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Dynamic Cooperative Localization Algorithm for Wireless Sensor Networks

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Abstract. *Dynamic localization is one of the important and difficult points of localization for WSN. To improve localization performance, a dynamic cooperative localization algorithm for WSN (DCLA) is proposed in this paper. The algorithm can solve the problem that the unknown node cannot be located when the number of its neighbor anchor nodes is less than three. Simulation results show that the localization success rate is improved by about* 53.16% *compared with TLA algorithm. Compared with MNPLA algorithm, the localization success rate is improved by about* 23.49%*, and the average relative error is reduced by about* $0.31r$.
Keywords: Wireless sensor networks, RSSI, Dynamic localization, Cooperative localization

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1. **Introduction.** In the key support technologies of Wireless Sensor Networks (WSN) [1, 2], localization technology is one of the core technologies [3, 4]. Most of the existing localization algorithms assume that the network is static and neglect the mobility of nodes. These algorithms are not suitable for some practical applications [5]. Therefore, dynamic localization is a worthier [6, 7]. The position relationship among nodes is related to each other in the localization process. In this case, the position information among different nodes and the position information of the same node in different time slots can help to locate cooperatively through exchanging the position information [8]. The cooperative localization has a better effect to improve the success rate and localization accuracy [9].

Reference [10] propose a mobile beacon-based localization using classical multidimensional scaling (MBL-MDS), the single moving anchor node sends packets during the moving process. The static unknown nodes can self-localized by using RSSI [11, 12] after receiving packets in different positions. The algorithm can only be used in the situation in which there is only one moving anchor node. Reference [13] presents a localization algorithm of path planning based on anchor node movement. The path planning problem is transformed into the issue of spanning tree and traversal of graph. The anchor node is used to complete the localization according to the planned path. Reference [14] presents a Predictive Localization Algorithm for Mobile Nodes (MNPLA). It combines the historical moving angles and gray prediction with Trilateration Localization Algorithm (TLA), which can solve the problem that the unknown node cannot be located when the number of its neighbor anchor nodes is less than three. But the algorithm does not analyze the cooperative relationship among nodes. Moreover, it has limited success rate and localization accuracy. The adaptive Monte Carlo mobile node localization algorithm [15] utilizes the influence on localization accuracy caused by sampling particles in different regions to adjust the weight of the sampling particles adaptively. At the same time, sampling particles of the last time slot are used to limit the conditions so as to improve localization accuracy.

In summary, the existing dynamic localization algorithms use range-free algorithms such as MCL and CDL algorithm in the situation that all the nodes are moving [16]. To solve the node localization problem when all the nodes move randomly, a dynamic cooperative localization algorithm (DCLA) based on RSSI is proposed in this paper.

2. **The basic principle of RSSI Ranging Method Uneven.** The RSSI is widely adopted in ranging technology. It calculates the distance between nodes based on attenuation characteristics of the signal. Within the wireless transmission process, Long-Distance Path Loss Model is the theoretical model commonly. The path loss can be defined as:

$$PL(d_{ij}) = PL(d_0) + 10 \cdot n \cdot \log(d_{ij}/d_0) + X_\sigma \tag{1}$$

where d_{ij} represents the distance between transmitting node i and receiving node j, $PL\left(d_{ij}\right)$ represents the path loss of signal for d_{ij}, $PL\left(d_0\right)$ represents the path loss of signal for the reference distance d_0, generally $d_0 = 1m$. n is the path loss exponent which changes with the environment, generally $n = 2 \sim 6$. X_σ represents Gaussian distribution random variable with zero mean, generally $\sigma = 4 \sim 6$.

The RSSI by receiver is defined as:

$$P\left(d_{ij}\right) = P_T + G - PL\left(d_{ij}\right) \tag{2}$$

where $P\left(d_{ij}\right)$ represents the received signal strength value at the receiver, P_T represents the transmitting power, G represents the antenna gain. According to (1) and (2), the distance between node i and j is:

$$d_{ij} = d_0 \cdot 10^{\frac{G+P_T-PL(d_0)-X_\sigma-P\left(d_{ij}\right)}{10\cdot n}} \tag{3}$$

3. **Dynamic Cooperative Localization Algorithm for WSN.** In order to make the simulation process more realistic, the network are supposed to contain anchor nodes and unknown nodes, and extra restrictions are set as follows.

(1) There are 400 nodes which are distributed randomly in the area of 400 m × 400 m. The proportion of anchor nodes is 30%.

(2) The communication radius of nodes is 15m.

(3) The velocity variation per unit time of all nodes is 0.3 m/s.

(4) The angle variation per unit time of all nodes is 15°.

