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Reference node placement and selection algorithm based on trilateration for indoor sensor networks

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Summary

The key problem of location service in indoor sensor networks is to quickly and precisely acquire the position information of mobile nodes. Due to resource limitation of the sensor nodes, some of the traditional positioning algorithms, such as two-phase positioning (TPP) algorithm, are too complicated to be implemented and they cannot provide the real-time localization of the mobile node. We analyze the localization error, which is produced when one tries to estimate the mobile node using trilateration method in the localization process. We draw the conclusion that the localization error is the least when three reference nodes form an equilateral triangle. Therefore, we improve the TPP algorithm and propose reference node selection algorithm based on trilateration (RNST), which can provide real-time localization service for the mobile nodes. Our proposed algorithm is verified by the simulation experiment. Based on the analysis of the acquired data and comparison with that of the TPP algorithm, we conclude that our algorithm can meet real-time localization requirement of the mobile nodes in an indoor environment, and make the localization error less than that of the traditional algorithm; therefore our proposed algorithm can effectively solve the real-time localization problem of the mobile nodes in indoor sensor networks. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: indoor sensor networks; reference node; RNST algorithm; trilateration location; localization error

1. Introduction

Wireless sensor networks (WSNs) have been attracting increasing research interest given the recent advances in miniaturization, low-cost, and low-power design. WSNs hold the promise of many new applications in the area of monitoring and control. Spatial localization (determining physical location) of a sensor node is an example of critical service for context-aware applications in WSNs. Examples include target tracking, intrusion detection, wildlife habitat monitoring, climate control, and disaster management [4]. Most of the applications are related to the positions of sensor nodes; sensing data without the position information of the sensor nodes are not useful, thus self-localization is the basic application in a WSN [1]. Sensor nodes often need to determine their further actions based on their physical locations. To precisely

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obtain the position information of a mobile node is the key of the location service, therefore how to efficiently and precisely acquire the mobile nodes' position information, and being able to provide the location service to the user, is one of the important problems in WSNs.

In an indoor environment, one of the major challenges for researchers is to localize the sensor nodes with relatively high localization precision. For military radio networks, knowing the precise location of each person with a radio can be critical. In offices and in warehouses, object localization and tracking applications are possible with large-scale ad-hoc networks of wireless tags. Existing geo-location systems such as GPS do not always meet the operational (e.g., power), environmental (e.g., indoors) or cost constraints in indoor sensor networks. It is also impractical to configure the position information for every node in an indoor environment. Therefore, reference nodes with their positions are vital aspects of nearly every localization system; the mobile nodes get their own positions based on the position information of reference nodes using localization techniques, including RSSI, AoA, ToA/TDoA, etc. In the past few years, a number of positioning algorithms have been proposed to reduce the localization error of the mobile nodes. Many researches dealt with the node localization issues without taking into account the ''reference node'' parameter, however reference node placement also strongly affects the quality of spatial localization [2,3].

In this paper, we analyze the localization error, which is produced when one tries to estimate the mobile node using trilateration method in the localization process. We draw the conclusion that the localization error is the least when three reference nodes form an equilateral triangle. Our analysis provides theoretical foundation for purposefully selecting the suitable reference nodes to reduce the localization error in indoor sensor networks. We improve the TPP algorithm and propose a novel RNST positioning algorithm, which can satisfy the real-time localization requirement of the mobile nodes. We also implement our proposed RNST algorithm using the network simulator OPNET and actual Zigbee sensor platform, and make a comparison with the TPP algorithm. The experimental results show that our algorithm can effectively meet real-time localization requirement of the mobile nodes with limited resources. Moreover our algorithm can also guarantee the minimum localization error within a short time period and effectively meet the localization precision requirement of the mobile nodes. Compared to the existing approaches, RNST algorithm is able to quickly estimate the position of the mobile node based on the received packets. To the best of our knowledge, this is the first comprehensive work on reference node selection algorithm based on trilateration.

This paper is organized as follows. In Section 2, we list the related work in more details. In Section 3, we present the theoretical background of our proposed RNST algorithm. We present our RNST algorithm and analyze the reasons of the localization error in Section 4. The simulation results and performance analysis are shown in Section 5. Finally, in Section 6 we summarize our results and predict future work.

2. Related Work

Since many applications need to know where objects or persons are and various location services need to be provided, the localization problem has received considerable attention in the past. Many localization approaches have been proposed specifically for sensor networks, which are generally classified into two phases [1]. The first phase mainly focuses on localization schemes tightly coupled to infrastructure frameworks, such as RADAR, active bat, active badge, smart rooms, etc. The second phase mainly focuses on localization schemes loosely coupled to infrastructureless frameworks, including cricket [5], self-positioning algorithm (SPA) [6], convex position estimation [7], ad hoc positioning system (APS) [18], cooperative ranging [8] and TPP [9] algorithm, ad-hoc localization system (AHLos) [10] and N-hop multilateration primitive [11], generic localized algorithms [19], MDS-MAP [20], etc. Recently researchers have focused on iterative precision algorithm, such as cooperative ranging, TPP algorithm, and N-hop multilateration primitive. The position information of the unknown node is initially estimated using the traditional algorithms, and is improved by iterative computation in the next phase. However, in order to get high localization precision, the traditional algorithms require too much processing power and energy. It is impractical to implement them in mobile nodes with limited resources, and these algorithms cannot meet the real-time localization requirement of a mobile node. The above-mentioned localization schemes do not consider the effect of geometrical relationship among reference nodes (except [2,3] and [12–15]), which, however, strongly affects the quality of localization.

