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Outlier-resistant Multi-hop Localization Based on Weighted Bounding-Box with the Virtual Anchor

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Abstract. Multi-hop localization has attracted considerable research interests, recently. Most of the existing methods assume that the distribution of anchors is non-collinear, which often does not represent real-world scenes, particularly for irregular networks. In this paper, we present a novel multihop localization scheme to address the ill-posed issue caused by the inappropriate distribution of anchors. First, we recognize whether the preliminary estimated location of non-anchor obtained from existing methods deviates from its true location. So it becomes a new anchor (also called the virtual anchor) after it is identified that the preliminary location of a nonanchor is within an unfit area. With the support of both the virtual anchor and other anchors, a smaller and delimited area can be found in which the target node is situated. Next, we employ the weighted Bounding-Box algorithm to compute the non-anchors' locations that are close to their true locations. We evaluate our scheme with different network topologies based on other state-of-the-art research and analyze its performance. The results demonstrate that our proposed scheme can improve the accuracy of localization with lower computation complexity.

Keywords: multi-hop localization, ill-posed issue, Bounding-Box algorithm

1 Introduction

Location-based services and location information sharing is the key foundation for supporting other wireless network functions and applications, such as routing, topology, and monitoring, etc [1-3]. However, under closed environmental conditions the signals from Global Navigation Satellite Systems (GNSS) are extremely weak and unreliable, resulting in poor localization accuracy [4-6]. Cost-effective alternative solutions to GNSS are the multi-hop localization scheme. The basic idea of the multi-hop localization scheme makes use of the relative connectivity information to approximate node-to-anchor distance calculation where anchor nodes are certain special nodes that can recognize their global locations. After being aware of three or more than estimated distances, each non-anchor starts to compute its location by multilateration technique.

Multi-hop localization scheme is an attractive research area in the wireless applications. And various multi-hop localization-based applications have been introduced in the literature. Multi-hop localization

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usually can be categorized into range-based algorithms vs range-free algorithms [7-10]. Range-based algorithms require all nodes to be fitted with ranging equipment. However, not all nodes have the requisite range capability. Thus, range-free is an enticing research field for wireless applications. Distance Vector (DV)-hop [11-12] is one of the most well-known range-free algorithms. First, the distance vector protocol is used to count the minimum number of hop counts between nodes. Then they are linearly mapped to the predicted distances by multiplying the expected average one hop distance. Wang et al. [13-14] proposed a Localization Algorithm using Expected hop Progress (LAEP) based on an accurate analysis of hop progress. LAEP will concurrently complete the function of setting up the network as well as the relative distance calculation between nodes simultaneously. Recently, Mavridopoulos et al. [15] proposed the Anchor-Free Distance Estimation (AFDE) algorithm which derived that the expected hop progress is inversely proportional to the average number of nodes per unit area.

Generally, nodes are placed randomly over the area of interest. Unfortunately, in reality, particularly nodes are scattered in unusual regions with holes or barriers, which may make some anchors be placed near a straight line. Such distribution of anchors may lead to an ill-posed issue in the location estimation process and makes the estimated position of the non-anchor deviate from their true position seriously [16]. To address this issue, another mechanism is to rectify the estimated distances before employing them to estimate non-anchor locations. Xiao et al. [17] proposed an approach called Reliable Anchor-based Localization (RAL), which can reduce the localization error for irregular networks with the help of a preset reliable anchor lookup table. Lee et al. [18] used the Reliable Anchor Pair Selection (RAPS) based on the geometric approximation of the node location to improve localization accuracy in the irregular networks. Zaidi et al. [19] introduced a novel Accurate Range Free Localization (ARFL) algorithm that derives the average Location Estimation Error (LEE) in closed-form. The ARFL claims that the localization accuracy is considerably better than the best representative algorithms in the literature. Nevertheless, the authors failed to show that the ARFL algorithm is still capable of achieving high localization accuracy in complicated scenes, such as irregular networks.

In this paper, we focus on addressing the ill-posed issue during nodes localization process. We are the first to determine whether the estimated location of a nonanchor provided by existing methods is an outlier location. When the estimated position is located far from the signal coverage region of the anchor, we upgrade it as a new anchor node (called virtual anchor). We then employ the weighted Bounding-Box algorithm [20] with the help of the virtual anchor to correct the outlier estimation. Compared with the previous range-free works, our scheme has two advantages. First, our proposed scheme is allowed to develop on the basis of other previous range-free works, and our scheme is thus highly adaptable. Second, our proposed scheme does not involve complicated computation and can inherit the advantages of parent algorithms.