3.1. **Dynamic cooperative localization between anchor nodes and unknown nodes.** In the first stage, the unknown nodes locate themself through the cooperative relationship between the unknown nodes and the anchor nodes

(1) If the unknown node X has three or more neighbor anchor nodes at time k. The unknown node will calculate its coordinate by TLA Algorithm and save the coordinate. The specific process is as follows: Assume that the RSSI of anchor nodes A, B and C received by unknown node X are $P\left(d_{AX}\right)$, $P\left(d_{BX}\right)$, $P\left(d_{CX}\right)$ separately. The corresponding distances d_{AX}, d_{BX}, d_{CX} can be obtained by (3). We can get three circles with center A, B, C, and radius d_{AX}, d_{BX}, d_{CX}. The intersection of the three circles is the location of the unknown node, which is shown in Fig.1 (a).

The position of unknown node X can be expressed as:

$$\begin{cases} (x - x_A)^2 + (y - y_A)^2 = d_{AX}^2 \\ (x - x_B)^2 + (y - y_B)^2 = d_{BX}^2 \\ (x - x_C)^2 + (y - y_C)^2 = d_{CX}^2 \end{cases} \tag{4}$$

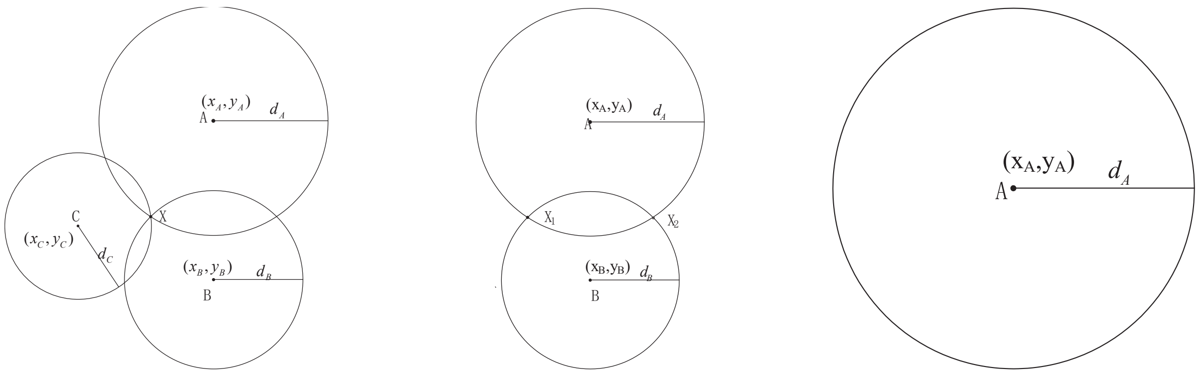
Where (x_A, y_A), (x_B, y_B) and (x_C, y_C) are the coordinates of the anchor node A, B, and C, (x, y) is the coordinate of the unknown node X.

(2) If the unknown node X has two neighbor anchor nodes A and B at time t, it is impossible to calculate its coordinate though the TLA algorithm. The distance between unknown node and corresponding neighbor anchor node can be calculated according to (3). We can get two circles with center A, B and radius d_{AX}, d_{BX}. The intersections of the two circles, $X_1(x_1, y_1)$ and $X_2(x_2, y_2)$ are the possible location of the unknown node according to (5). The coordinates are $X_{t-1}(x_{t-1}, y_{t-1})$ and $X_{t-2}(x_{t-2}, y_{t-2})$ respectively. The coordinate of the unknown node is one of the two intersections, which is shown in Fig.1 (b).

The coordinates of the intersection points $X_1(x_1, y_1)$ and $X_2(x_2, y_2)$ can be obtained as:

$$\begin{cases} (x - x_A)^2 + (y - y_A)^2 = d_{AX}^2 \\ (x - x_B)^2 + (y - y_B)^2 = d_{BX}^2 \end{cases} \tag{5}$$

(3) If the unknown node X has one neighbor anchor node A at time t, it is impossible to calculate its coordinate though the TLA algorithm. But its range can be found according to the RSSI. The distance between unknown node and corresponding neighbor anchor node can be calculated according to (3). We can get one circle with center A and radius, which is shown in Fig.1 (c).



(a) (b) (c)

FIGURE 1. Dynamic cooperative relationship between unknown nodes and anchor nodes

3.2. **Dynamic cooperative localization between adjacent time slots.** In the second stage, when the unknown node has only two or one neighbor anchor node, it uses the dynamic cooperative relationship between adjacent time slots. The number of neighbor anchor nodes is divided into the following cases according to time $t-1$ and time t. There are three anchor nodes at time $t-1$, two anchor nodes at time t, which is recorded as (3, 2). In this analogy, there are six cases in which (3, 2), (3, 1), (2, 2), (2, 1), (1, 2), and (1, 1).

