Node Localization Based on Multiple Radio Transmission Power Levels for Wireless Sensor Networks

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Abstract. The range-free node localization techniques are attractive in wireless sensor networks. However, only based on the connectivity information, the range-free schemes are usually not accurate. The transmission radio power of the sensor nodes is often adjustable and multiple levels of the transmission power correspond to multiple levels of the communication radius. Thus an improved range-free node localization algorithm inspired by multiscale virtual forces is proposed, which adopts multiscale connectivity information. The simulation results showed that the proposed approach performs well in various scenario and the localization accuracy is improved.

Keywords: Node localization · Range-free · Wireless sensor networks
Virtual force field · Multiscale virtual forces

1 Introduction

The Internet of Things (IOT) in 5G wireless networks is predicted to connect billions of smart devices over the next decades [1]. Wireless Sensor Networks (WSN) [2–4] are fundamental in the IOT. The position information of sensor nodes is widely used in many areas such as routing, surveillance and monitoring. A large number of localization algorithms have been proposed.

The node localization can be obtained with the Global Positioning System (GPS). However, it requires that all the devices are equipped with GPS modules and thus it is considered to be a costly solution in terms of money and power consumption. Also, the node position can be calculated with the help of anchor nodes. These techniques are usually economical [5] and can be classified into two categories: range-based techniques and range-free ones.

The range-based techniques usually need to measure distance with additional devices. The range-based techniques perform well with accurate distance measurements. On the contrary, the range-free algorithms only depend on the connectivity information among sensor nodes, which have some advantages such as low energy

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consumption, low cost, low noise sensitivity and high-efficiency. Many improved range-free algorithms have been proposed, and there is still a great room for improvement in localization accuracy of such range-free algorithms [6].

Note that the Radio Frequency (RF) chips which are equipped in the sensor nodes can broadcast packets with different radio power levels, and different power levels have different communication ranges. This feature may help the range-free localization schemes to obtain high localization accuracy. In this paper, an improved range-free node localization algorithm inspired by Multiscale Virtual Forces (MVF) based on multiple transmission power levels is proposed.

The organization of the paper is as follows. In Sect. 2, we review the related to range-free algorithms. In Sect. 3, we present the system model and the details of MVF algorithm. In Sect. 4, we present simulation results in various situations. Section 5 concludes this paper.

2 Related Work

Nodes localization problems have been studied for many years. A number of techniques are proposed.

Distance Vector-Hop (DV-Hop) [7] is a kind of typical range-free localization algorithm. The location process is divided into the three phase. In the first phase, nodes obtain the smallest hop-count from anchor nodes using typical distance vector exchange protocols. In the second phase, the distance matrix between nodes and anchor nodes is estimated. In the third phase, the nodes calculate their own position using the maximum likelihood estimation method [8]. Multidimensional Scaling (MDS-MAP) [9, 10] is another kind of typical localization algorithm for both range-free and range-based circumstances. It uses the distance matrix or hop matrix to solve the eigenvectors related to the top two maximum eigenvalues to construct a two-dimensional relative map. Although many improved algorithms have been proposed, the range-free techniques also suffer from the low localization accuracy and the high computational complexity.

The Virtual Forces algorithm (VF) [11] aims to get effective deployment which can provide good coverage and connectivity. Each sensor node behaves as a source of virtual force. If two sensor nodes are placed close enough, i.e. the distance between two nodes is shorter than the threshold, there will exist a virtual repulsive force. On the contrary, if a pair of nodes is too far apart from each other, there will be a virtual attractive force.

The VF algorithm combines the ideas of potential field and disk packing. The idea of VF algorithm can also be used in node localization [12]. If we consider the connectivity between any pair of nodes in the wireless sensor network as a constraint condition and construct virtual force model according to these conditions. We can use these virtual forces to push the unknown nodes to where they should be. The VF algorithm uses the neighbor lists of sensor nodes to estimate the absolute location with the help of anchor nodes. This algorithm belongs to Heuristic-based location estimation techniques. The VF algorithm can usually obtain high localization accuracy than other range-free algorithms.

3 Node Localization Algorithm with Multiscale Virtual Forces

We propose a novel algorithm named Multiscale Virtual Forces (MVF). This new algorithm extends the advantages of range-free localization algorithm: low energy consumption, low cost and low noise sensitivity. Compare with the traditional VF algorithm, the new algorithm uses multiple groups of neighbor information of each sensor node. Each sensor node broadcasts packets with multiple transmission power, each different transmission power level leads to different information. Thus it help obtain higher accuracy than the traditional virtual force algorithm.

