A Novel Multihop Range-Free Localization Algorithm Based on Reliable Anchor Selection in Wireless Sensor Networks

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Abstract

Range-free localization algorithm computes a normal node's position by estimating the distance to anchors which know their actual position. In recent years, reliable anchor selection research has been gained a lot of attention because this approach improves localization accuracy by selecting the only subset of anchors called reliable anchor. The distance estimation accuracy and the geometric shape formed by anchors are the two important factors which need to be considered when selecting the reliable anchors. In this paper, we study the relationship between a relative position of three anchors and localization error. From this study, under ideal condition, which is with zero localization error, we find two conditions for anchor selection, thereby proposing a novel anchor selection algorithm that selects three anchors matched most closely to the two conditions, and the validities of the conditions are proved using two theorems. By further employing the conditions, we finally propose a novel range-free localization algorithm. Simulation results show that the proposed algorithm shows considerably improved performance as compared to other existing works.

Keywords: localization; multilateration; range-free; reliable anchor selection; wireless sensor networks;

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1. Introduction

Wireless sensor networks (WSN) have been widely used in various fields such as environmental monitoring, medical care, military monitoring, and disaster relief. Since most of these applications require the physical position of wireless sensor nodes, identifying the location of a sensor node (*localization*) is an important role in wireless sensor networks [1].

Generally, each normal node, which does not have its position, estimates its position by using anchors which have their positions. Localization schemes can be roughly classified into range-based schemes and range-free schemes [2]. The range-based scheme measures the distances to anchors based on range information such as Received Signal Strength Indicator (RSSI) [3], Time of Arrival (TOA) [4], or Angle of Arrival (AOA) [5]. The main drawback of this method is that it requires additional hardware devices which consume more energy and increase cost. In contrast, the range-free scheme is cost-effective and does not require any additional hardware. It utilizes connectivity information (e.g., hop count between sensor nodes) to estimate normal node's position. In this scheme, each normal node calculates its position by utilizing the following information: hop count of the shortest hop path between anchors, hop count of the shortest hop path between an anchor and a normal node, and position of anchors.

In most existing range-free localization algorithms, each normal node estimates its Euclidean distance to anchors, and then calculates its location by multilateration technique [6]. DV-Hop [7] is one of the most well-known range-free localization algorithm, which utilizes all anchors in a network and uses average hop length to estimate Euclidean distance between an anchor and a normal node (called as A2N distance in our article). But, since it only depends on connectivity information (e.g. hop count), it is difficult to estimate the distance accurately which indirectly implies for localization error to become large.

However, instead of utilizing all anchors like in DV-Hop, a location of a normal node can be computed more accurately with only utilizing three anchors. That is, each normal node does not need to estimate the distances to all anchors. Consequently, there have been some studies which focused on selecting subset of anchors that can give a lower localization error. The two important considerations for selecting such anchors are: 1) the accuracy of A2N distance estimation and 2) good geometrical shape formed by the selected anchors.

A localization error by the multilateration-based localization algorithm is considerably affected by an accuracy of the A2N distance estimation. One or two estimated A2N distances with large error lead to a large localization error, even though the rest of the A2N distances are estimated accurately. Also, the localization error is highly affected by relative locations of the anchors. For example, even if the A2N distance estimation is accurate, a localization error may increase when anchors are not well distributed. For instance, an unknown node may select the anchors which can improve the distance estimation but if the selected anchors are deployed together at one point, then a localization accuracy will be degraded.

A few studies in range-based localization algorithm have focused on a relationship between geometrical shape formed by anchors and its localization error. The works at [8][9] deal with an optimal anchor shape that minimizes the variance of a localization error. They found that the localization error becomes minimal when anchors form a regular shape. Even though it is very useful in a range-based algorithm, it is difficult to apply in range-free localization algorithm. This is due to the fact that the range-free localization algorithm can have several hop counts between nodes and consequently cannot measure distance directly, while range-based localization algorithm can measure distance directly to an anchor.

In this paper, being motivated by reducing a localization error by considering geometric shape formed by anchors and distance estimation error, we propose a range-free localization algorithm that selects three reliable anchors and estimates unknown position with utilizing them. We aim in selecting three anchors which can estimate distances well and also form a good geometry. To do that, we study a relationship between the geometric shape formed by selected three anchors and a localization error. From the study, ideal anchor selection conditions are formed. Neverthless, since a normal node cannot always select three anchors matched perfectly to the conditions, we propose a reliable anchor selection algorithm which selects three anchors matched most closely to the conditions.

The rest of this paper is organized as following: section 2 introduces the related works; section 3 presents a novel multihop range-free localization algorithm based on reliable anchor selection; section 4 illustrates theoretical and simulation results; section 5 gives a conclusion.

2. Related Work

There are two kinds of sensor nodes: normal nodes(N) and anchors(A). Generally, each normal node and anchor node finds its hop count of the shortest hop path from all other anchors and the coordinates of that anchors through flooding [10]. Let $\mathbf{p}_i = [x_i, y_i]^T$ be the x - y coordinates of sensor node i, and $\hat{\mathbf{p}}_i$ be the estimated location of the sensor node i. Transmission range of a sensor node is defined as t. The distance between the sensor nodes i and j is $d_{ij} = \|\mathbf{p}_i - \mathbf{p}_j\|$ where $\|\cdot\|$ is the 2D Euclidean norm, and $\hat{d}_{ij}$ be the estimated value of d_{ij}. Let h_{ij} be the minimum hop count between the sensor nodes i & j, and Ω_A denotes the set of all anchors in the network.