In the case of (3, 2), The unknown node X has two neighbor anchor nodes D and E at time t, and there are three neighbor anchor nodes A, B and C at time $t-1$, The coordinate $X_{t-1}\,(x_{t-1}, y_{t-1})$ can be located at time $t-1$ by TLA algorithm. If the coordinate $X_{t-2}\,(x_{t-2}, y_{t-2})$ of unknown node X has been located at time $t-2$, The moving distance d of the unknown node X between adjacent time slots can be obtained according to the coordinates saved at time $t-2$ and time $t-1$, as shown in formula (6). Set $\Delta t = 1s$, the moving velocity of unknown node X is $d/\Delta t = d$. According to the set value of velocity change Δv per unit time, the velocity range at the next time can be obtained as $(d - \Delta v, d + \Delta v)$, and the move range at the next time is $(d - \Delta v, d + \Delta v)$. With unknown node $X_{t-1}\,(x_{t-1}, y_{t-1})$ as the center, and using $d - \Delta v$ and $d + \Delta v$ as the radius for the circle, the circular area between the two circles is the moving area at the next time slot, If the possible coordinate located by the two neighbor anchor nodes at time t is in the annular region, that is the coordinate of the unknown node X at time t. It is shown in Fig.2 (a).

In the case of (3, 1), the moving range $(d - \Delta v, d + \Delta v)$ of the unknown node X can be obtained at time t. According to the third condition of the first stage, it is known that the unknown node X is on the circle with the anchor node D as the center and d_{DX} as the radius. This circle intersects with the moving area at time $t-1$ in an arc. The intersecting range is further reduced according to the amount of angle change $\Delta\theta = 15°$ per unit time. Finally, the midpoint of intersection arc is taken as the coordinate of unknown node X at time t. As shown in Fig.2 (b).

$$d = \sqrt{(x_{t-1} - x_{t-2})^2 + (y_{t-1} - y_{t-2})^2} \tag{6}$$

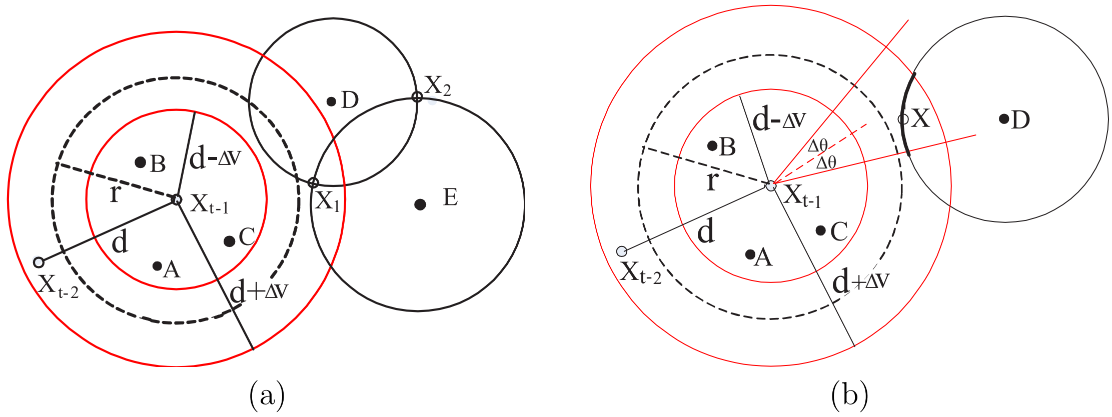


FIGURE 2. Dynamic cooperative relationship between adjacent time at (3, 2) and (3, 1)

In the case of (2, 2), The unknown node X has two neighbor anchor nodes A and B at time $t-1$, the unknown node X can find two possible coordinates $X_1\,(x_1, y_1)$ and $X_2\,(x_2, y_2)$. There are two neighbor anchor nodes D and E at time t, the unknown node X can find two possible coordinates $X_3\,(x_3, y_3)$ and $X_4\,(x_4, y_4)$. Assuming that the coordinate of unknown node X is X_{t-2} at time $t-2$, it first assumes that $X_1\,(x_1, y_1)$ is the coordinate of unknown node X at time $t-1$, and the moving range at the next time is obtained by using (3, 2) through X_{t-2} and $X_1\,(x_1, y_1)$, If the coordinates X_3 or X_4 are within the moving range, the coordinate X_1 is the coordinate of the unknown node X at time $t-1$, otherwise the coordinate X_2 is the coordinate of the unknown node X at time $t-1$. After finding the coordinates of unknown node X at time $t-1$, we get the coordinates of unknown node X at time t according to (3, 2). As shown in Fig.3 (a).