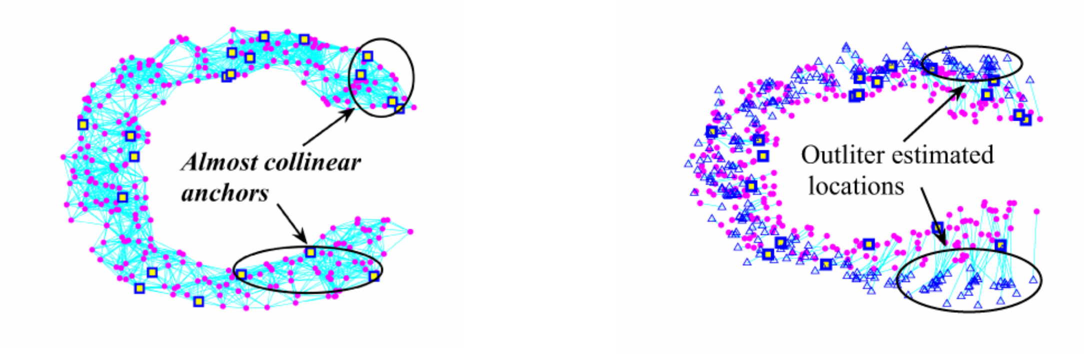
The remainder of the paper is organized as follows. Section 2 describes the localization problem. Section 3 introduces our localization scheme. Performance evaluations are provided in Section 4, and Section 5 concludes this paper.

2 Localization Problem Statement

Consider a network in a bidimensional plane region with n nodes. All nodes are deployed in this region, randomly and independently. Let the first m nodes represent anchors that are fitted with GNSS or manually pre-positioned, while the rest of the *n-m* non-anchors need to be estimated using the anchors and other information. Let the position of the anchor a represented $p_a=(x_a,y_a)$, for all $a=1,\cdots,m$, where $m<<n$. The non-anchor u 's true and estimated locations are expressed as $p_u=(x_u,y_u)$ and $\hat{p}_u=(\hat{x}_u,\hat{y}_u)$, respectively, for all $u=m+1,\cdots,n$. The estimated distance from u to a is described as $\hat{d}_{u\leftrightarrow a}$.

It is presumed that all nodes are fitted with omnidirectional antennas and have the capacity to transfer the packet to all its neighbors, up to a certain transmitted power. Since given the power constraints of nodes if two nodes are remote from each other, they will exchange information indirectly through relay nodes, where the number of relay nodes is defined as hop-count. All nodes are assumed to be equipped with omnidirectional antennas and have the ability of transfer the packet to all of their neighbors, up to a determined transmitted power (*i.e.,* transmission range r). Due to the power constraints of nodes if two nodes are far away from each other, they will indirectly exchange information through relay nodes, where the number of relay nodes is defined as hop-count. Most algorithms intend to choose the delivery route with minimum relay nodes.

However, in practice, the network topology may appear as irregular shape due to obstacles or nodes losing control. Fig. 1(a) presents one common network topologies example with 20 anchors (hollow squares) and 280 non-anchor (solid circles). Clearly, the presence of a "hole" would also push some anchors used for localizing to be located along a straight line which would lead to another serious issue, i.e. the ill-posed issue. The ill-posed issue can make the estimated location significantly deviate from the true location. Fig. 1(b) shows the localization results using RAL algorithm for nodes distribution as shown in Fig. 1(a). Triangles are non-anchor estimation positions, and each line links a true non-anchor position to its estimation. The length of each line shows the non-anchor calculation error. Fig. 1(b) clearly states that certain non-anchors have larger estimation errors around the anchor nodes which are almost collinear (on the left side of Fig. 1(b)).



(a) nodes are distributed in an irregular network, and several anchors are placed near a straight line

(b) localization result with RAL

Fig. 1. Ill-posed issue

The goal of our localization scheme is to correct outlier estimations of non-anchors with high localization accuracy and low complexity.

