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Research on Relative Coordinate Localization of Nodes Based on Topology Control

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Abstract. *The global energy and time overhead of the network is affected by the number of anchors and topology structures in wireless sensor network localization. A relative coordinate localization algorithm based on topology control is proposed for shortening time overhead and reducing the number of anchors in positioning stage. This algorithm makes unknown nodes be localized in the deployment of network and provide new thinking on co-designing between topology and node localization based on cross-layer design. At the beginning of the formation of network topology, when information is exchanged between nodes, pass the distance information and make use of it to generate the relative coordinates of the unknown node without anchors introduced.*
Keywords: Topology control, Anchor free, Cross-layer design, Relative coordinate

1. **Introduction.** Wireless sensor network localization problem with given or measured data among neighbor nodes (such as hops, distance, angle, etc.) is to find precisely estimated coordinates of all unknown sensor nodes. In general, sensor nodes which are typically deployed in a variety of conditions cooperate with each other in a self-organized and multi-hop manner to accomplish specific monitoring tasks. The sensor nodes that are randomly deployed cannot obtain their own location information that is a necessary condition to ensure that the sensor can provide effective service. Only when the perceptual data obtains the position of target objects, does the data information obtained has practical significance [1]. For example, pedestrian navigation in the ubiquitous environment requires real-time positioning, how to obtain the vehicle's own location information accurately in vehicular ad hoc network to accommodate special traffic environment, the target object tracking and so on. At the same time, node location is also the supporting information of routing algorithm design in WSN. In the wireless multi-hop communication network, pan-routing technology and network cross-layer optimization design need to be assisted by localization technology [2]. The location-aided routing algorithm can be a good extension of networking flexibility in smart home, and a variety of heterogeneous network interconnection problems can be solved. Therefore, the sensor nodes need to use a certain localization algorithm to perform real-time self-positioning after deploying randomly to ensure that the receiving terminal can obtain the exact location of monitored objects.

Topology control is the sandwich between MAC layer and network layer between, belonging to cross-layer design areas. The technology was originally applied to WSN, ad-hoc and other networks, used to reduce network energy consumption and interference, is the bridge to connect the network routing, the network MAC layer and the physical layer [3].

What topology control algorithm studied is how to adjust the working status of network nodes dynamically in order to prolong the network lifetime, reduce communication interference of nodes and optimize the network structure of data forwarding under the premise of maintaining good network connectivity [4]. At present, most of the researches focus on the optimization of network topology, and [5] proposed a distributed topology control protocol restricted information exchange among neighboring nodes. The topology control problem is considered, creating an energy-efficient topology of wireless network in presence of selfish nodes. A non-cooperative game framework is established to describe the interaction of nodes in the topology construction process. Some specific characteristics of Nash equilibrium topologies are analyzed. In [6] [7], a hierarchical topology generation algorithm (HTGA) is proposed for wireless sensor networks. In the cluster head election process, the energy, density, distance, and the number of times the cluster head was elected are introduced as the limiting parameters, and node with optimal comprehensive performance has a higher probability of being elected cluster head. Node degree parameters other regulatory factors are also set to improve adaptability and adjustability of the algorithm for different network environment, which is to construct the optimal network topology. In the above-mentioned algorithms, the common target mainly includes, ensuring the reachability between nodes, reducing energy loss, improving network capacity, reducing channel interference and enhancing spatial multiplexing.

How to form the optimal topology of the network by combining topology control with node localization effectively is the key technology of the cross-layer design in the sensor network. It is also the main point of this paper. Therefore, this paper proposes a relative coordinate localization algorithm based on topology control. According to the difference of measurement methods, the relative localization mainly includes the following ways, RFID relative localization, network connectivity relative localization, ranging relative localization and so on. Because there are very different aspects of the measurement result, measurement accuracy, transmission ranges and so on, the mathematical modeling and solving methods of the various localization methods are very different [8]. In this paper, we adopt the ranging relative localization algorithm to obtain the distance information between nodes based on Time Difference of Arrival (TDOA). In the localization mechanism based on the TDOA, the transmitting node simultaneously transmits two kinds of wireless signals with different propagation speed. The receiving node calculates the distance of the two nodes according to the time difference between the two signals and the propagation speed of the two signals. And then calculate the location of the node through the basic positioning algorithm. The algorithm does not need time synchronization, and it has high positioning accuracy and anti-interference ability. In the establishment of the relative coordinate system stage, the angle of the key nodes is obtained by using Angle of Arrival (AOA). The technique needs to set the directional antenna at two or more nodes to sense the arrival direction of the transmitting node signal, to calculate the relative azimuth or angle between the receiving node and the anchor node. And the relative coordinates of unknown nodes can be determined by estimating the distance between unknown nodes and key nodes, and then depending on trilateration for successful node localization.