In the case of (2, 1), The unknown node X has one neighbor anchor nodes D at time t, the unknown node X can find the coordinate on a circle based on neighbor anchor node D. There are two neighbor anchor nodes A and B at time $t-1$. the unknown node X can find two possible coordinates $X_1(x_1, y_1)$ and $X_2(x_2, y_2)$ according to two neighboring anchor nodes A and B. Assuming that the coordinate of unknown node X is X_{t-2} and X_{t-3} at time $t-2$ and $t-3$. The coordinate of unknown node X at time $t-1$ is obtained by (3, 2). Finally, the coordinate of unknown node X at time t is obtained by (3, 1). As shown in Fig.3 (b).

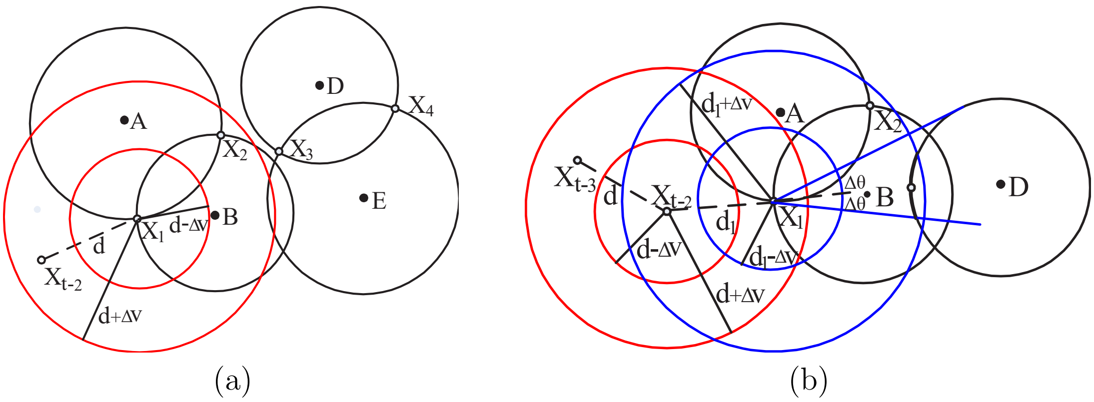


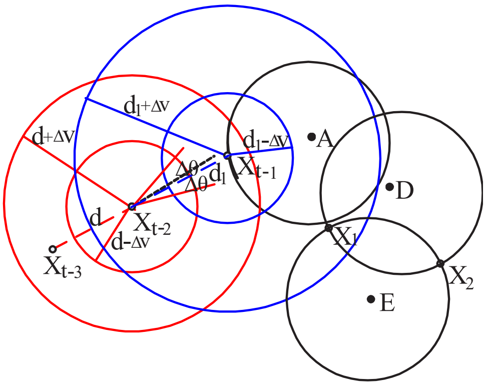
FIGURE 3. Dynamic cooperative relationship between adjacent time at (2, 2) and (2, 1)

In the case of (1, 2), The unknown node X has two neighbor anchor nodes D and E at time t, the unknown node X can find two possible coordinates $X_1(x_1, y_1)$ and $X_2(x_2, y_2)$ according to two neighboring anchor nodes D and E. There is one neighbor anchor node A at time $t-1$, the unknown node X can find the coordinate on a circle based on neighbor anchor node A. Assuming that the coordinate of unknown node X is X_{t-2} and X_{t-3} at time $t-2$ and $t-3$. The coordinate of unknown node X at time $t-1$ can be obtained by (3, 1). Finally, the coordinate of unknown node X is obtained by (3, 2). As shown in Fig.4 (a).

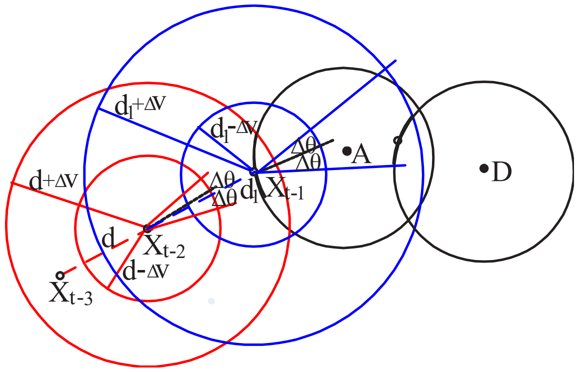
In the case of (1, 1), the unknown node X has one neighbor anchor node D at time t, the unknown node X can find the coordinate on a circle based on neighbor anchor node D. There is one neighbor anchor node A at time $t-1$, the unknown node X can find the coordinate on a circle based on neighbor anchor node A. Assuming that the coordinate of unknown node X is X_{t-2} and X_{t-3} at time $t-2$ and $t-3$. The coordinate of unknown node X at time $t-1$ can be obtained by (3, 1). Finally, the coordinate of unknown node X is obtained by (3, 1). As shown in Fig.4 (b).