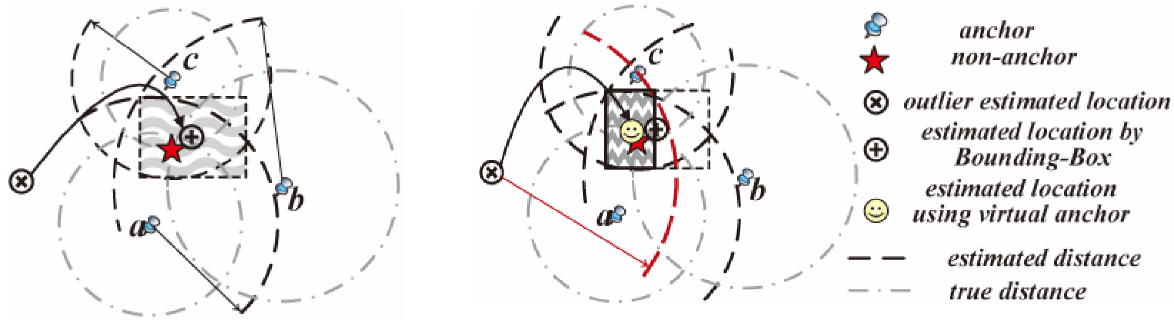
3 Localization Algorithm

3.1 Bounding-Box Algorithm Using Virtual Anchor

Fig. 2 shows an example of multilateration that uses three connected anchors only, i.e., a, b and c. Ideally, the target node is located at the intersection of three disks (pointed line) that are centered at each location of the anchor. However, errors for the estimated distance between anchor and non-anchor are always unavoidable, resulting in that the disks may not always intersect at one point. Unfortunately, obstacles may move anchors close to a straight line, making the coarse estimated location obtained by existing methods seriously deviate from the true localization. An outlier estimated position is regarded as a serious estimation mistake, one that deviates greatly from the true position. A simple approach called the Bounding-Box algorithm which corrects the problem of outlier estimation. It uses the overlapping region centroid of all bounding boxes which are defined by anchors as the potential locations of unknown nodes. As shown in Fig. 2(a) the Bounding-Box algorithm overlapping area can be easily determined by

$$(\hat{x}_u,\hat{y}_u)\in[max(x_a-d_{u\leftrightarrow a}),min(x_a+d_{u\leftrightarrow a})]\times[max(y_a-d_{u\leftrightarrow a}),min(y_a+d_{u\leftrightarrow a})],\ a=1,\ldots\ldots,k \quad \textbf{(1)}$$

where (x_a,y_a) is the location of connected anchor a, $d_{u\leftrightarrow a}$ is the estimated distance from target u to anchor a.



(a) the Bounding-Box algorithm (b) the Bounding-Box algorithm with a virtual anchor

Fig. 2. Correction of outlier estimated location

Inspired by the work of the Bounding-Box algorithm, the idea proposed in this paper is to correct the estimated outlier position as close as possible to the true position. Initially, a non-anchor is localized on the basis of existing methods. Following, our algorithm is to determine whether or not this estimated location is significantly deviating from the true location, that is to say, the preliminary estimated location is an estimated outlier location. An estimated outlier location occurs if the estimated distance $\hat{d}$ is larger than the calculated distance $\tilde{d}$. Otherwise, the preliminary estimated location is closer to the true location. The calculated distance is defined as the Euclidean distance from the preliminary estimated location to the connected anchor node. Once the non-anchor is aware of the estimated outlier location, the virtual anchor appears in this temporary estimation location. Finally, as shown in Fig. 2(b), our scheme can find a smaller limiter area with the aid of the virtual anchor and the Bounding-Box algorithm, and thus achieves finer division. Considering that the virtual anchor is derived from the true location of non-anchor, there must be a certain relation between them. Define a new disk that centers on the position of the virtual anchor with radius $\hat{d}_{V\leftrightarrow N}$ which is the estimated distance from the virtual anchor to a nearest anchor. Therefore, the non-anchor must appear in this new disk. In geometry, there is a significantly smaller overlapping region, consisting of a new disk and bounding boxes identified by the original Bounding-Box algorithm. As a result, the new overlapping area of the Bounding-Box algorithm using a virtual anchor could be calculated as

$$(\hat{x}_u,\hat{y}_u)\in\{max[max(x_a-\hat{d}_{u\leftrightarrow a}),(V_x-\hat{d}_{V\leftrightarrow N})]\}\times\{min[min(y_a-\hat{d}_{u\leftrightarrow a}),(V_y-\hat{d}_{V\leftrightarrow N})]\},\ a=1,\ldots\ldots,k \quad \textbf{(2)}$$

where (V_x, V_y) is the location of virtual anchor.

