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# LMAT: Localization with a Mobile Anchor node based on Trilateration in Wireless Sensor Networks

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***Abstract*—Currently, in Wireless Sensor Networks (WSNs), the main idea in most localization algorithms has been that a mobile anchor node, e.g., GPS-equipped (Global Positioning System) nodes, broadcasts its coordinates to locate unknown nodes. In this case, a basic problem is the path planning of the mobile anchor node which should move along the trajectory to minimize the localization error and locate the unknown nodes. In this paper, we propose a Localization algorithm with a Mobile Anchor node based on Trilateration (LMAT). LMAT algorithm uses a mobile anchor node to move according to the equilateral triangle trajectory in deployment area. Simulation results show that the performance of our LMAT algorithm is better than that of other similar algorithms, e.g., SPIRAL, SCAN, DOUBLE SCAN and HILBERT algorithms.**

## I. Introduction

One critical research issue in WSNs is to determine the physical locations of unknown nodes. Sensed data in WSNs is meaningful to most applications only when it is labeled with geographical information. In addition, location information is essential to many location-aware sensor network communication protocols, e.g., geographical routing. It has been a challenging task to design a practical localization algorithm for nodes due to the limited resources imposed on sensors, e.g., energy.

Existing localization algorithms [1], [2], [3], [4], [5], [6] are mostly classified into two categories: anchor node-based and anchor node-free [1], [2]. In anchor node-based schemes, an anchor node can acquire its own position in advance using GPS systems or artificial arrangement to locate unknown nodes. In anchor node-free schemes, the unknown nodes are located using the connectivity information between unknown nodes and anchor nodes. Compared to anchor node-free schemes, anchor node-based schemes achieve better localization accuracy. However, some anchor node-based schemes [3], [4], [5], [6] require a large number of anchor nodes to locate unknown nodes, which increases the energy consumption and hardware cost of WSNs. Thus, using mobile anchor nodes is considered to maximize the localization accuracy and decrease the energy consumption of WSNs.

In this case, the path planning of the mobile anchor node becomes a fundamental research problem [7]. The problem is discussed in [8], in which the researchers draw two important conclusions. First, when a mobile anchor node closes to an unknown node, the unknown nodes can be located with high accuracy. Because in that case the Received Signal Strength (RSS) value of the unknown node is the largest. Second, if three beacon positions of the anchor node are in one line with an unknown node, the node cannot determine on which side of the line it is, thus the unknown node cannot be located. However, in this research they neglect to consider any specific trajectory for the mobile anchor node. To solve the trajectory problem for the mobile anchor node, we need to find answers for several basic issues, i.e., 1) what the optimal path of the mobile anchor node is, while the travelling anchor node must cover the entire WSN during the localization process of unknown nodes and the travelling trajectory length of the anchor node should be as short as possible to guarantee the localization efficiency, 2) when and where the anchor node should send its position information to the unknown nodes.

In this paper, LMAT is proposed based on the idea of RNST (Reference Node placement and Selection algorithm based on Trilateration) [9]. In LMAT, the mobile anchor node traverses the entire WSN along the boundaries of the equilateral triangles. The proposed equilateral triangle trajectory can guarantee all the unknown nodes receive message packets and obtain their estimated positions. Compared to random movement of the anchor node, LMAT can significantly reduce the localization error. Furthermore, LMAT is compared with four different deterministic trajectories, namely SCAN, DOUBLE SCAN, HILBERT [7], and SPIRAL [10]. Simulation results show that the proposed LMAT algorithm offers better performance than that of the above four trajectories.

The rest of paper is organized as follows. Section 2 describes the theoretical background of the proposed LMAT algorithm. Details of the LMAT algorithm are discussed in Section 3. Simulation results and performance analysis are shown in Section 4. Finally, Section 5 summarizes our results.

## II. Network Model and Background Information

### A. Network Model

The considered WSN consists of a number of randomly deployed unknown sensor nodes, and one mobile anchor node. The WSN has the size $L \times h$. All unknown nodes and the mobile anchor node have the same communication radius $r$, which is adjustable. The mobile anchor node periodically sends position message packet with itself coordinates. When an unknown sensor node receives three message packets, it can calculate itself coordinates using the trilateration method. We assume that the distance between the mobile anchor node and any unknown node is estimated using RSSI technique. Taking into account the radio signal propagation loss, we assume beacon packet can only be received by unknown nodes in a circular region within the communication radius.