WSN is usually application-oriented, so a specific localization algorithm is not universal, and it achieves a certain positioning accuracy only in a specific network environment. In addition, the existing localization methods basically use a certain proportion of anchors to assist in positioning, which not only increases the global energy and time overhead, but also has some limitations in the environment that is not suitable for the deployment of anchors. In this paper, a localization method which combines topology control with node localization are proposed to obtain the relative coordinates of each node in the network environment with positioning error caused by anchor-free. Meanwhile, the coordinates of unknown nodes obtained at the beginning of the formation of network topology are prerequisite and basis in the process dividing and merging. It is also the first step to study the problems of MAC, routing, security and energy saving [9].

2. Node Localization Mechanism Based on Topology Control.

How to obtain the relative position of nodes is the primary problem that must be considered in topology control and node localization at the beginning of the formation of network topology without anchors. The sensor nodes transmit data by utilizing short-range wireless communication technology with the energy constraints of nodes. With reference to the Open System Interconnection Reference Model (OSI-RM) and WSN communication protocol stack system, the physical layer of the sensor is responsible for the management and control of the information transmitted and received by each sensor device. Localization mechanism involves four levels of WSN [10], first , a variety of monitoring signals is collected by the sensors in the physical layer, and then transmitted them to the data link layer where network topology structure is formed via sink nodes or base stations in WSN. Second, the data stream detected will be fused (pre-processing) in the network layer and be accessed to the core network through the bridge, gateway, routing and other network equipment. Third, the transmitted data through transmission layer is stored in the corresponding server to achieve localization according to localization model or localization algorithm. Finally, on the one hand, the positioning results are presented to the administrator in the application layer. On the other hand, the results will be fed back to the physical layer in terms of the application needs.

WSN node resources are limited, in order to prolong the network lifetime as much as possible to meet the oriented-application QoS requirements and dynamic network topology [11], which requires coordination of various parameters scattered in the different layers to enhance the overall performance of the network. Using the cross-layer design method, it can improve the performance of the network by the interactions between parameters of different layers. In the process of node localization, the information interaction of different layers is bound to increase the global energy and time cost of the network. In the process of selecting cluster head and forming node relationship, the distance parameter between the nodes is exchanged, make it serve for cluster head in network layer, which will greatly simplify the complexity of cluster head control and achieve the relative localization. Therefore, the cross-layer design of topology control and node localization is very attractive, which is also the key point in this paper. It aims to provide new thinking for cross-layer design between topology control and node localization and implement a localization algorithm for unknown nodes without anchors .

2.1. System Initialization.

The sensor nodes are randomly deployed in the work area. From the user's point of view, minimizing the number of anchors when the other requirements and targeting indicators are not changed is highly desirable. On the one hand, the network overhead can be reduced. On the other hand, this scenario provides the possibility of localization for the location environment that cannot be deployed anchors. However, the proportion of the anchors directly affects the positioning area and positioning accuracy, provided that we need to obtain a more accurate positioning value, the proportion of the anchors is generally 0.1 or more. Based on the idea of relative localization, a combination of distance and angel in this paper are introduced to estimate ranges between neighboring nodes in the network environment without anchors, which can obtain the relative coordinates of each unknown node in the initial stage of node deployment to realize local relative localization. The algorithm introduced in this paper assumes that the network environment has the following properties.

1. All nodes are homogenous common nodes. They have the same hardware capability and the ability of data fusion, and each one has the uniquely identifiable ID.
2. The node communication link is symmetric, that is the communication among the nodes using the same energy for transmission.
3. The nodes do not have any position information, but the node can calculate the relative distance from the signal-originating node based on the received signal strength.
4. Each sensor node corrects the clock by referring to Location Measurement Unit (LMU) to minimum the clock error.

2.2. **Reflection Problem Analysis.** At the system initialization stage, the distance between the two nodes can be measured by introducing ranging method TDOA. In the network environment without anchors, if the randomly deployed nodes only rely on the distance among nodes to locate, there will be a reflection problem. Assume that A, B, C and D are four unknown nodes, and the distance between any two nodes is known. As is shown in Fig. 1.

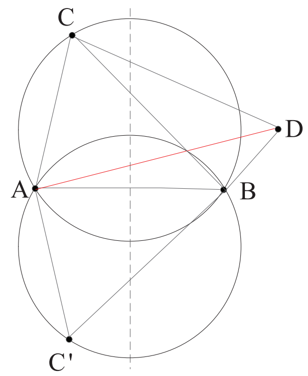

FIGURE 1. Reflection Problem

First, according to the distance among the nodes A, B, C to determine whether the three points collinear (if $AB + BC \leq AC$, collinear), for the establishment of the relative coordinate system later. Second, if the three nodes are non-cllinear, then A is the coordinate origin, B is on the $+x$ axis, the angle can be determined through the cosine theorem, but C is in the clockwise or counterclockwise of AB is not sure. Likewise, if a new node D is added, nodes A, B, and D also has this problem similar to C. Hence, the exact orientation of each node cannot be obtained only based on distance parameter, and the reflection (i.e., symmetry point) of each node may be obtained, so the coordinate calculation cannot be performed. For this, azimuth information between nodes can be measured by means of the direction sensor compass to eliminate the reflection problem caused by the positioning of the distance parameter only.