In this section, we discuss DV-Hop algorithm and other reliable anchor selection schemes in detail. First, in DV-Hop, each anchor broadcasts its position into the network through flooding. After that, each sensor node obtains its minimum hop count to all anchors, and finally each anchor calculates its average hop length and broadcasts it into the network. That is, for anchor i, its average hop length r_i is computed as

$$r_i = \frac{\sum_{j \neq i, j \in \Omega_A} d_{ij}}{\sum_{j \neq i, j \in \Omega_A} h_{ij}}. \tag{1}$$

Once the average hop length is obtained, each normal node estimates its distances to the anchors by multiplying the average hop length of the anchor with its minimum hop count to the anchors. That is, a normal node n estimates its distance to an anchor i as

$$d_{ni} = r_i \times h_{ni}. \tag{2}$$

Finally, each normal node computes its position by multilateration method. There are two main drawbacks in the DV-Hop method. First, it estimates the distance to every anchor. Most of the algorithms use all anchors to estimate an unknown position. However, it is difficult to estimate the distance to all anchors. So each normal node should select the anchors which can estimate the position accurately. Second, each anchor calculates its average hop length by using all other anchors in the network. Additionally, the accuracy of average hop length can be degraded if the network irregularity is high. Therefore, to compute the average hop length accurately, each anchor should not calculate its average hop length by using all other anchors.

To reduce a localization error, there have been two types of research on calculating the average hop length and selecting the reliable anchors:

1) First is to improve the accuracy of the A2N distance estimation; [11][12] proposed algorithms that improve the accuracy of the average hop length through they approached it differently. The work of [11] considered the number of neighboring nodes in calculating the average hop length. It uses the neighboring nodes to calculate average hop length in a local network. However, this method assumes that the neighboring node deployment is uniform. On the other hand. [12] found an average hop length which minimizes the sum of squares of distance estimation errors between all anchors in the network. In this method, all normal node use the same average hop length. Hence, in a heavily detoured path, this approach results in large distance estimation error.

2) Second is to select the subset of anchors which can estimate the distance accurately and also have a good geometric shape, instead of estimating the distance to all anchors. Authors at [13][14][15] proposed schemes to select anchors which can estimate the A2N distance accurately.
   - In [13](called this algorithm as “4-Nearest anchor algorithm” in our article), each normal node estimates the distance only to four nearest anchors which have small hop count from itself only. It is because that the distance estimation error becomes lower when hop count between a normal node and an anchor is small.
   - [14] used the fact that the accuracy of A2N distance estimation becomes lower, when the shortest hop path is a heavily curved shape. Hence, in this scheme, normal nodes do not estimate its distance to the anchors which have curved shortest hop path. To distinguish the anchors having curved shortest hop paths, this method utilizes the ratio of hop counts to the Euclidean distance.
   - [15] proposed an algorithm that selects a subset of anchors which produces a small distance error. In this method, each anchor selects a subset of anchors to which it can estimate the distance accurately and broadcasts the result to neighboring normal nodes. Then, each normal node uses only these anchors to estimate the distance and calculate its position by multilateration. In order to select the suitable anchors, each anchor estimates the distances to other anchors with the average hop length and the hop count, and then it compares the estimated distances to other anchors with the known coordinates. Each anchor selects the anchors which have a small difference between these two distances.

Generally, in [13][14][15], each normal node selects the anchors which can estimate the distance accurately. However, they did not consider the geometrical shape while selecting the anchors. The authors of [16] (called this algorithm as “RARL” in our paper) have proposed a heuristic algorithm that selects three anchors which includes a normal node in a triangle formed by them with an area as small as possible and then localizes the normal node's position by multilateration with estimated distances to the selected anchors. However, the authors have not explained any theoretical reason why a normal node can reduce localization error by selecting three anchors which form a triangle with an area as small as possible. Furthermore, in [17] each normal node selects three anchors connected to itself with a specific condition, then computes its position directly from a geometric relationship between the three anchors and itself. Explicitly, [17] has a feature that compute an unknown position geometrically without estimating the distance between nodes. That is, it does not utilize multilateration scheme to estimate an unknown position. However, a normal node cannot always find such anchors which satisfy the geometrical condition.

Resultantly, after thorough study of these previous works, we have found that 1) the localization accuracy can be improved when a normal node utilizes a few reliable anchors instead of utilizing all the anchors, 2) the accuracy of the A2N distance estimation and the geometrical shape formed by anchors are important in selecting the reliable anchors.

3. A Novel Range-Free Localization Algorithm Based on Reliable Anchor Selection

A novel range-free localization algorithm based on reliable anchor selection will be described as per the following steps. Firstly, in section 3.1, we will find an ideal anchor selection rule, which nulls localization error, by studying a relationship between localization error and relative position of three anchors. Secondly, in section 3.2, we will propose a reliable anchor selection algorithm in order to select three anchors which are matched most closely to the anchor selection rule. Finally, in section 3.3, we will propose a novel range free localization algorithm using selected reliable anchors.

3.1 An ideal anchor selection rules

Generally, localization accuracy by multilateration is related with a distance estimation accuracy and relative positions of anchors. To study these relationships, we assume that anchors 1, 2, and 3 have an identical transmission range T and are 1-hop from the normal node as shown in fig.1. We can observe that localization result depending on the geometric shape formed by the three anchors. Since the normal node is 1-hop from the three anchors, the real position of the normal node should be located within the overlapping area of the transmission ranges of these anchors, and due to the fact that the estimated distances to the anchors are the same, the estimated position should be the center of the overlapping area. For this reason, the maximum localization error can be represented as the red line.

Fig. 1-(a),(b) compare the maximum localization error with respect to the ways anchors are arranged. As shown in the figures, the maximum localization error increases when three anchors are placed in a straight line, and it decreases when the anchors are distributed in a triangular form. Furthmore, **Fig. 1-(b),(c)** compare the maximum localization error with respect to the areas of the triangles. The maximum localization error decreases when an area formed by three anchors is larger as in the case of (c). Accordingly, it is so important to consider an area of a triangle formed by the three anchors while selecting the anchors. From these studies, we define the next two theorems.