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In [5], the researchers only give some guiding instructions of reference node placement in Cricket indoor localization schemes. Bulusu *et al*. [2] analyze three adaptive reference node placement algorithms (Random, Max, and Square-grid) using a mobile human or robot agent for localization based on RF-proximity, and they also evaluate different placement algorithm against both coverage and localization issue. In [3], the researchers propose HEAP (an incremental reference placement algorithm) for low-density regimes and STROBE (an adaptive density algorithm) for high-density regimes. The localization precision can be improved by moving the nodes or adding some new nodes by a mobile human or robot agent based on the simulation results. The researchers in [12–14] propose some spherical localization schemes to achieve the tracking task by adding or moving nodes by outside forces (manpower or robot). It is impractical or infeasible to precisely locate by adding or moving reference nodes in an indoor environment. There are also some limitations to be used in real applications. Volkan [15] proposes an approximation algorithm for placement and distributed deployment of sensor camera teams, which form right-angled triangle based on triangulation to track the mobile nodes. However, the algorithm needs heavy computations and communications, so it hardly satisfies real-time localization requirement of the mobile nodes. The idea of equilateral triangulation, based only on intuition though, was briefly mentioned [21] in designing APS using AoA.

3. Theoretical Background

Consider three distinct reference nodes $p_i = (x_i, y_i)$, $i = 1, 2, 3$ in $\mathbb{R}^2$. We want to calculate the coordinate $(x_0,\ y_0)$ of an unknown node p according to r_i (the distances between p_i and p). We have the following system of equations based on trilateration location method:

$$\begin{cases} (x_0 - x_1)^2 + (y_0 - y_1)^2 = r_1^2 \\ (x_0 - x_2)^2 + (y_0 - y_2)^2 = r_2^2 \\ (x_0 - x_3)^2 + (y_0 - y_3)^2 = r_3^2 \end{cases} \tag{1}$$

Solving system (1), we derive the position of unknown node p

$$\begin{cases} x_0 = \frac{1}{\Delta}(2T_1(y_1 - y_3) - 2T_2(y_1 - y_2)) \\ y_0 = \frac{1}{\Delta}(2T_2(x_1 - x_2) - 2T_1(x_1 - x_3)) \end{cases} \tag{2}$$

where $\Delta = 4((x_1 - x_2)(y_1 - y_3) - (x_1 - x_3)(y_1 - y_2))$, $T_1 = r_2^2 - r_1^2 - x_2^2 + x_1^2 - y_2^2 + y_1^2$, and $T_2 = r_3^2 - r_1^2 - x_3^2 + x_1^2 - y_3^2 + y_1^2$.

If the Δ is equal to 0, three reference nodes are on a straight line and the unknown node cannot be determined. The above analysis indicates that an unknown point p can be determined by three reference nodes p_1, p_2, and p_3 if these three nodes are not on a straight line. In real applications, we can place the reference nodes to form a sharp triangle to make sure Δ to be relatively large. Moreover nodes p_1, p_2, and p_3 should not be too close to each other, otherwise Δ will become too small for estimating the unknown node. Intuitively this is easily understandable, three nodes will act like just one node if they are too close to each other, so they will not effectively determine the position of an unknown node. Previously we assume that the measurement of the distance is absolutely precise, however inevitably the measurement error will exist.

As explained above, any three reference nodes can give us an estimation of (x_0, y_0). Solving Equation (1) associated with all the possible three reference nodes, we obtain the estimated coordinates of (x_0, y_0) : $(x_0^{(1)}, y_0^{(1)}), \cdots\cdots, (x_0^{(n)}, y_0^{(n)})$. Then $\bar{x}$, $\bar{y}$, defined as $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_0^{(i)}$, $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_0^{(i)}$, is the collective average of these n estimations. During this process, the *localization error* is defined to be $\Delta r = \sqrt{\Delta x^2 + \Delta y^2}$, where $\Delta x = |x_0 - \bar{x}|$, $\Delta y = |y_0 - \bar{y}|$.

As shown in Figure 1, if there exists the localization error, three circles can form a small region, the size of the small region can be regarded as the size of the

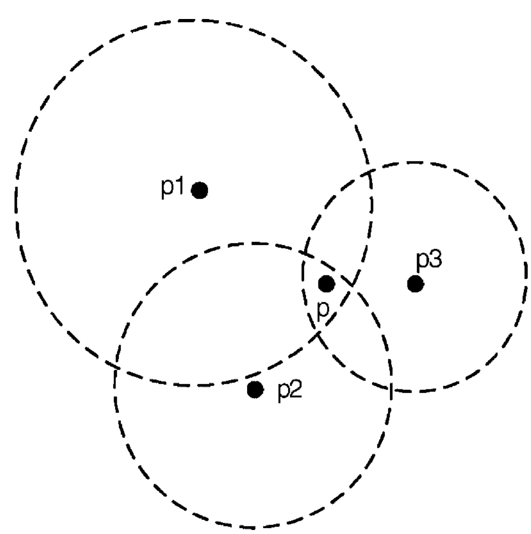

Fig. 1. Region of localization error.