3.2 Weighted Bounding-Box Algorithm

In fact, more hops between the non-anchor and the anchor will lead to a larger error in the distance calculation. Therefore, our scheme uses a weighted function to adjust non-anchor positions to boost their localization accuracy based on smaller overlapping areas. The weighted function gives different weights to the four vertexes of the rectangular overlapping area. The estimated location after using the weighted Bounding-Box algorithm is given as

$$(\hat{x}_u,\hat{y}_u)=\left(\frac{\sum_{i=1}^{4}\omega(x_i)\cdot x_i}{\sum_{i=1}^{4}\omega(x_i)},\frac{\sum_{i=1}^{4}\omega(y_i)\cdot y_i}{\sum_{i=1}^{4}\omega(y_i)}\right) \quad \textbf{(3)}$$

where $(\hat{x}_i,\hat{y}_i),\ i=1,\ldots\ldots,4$ is the locations of the four vertexes of the rectangular overlapping region obtained by Eq.(2). The weight function $\omega(i)$ can be described as

$$\omega(i)=\frac{1}{\sum_{i=1}^{m}\sqrt{D_{i\leftrightarrow j}^2-\hat{d}_{i\leftrightarrow u}^2}} \quad \textbf{(4)}$$

where $D_{i\leftrightarrow j}$ is the distance from anchor j to vertex i, and $\hat{d}_{i\leftrightarrow j}$ is the estimated distance from anchor j to non-anchor u. The pseudo-code of our scheme is outlined in Algorithm 1.

Algorithm 1. The weighted Bounding-Box with the virtual anchor

Input: m anchors and their locations $p_a = (x_a, y_a), a = 1, \cdots, m$; n non-anchors; preliminary estimated location $\hat{p}^{\dagger}$ obtained by other works; the estimated distance $\hat{d}$ **;** the calculated distance $\tilde{d}$.

Output: $n-m$ non-anchors' estimated locations $p_u = (\hat{x}_u, \hat{y}_u), u = m+1, \cdots, n$.

```
for u = m+1 : n do
   if neighbor_anchor_n >= 3 then
      if find((d̂(u,:) − d̃(u,:)) < 0) then
         final_loc(u,:) ← using Eq.(3);
      else
         final_loc(u,:) = p̂†
      End
      p̂_u(u,:) = final_loc(u,:);
   end
end
return p̂_u;
```

4 Performance Evaluations

To evaluate the performance of our scheme, we conduct simulations on the basis of two previous methods: (1) AFDE proposed in [15]; (2) ARFL proposed in [19]. We also compare the two original approaches and the hybrid approaches on the basis of them and our scheme. In this section, we consider that nodes and anchors are uniformly and randomly distributed in a typical letter-shaped irregular network topology, *i.e.* a C-shaped network. The maximum length and width of these irregular regions of the network is set to 300. We suggest that the Root Mean Square (RMS) [21] be used as an evaluation criterion for the accuracy of the location estimation described as follows.

$$RMS = \sqrt{\frac{\sum_{u=m+1}^{n}\left((\hat{x}_u - x_u)^2 + (\hat{y}_u - y_u)^2\right)}{n-m}} \quad \textbf{(5)}$$

where (x_u, y_u) is the true location of the non-anchor u, the estimated location of the on-anchor u is $(\hat{x}_u, \hat{y}_u)$, and $n-m$ is the total number of the non-anchors in the irregular network.