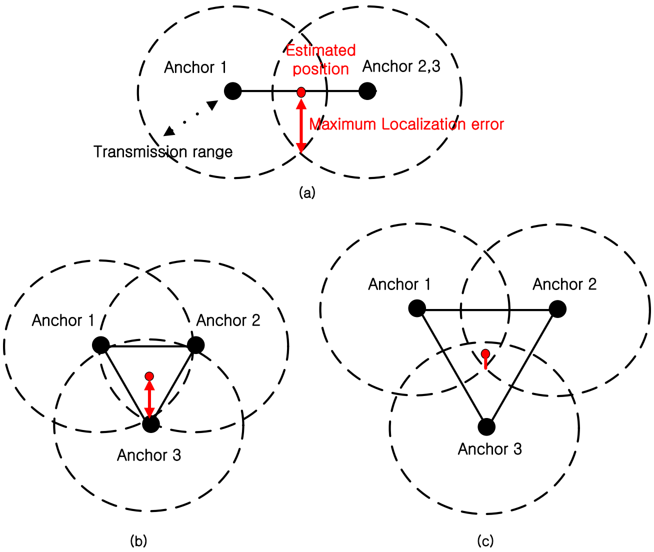

Fig. 1. Examples of the relationship between the maximum location estimation error and the geometric shape formed by three anchors: (a) when the anchors form a straight line, (b) when the anchors form a small regular triangle, (c) when the anchors form a larger regular triangle.

Theorem 1. Assume that three anchors with an identical transmission range t are 1-hop from a normal node. The maximum localization error is minimized when three anchors form a regular triangle.

proof. The proof of theorem 1 has been already discussed in many studies. Hence, we replace this proof with references [8][9].

Theorem 2. Assume that the three anchors with an identical transmission range t are 1-hop from a normal node and form a regular triangle. The maximum localization error is minimized when an area formed by a triangle becomes maximum.

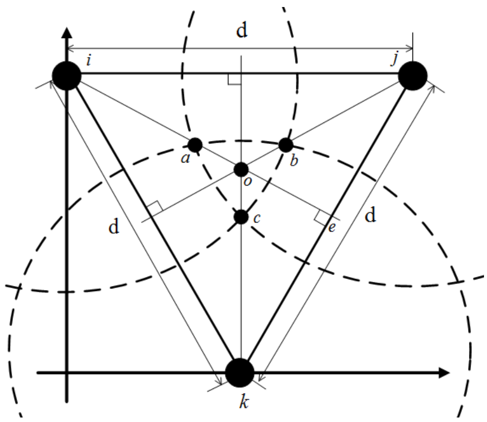

Fig. 2. An illustration for proving Theorem 2.

proof. As shown in **Fig. 2**, when three anchors $i, j,$ and k are 1-hop from a normal node and form a regular triangle, the estimated location of a normal node is at position o which is at the center of mass of the triangle. In this case, the maximum localization error will be d_{ao}, d_{bo}, and d_{co} which are all the same. The maximum localization error Max_error is calculated as

$$Max\_error = \sqrt{t^2 - (\frac{d}{2})^2} - \frac{\sqrt{3}}{6}d. \quad (3)$$

When the points a, b, and c are gathered at point o (the area of the triangle reaches the maximum), we can calculate the area as $\frac{\sqrt{3}}{4}d^2$ where d is $\sqrt{3}t$. The area of the triangle reaches the maximum when d is $\sqrt{3}t$. Finally, Max_error becomes 0 when d is $\sqrt{3}t$ in equation (3). It means that if the area of the triangle reaches the maximum, then the maximum location error becomes zero.

Conclusively, from these two theorems, when three anchors are 1-hop from a normal node the obtained ideal anchor selection conditions are as follows: 1) a triangle formed by three selected anchors should be a regular triangle. 2) a triangle formed by three selected anchors should have the maximum area.

However, difficulties lie on applying these theorems to multihop network. Firstly, each normal node cannot always select three anchors within its transmission range especially when the anchor's density is low. Secondly, in multihop network, since there may be various combinations of hopcount between a normal node to three anchors, it is difficult to select an optimal combination among them. Thus, in order to select three anchors, which best meet the two conditions in a multihop network, we propose a reliable anchor selection algorithm based on a normlized area.

3.2 Reliable anchor selection algorithm

According to the two theorems discussed above, in order to reduce a localization error, it is required to select three anchors that form a shape which is close to a regular triangle as much as possible with an area as large as possible. However, as outlined above, difficulties lie in applying these theorems to a multihop network. In that case, we have to select a regular triangle in which hop counts from a normal node and the anchors are more than one hop. To handle this, we define a normalized area of a triangle to apply the theorems in multihop case, and it is defined as an area of a triangle which is normalized with respect to one hop. That is, the normalized area $Normalized\_Area(i,j,k)$ of a triangle formed by anchors $i, j,\ and\ k$ is calculated by a normal node n as:

$$Normalized\_Area(i,j,k) = \frac{Area(i,j,k)}{h_{ni} \times h_{nj} \times h_{nk}} \quad (4)$$

where $Area(i,j,k)$ is the area of a triangle formed by anchors i,j,k, which can be calculated by using the known position of the anchors.

In the proposed reliable anchor selection algorithm, each normal node aims to select the three anchors that form a shape which is close to the regular triangle as much as possible with a normalized area as large as possible. To do that, each normal node selects three anchors which is the closest to the regular triangle within the proper range from the maximum normalized area which can be formed by the three anchors. To select the three anchors, we formulate an optimization problem as follows:

$$\arg\min_{i,j,k} var(d_{ij}, d_{jk}, d_{ki}) \quad (5)$$

$$\text{s.t.} \quad Normalized\_Area(i,j,k) \geq \alpha \times Max\_Area \quad (6)$$

$$i,j,k \in \Omega_A, i \neq j \neq k \quad (7)$$

where $var(d_{ij}, d_{jk}, d_{ki})$ is the variance of the distances between the three anchors. Max_Area is the maximum normalized area among the available three anchors. We select α as 0.93~0.98 generally. From this optimization problem, each normal node computes its location by using the selected reliable anchors.

From this reliable anchor selection algorithm, each normal node selects the most matched anchors with the two theorems. It is not likely of only increasing the possibility that a normal node is located inside of the triangle but also increasing the possibility that the three anchors are distributed evenly around the normal node as shown in fig. 2. However, it is not guaranteed always. If a normal node is located on an edge of a network, the selected anchors are likely to be located in one direction. In this case, localization error will be increased and it is common for all range-free localization algorithms.

