (700)	0.02 (800)	0.0225 (900)	0.025 (1000)
20		0.45	0.5	0.55	0.6	0.65	0.65	0.7	0.7
30		0.6	0.65	0.7	0.7	0.7	0.7	0.75	0.75
40	α value of best performance	0.65	0.7	0.7	0.7	0.7	0.7	0.75	0.75
50		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
60		0.65	0.65	0.65	0.7	0.7	0.7	0.7	0.7

Figures 5 and 6 show the location errors and range errors of the FMLM and the CMM with the best performance α values for different communication ranges and number of sensors. As expected, location error decreases as the sensor density increases for both FMLM and CMM. The simulation clearly shows that the CMM does improve the performance of FMLM significantly. The error ranges of FMLM are between 0.4 and 0.6 when communication ranges are greater than or equal to 30m. However, the error ranges of CMM are between 0.2 and 0.4 under the same conditions.
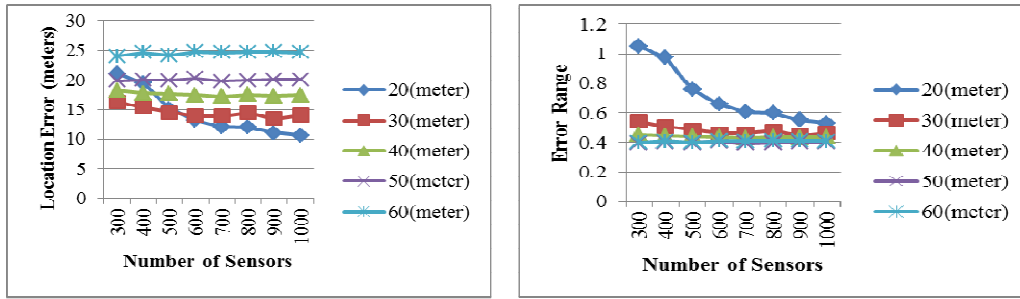
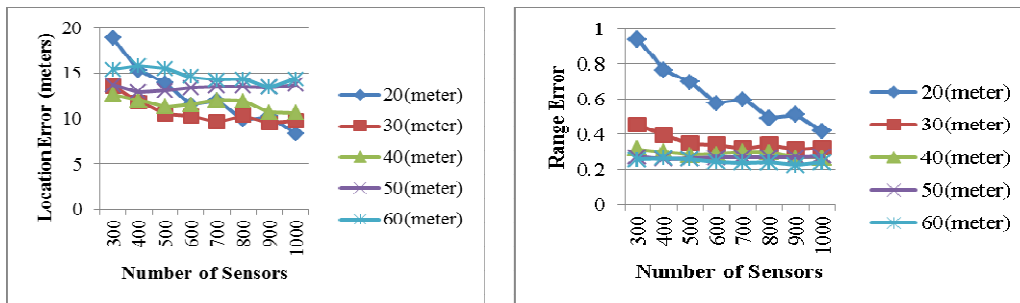Figure 5: Location error and Range Error of the FMLM

Figure 6: Location error and Range Error of the CMM

From Figures 7-9, we can see that both FMLM and CMM outperform DV-Hop no matter under low sensor density or high sensor density for various communication ranges. Note that our methods only use two anchor nodes(Sink X and Sink Y) and simply circle-circle intersection calculation, however, DV-Hop use 20% of sensors as anchor nodes and more complex trilateration operations in the simulation. The simulation results clearly show that our proposed methods are cost effective (only need two nodes with known position) and more accurate than the well-known DV-Hop method.
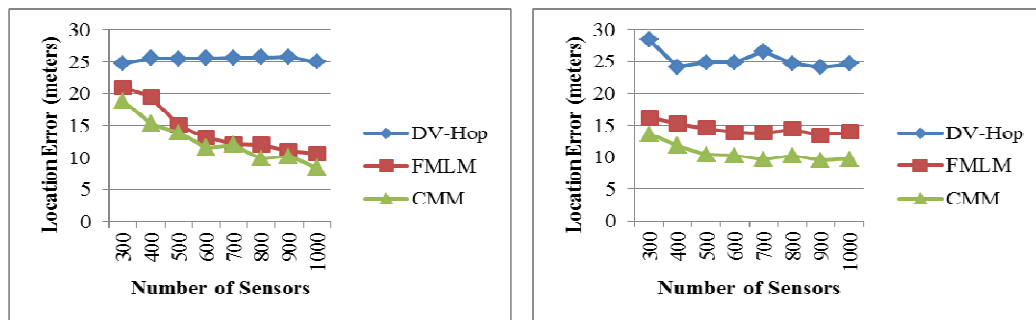