3.3. **Relative localization and absolute localization.** In the third stage, when the unknown node has not been successfully located at the previous time slots, the node can be located by dynamic cooperative relationship of relative localization and absolute localization. The relative position can be obtained by MDS-MAP algorithm [17].

The MDS-MAP algorithm, which is a centralized localization algorithm, can be operated in ranging and non-ranging situations by the communication information between nodes. Assume the number of nodes in the network is n, the coordinate vector matrix is $X = [X_1, X_2, \cdots, X_i, \cdots, X_n]^T$, where $X_i = [x_i, y_i]$ represents the two-dimensional coordinates of node X_i. $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ represents the Euclidean distance



(a)



(b)

FIGURE 4. Dynamic cooperative relationship between adjacent time at (1, 2) and (1, 1)

between node X_i and X_j. The distance matrix $D^2 = d^2_{ij\,n\cdot n}$.

$$D^2 = \begin{bmatrix} 0 & d_{12}^2 & d_{13}^2 & \cdots & d_{1N}^2 \\ d_{21}^2 & 0 & d_{23}^2 & \cdots & d_{2N}^2 \\ d_{31}^2 & d_{32}^2 & 0 & \cdots & d_{3N}^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ d_{N1}^2 & d_{N2}^2 & d_{N3}^2 & \cdots & 0 \end{bmatrix} \tag{7}$$

The formula $B = -\frac{1}{2}JD^2J$ is obtained by double centering the distance matrix D^2, where J is the center matrix which is defined as $J = I - n^{-1} \cdot E$. I is an n_- order square matrix and E is an n -order full 1 square matrix. Set node coordinate vector matrix is $X = [X_1, X_2, \cdots, X_n]^T$, where $X_i = [x_i, y_i]$, so B can be transformed into $B = XX^T$. $B = QAQ^T$ by using singular value decomposition for B. According to $B = XX^T$ and $B = QAQ^T$, The relative coordinate matrix can be obtained by $X = QA^{1/2}$.

In 2-D space, coordinate transformation process requires at least three anchor nodes. Assume $R = (R_1, R_2, \ldots, R_n)$ is the relative coordinate matrix and $T = (T_1, T_2, \ldots, T_n)$ is the absolute coordinate matrix. Translation transformation is the coordinate vector R_i through the offset K to get $R_i^1 = R_i + K$, the rotation transformation is the coordinate vector R_i through the rotation angle α to get $R_i^2 = Q_1 R_i$, where

$$Q_1 = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \tag{8}$$

The mirror transformation is the reflection of the coordinate vector R_i relative to the line L, and then there is $R_i^3 = Q_2 R_i$, where