3.3 Proposed localization algorithm

The proposed localization algorithm consists of two steps: 1) A2N distance estimation, and 2) localization. Basically, the A2N distance is estimated by multiplying the average hop length with the hop count of the corresponding shortest hop path. This method is similar to DV-Hop, but there is an important difference in calculating the average hop length. In the DV-Hop, the average hop length of an anchor is calculated on the entire network by using all of the anchors. However, in the proposed algorithm, the average hop length of each anchor is computed by utilizing the selected three anchors. This method can improve the accuracy of the average hop length by considering around normal node only. According to the proposed method, if we assume that a normal node n selects anchors 1,2, and 3 as the reliable anchors, the corresponding average hop length of each anchors $r_1, r_2,$ and r_3 are calculated as

$$r_1 = \frac{d_{12}+d_{13}}{h_{12}+h_{13}}, \ r_2 = \frac{d_{21}+d_{23}}{h_{21}+h_{23}}, \ r_3 = \frac{d_{31}+d_{32}}{h_{31}+h_{32}}. \quad (8)$$

After calculating the average hop length, the reliable anchors 1,2, and 3 send their average hop length to the normal node n. Then, the normal node n estimates the distance to these three anchors. Estimated distances $\hat{d}_{n1}, \hat{d}_{n2},$ and $\hat{d}_{n3}$ between the normal node n and its reliable anchors 1,2, and 3 are given as follows:

$$\hat{d}_{n1} = r_1 \times h_{n1}, \ \hat{d}_{n2} = r_2 \times h_{n2}, \ \hat{d}_{n3} = r_3 \times h_{n3}. \quad (9)$$

After estimating the distances to the selected anchors, each normal node calculates its location. The location's estimation is performed by multilateration based on the least square estimation. The technique is well-known and commonly used in range-free localization algorithms, and the detailed process is explained in [6]. Using the estimated distnaces, we can formulate an optimization problem to estimate the position of the normal node n,

$$\arg \min_{[\hat{x}_n, \hat{y}_n]^T} \{(\hat{d}_{n1} - d_{n1})^2 + (\hat{d}_{n2} - d_{n2})^2 + (\hat{d}_{n3} - d_{n3})^2\}. \tag{10}$$

Equation (10) is modeled to calculate a normal node position $\hat{x}_n, \hat{y}_n$ by minimizing the sum of squared error between estimated distances $\hat{d}_{n1}, \hat{d}_{n2}, \hat{d}_{n3}$ and real distances d_{n1}, d_{n2}, d_{n3} . However, since equation (10) is non linear, we can not find a solution directly. To solve this model, we can obtain the following linear measurement equations from equation (10).

$$-2x_{\mathrm{n}}(x_1 - x_2) - 2y_{\mathrm{n}}(y_1 - y_2) = \hat{d}_{n1}^2 - \hat{d}_{n2}^2 - \|\mathbf{p}_1\|^2 + \|\mathbf{p}_2\|^2, \tag{11}$$
$$-2x_{\mathrm{n}}(x_1 - x_3) - 2y_{\mathrm{n}}(y_1 - y_3) = \hat{d}_{n1}^2 - \hat{d}_{n3}^2 - \|\mathbf{p}_1\|^2 + \|\mathbf{p}_3\|^2, \tag{12}$$
$$-2x_{\mathrm{n}}(x_2 - x_3) - 2y_{\mathrm{n}}(y_2 - y_3) = \hat{d}_{n2}^2 - \hat{d}_{n3}^2 - \|\mathbf{p}_2\|^2 + \|\mathbf{p}_3\|^2. \tag{13}$$

The location of a normal node n is estimated with the least square estimation,

$$\hat{\mathbf{p}}_n = [\hat{x}_n, \hat{y}_n]^T = (\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{z}_n, \tag{14}$$

where measurement matrix H is

$$\mathbf{H} = -2 \times [(\mathbf{p}_1 - \mathbf{p}_2), (\mathbf{p}_1 - \mathbf{p}_3), (\mathbf{p}_2 - \mathbf{p}_3)]^T \tag{15}$$

and measurement vector z_n is

$$\mathbf{z}_n = \begin{bmatrix} \hat{d}_{n1}^2 - \hat{d}_{n2}^2 - \|\mathbf{p}_1\|^2 + \|\mathbf{p}_2\|^2 \\ \hat{d}_{n1}^2 - \hat{d}_{n3}^2 - \|\mathbf{p}_1\|^2 + \|\mathbf{p}_3\|^2 \\ \hat{d}_{n2}^2 - \hat{d}_{n3}^2 - \|\mathbf{p}_2\|^2 + \|\mathbf{p}_3\|^2 \end{bmatrix}. \tag{16}$$

4. Performance Evaluation

In this section, we analyze communication overhead incurred by the algorithms and simulation results. We compare our algorithm with DV-Hop, 4-Nearest Anchor, and RARL.

4.1 Overhead analysis

The overall communication overhead of the proposed algorithm is smaller than that of DV-Hop, 4-Nearest anchor and RARL. The overall communication overhead caused by DV-Hop, 4-Nearest anchor and RARL are known to be $2O(AS)$ [7][13][16], where A and S denote the number of anchors and the number of sensor nodes (anchors and normal nodes). Basically, these algorithms require twice floodings in a network. The first flooding is required when each sensor node obtains the minimum hop count information from all anchor, then each anchor computes its average hop length. And the second flooding is required when each anchor broadcasts its average hop length to an entire network. On the other hand, the overall communication overhead caused by the proposed algorithm is $O(AS)$. In the proposed algorithm, each normal node can select three reliable anchors by one flooding. Then, it both request and receive average hop length to the selected anchors by using unicast. Most of communication overhead is generated by a flooding step in order to select three anchors. In contrast, communication overhead to obtain average hop length between a normal node and three anchors is very small and it is irrelevant to the network size.

4.2 Simulation analysis

In this section, we compare the localization error of the four algorithms. The localization error is defined as the Euclidean distance between the actual position and the estimated position of a normal node. We randomly deploy the sensor nodes (normal nodes + anchors) which have a transmission range t over $10 \times 10m^2$ deployment area. We simulate it 100 times for each node deployment and compute the average of each simulation results. In the case of RARL algorithm, a normal node cannot always estimate its position by satisfying the condition that a normal node should be included within a triangle formed by three anchors. Hence, to evaluate the localization performance correctly, we compare the localization error of normal nodes which can be estimated only by all four algorithms.