In this section, we will propose a node localization algorithm inspired by the multiscale virtual forces corresponding to multi-level transmission power in wireless sensor networks. The underlying assumptions and the localization algorithm are described as follows.

3.1 Assumptions

We have the following assumptions:

- Each sensor node has its unique ID (identification) and can set its RF chip to various radio power levels.
- Each sensor node is fixed during the positioning process.
- For any pair of sensor nodes there exists at least one routing path, i.e. all sensor nodes are connected.
- There are a certain number of anchor nodes, which have the GPS modules. It means these anchor nodes can obtain the location information.

3.2 System Model

All the N sensor nodes including anchor nodes are $s_1, s_2, \cdots, s_N$ deployed in the sensing field. The coordination of node $s_i (1 \le i \le N)$ is (x_i, y_i). We also let $\vec{s}_i$ denote the vector (x_i, y_i). Each sensor node has K transmission power levels: $P_1, P_2, \cdots, P_K$ $(P_1 < P_2 < \cdots < P_K)$, which corresponds to a series of communication radius: $r_1, r_2, \cdots, r_K$ $(r_1 < r_2 < \cdots < r_K)$ (Fig. 1).

For any pair of sensor node (s_i, s_j), we define neighbor index $n_1(i,j)$, $n_2(i,j), \cdots, n_K(i,j)$ as

$$
\begin{aligned}
n_1(i,j) &= \begin{cases} 1, & d_{ij} \le r_1 \\ 0, & d_{ij} \ge r_1 \end{cases} \\
n_2(i,j) &= \begin{cases} 1, & d_{ij} \le r_2 \\ 0, & d_{ij} \ge r_2 \end{cases} \\
&\vdots \\
n_K(i,j) &= \begin{cases} 1, & d_{ij} \le r_K \\ 0, & d_{ij} \ge r_K \end{cases},
\end{aligned}
\tag{1}
$$

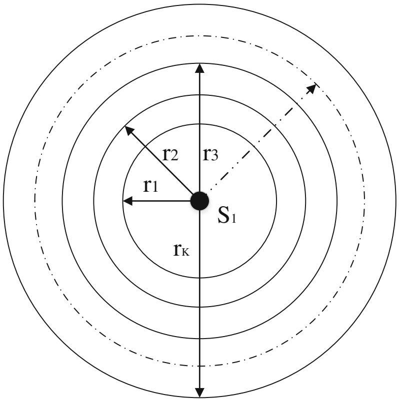

Fig. 1. Multiscale communication radius

where d_{ij} is the Euclidean distance between s_i and s_j.

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{2}$$

Every sensor node has an initial position. We assume that the initial position of unknown node s_i is $\vec{\hat{s}}_i = (\hat{x}_i \ , \hat{y}_i)$, where $\hat{x}_i$ and $\hat{y}_i$ generated randomly. For each anchor nodes s_i, the initial position $(\hat{x}_i \ , \hat{y}_i)$ is its actual position (x_i, y_i).

We define multiscale virtual force $f_1(i,j), f_2(i,j), \cdots, f_K(i,j)$ as

$$\vec{f}_1(i,j) = \begin{cases} \lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j), & \hat{d}_{ij} > r_1 \ and \ n_1(i,j) = 1 \\ -\lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j), & \hat{d}_{ij} < r_1 \ and \ n_1(i,j) = 0 \\ 0, & else \end{cases}$$
$$\vec{f}_2(i,j) = \begin{cases} \lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j), & \hat{d}_{ij} > r_2 \ and \ n_2(i,j) = 1 \\ -\lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j), & \hat{d}_{ij} < r_2 \ and \ n_2(i,j) = 0 \\ 0, & else \end{cases} \tag{3}$$
$$\vdots$$
$$\vec{f}_k(i,j) = \begin{cases} \lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j), & \hat{d}_{ij} > r_k \ and \ n_k(i,j) = 1 \\ -\lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j), & \hat{d}_{ij} < r_k \ and \ n_k(i,j) = 0 \\ 0, & else \end{cases},$$

$$\hat{d}_{ij} = \sqrt{(\hat{x}_i - \hat{x}_j)^2 + (\hat{y}_i - \hat{y}_j)^2}, \tag{4}$$

where $\hat{d}_{ij}$ is the Euclidean distance between estimated nodes location $\vec{\hat{s}}_i$ and $\vec{\hat{s}}_j$;λ is a positive parameter called the learning rate; $\lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j)$ represents the attractive force between two nodes, and $-\lambda(\vec{\hat{s}}_i - \vec{\hat{s}}_j)$ represents the repulsive force.