### *B. Energy Model*

Based on the first order model [11], the energy consumption of an anchor node for sending a message with $k$ bits to an unknown node is calculated by

$$E_{Tx}(k, \tilde{d}) = E_{Tx} \times k + \varepsilon_{amp} \times k \times \tilde{d}^2 \tag{1}$$

where $\tilde{d}$ is the calculated communication distance between the anchor and unknown node, $\tilde{d} \leq r$.

### *C. Optimal Beacon Position Problem*

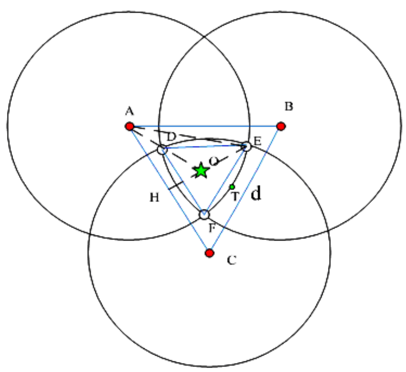


Fig. 1. Optimal Beacon Position. Three circles intersect each other. The centers of three circles are denoted as A, B, C, respectively. The lengths of AB, BC and AC are $d$. H represents the midpoint of AC.

The geometric problem of the optimal beacon position for mobile anchor nodes is how to use the minimum number of beacon message packets to cover the deployment area, and each node at least are covered by 3 circles, as shown in Fig.1.

**Theorem 1** In a WSN area, a mobile anchor node moves along the equilateral triangle trajectory with the communication radius $r$. When the side length of the equilateral triangle is $\sqrt{3}r$, the coverage area without hole is the largest.

**Proof:** As shown in Fig.1, $HE = \sqrt{AE^2 - AH^2} = \sqrt{r^2 - \frac{d^2}{4}}$ and $OH = \frac{\sqrt{3}}{6}d$. Therefore,

$$OE = HE - OH = \sqrt{r^2 - \frac{d^2}{4}} - \frac{\sqrt{3}}{6}d \tag{2}$$

Since $OE = \frac{\sqrt{3}}{3}DE$, we can derive $DE = \sqrt{3r^2 - \frac{3}{4}d^2} - \frac{1}{2}d$ and $S_{\Delta DEF} = \frac{\sqrt{3}}{4}DE^2$. Then since $S_{\widehat{D}\widehat{E}\widehat{F}} = S_{\Delta DEF} + 3\mathrm{S}_{\mathrm{ETF}}$. Thus

$$\mathrm{S_{ETF}} = \mathrm{S}_{\widehat{\mathrm{A}}\widehat{\mathrm{E}}\widehat{\mathrm{F}}} - \mathrm{S}_{\Delta \mathrm{AEF}} = r^2 \arcsin\frac{DE}{2r} - \frac{DE}{4}\sqrt{4r^2 - DE^2} \tag{3}$$

can be deduced as

$$S_{\widehat{D}\widehat{E}\widehat{F}} = \frac{\sqrt{3}}{4}\left(\sqrt{3r^2 - \frac{3}{4}d^2} - \frac{1}{2}d\right)^2 + 3r^2 \arcsin\frac{DE}{2r} - \frac{3DE}{4}\sqrt{4r^2 - DE^2} \tag{4}$$

To maximize the coverage area without hole, then the overlap region $S_{\widehat{D}\widehat{E}\widehat{F}}$ of three circles needs to be minimized. Thus, when $\frac{\partial S_{\widehat{D}\widehat{E}\widehat{F}}}{\partial d} = 0$, we can obtain $d = \sqrt{3}r$. ■

According to Theorem 1, when all sensor nodes use the same communication radius to cover the entire WSN area, the problem of minimum beacon packets is equivalent to minimize the overlap region among nodes. When a mobile node moves along the boundaries of the equilateral triangles and the side of each equilateral triangle is $\sqrt{3}r$, the node coverage without hole reaches the best. And all unknown nodes can receive at least 3 non-collinear beacons to estimate their coordinates.