4.2.1 Localization error under different network topology's shape

Since these four algorithms utilize the connectivity information to estimate the unknown position, the result may be affected by the nodes' deployment topology. Hence, we compare the localization error of the four algorithms in the Regular-, C-, and, O- shaped topologies. **Fig. 3** illustrates examples of the three topologies.

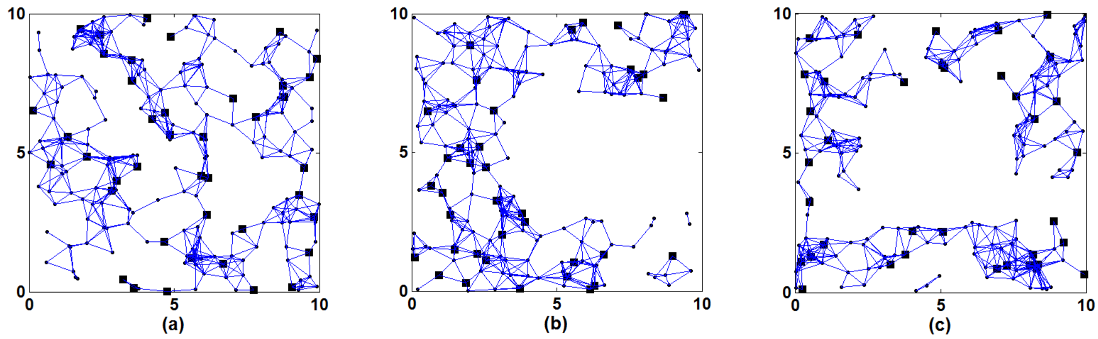

Fig. 3. Examples of nodes' deployment ((a): Regular-shaped topology, (b): C-shaped topology, and (c): O-shaped topology)

We divided the entire network under each mentioned topology into a large number of grids and an average localization error is obtained for each normal node, which is located in each grid. In this experiment, we set node density as 2 $nodes/m^2$ and an anchor ratio as 20% of total sensor nodes. And, we fixed transmission range t of all nodes as $1m$. Generally, as **Fig. 4,5 and 6** show, the localization error of the proposed algorithm is approximately about 0.4m and it is steady at this value regardless of both node's location and network's topology; whereas, at different locations, it is unstable for DV-Hop, 4-Nearest Anchor, and RARL: especially, at the boundaries, beginnings and ends of C- and O-shaped topologies, it has significantly increased. Moreover, comparatively, the proposed algorithm shows less localization error than those of the DV-Hop, 4-Nearest Anchor, and RARL algorithms at any locations under any of the exemplified network's topology.

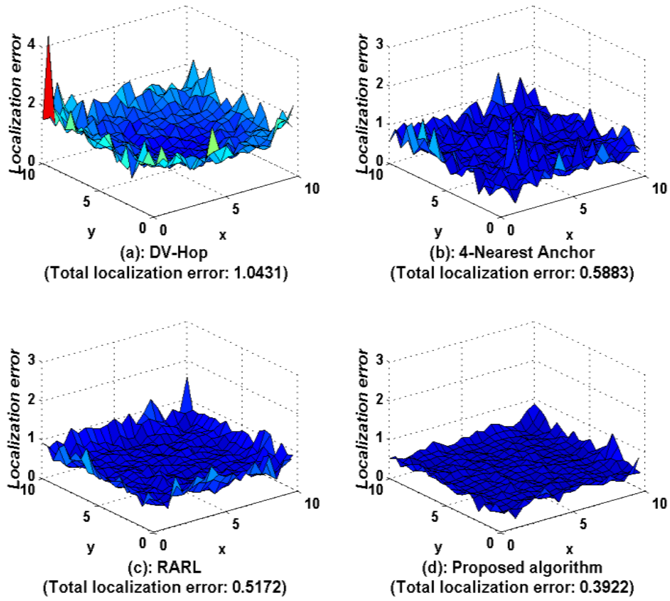

Fig. 4. Localization error at different node's locations in a Regular-shaped topology