$$L = \begin{bmatrix} \cos(\beta/2) \\ \sin(\beta/2) \end{bmatrix} \tag{9}$$

$$Q_2 = \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \tag{10}$$

According to the rules of linear transformation rules,

$$(T_1 - T_1, T_2 - T_1, T_3 - T_1) = Q_1 Q_2 (R_1 - R_1, R_2 - R_1, R_3 - R_1) \tag{11}$$

So,

$$Q = Q_1 Q_2 = (T_1 - T_1, T_2 - T_1, T_3 - T_1)/(R_1 - R_1, R_2 - R_1, R_3 - R_1) \tag{12}$$

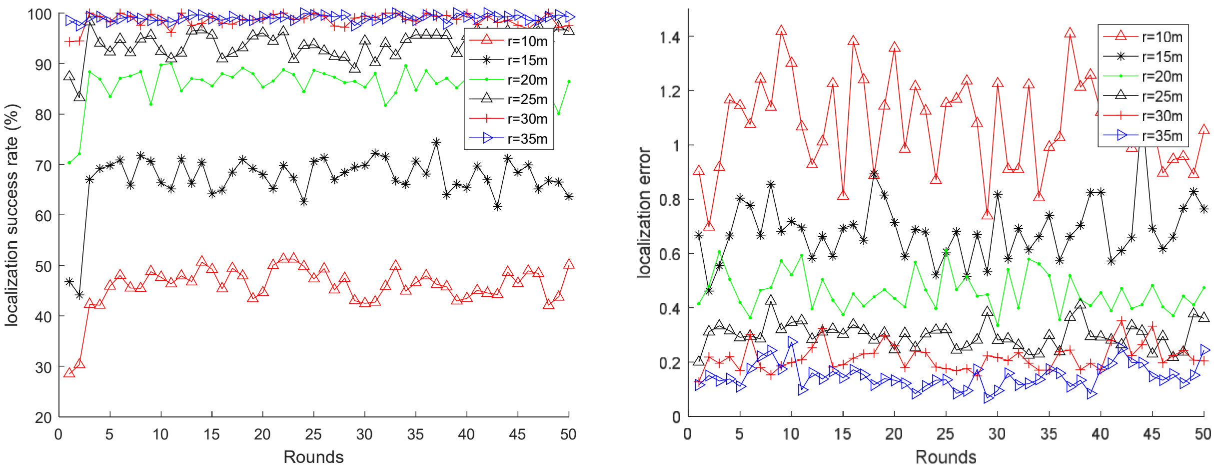
The formula (12) can be used to calculate the absolute coordinates of other nodes.

$$(T_4, T_5, \ldots, T_n) = Q\left(R_4 - R_1, R_5 - R_1, \ldots, R_n - R_1\right) + (T_1, T_1, \ldots, T_1) \qquad (13)$$

In this phase, by coordinating the connectivity information between nodes in a network and locating multiple nodes at the same time, only a few anchor nodes are needed to achieve a good location effect.

4. **Experimental simulation and analysis.** In MATLAB 7.0, all the nodes are deployed in a square area of 400 m × 400 m. The nodes can move randomly in the area.

Fig. 5 shows the influence of communication radius on the proposed DCLA. As can be seen from (a), with the increase of the communication radius, the success rate of localization is getting increasingly high. When the communication radius is increased from $r = 10$ m to $r = 35$ m, the success rate of localization increases from 45.83% to 99.05%, it is because when the communication radius increases, the number of neighbor anchor nodes also increases. As can be seen from (b), the average relative error decreases with the increase of the communication radius. When the communication radius increases from $r = 10$ m to $r = 35$ m, the average relative error is reduced from $1.08r$ to $0.15r$. It is because when the communication radius is larger, the unknown node can communicate with more anchor nodes, thus the unknown node localization error will be smaller. Considering the localization success rate and average relative error, this algorithm selects $r = 10$ m.



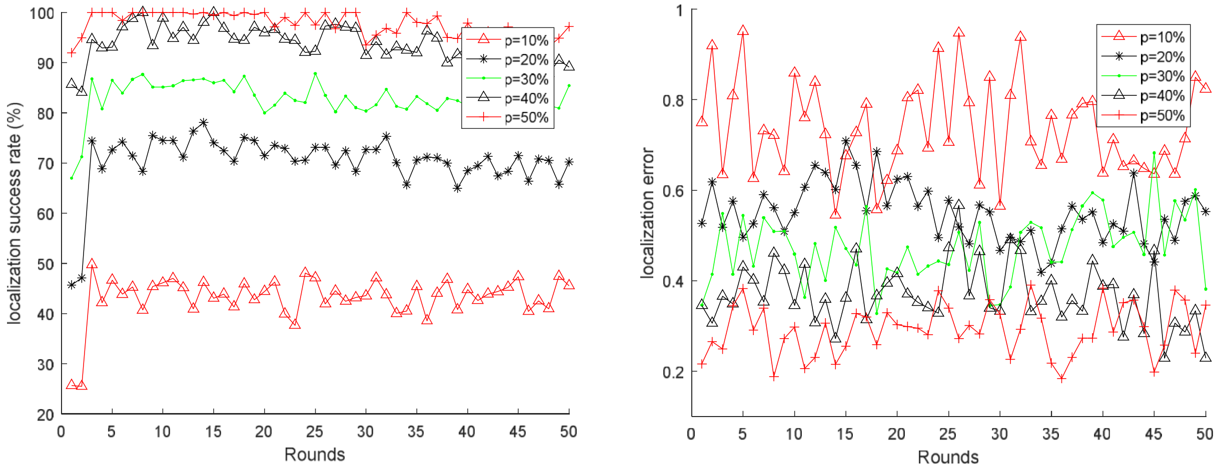
(a) The influence of communication radius on the success rate of localization

(b) The influence of communication radius on the average relative error

Figure 5. The influence of communication radius on DCLA

Fig. 6 shows the influence of anchor node proportion on DCLA. As can be seen from (a), with the increase of anchor node proportion, the success rate of localization is getting increasingly high. When the anchor node proportion increases from $p = 10\%$ to $p = 50\%$, the success rate of localization increases from 43.18% to 97.72%. As can be seen from (b), the average relative error decreases with increase of anchor node proportion. When the anchor node proportion increases from $p = 10\%$ to $p = 50\%$, the average relative error is reduced from $0.74r$ to $0.29r$. Considering the localization success rate and average relative error, this algorithm selects $p = 20\%$.