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localization error [17]. Thus, if we can reduce the size of the small region, then we can also decrease the size of the localization error. Under the above-mentioned assumption, Equation (1) will not give the precise computation for the unknown node. In fact as we shall analyze in the sequel, the exact solution for the unknown node will be located in a neighborhood of the node given by Equation (1). In the following we assume that the error will range between $(-\varepsilon, \varepsilon)$.

Now for $i = 1, 2, 3$ we define

$$C_{p_i} = \Big\{(x,y) \in \mathbb{R}^2 | (x-x_i)^2 + (y-y_i)^2 \leq (r_i+\varepsilon_i)^2, (x-x_i)^2 + (y-y_i)^2 \geq (r_i-\varepsilon_i)^2\Big\} \tag{3}$$

Note that when $\varepsilon_i = 0$, $\cap_i C_{p_i}$ will consist of one point, which corresponds to the point given by Equation (1). However if these is measurement error, namely when $\varepsilon_i > 0$, $\cap_i C_{p_i}$ will be a region with positive area. We denote the circle $\{(x,y)|(x-x_0)^2 + (y-y_0)^2 = \varepsilon^2\}$ by S_p. Let l_{p,p_i} be the straight line passing through both p and p_i, then l_{p,p_i} shall intersect with S_p at two points $q_{i,1}$ and $q_{i,2}$. For $j = 1, 2$, we denote the line passing through $q_{i,j}$ and tangent to S_p by $\tilde{l}_{q_{i,j}}$. Then the region $\tilde{C}_{p_i}$ shall be the region in between the two lines $\tilde{l}_{q_{i,1}}$ and $\tilde{l}_{q_{i,2}}$, as shown in Figure 2.

When the measurement error ε is relatively small, at certain neighborhood of p, C_{p_i} can be linearized and approximated by $\tilde{C}_{p_i}$ and $area(C_{p_i})$ can be approximated by $area(\tilde{C}_{p_i})$. Certainly an optimal configuration of the three reference nodes will minimize $C = \cap_i area(C_{p_i})$ (approximately $\tilde{C} = \cap_i area(\tilde{C}_{p_i})$ when ε is small). We shall prove that when the reference nodes are placed in a symmetrical way, the optimal configuration can be achieved. Let $\alpha_{i,j}$ be the angle between $\overrightarrow{pp_i}$ and $\overrightarrow{pp_j}$ in Figure 2. Then we have

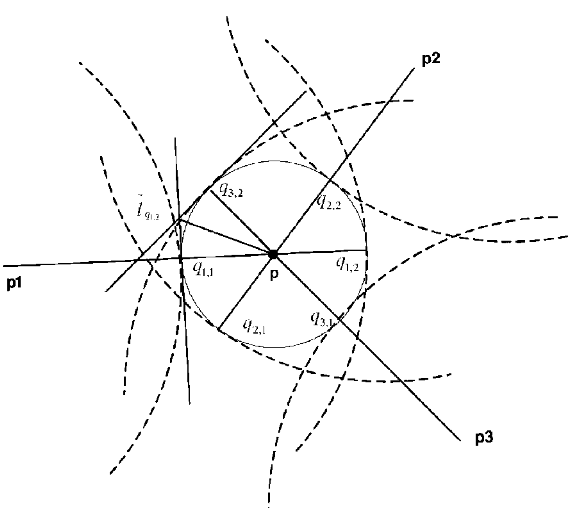

Fig. 2. Analysis of localization error.

Theorem 1. *$area(\tilde{C}_{p_i})$ reaches its minimum when $\alpha_{1,2} = \alpha_{2,3} = \alpha_{3,1} = \pi/3$. In other words, symmetrical reference nodes (in the sense of the angle direction) form an optimal configuration.*

Proof. Simple computations will lead to

$$area(\tilde{C}) = 2\varepsilon^2\left(\tan\frac{\alpha_{1,2}}{2} + \tan\frac{\alpha_{2,3}}{2} + \tan\frac{\alpha_{3,1}}{2}\right)$$

Note that

$$\alpha_{1,2} + \alpha_{2,3} + \alpha_{3,1} = \pi$$

Since $(\tan x)'' = 2\tan x(1+\tan x) \geq 0$ when $0 \leq x \leq \pi/2$. We derive

$$\begin{aligned} area(\tilde{C}) &= 6\varepsilon^2 \frac{1}{3}\left(\tan\frac{\alpha_{1,2}}{2} + \tan\frac{\alpha_{2,3}}{2} + \tan\frac{\alpha_{3,1}}{2}\right) \\ &\geq 6\varepsilon^2 \tan\frac{\alpha_{1,2}+\alpha_{2,3}+\alpha_{3,1}}{6} = 6\varepsilon^2\tan\frac{\pi}{6} \end{aligned}$$

The equality holds when

$$\alpha_{1,2} = \alpha_{2,3} = \alpha_{3,1} = \pi/3 \qquad \blacksquare$$

In other words, the optimal configuration is reached when the reference nodes are placed symmetrically. In order to get more precise position information of the mobile nodes in indoor sensor networks, we can place three reference nodes, which form an equilateral triangle. If the coverage area of the sensor network is too large, we also need to place new reference node in adjacent position of the original equilateral triangle to extend the coverage area of the reference nodes, as shown in Figure 3.