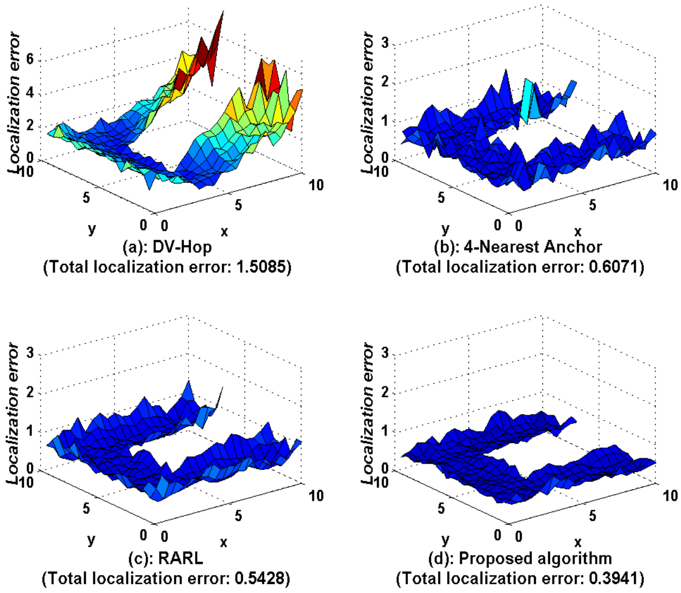

Fig. 5. Localization error at different node's locations in a C-shaped topology

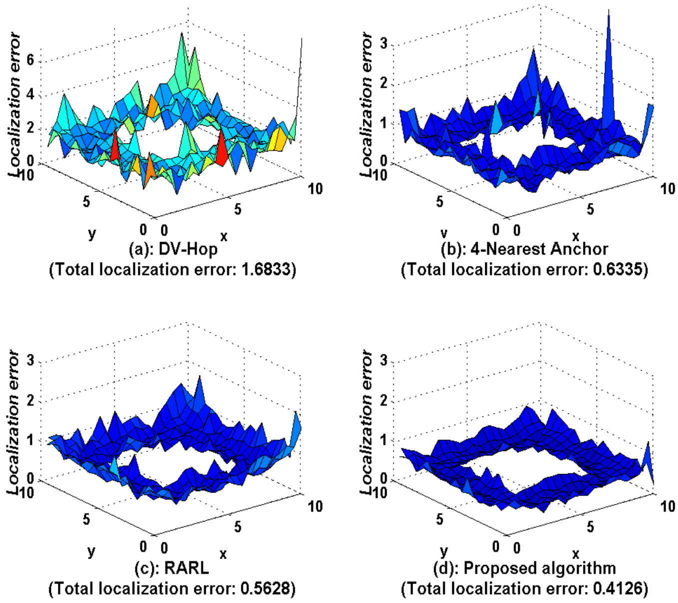

Fig. 6. Localization error at different node's locations in a O-shaped topology

The node's location in the network is highly related with the geometrical shape of anchors under each of the algorithms. Considering the DV-Hop algorithm, since it uses all anchors, localization error can be increased when a normal node is located at the corners or at the boundaries of the networks; because the anchors may be gathered at one direction. And in the case of the 4-Nearest Anchor algorithm, each normal node utilizes only four nearest anchors to estimate its position. The algorithm considers only the hop count information in an anchor selection. That is, it does not consider the situation where anchors are located whether in a line or a point. For this reason, it shows an unstable performance in the C- and O- shaped topologies. In particular, localization error is high at the boundaries of topologies. On the other hand, the RARL algorithm considers the A2N distance estimation accuracy and the geometric shape formed by the anchors unlike the 4-Nearest Anchor, thus it shows stable and lower localization error than DV-Hop and 4 Nearest Anchor.

RARL algorithm differs from the proposed algorithm in three ways. Firstly, it calculates the average hop length by considering an entire network, which can not consider the local characteristic of a topology. This mechanism may degrade performance at the boundaries of the C- and O- shaped topologies. Secondly, it utilizes the estimated A2N distances when it selects the reliable anchors, and this may cause a problem in C- and O- shaped topologies where the shortest paths between anchors and normal nodes are different from their Euclidean distances. And finally, it cannot always estimate all normal nodes because of some constraints in selecting the reliable anchors.However, Our scheme shows the lowest and the most stable localization error in Regular-, C-, and, O-shaped topologies. It has three main advantages: First, it considers the A2N distance estimation accuracy and the geometric shape formed by anchors to select the three reliable anchors. Second, it utilizes only exact information (the coordinates of anchors) to select three reliable anchors. Third, it considers the local characteristic of a network by computing average hop length only for specific hop paths. These advantages bring a stable performance in every scenarios.

4.2.2 Localization error when varying node density and anchor ratio

Here, we compare the localization error of the four algorithms when a node density increases from 2 (low density) and to 3.5(high density) by setting an anchor ratio at 15% and 20% under each of the network's topologues. Transmission range *t* is fixed at 1*m*.