## III. LMAT Algorithm

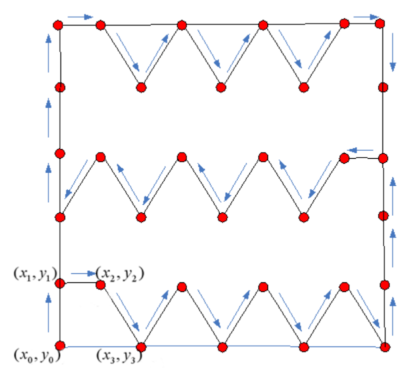


Fig. 2. Travelling trajectory of an anchor node in LMAT algorithm.

We propose the equilateral triangle trajectory based on the idea of Optimal Beacon Position Problem. The steps of our proposed algorithm LMAT are shown in Table I and illustrated by the example in Fig.2, where the trajectory of an anchor node from $(x_0, y_0)$ has been indicated by concatenated arrows.

TABLE I
Steps of LMAT algorithm

| | |
|---|---|
| 1 | An anchor node moves based on the equilateral triangle trajectory in a WSN area (the detail trajectory of the anchor node is explained in Fig.2). The mobile anchor node periodically broadcasts position messages to unknown nodes at each red point in Fig.2, which denotes the message sending time and place of the anchor node. |
| 2 | The unknown nodes calculate the distances based on the received three position messages using RSSI technique, then judge if the three messages can form an equilateral triangle. |
| 3 | Compute the estimated locations of the unknown nodes based on the trilateration method. If the unknown nodes are on the border of the deployment area, we can compute the estimated locations of the unknown nodes using the approximate equilateral triangles, which can be obtained by adjusting the communication radius based on the length or width of the deployment area. |

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### A. LMAT Contribution: Trajectory Optimization Strategy

In a real environment, most localization algorithms do not take different shapes of the WSN area into consideration. To improve the localization coverage and accuracy of unknown nodes, LMAT algorithm optimizes the travelling trajectory of an anchor node by adjusting the communication radius to suit the different sizes of the deployment area in a WSN.

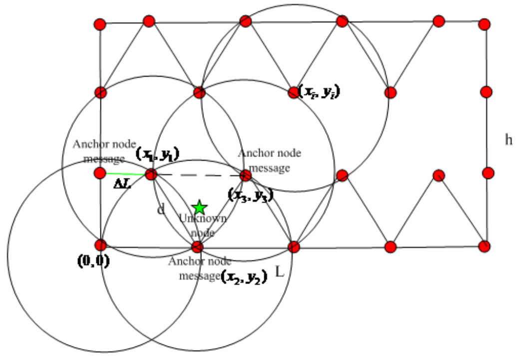


Fig. 3. Deployment area.

**Theorem 2** $n_L$ and $n_h$ are calculated by $n_L = \lceil \frac{L}{d} \rceil$, $n_h = \left\lceil \frac{2h}{\sqrt{3}d} \right\rceil$, where $n_L$ and $n_h$ denote the minimum number of transmission message packets when the deployment area is $L \times h$, and L, h denote the length and width of the deployment area, respectively.

**Proof:**

As shown in Fig. 3, $\Delta L = d \times \cos\frac{\pi}{3}$. To guarantee each unknown node in the WSN can receive at least three position message packets, $n_L$ and $n_h$ are required to meet the following inequality:

$$n_L \geq \frac{L + d - 2\Delta L}{d} = \frac{L + d - 2d \times \cos\frac{\pi}{3}}{d} = \frac{\mathrm{L}}{d} \tag{5}$$

and

$$n_h \geq \frac{2h}{\sqrt{3}d} \tag{6}$$

Simple computations can get $n_L = \lceil \frac{L}{d} \rceil$ and $n_h = \left\lceil \frac{2h}{\sqrt{3}d} \right\rceil$

In order to obtain the highest localization coverage and accuracy, the side of equilateral triangle $d$ should be appropriate to the length and width of the deployment area to guarantee that $\frac{L}{d}$ and $\frac{2h}{\sqrt{3}d}$ are close to an integer. The value of $d$ can be adjusted by the communication radius $r$ to ensure the unknown nodes on the edge of the WSN can be located.