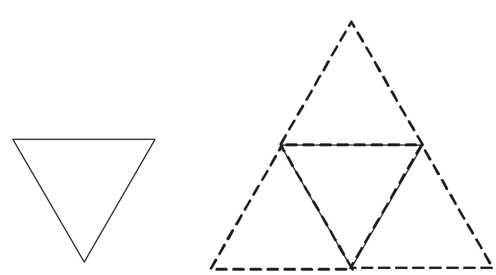

Fig. 3. Expansion of reference node.

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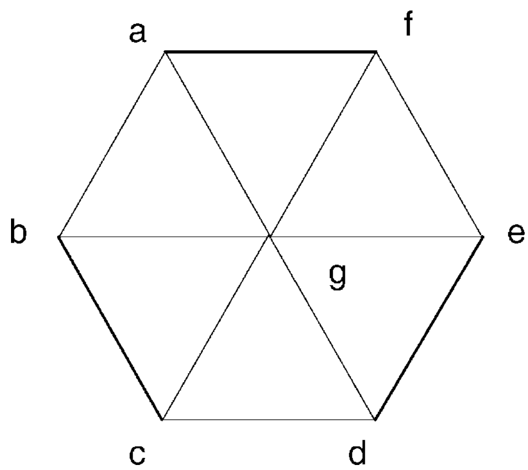

Fig. 4. Placement of reference node.

Table I. TPP algorithm.

Step 1	A mobile node broadcasts a location message to its neighboring reference nodes, and then the reference nodes return a confirmed location message containing $\{\mathrm{ID}, T_{\mathrm{send}}, (a, b)\}$, where ID denotes the ID of reference node, T_{send} denotes the sending time by reference node, and (a, b) denotes the coordinate of reference node.
Step 2	The mobile node receives many location messages of reference nodes, and then it calculates the distances between the mobile node and every reference node.
Step 3	As for each three reference nodes, the mobile node judge if the three reference nodes are on a straight line.
Step 4	Compute the estimated locations of the mobile node using any three reference nodes that are not a straight line.
Step 5	Finally, the mobile node calculates the average location value.

As shown in Figure 3, we place a new reference node based on the original equilateral triangle, which form a new equilateral triangle. Based on the geometrical relationship of equilateral triangle, the position information of the new node can be calculated. Since the cost of reference node is expensive, so we should place the reasonable number of reference nodes to decrease the localization error of the unknown node.

Certainly we want to use as few reference nodes as possible and decrease the localization error to the greatest extent.

In Figure 4, we place seven reference nodes, which consist of eight equilateral triangles, including six small equilateral triangles, they are Δabg, Δcbg, Δcgd, Δdge, Δgef, Δafg and two big equilateral triangles, they are Δace, Δbfd. Thus, we can place eight equilateral triangles using seven reference nodes. In our scheme, we can fully use the fact that the equilateral triangle is the best location strategy to reduce the localization error of the mobile nodes during the localization process.

4. RNST Algorithm and Localization Error Analysis

Due to resource limitation of the sensor nodes, some of the traditional positioning algorithms, such as TPP algorithm, are too complicated to be implemented and they cannot provide the real-time localization of the mobile node. Before introducing our algorithm, we first summarize the procedure of traditional TPP algorithm in Table I.

As analyzed in previous section, the geometrical relationship of reference nodes has great effect on the localization error of unknown node; however, TPP algorithm does not consider this factor. In this section, we improve the TPP algorithm, and propose RNST positioning algorithm which can provide real-time localization service. In our algorithm, we position the reference nodes to form an equilateral triangle in an indoor environment to minimize the localization error and improve the real-time localization performance. During our localization process, a mobile node can purposefully select suitable reference nodes to estimate its position; the procedure of our proposed algorithm is listed in Table II.

In real applications, the localization error always exists, no matter what location scheme or advanced location technique we use. In [17], the author mentions the reasons of the localization error based on multilateration, which mainly consist of time measurement error and the error caused by geometrical relationship of reference nodes. As we mentioned before, we mainly analyze the latter in this paper.

Table II. RNST algorithm.

Step 1	A mobile node broadcasts a location message to its neighboring reference nodes, then the reference nodes return a confirmed location message containing $\{\mathrm{ID}, T_{\mathrm{send}}, (a, b)\}$, where ID denotes the ID of reference node, T_{send} denotes the sending time by reference node, and (a, b) denotes the coordinate of reference node.
Step 2	The mobile node calculates the distances between each pair of nodes and judge if any of the three reference nodes can form almost equilateral triangle.
Step 3	Compute the estimated locations of the mobile node using each of the possible equilateral triangles.
Step 4	Finally, the mobile node calculates the average location value.