Fig. 7 shows the influence of moving velocity on DCLA. As can be seen from (a), with the increase of moving velocity, the success rate of localization ranges between 75.12% and 80.21%. This shows that the algorithm has a good adaptability to moving velocity. As can be seen from (b), with the moving velocity increases, the average relative error

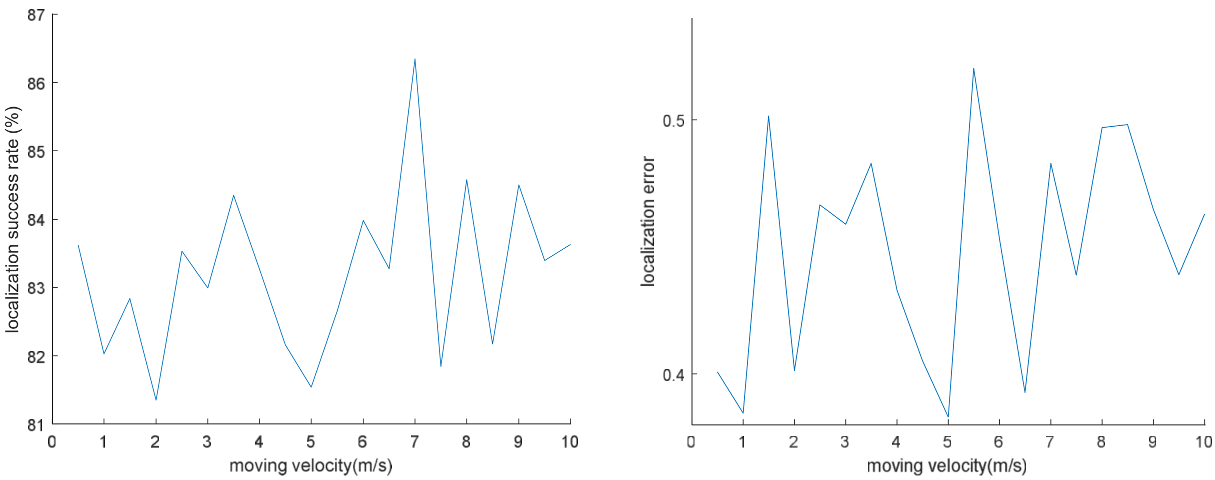


(a) The influence of anchor proportion on the success rate of localization

(b) The influence of anchor proportion on the average relative error

FIGURE 6. The influence of anchor proportion on DCLA

tends to rise slowly, but the increase trend is not obvious. Considering the success rate of localization and average relative error, this algorithm selects $2.8m/s$.



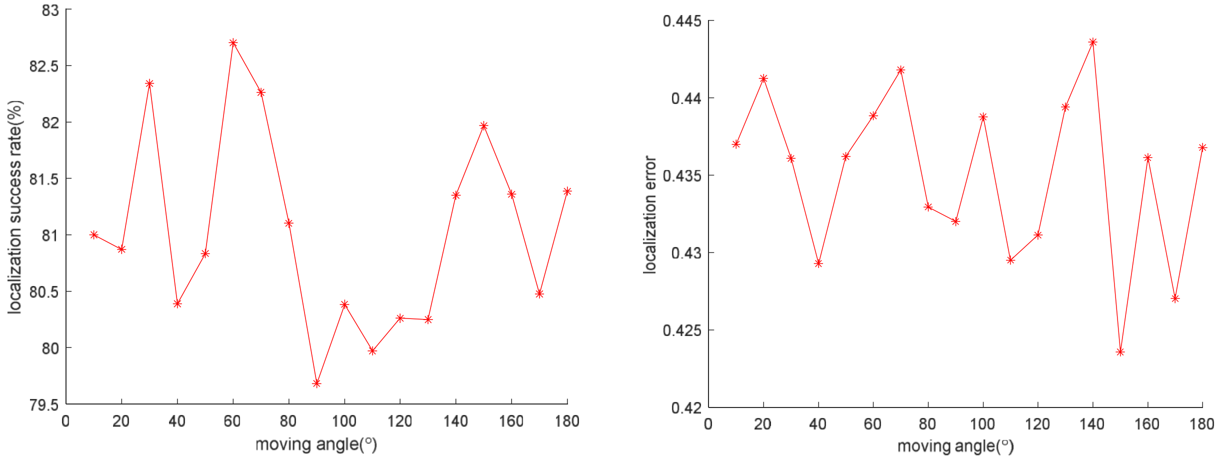
(a) The influence of moving velocity on the success rate of localization

(b) The influence of moving velocity on the average relative error

FIGURE 7. The influence of moving velocity on DCLA

Fig. 8 shows the influence of moving angle on DCLA. As can be seen from (a), with the increase of θ, the success rate of localization ranges between 79.68% and 72.61%. As can be seen from (b), with the increase of θ, the average relative error ranges between $0.423r$ and $0.443r$. This shows that the algorithm has a good adaptability to moving angle. Considering the success rate of localization and average relative error, this algorithm selects $30°$.