### B. The energy consumption of anchor node in the LMAT algorithm

The energy consumption of the mobile anchor node is composed of two parts: the energy consumption for sending messages $E_{sen}$ and travelling $E_{tra}$. Thus, the total energy consumption of the mobile anchor node can be calculated by $E_{total} = E_{sen} + E_{tra}$. $E_{sen} = m \times E_{T_x}(k, \tilde{d})$ and $E_{tra} = l \times E_{ave}$, where $m$ and $l$ denote the total number of messages and the travelling length of the anchor node, $E_{T_x}(k, \tilde{d})$ is the energy consumption for sending each message, and $E_{ave}$ denotes the energy consumption for travelling 1 meter.

*1) Trajectory based on length L:* For trajectory based on length L,

$$l = \frac{2Lh}{\sqrt{3}r} + h + \sqrt{3}r \tag{7}$$

$$m = \frac{2Lh}{\sqrt{3}r^2} + \frac{2h}{\sqrt{3}r} \tag{8}$$

therefore,

$$\begin{aligned} E_{total}(L) = &(\frac{2Lh}{\sqrt{3}r^2} + \frac{2h}{\sqrt{3}r}) \times E_{T_x}(k, \tilde{d}) \\ &+ \left(\frac{2Lh}{\sqrt{3}r} + h + \sqrt{3}r\right) \times E_{ave} \end{aligned} \tag{9}$$

*2) Trajectory based on width h:* For trajectory based on width h,

$$l = \frac{2Lh}{\sqrt{3}r} + L + \sqrt{3}r \tag{10}$$

$$m = \frac{2Lh}{\sqrt{3}r^2} + \frac{2L}{\sqrt{3}r} \tag{11}$$

therefore,

$$\begin{aligned} E_{total}(h) = &(\frac{2Lh}{\sqrt{3}r^2} + \frac{2L}{\sqrt{3}r}) \times E_{T_x}(k, \tilde{d}) \\ &+ \left(\frac{2Lh}{\sqrt{3}r} + L + \sqrt{3}r\right) \times E_{ave} \end{aligned} \tag{12}$$

If $h < L$ and $E_{total}(h) < E_{total}(L)$, trajectory based on width $h$ is used to save the energy consumption, and other else $h > L$ and $E_{total}(h) > E_{total}(L)$, trajectory based on length $L$ is chosen.

### C. The travelling length of anchor node in the LMAT algorithm

We assume $L = h$, the travelling length of an anchor node in LMAT, SPIRAL, SCAN, DOUBLE SCAN and HILBERT algorithms are calculated respectively as

$$D_{LMAT} = \frac{2}{\sqrt{3}} \times L \times \left\lceil \frac{L}{r} \right\rceil + (L + \sqrt{3}r) \tag{13}$$

$$D_{SPIRAL} = \sum_{t=1}^{\lceil \frac{L}{r} \rceil} \sqrt{r^2 + 4r^2\pi^2t^2 + 4r^2t\sin 4\pi t} \tag{14}$$

$$D_{SCAN} = (\frac{L}{r} + 2) \times L \tag{15}$$

$$D_{DOUBLESCAN} = 2\left[\left(\frac{L - r}{2r} + 2\right) \times L - r\right] \tag{16}$$

$$D_{HILBERT} = \frac{(L + r)^2}{r} \tag{17}$$

When the communication radius of the mobile anchor node is 40m and the deployment area is 100m*100m, we can calculate the anchor node's travelling length of LMAT algorithm is 459m, which of SPIRAL, SCAN, DOUBLE SCAN and HILBERT algorithms are 493m, 450m, 470m and 490m, respectively.