We define the net force on a node s_i is the vector sum of all the above the forces:

$$F_i = \sum_{L=1}^{K} \sum_{j=1, i \neq j}^{N} \vec{f}_L(i,j) \tag{5}$$

3.3 Operation of the Localization Algorithm

The detailed steps of the MVF algorithm are as follows:

Step 1. All the sensor nodes broadcast packets with transmission power: $P_1, P_2, \cdots, P_K$. The data packets include ID of the source node, the information of

ID	Power level P_i	Position (x_i, y_i)

Fig. 2. The packet structure

transmission power level and the current position of the sensor node (Fig. 2).

Step 2. If node s_i can receive the packets broadcasted with power P_K from s_j, we can know that $d_{ij} \leq r_k$. Node receives all the packets and organizes the information

Table 1. The information of packets that the sensor node receives and organizes

j	1	2	…	N
$n_1(i, j)$	1	1	…	0
$n_2(i, j)$	1	1	…	0
…	…	…	…	…
$n_K(i, j)$	0	1	…	0

into Table 1 where i and j are ID of the destination node and source node:

Step 3. Each sensor node sends the table to the center node.

Step 4. The center node collects all the table of sensor nodes. Then the location data is calculated with the following algorithm.

We assume that the initial position of each unknown node is $\vec{\hat{s}}_i^{(0)} = (\hat{x}_i^{(0)}, \hat{y}_i^{(0)})$, $1 \leq i \leq N$. Then we can use (3) (4) to calculate $f_1^{(0)}(i,j), f_2^{(0)}(i,j), \cdots, f_K^{(0)}(i,j)$ and use (5) to calculate the net force $F_i^{(0)}$. New estimated by locations $(\hat{x}_i^{(1)}, \hat{y}_i^{(1)})$ are calculated.

$$(\hat{x}_i^{(1)}, \hat{y}_i^{(1)}) = \vec{\hat{s}}_i^{(1)} = \vec{\hat{s}}_i^{(0)} + \alpha F_i^{(0)} \tag{6}$$

Here the symbol α is a coefficient to indicates the virtual inertia of the nodes.
Step 5. We use the new locations to repeat Step. 4 for the next movement. After the number of iteration reaches M (the max number of iterations), the algorithm stops. We denote the final results as

$$\vec{\hat{s}}_i = \vec{\hat{s}}_i^{(M)} = (\hat{x}_i^{(M)}, \hat{y}_i^{(M)}), 1 \le i \le N \tag{7}$$

Step 6. The center node sends the final positions to all sensor nodes.

4 Performance Evaluation

In order to assess and verify the performance of the proposed algorithm, multiple simulations have been done using python, numpy and matplotlib. All the sensor nodes in the network are deployed randomly in area 100 × 100 (where the distance unit is arbitrary) and the number of sensor nodes is N. We compare the MVF algorithm and other similar algorithm, including the basic DV-Hop algorithm, MDS-MAP algorithm and the VF algorithm. In all of the experiments, the metric used to evaluate the localization methods is the Mean Localization Error (MLE).

$$MLE = \frac{1}{N}\sum_{i,j=1}^{N} \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2}, \tag{8}$$

where $(\hat{x}_i, \hat{y}_i)$ are the coordinates of the estimated location of s_i and (x_i, y_i) are the coordinates of the actual location of node s_i.

We denote VF(r) as the node localization algorithm with Single Virtual Force, MDS-MAP(r) as the algorithm with MDS-MAP, DV-Hop(r) as the node localization algorithm with DV-Hop, where r represents the communication radius corresponding to the power. We denote MVF $(r_1, r_2, \cdots, r_K)$ as the node localization algorithm with Multiscale Virtual Forces, $r_1, r_2, \cdots, r_K$ represent the multiscale communication radius sequence.