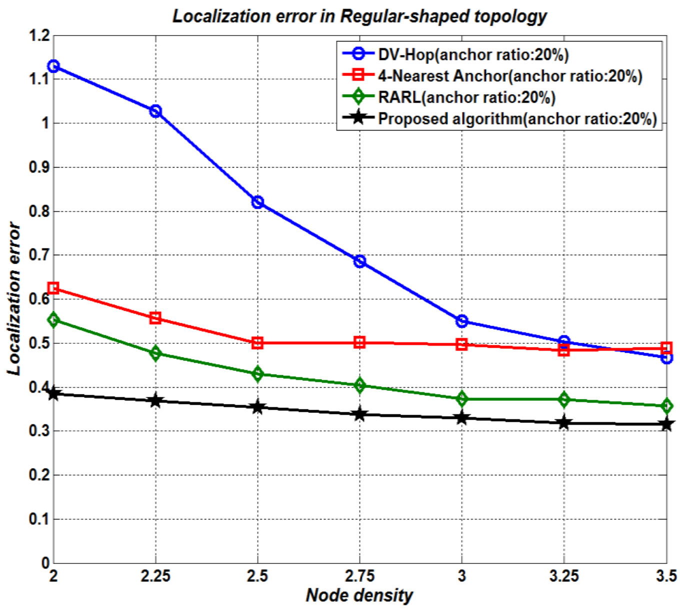

Fig. 7. Localization errors in Regular-shaped topology

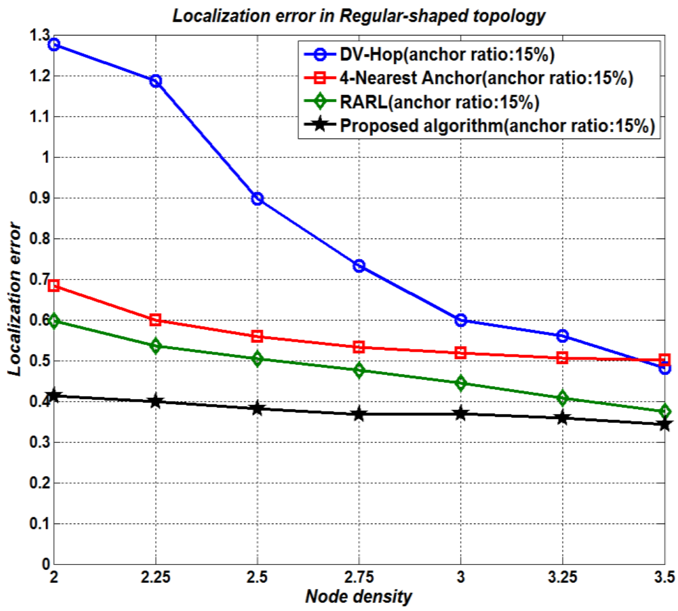

Fig. 8. Localization errors in Regular-shaped topology

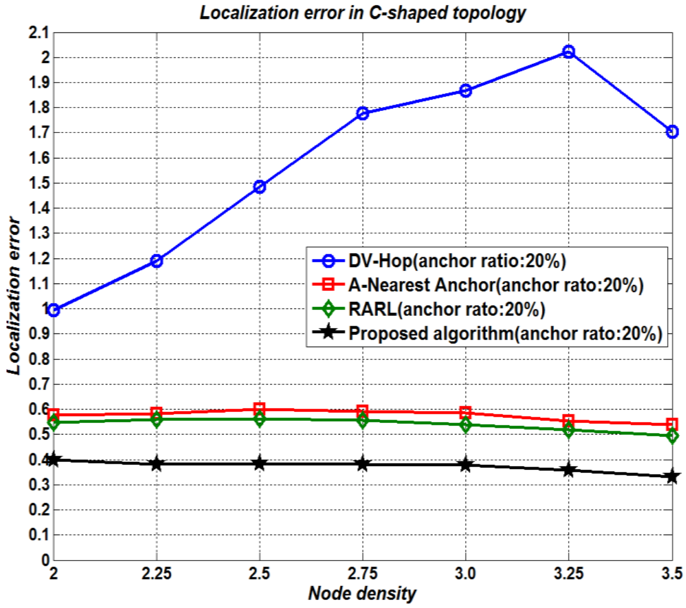

Fig. 9. Localization errors in C-shaped topology

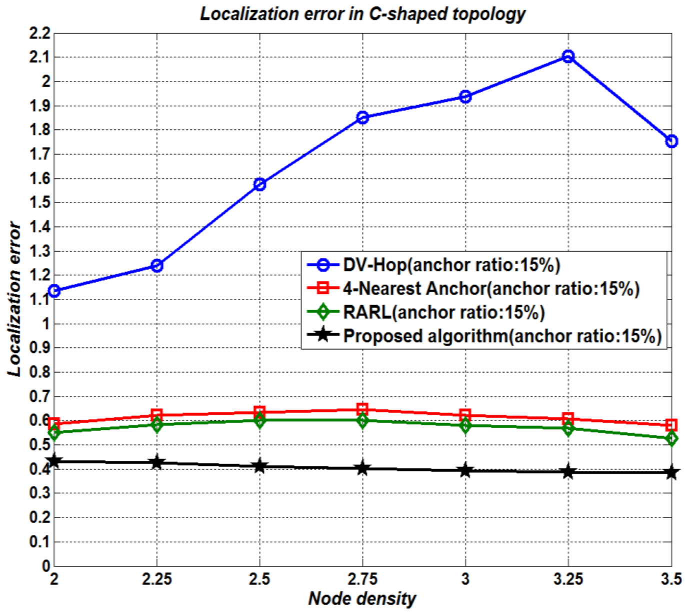

Fig. 10. Localization errors in C-shaped topology

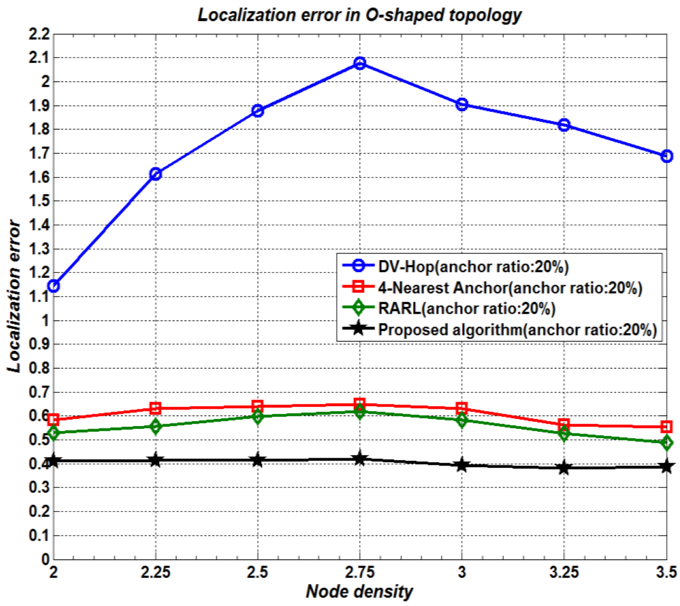

Fig. 11. Localization errors in O-shaped topology

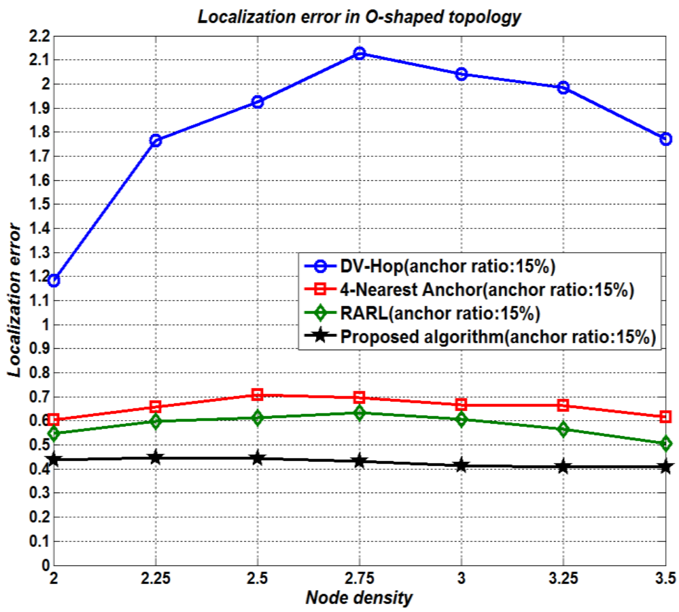

Fig. 12. Localization errors in O-shaped topology

As shown in the figures, unlike the rest of the algorithms, the proposed algorithm shows a stable performance and achieves the lowest localization error despite the node density, and the topologies are varied, whereas DV-hop shows the worst performance.

Specifically, under C- and O-shaped topologies, RARL and 4-nearest Anchor algorithms almost have a constant performance with an insignificant deviation between them. Furthermore, we can see that, under any of the topologies, setting an anchor ratio at 20% resulted to performance improvement than setting it at 15% though the improvement is to a small degree.