TABLE II
SIMULATION PARAMETERS

| Parameter | Value |
|---|---|
| Network size (m) | 100*100 |
| Unknown nodes' number (n) | 100 |
| Radio range (m) | 10, 15, 20, 25, 30, 35, 40 |
| Moving speed ( v m/sec) | 0.5, 1, 2, 3, 4 |
| Node density ($\rho$) | 3.53, 5.46, 9.73, 12.36, 16.12, 19.47 |
| Standard deviation of noise ($\sigma$) | 2, 4, 6, 8, 10, 12, 14 |

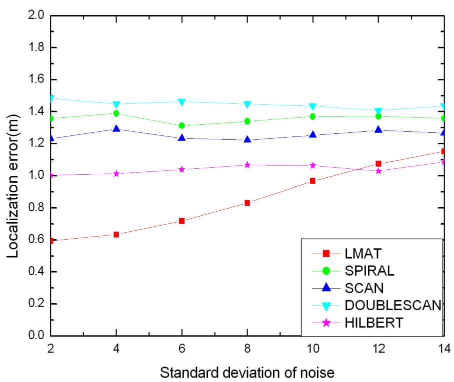


Fig. 4. Localization error vs. standard deviation of noise.

## IV. PERFORMANCE ANALYSIS AND COMPARISON

Our simulations are performed using NS2 simulator [12]. We implemented two different sets of simulations. First, we compare the robustness of the five different travelling trajectories, namely LMAT, SPIRAL, SCAN, DOUBLE SCAN and HILEBERT algorithms based on different influence factors. Then, we evaluate the localization accuracy of the five travelling trajectories under the same simulation conditions. The deployment area is set to be 100m*100m. Each position information packet has 512bits, carrier frequency is 914MHz, and transmission rate is 100kbps. Other parameters are listed in Table II. In all scenarios, unknown nodes are static with an anchor node moving based on the specific trajectory.

### *A. The robustness of the five different travelling trajectories*

*1) Standard deviation of noise:* The localization algorithms need a good environment and a reliable wireless communication device to locate unknown nodes. However, in a realistic environment, multipath fading due to phenomenon, such as reflections, scatterings, etc., cause large random signal variations. Hence, the distance measurement technology is important. We have done simulations for the scenarios where

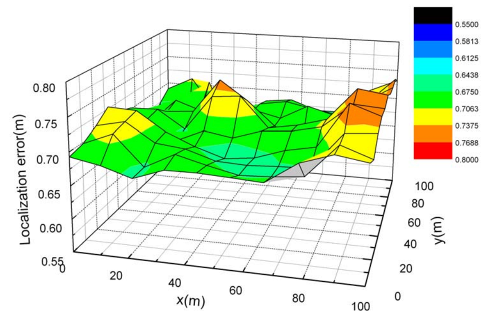


Fig. 5. Standard deviation of localization error is 6.

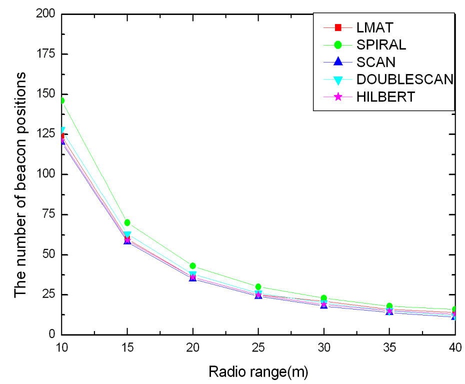


Fig. 6. The number of beacon positions vs. radio range.

the communication radius of an anchor node is 10m and the standard deviation of noise ranges from 2 to 14. It is observed (see Fig.4 and Fig.5) that LMAT algorithm is sensitive to the standard deviation of noise. The distance measurement error increases as the standard deviation grows, hence the localization error increases.