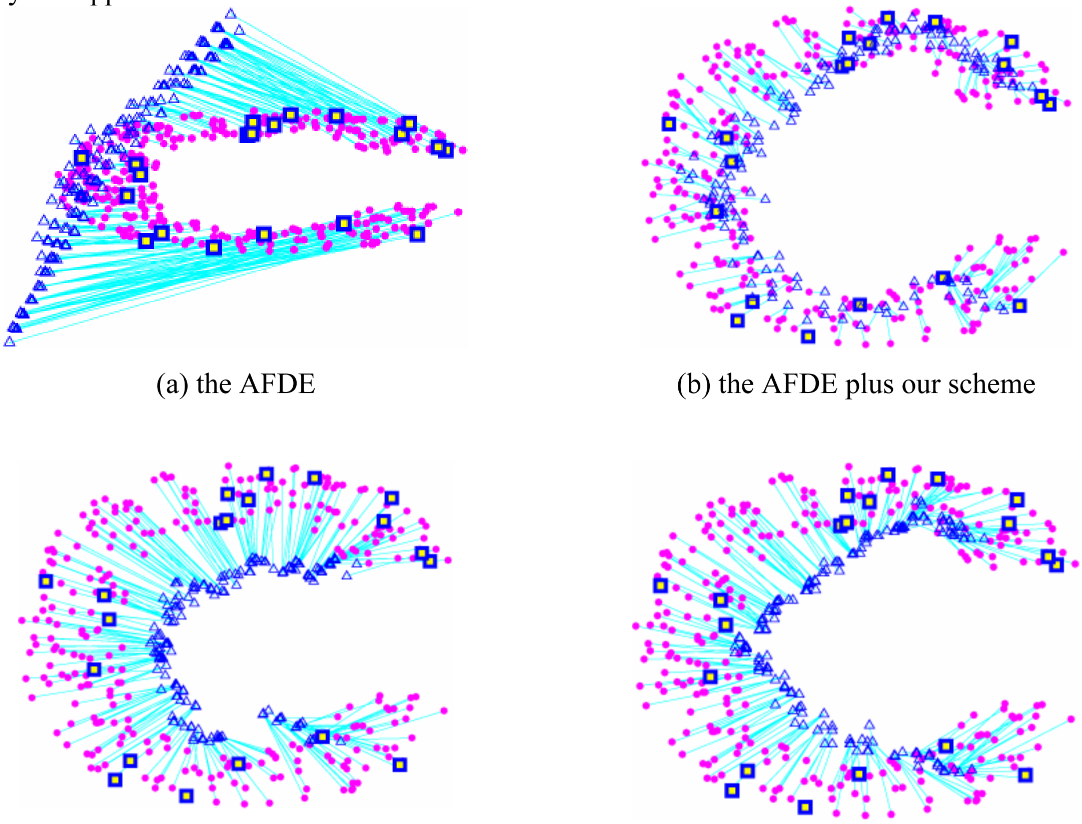
4.1 Localization Results with Irregular Deployed Nodes

In this set of simulations, 280 non-anchors are uniformly and randomly deployed in a C-shaped network (as shown in Fig. 1(a)), and 20 anchors are also uniformly and randomly deployed. Fig. 3 shows the location estimation results for each non-anchor with different localization schemes in a C-shaped network.

In this group of simulation, the maximal contact range of each node is set at $r = 34$, and the location estimation result of each node of the non-anchor is plotted in Fig. 1(a-d). The AFDE and ARFL Root-Mean-Square (RMS) errors are roughly 242.64 and 61.54, respectively. On the basis of our scheme, the RMS of AFDE and ARFL are decreased to 33.24 and 56.56 respectively.

4.2 Localization Results with Different Number Anchors

In this set of simulations, we vary the number of anchors to observe its impact on the accuracy of the location estimation. We fix the total number of nodes to 300, and set the number of anchors to range from 10 to 30 with an interval of 5. All of the reported results are re-executed 100 trials in similar scenarios per algorithm. Fig. 4 compares AFDE, ARFL, and hybrid approaches based on our scheme. The localization accuracies of two-hybrid approaches are significantly improved with the increase of anchors numbers. We can also see simultaneously that the distribution scope and median of the RMS of these hybrid approaches are the narrowest and the smallest under different anchors numbers.



(a) the AFDE (b) the AFDE plus our scheme

(c) the ARFL (d) the ARFL plus our scheme

Fig. 3. Localization results with

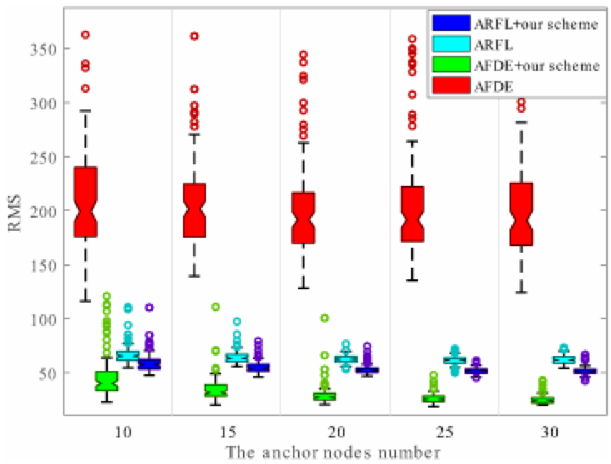


Fig. 4. Root-mean-square (RMS) error under different anchors number

5 Conclusion

In this paper, we propose a novel scheme to correct the estimation outlier of previous studies by restricting the new location toward a small area. In our scheme, we first judge whether the estimated location of the node obtained by the previous algorithm is the outlier. Then, set a virtual anchor node at the outlier estimation location, and with the help of this virtual anchor, find a smaller area where unknown nodes may exist. Finally, with the help of the weighting function, the estimation accuracy of unknown nodes is further improved. It has been demonstrated via extensive computer simulations that our scheme can effectively promote the positioning accuracy of the previous studies in the complex environment.

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