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An interesting problem is how much the equilateral triangle placement of the reference nodes can improve the precision than the random placement or Square-grid placement of the reference nodes. In the following, we show that the localization precision can be remarkably improved if the best placement is employed.

As shown above, the error region size $\tilde{C}$ is equal to

$$area(\tilde{C}) = 2\varepsilon^2\left(\tan\frac{\alpha_{1,2}}{2} + \tan\frac{\alpha_{2,3}}{2} + \tan\frac{\alpha_{3,1}}{2}\right) \quad (4)$$

The minimum area $area(\tilde{C}) = 2\sqrt{3}\varepsilon^2$ can be attained when $\alpha_{1,2} = \alpha_{2,3} = \alpha_{3,1} = \pi/3$. We now calculate the $E(area(\tilde{C}))$ (the expectation of $area(\tilde{C})$) when the reference nodes are randomly selected, using the fact that $\alpha_{1,2} + \alpha_{2,3} + \alpha_{3,1} = \pi$.
Now,

$$E(area(\tilde{C})) = 2\varepsilon^2 E\left(\tan\frac{\vec{x}}{2} + \tan\frac{\vec{y}}{2} + \cot\left(\frac{\vec{x}}{2} + \frac{\vec{y}}{2}\right)\right)$$

where $(\vec{x}, \vec{y})$ is a random vector with uniform distribution on the following region:

$$D = \{(x, y)|x \geq 0, y \geq 0, x + y \leq \pi\}$$

Therefore, the probability density function of $(\vec{x}, \vec{y})$ is $p(\vec{x}, \vec{y}) = 2/\pi^2$. Then

$$\begin{aligned} &E(area(\tilde{C})) \\ &= \frac{4\varepsilon^2}{\pi^2}\int\int_D \tan\frac{x}{2} + \tan\frac{y}{2} + \cot\left(\frac{x}{2} + \frac{y}{2}\right) dx\, dy \\ &= \frac{4\varepsilon^2}{\pi^2}\left(-2\int_0^\pi \ln\cos\frac{x}{2}dx - 4\int_0^\pi \ln\sin\frac{x}{2}dx\right) \end{aligned}$$

Applying necessary change of variables, we calculate the error region size

$$E(area(\tilde{C})) = \left(\frac{24}{\pi}\ln 2\right)\varepsilon^2$$

Thus, the equilateral placement of the reference nodes can greatly improve the estimation than randomly placement of the reference nodes by

$$\beta = \left\{\left(\frac{24}{\pi}\ln 2\right)\varepsilon^2 - 2\sqrt{3}\varepsilon^2\right\}\Big/\left(\frac{24}{\pi}\ln 2\right)\varepsilon^2 = 34.9\%$$

As for the Square-grid placement, if we choose three reference nodes, then we have

$$area(\tilde{C}) = 2\varepsilon^2\left(\tan\frac{45}{2} + \tan\frac{45}{2} + \tan\frac{90}{2}\right) = 3.657\varepsilon^2$$

Therefore, the estimation is improved by 5.3%. Based on the above analysis, the localization error of our proposed scheme is the least when the equilateral triangle placement is employed. The unknown node can purposefully select the suitable reference nodes to reduce the localization error during the localization process in WSNs.

5. Performance Analysis and Comparison

We have implemented our proposed RNST algorithm and TPP algorithm both in the network simulator OPNET version 10 and on the Zigbee sensor platform, respectively.

5.1. Design of Experiments

To testify our proposed RNST algorithm, we design the experiment consisting of several phases. First, we test the real-time localization using the Zigbee sensor platform. The goal of this test is used to prove if our RNST algorithm can effectively meet the real-time localization requirement of the mobile nodes with limited resources in an indoor environment. Second, we track a mobile node using our proposed RNST algorithm and the TPP algorithm in a room. Finally, we compare and analyze the data obtained from our experiments.

In our experiments, 21 reference nodes are uniformly distributed based on equilateral triangle in a region of $21 \times 15\,\text{m}^2$, the distance between adjacent nodes is 4.6 m and one mobile node is also randomly located in the same area, as shown in Figure 5. Generally, the reference nodes of the traditional algorithm are placed according to Square-grid or random placement, however in order to compare the performance of our algorithm with that of the traditional algorithm, the same simulation environment is adopted in our experiments.