As shown in Fig.4, the localization error increases as the standard deviation increases from 2 to 10. We can see that LMAT algorithm outperforms other algorithms. Because the received message packets of the anchor node form an equilateral triangle to minimize the localization error. But the positions of sending message packets in other algorithms are random. In Fig.4, it is observed that the standard deviation of noise has little influence on SPIRAL, SCAN, DOUBLE SCAN and HILEBERT algorithms. These algorithms calculate the estimated coordinates of unknown node using the centroid formula. In this case, the beacon positions are in the range of unknown nodes, so the localization errors of those algorithms almost do not change. When the standard deviation of noise is 2, the localization error of LMAT algorithm is only 0.5944m, while that of SPIRAL, SCAN, DOUBLE SCAN and HILEBERT algorithms are 1.3572m, 1.2319m, 1.4852m and 1.0034m, respectively. Fig.5 shows the three-

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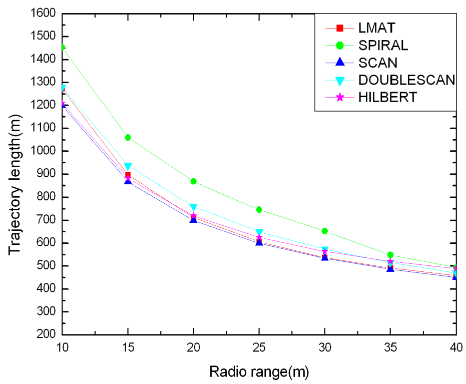


Fig. 7. Travelling length vs. radio range.

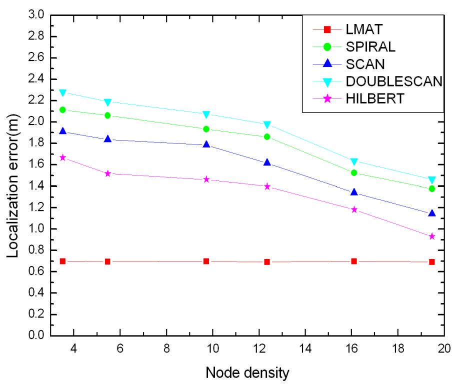


Fig. 8. Localization error vs. node density.

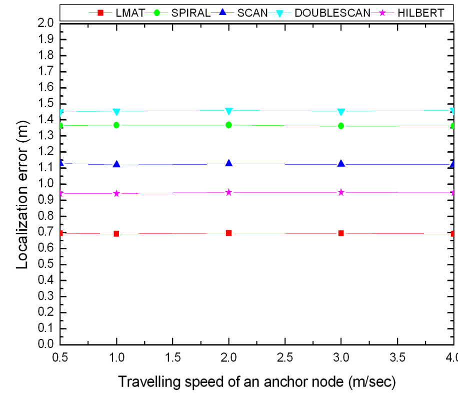


Fig. 9. Localization error vs. travelling speed of an anchor node.

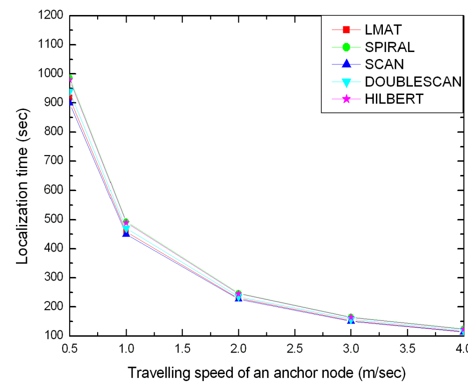


Fig. 10. Localization time vs. travelling speed of an anchor node.

dimensional distribution of LMAT's localization error. The standard deviation of the localization error is 6. We can see that the localization error of most unknown nodes is less than 0.75m. Only few nodes are located with a maximum localization error about 0.7625m. This is because the beacon positions near the border of the deployment area cannot form an equilateral triangle.

*2) Radio range:* As shown in Fig.6 and Fig.7, for each algorithm, the number of beacon positions and the travelling length decrease as the radio range increases. It shows that LMAT algorithm has better performance than SPIRAL, SCAN, DOUBLE SCAN and HILEBERT algorithms. In particular, the number of beacon positions and trajectory length of SPIRAL are significantly greater than that of LMAT. Although the number of beacon positions and trajectory lengths of SCAN and HILEBERT are relatively small, the beacons of two algorithms cannot completely cover the deployment area. Therefore, the localization accuracies of them are low. Compared with SCAN and HILEBERT algorithms, LMAT algorithm can be used in deployment areas with various types of shapes and certain level of irregularities.