Figure 7: Location errors of our proposed methods (FMLM and CMM) vs. DV-HOP (CR=30 and CR=40)
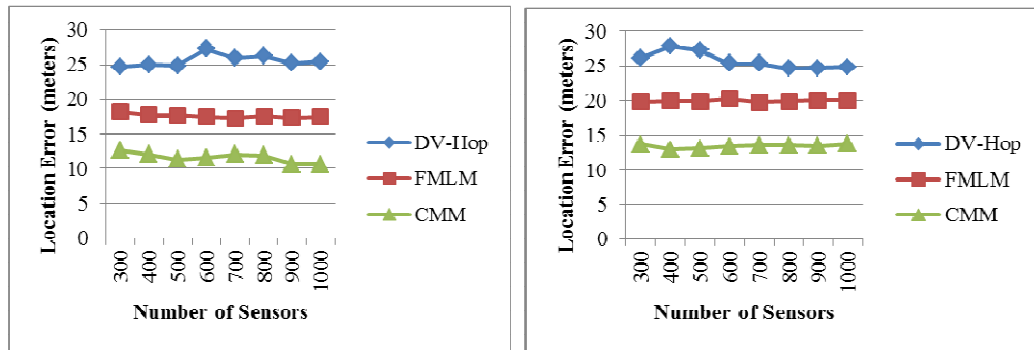
Figure 8: Location errors of our proposed methods (FMLM and CMM) vs. DV-HOP (CR=40 and CR=50)
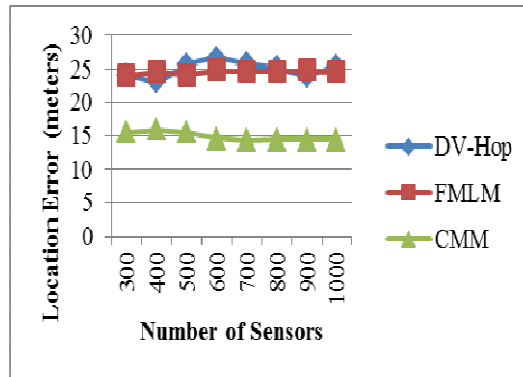

Figure 9: Location errors of our proposed methods (FMLM and CMM) vs. DV-HOP (CR=60)

6. CONCLUSION AND FUTURE WORK

There are a lot of researches on solving the range free localization problems of WSN. Most of them require a large amount of anchor nodes with known positions. In this paper, we propose a range free localization method for the wireless sensor networks. Our method use only two anchor nodes to estimate the positions of all the sensors, and the error range is less than 0.3 for all the cases that communication ranges are greater or equal to 40 meters in our simulation. Almost all the simulation results of our method are better than the DV-Hop method which requires large amount of anchor nodes.

In the paper, we suggest the best performance value α (the ratio for estimate hop size of each hop count) for different combination of communication ranges and number of sensor nodes. We further adjust the coordinate of sensors according to the sensor locations within the zones they belongs to. The simulation results show that this adjustment does significantly improve the performance of location estimation of sensors.

In the future, we will work on other shapes of monitor regions. We also plan to implement the proposed methods in a real WSN to show the usefulness of these methods.

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