Fig. 9 is the performance comparison about the proposed DCLA, the MNPLA [16], and TLA algorithm. The proportion of anchor node is $p = 20\%$. The communication radius is $r = 10\,\text{m}$. The movement angle θ is $30°$. The moving velocity is $2.8m/s$. As can be seen from (a), the average success rate of localization of TLA, MNPLA, and DCLA is 17.90%, 48.17%, 71.66%. The DCLA algorithm proposed in this paper from the third round began to increase from 56.52% to 78.46%. The localization success rate is improved by about

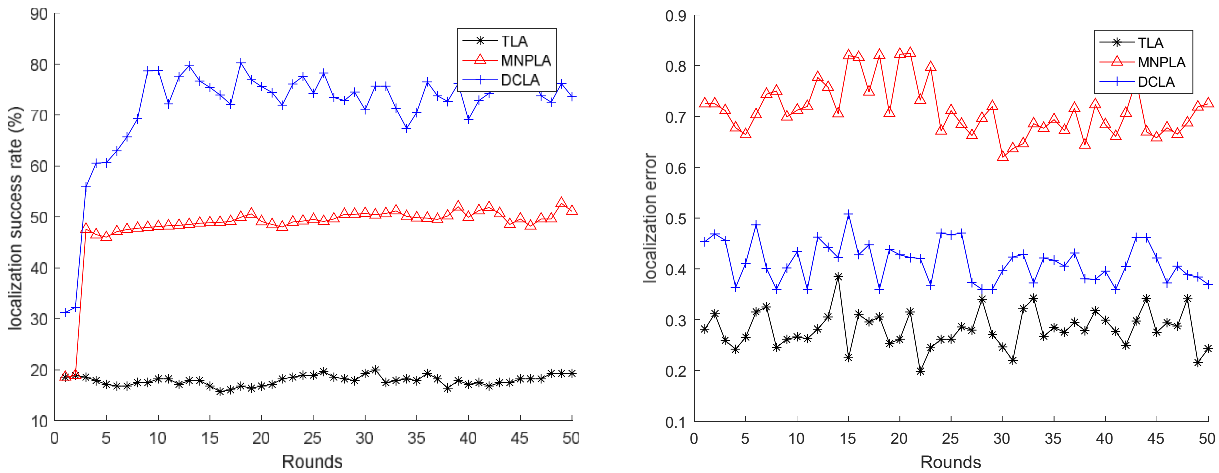


(a) The influence of moving angle on the success rate of localization

(b) The influence of moving angle on the average relative error

FIGURE 8. The influence of moving angle on DCLA

53.16% compared with TLA algorithm, and the localization success rate is improved by about 23.49% compared with MNPLA algorithm. As can be seen from (b), the average relative error of TLA, MNPLA, and DCLA is $0.28r$, $0.71r$, and $0.40r$. The average relative error is reduced by about $0.31r$ compared with MNPLA algorithm.



(a) The comparison of the success rate of localization

(b) The comparison of the average relative error

FIGURE 9. The performance comparison of different algorithms

5. **Conclusions.** This paper presents a dynamic cooperative localization algorithm for WSN (DCLA). In this paper, RSSI localization algorithm is applied in wireless sensor networks where all anchor nodes and unknown nodes move randomly. Each unknown node locates its location by the cooperative relationship when the number of neighbor anchor nodes for an unknown node is more than three. When the number of neighbor anchor nodes is less than 3 and the location of node has been located in the past two time slots, it can be located through cooperative relationship between the adjacent time slots. If the location in the past two time slots has not been located, the cooperative relationship between relative localization and absolute localization based on the multi-dimensional scaling-MAP algorithm (MDS-MAP) is used for localization. Therefore the

algorithm successfully solves the problem that the unknown nodes cannot be located when the number of anchor nodes is less than three. Simulation results show that the localization success rate of DCLA is 53.16% higher than that of TLA. Compared with MNPLA, the localization success rate is improved by about 23.49%, and the average relative error is reduced by about $0.31r$.

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