5.2. Localization Error Analysis

In the traditional positioning algorithms, such as TPP algorithm, an unknown node first randomly selects several reference nodes to compute its initial position,

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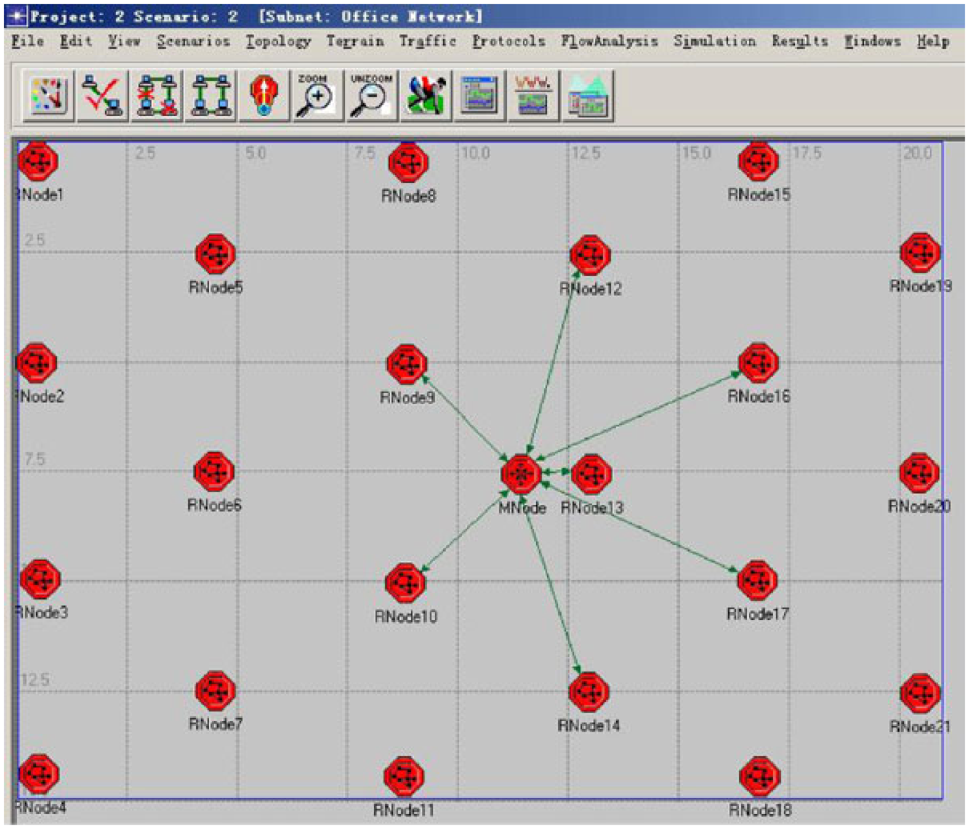

Fig. 5. Simulation environment.

then iteratively improves the localization precision using the position information of more reference nodes. In our test, we run the simulation 100 times and averaged data over these 100 runs. In the following, we compare the localization error of the unknown node with increasing the number of the reference nodes using RNST algorithm and TPP algorithm, respectively, as shown in Figure 6, where *x*-axis represents the number of the reference nodes, and *y*-axis represents the localization error of the mobile node.

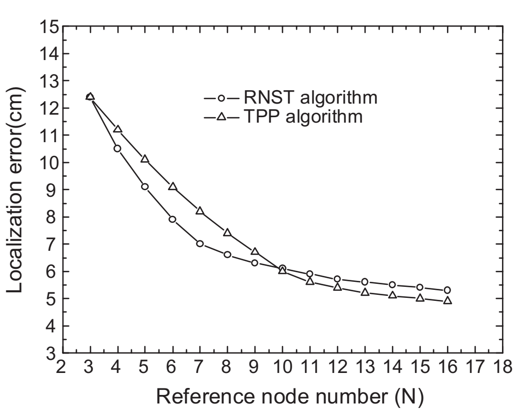

Fig. 6. Comparison of localization error.

As shown in Figure 6, with increasing number of the reference nodes, the localization error value of the unknown node decreases drastically in the beginning, however the curve becomes almost flat afterward. When the number of the reference nodes is 7, the localization error values of TPP algorithm and RNST algorithm are 8.2 and 7.1 cm, respectively, thus the localization error of RNST algorithm can improve by 13.4% than that of TPP algorithm. However, when the number of the reference node is more than 10, the localization error value of TPP algorithm is smaller than that of RNST algorithm. The reason is that RNST algorithm only select the reference nodes which form equilateral triangle, whereas TPP algorithm uses any reference nodes to calculate the position of the unknown node, the increasing number of equilateral triangle is fewer than non-equilateral triangle at the same time, thus the error value of TPP algorithm is less than that of RNST algorithm when the number of the nodes involved in the position estimation of the unknown node gets more than certain threshold.

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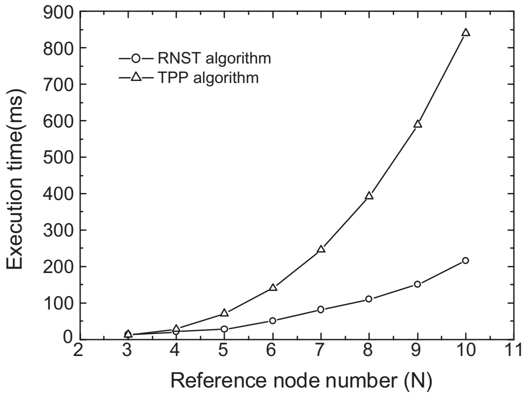

Fig. 7. Comparison of location time.

Apparently compared to TPP algorithm, our proposed RNST algorithm can greatly decrease the localization error in a shorter period of time.