*3) Node Density of unknown nodes:* Node density in a deployment area is of great significance to the performance of the localization algorithm, since high density of unknown nodes increases not only network energy consumption but also the communication overload among sensor nodes. As shown in Fig.8, node density, when ranging from 3.53 to 19.47, has little influence on LMAT, which outperforms other algorithms with higher localization accuracy.

*4) Travelling Speed of Anchor Node:* Fig.9 and Fig.10 plot the localization error, localization time of an unknown node against the travelling speed (from 0.5m/sec to 4m/sec) of an anchor node, respectively. It shows that, while the travelling speed greatly influences the localization time, it barely affects the localization error. It also shows that LMAT significantly outperforms other algorithms, since the equilateral triangle trajectory in LMAT can guarantee the least localization error of an unknown node.

### *B. The localization accuracy of the five travelling trajectories*

*1) Comparison of the localization error:* We compare the localization error of SPIRAL, SCAN, DOUBLE SCAN, HILEBERT, and LMAT algorithms. As shown in Fig.11, it is obvious that the performance of the LMAT algorithm is better than that of other algorithms. When the communication radius of the anchor node is 40m, LMAT has the least localization error about 0.68m.

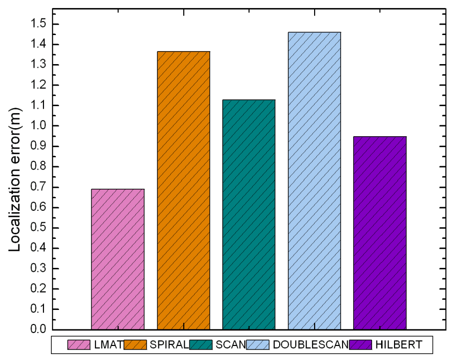


Fig. 11. Localization error of different trajectories.

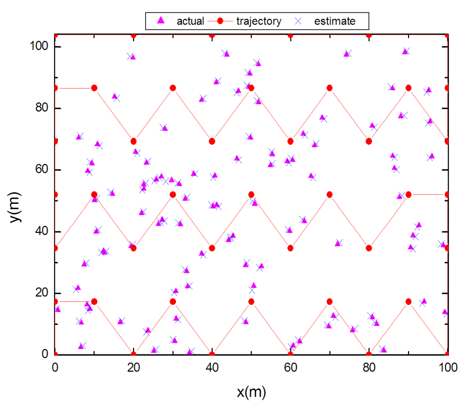


Fig. 12. Comparison of real and estimated positions in a deployment area.

*2) The localization accuracy of LMAT:* When the deployment area is 100m*100m, the mobile anchor node cannot form an equilateral triangle on the border of the deployment area, due to the fact that $\frac{h}{\sqrt{3}r}$ is not an integer. Thus the localization of the unknown nodes, which are located near the border of deployment area, is not accurate. To solve this problem, we virtually extend the dimensions of the deployment area by 4m on $h$ side ao that $\frac{h}{\sqrt{3}r}$ is an integer.

Fig.12 shows comparison between the real and estimated positions of the unknown nodes and the trajectory of the mobile anchor node in the deployment area. We observe that most of estimated positions are very close to real positions of unknown nodes. We can also see one special case described above, the localization error of the unknown nodes near the border is bigger. When the three beacon positions on the border of the deployment area do not form an equilateral triangle, the localization error of the unknown node is large.

## V. CONCLUSION

In this paper, we draw a conclusion that the path planning of a mobile anchor node directly affects the performance of localization in a WSN. In the path planning of the anchor node, there are two main factors need to be considered: the localization accuracy and the energy consumption of WSN. A specific trajectory can significantly decrease the localization error of unknown nodes, compared to a random one, and also guarantee that unknown nodes can obtain high localization accuracy. The comparison between the five trajectories shows that LMAT algorithm outperforms SPIRAL, SCAN, DOUBLE SCAN, and HILBERT algorithms. We analyze the localization error of unknown nodes and draw the conclusion that the localization error of unknown nodes is the least when the trajectory of mobile anchor node forms equilateral triangles. Simulation results show that our LMAT algorithm can greatly improve the localization accuracy of unknown nodes.

## ACKNOWLEDGMENT

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