Figure 3 shows the iteration times of two localization algorithm with VF and MVF. The number of sensor nodes is 100 and the density of anchor nodes is 15%. The communication radius of MVF algorithm is set to 10, 15, 20. In order to compare VF and MVF algorithm, the communication radius of VF algorithm is set to 10, 15, 20 respectively. We find that when the iteration count of VF and MVF algorithms increase, the localization errors of the algorithm decreases. When the iteration count reach about 100, the localization errors of both VF and MVF algorithms tend to be

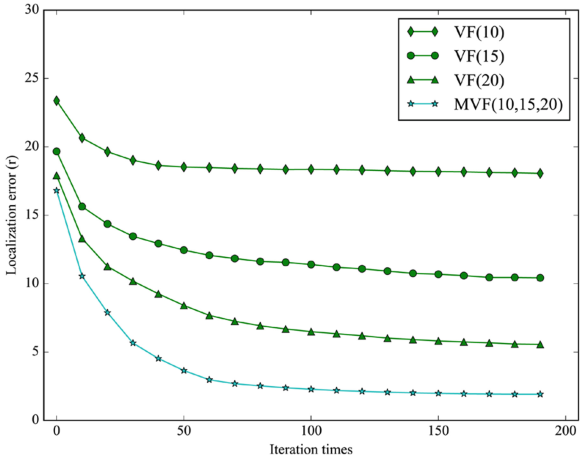

Fig. 3. Localization performance comparison at different iteration times

steady. The localization errors of MVF algorithms are lower than all the VF algorithms obviously.

Figure 4 shows the localization errors of MVF algorithm is lower than other algorithm if the ratio of the anchor nodes is big enough. Note that the MVF algorithm uses the multiple communication ranges. The wide communication range is for coarse-grained positioning and the narrow communication range is for fine-grained

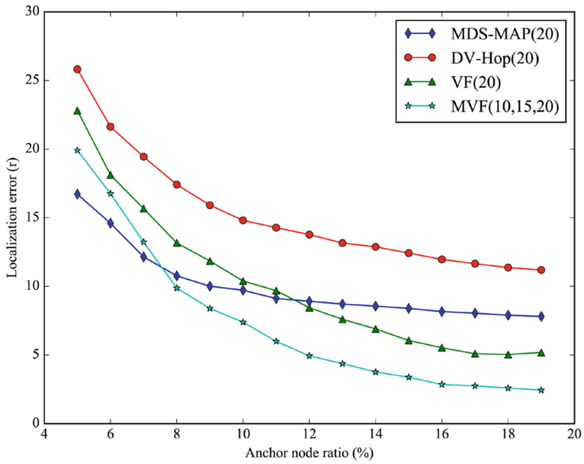

Fig. 4. Localization performance comparison at different ratio of anchor node

positioning. Thus the connectivity information for different communication range improves the performance of the MVF algorithm.

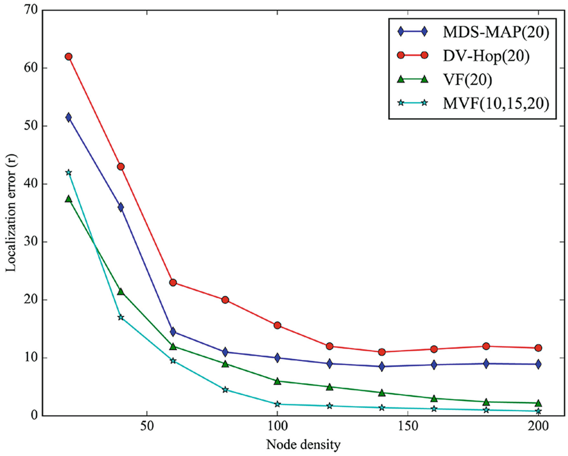

Fig. 5. Localization performance comparison at different node density

Figure 5 shows the localization error at different node density. The iteration count is 100 and the ratio of anchor nodes is 15%. We find that with the increasing of the node density, the localization errors of these algorithm decreases. When the node density is greater than 100, the localization errors of these algorithms tend to be steady. The localization error of MVF algorithm is lower than other algorithms if the node density is reasonable high.

5 Conclusion and Future Work

Positioning is an important technology for the IOT. This paper proposes an improved node localization algorithm in wireless sensor networks. It does not require additional hardware and thus suits for a wide range of application scenarios. It depends on multiple radio power levels to reach high-precision positioning. The results show that our algorithm can obtain higher localization accuracy than other existing algorithms in the dense networks. Our future work will address the fundamental questions of how to choose the best group of transmission power levels.

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