5.3. Real-time Localization Analysis

As for real-time localization of positioning algorithm, we implement RNST algorithm and TPP algorithm in Zigbee platform, respectively and test them. The execution time of those two algorithms with increasing number of reference nodes is shown in Figure 7, where x-axis represents the number of the reference nodes, and y-axis represents the execution time of positioning algorithm.

As shown in Figure 7, when the number of the reference nodes is 7, the execution time of TPP algorithm and RNST algorithm are 245 and 75 ms, respectively. With the increasing number of the reference nodes, the execution time of TPP algorithm is exponentially increasing, whereas the execution time of RNST algorithm is only slowly increasing. On the other hand, in order to get precise position information, TPP algorithm needs heavy computation and communication. Thus, our proposed RNST algorithm can efficiently meet the real-time localization requirement of the mobile node in an indoor environment.

It is important to guarantee smaller localization error and meet the real-time localization requirement of the mobile node at the same time during the localization process. The balance point of two effect factors is that the number of reference node is 7 based on the analysis of experimental data, as shown in Figure 8.

When the mobile node covers 7 reference nodes (polygon *bcefhi* in Figure 8), the transmission radius of the mobile node is equal to l, here l is the length of the side of equilateral triangle. When the mobile node

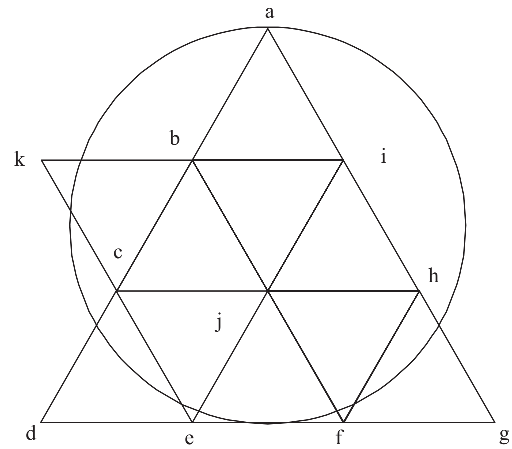

Fig. 8. Transmission scope of reference point signal.

covers six reference nodes (equilateral triangle Δach), the transmission radius of the mobile node is equal to $2\sqrt{3}l/3$; when the mobile node covers less than five reference nodes, the transmission radius of the mobile node is less than l, so the minimum transmission radius of the reference node is equal to $2\sqrt{3}l/3$. We can also calculate that the maximum transmission radius of the reference node is equal to $3\sqrt{3}l/4$, thus the transmission range of the reference node is $2\sqrt{3}l/3 \leq R_{\text{scope}} \leq 3\sqrt{3}l/4$, where R_{scope} denotes the transmission range of the reference node. Therefore, in the real application of an indoor environment, we can adjust the coverage area of the mobile node is not more than seven reference nodes and also guarantee the localization error of the mobile node is the least and meet the high real-time localization requirement of the mobile node.

The total location time of a mobile node T_{all} can be represented using $T_{\text{all}} = T_{\text{execution}} + T_{\text{delay}} + T_{\text{propagation}}$, where $T_{\text{execution}}$ denotes the execution time of the positioning algorithm, T_{delay} the delay time of signal transmission, $T_{\text{propagation}}$ the time difference of transmission between the reference node and the mobile node. Typically, the walking speed of an adult is 0.7 m/s in an indoor environment. The side length of equilateral triangle is 4.6 m in the simulation environment, then the optimal transmission range of the mobile node is $2\sqrt{3}l/3 \leq R_{\text{scope}} \leq 3\sqrt{3}l/4$, so we can calculate that the time range of signal transmission is $11.9\,\text{ms} \leq T_{\text{propagation}} \leq 17.1\,\text{ms}$. When the number of reference node chosen by the mobile node is 7, the execution time of our proposed algorithm $T_{\text{execution}}$ is 75 ms; however the execution time of the TPP algorithm is 245 ms in the same condition and can not guarantee the real-time localization. If our

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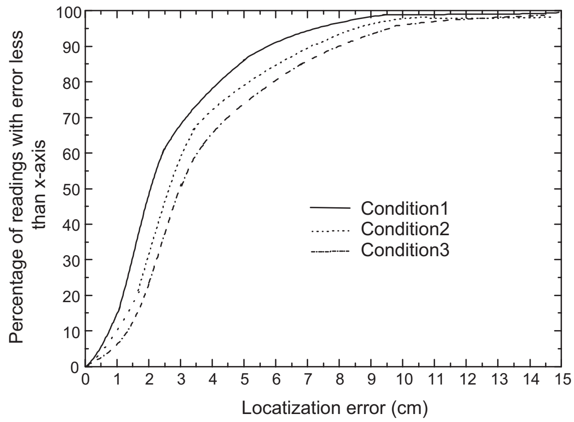

Fig. 9. Localization precision of RNST algorithm.

algorithm can meet the real-time localization of the mobile node and the effective positioning time T_{all} is less than 100 ms, thus the range of signal transmission delay is $7.9\,\text{ms} \leq T_{\text{delay}} \leq 13.1\,\text{ms}$, which shows that our algorithm can effectively guarantee the real-time localization.