DV-Hop, 4-nearest Anchor, and RARL algorithms utilize average hop length which is calculated in an entire network (equation (1)) to estimate a distance between an anchor and a normal node. Especially, RARL algorithm utilizes this average hop length to select reliable anchors also. Basically, an accuracy of an average hop length which is calculated in an entire network will degrade considerably when a node density is low or non-uniform and also when a topology is irregular such as C and O shaped topologies. Hence, localization errors of the three algorithms are higher than the localization error of the proposed algorithm in low density of the Regular-, C- and O- shaped topologies. On the other hand, in the proposed algorithm, an average hop length is computed only by using selected reliable anchors instead of using all anchors. From this, we can reduce the effect of both non uniform node density and irregular topology. Hence, the proposed algorithm shows a stable performance in all the cases regardless of varying node density and the topology's shape.

4.2.3 Localization error when varying DOI

In this experiment, we compare localization error when DOI(degree of radio irregularity) is varied in order to consider real communication's environment like fading effect. When a transmission range t has a random value between 1-DOI m and 1m, probability $P(d)$ that a link is established between two nodes with distance d is:

$$P(d) = \begin{cases} 1, & \frac{d}{t} < 1 - DOI \\ \frac{1}{\text{DOI}}\left(\frac{d}{t} - 1\right) + 1, & 1 - \text{DOI} \le \frac{d}{t} \le 1 \\ 0, & \frac{d}{t} > 1. \end{cases} \quad (17)$$

When a connection of a link between two nodes is decided with probability $P(d)$, we compare localization errors of the four algorithms in the Regular-shaped topology. In this experiment, we set the number of nomal node as 200 and the number of nomal node as 20, 40 and 60.

As it is clearly shown in **Fig. 13**, for the four algorithms, localization error increased with an increase in DOI though the rates of increase are gradually for all of them except for DV-hop algorithm at DOI values of 0.125, and 0.15 at which it has climbed up faster. However, in spite of the increase of the error with DOI increase, still the proposed algorithm has the best performance while DV-hop has the worst one. And RARL and 4-Nearest Anchor algorithms have come at the top of the proposed algorithm, respectively.

The performance's differences are related with hopcount between a normal node and anchors utilized for localization. When DOI increases, hopcount between a normal node and an anchor also increases. As a result, implying for an increase of distance estimation error. So, localization error of DV-Hop using all anchors is very high when DOI is large. On the other hand, the rest of the algorithms utilize anchors having small hopcount only; making them have relativlely small error compared with DV-Hop.

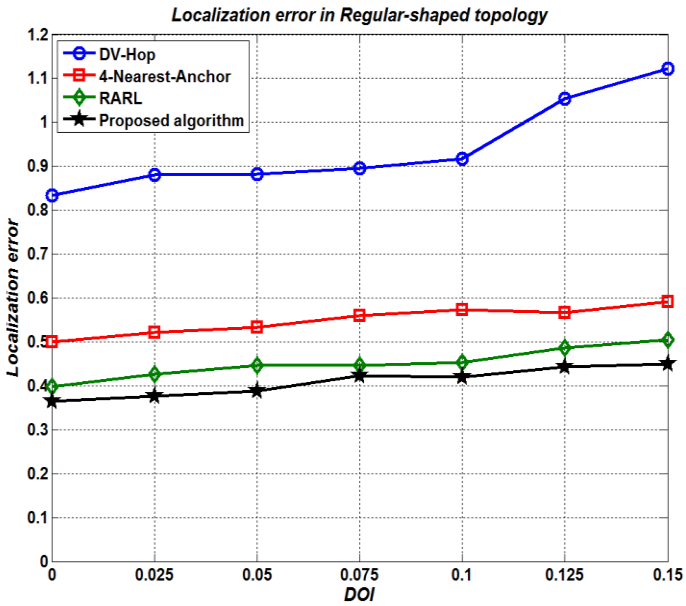

Fig. 13. Localization errors when DOI increases

4.2.4 Localization success ratio

Since requirements to success localization for the four algorithms are different, we compared localization success ratio of the four algorithms. Localization success ratio is defined as a number of normal nodes which estimate its position. We fixed transimssion range *t* of all nodes at 1m and performed this experiment in Regualr-shaped topoloies. And we also fixed the number of normal nodes as 200 and changed the number of anchor nodes as 20, 40, 60.

As shown at table 1, almost having the same values, proposed algorithm, 4-Nearest-Anchor and DV-Hop algorithms show the largest localization success ratio while RARL algorithm shows the lowest. Moreover, except for RARL which shows significant increase, the success ratios moderately increased for the rest of the algorithm as the number of anchor nodes increased.

The reasons beside the results observed in **Table 1** are the minimum requirements to estimate an unknown position of the four algorithms which are as follows: 1) DV-Hop and proposed algorithm: a normal node needs three anchors, 2) 4- Nearest Anchor: a normal node needs four anchors, 3) RARL algorithm: a normal node needs three anchor which must include itself in a triangle formed by them. Therefore, a normal nodes which can be localized by the proposed algorithm can also be localized by DV-Hop. However, some of the normal nodes which can be localized by proposed algorithm and DV-Hop cannot be localized by 4- Nearest Anchor and RARL algorithm. Since 4- Nearest Anchor algorithm needs one more anchor for localization than DV-Hop and proposed algorithm, some normal nodes which are connected with only three anchors, they can not estimate thier position by 4- Nearest Anchor algorithm. In case of RARL algorithm, if a normal node is located on the edge, it can not select three anchors including itself whithin a triangle.

Table 1. Localization success ratio in Regular-shaped topology

	DV-Hop	4-Nearest Anchor	RARL	Proposed algorithm
Normal nodes: 200 Anchor nodes: 20	95.62%	94.87%	45.15%	95.62%
Normal nodes: 200 Anchor nodes: 40	99.66%	99.06%	59.27%	99.66%
Normal nodes: 200 Anchor nodes: 60	100%	100%	68.89%	100%

5. Conclusion

In this paper, we have proposed a novel range-free localization algorithm based on a reliable anchor selection. We have studied two requirements for an optimal triangle formed by three anchors to minimize a location estimation error in a single-hop environment, and then we have proposed a solution for applying these two requirements in a multihop environment. In the proposed algorithm, each unknown node selects three anchors that form a shape which is close to a regular triangle as much as possible and has an area as large as possible. From this reliable anchor selection, a localization error can be reduced greatly. From the simulation results, we have showed that the proposed algorithm offers considerably an improved performance as compared to the other existing studies.

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