In the analysis above, we only consider the execution time of our proposed algorithm. In the real application, we also need to consider some other factors, such as the time difference of signal transmission. When the number of reference node chosen by the mobile node is 7, the update rate of positioning algorithm is about 9–10 times/s, thus our proposed algorithm can effectively meet the positioning requirement for an indoor environment.

5.4. Positioning Algorithm Evaluation

We place the reference nodes according to Figure 5 and simulate RNST algorithm under the following three different conditions: (1) No interference signal, only location signal; (2) Location signal and little noise signal; (3) Location signal, little noise signal and interference signal. We randomly choose 200 nodes to run simulation 500 times and average data over these 100 runs. In order to evaluate the algorithm performance, we compare the estimated values obtained from our simulation experiment with the actual values, the localization error distribution condition of RNST algorithm as shown in Figure 9, where *x*-axis represents the localization error value, and *y*-axis represents the percentage of reading with error less than *x*-axis.

As shown in Figure 9, the localization error of RNST algorithm is less than 7.1 cm in the 95% confidence level, which is high localization precision,

Table III. Performance of RNST algorithm.

Test condition	**Readings return (%)**	**95% confidence level (cm)**
1	93	7.1
2	75	8.2
3	62	10.6

and the localization precision of RNST algorithm in different condition is shown in Table III.

As shown in Table III, the localization error of RNST algorithm reaches 7.1 cm in the 95% confidence level of condition one. The bigger the interference, the smaller localization error is. The simulation results are better suitable for the real conditions of an indoor environment. We also simulate to track the path of the mobile node in a room. The mobile node is tracked in the environment of Figure 5 using RNST algorithm and TPP algorithm respectively, the tracking path comparison of both algorithms is shown in Figure 10, where *x*-axis represents the length of the room, and *y*-axis represents the width of the room.

As shown in Figure 10, based on the estimated and actual tracking path, the path of our proposed RNST algorithm is a little closer to the actual tracking path than that of TPP algorithm. However, when the mobile node is located in the border of the room, since only a few reference nodes are involved in the computation of the position of the mobile node, thus the localization error of the mobile mode is bigger. The comparison of the mobile node's RMSE is shown in Figure 11, where *x*-axis represents the number of the test point, and *y*-axis represents the value of RMSE. Based on the comparison of RMSE changing trend, we draw the conclusion that it also coincides with in Figure 10.

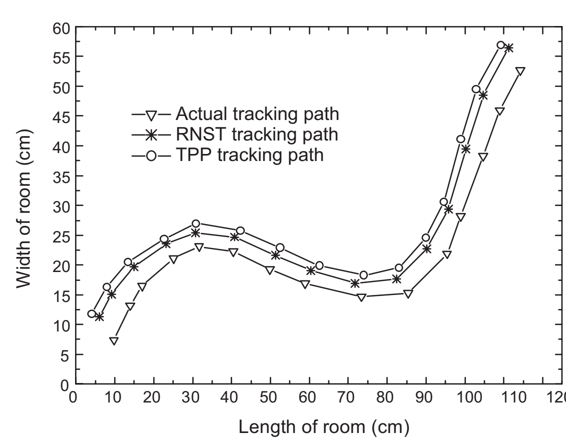

Fig. 10. Comparison of mobile node tracking path.

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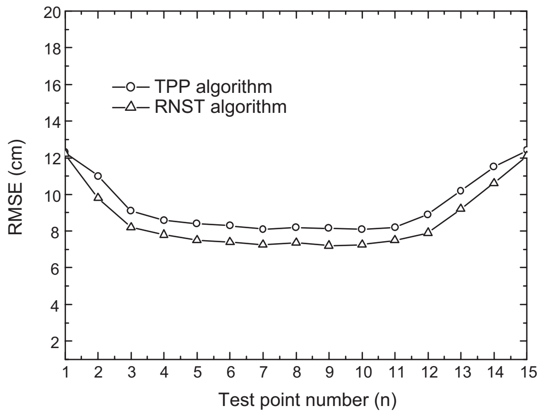

Fig. 11. Comparison of RMSE.

As expected from above-mentioned analysis, we conclude that RNST algorithm can meet the real-time localization requirement of the mobile node with limited resources in an indoor environment, and make the localization error of RNST algorithm less than that of the traditional TPP algorithms.

6. Conclusions and Future Work

In this paper, we analyze the localization error of a mobile node and draw the conclusion that the localization error is the least when three reference nodes form an equilateral triangle. The equilateral triangle placement of the reference nodes can greatly improve the position estimation than the random placement or the Square-grid placement of the reference nodes. We improve the TPP algorithm and propose a novel RNST algorithm for the mobile node in indoor sensor networks. The simulation results show that our proposed RNST algorithm can greatly improve the localization precision of the mobile node, meanwhile satisfying the time constraints and guaranteeing the minimum localization error in a short period. The paper raises interesting questions for future research directions; we plan to extend our RNST algorithm to outdoor environment. We also plan to conduct further research on the deployment problem of the reference nodes based on other positioning techniques.

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