2.3. **Cross-layer Design between Topology Control and Node Localization.** At the beginning of the formation of node neighbor relationship, the relative coordinates of unknown nodes are obtained at the same time for saving energy and management consumption, which is the fundamental goal cross-layer design. For this, a local relative coordinate localization algorithm based on topology control is proposed. The algorithm uses the time-difference positioning system to provide the position information of part nodes in a certain range. Then, through the algorithm introduced in this paper, unknown nodes are localized with the formation of the network topology. As the message propagates in the network, the topology is formed in turn, and the relative coordinates of the nodes are successively obtained. Based on the above ideas, the algorithm is described as follows.

1. According to node competition mechanism, message information for the discovery of neighbor nodes is sent by any node i, it carries the ID number, communication radius and distance information of each node.
2. Neighbor nodes give a reply to i immediately after receiving message sent by i, then establish the relative coordinate system with two non-collinear nodes j and k for the first reply. Three nodes start compass to get the azimuth between nodes to eliminate the reflection problem. Calculate the relative coordinates of the three nodes.
3. Start the first round of localization, according to the distance obtained in initialization, and then locate the neighbor nodes within the communication radius in the relative coordinate system. The coordinates of the localized nodes are stored in the positioning table in order of localization.
4. The nodes localized serves as anchors to locate its neighbor nodes, and the newly added coordinates in the next round are compared with the data already existing in the positioning table. If the data already exist, the localization process is not performed, otherwise it is performed according to step 3, and then updates the data contained in positioning table.
5. Repeat step 4 until the data in the positioning table no longer changes.

2.3.1. *Establish Relative Coordinate System.* The establishment of relative coordinate system is one of the key problems in the whole positioning system. It refers to establish a system based on one node according to distance information without anchors introduced. Specific principle is as follows, when one node i is elected to the starting node according to the competition mechanism, it is the coordinate origin, which ensures the flexibility of the selection mechanism and follows the principle of selecting the center node as much as possible to reduce the overhead. And then broadcast the message within the communication radius, according to the first step 1 to establish the relative coordinate system. i is the coordinate origin, j is on the $+x$ axis, k is on the same side of the $+y$ axis, and the coordinate system satisfies the right hand rule. In this way, we can establish the relative coordinate system RCS_i (Relative Coordinate System) with i as the coordinate origin, as is shown in Fig. 2.

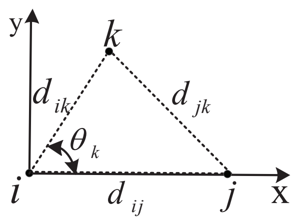

FIGURE 2. Establish Relative Coordinate System

2.3.2. *Calculate Relative Coordinate.* After RCS_i is established, the relative coordinates of nodes j and k are recorded as $P_j(j_x, j_y)$ and $P_k(k_x, k_y)$. As is shown in Fig. 2, the coordinates of nodes j and k are,

$$\begin{cases} j_x = d_{ij} \\ j_y = 0 \end{cases} \tag{1}$$

$$\begin{cases} k_x = d_{ij} \cdot cos\theta_k \\ k_y = d_{ik} \cdot sin\theta_k \end{cases} \tag{2}$$

Taking into account the accuracy requirements, the calculation of $\theta_k \in (0, \pi)$ does not use angle measurement directly, and use distance information combined with the trigonometric function to calculate, then

$$\theta_k = arccos\frac{d_{ik}^2 + d_{ij}^2 - d_{jk}^2}{2d_{ik}d_{ij}} \tag{3}$$

Thus, the relative coordinates of the unknown neighbor nodes can be calculated in turn using the three known nodes, as is shown in Fig. 3.

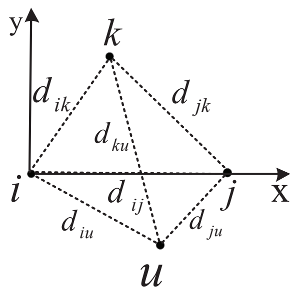

FIGURE 3. Calculate the Relative Coordinates of the Unknown Node u

u is the neighbor node of node i, j, k, then the relative coordinates of node u can be obtained according to the trilateration, recorded as $P_u(u_x, u_y)$. The coordinates of u are calculated as follows,

$$\begin{cases} u_x^2 + u_y^2 = d_{iu}^2 \\ (u_x - j_x)^2 + u_y^2 = d_{ju}^2 \\ (u_x - k_x)^2 + (u_y - k_y)^2 = d_{ku}^2 \end{cases} \tag{4}$$

Solution of the equation is

$$\begin{cases} u_x = \dfrac{j_x^2 + d_{iu}^2 - d_{ju}^2}{2j_x} \\ u_y = \dfrac{d_{ju}^2 - d_{ku}^2}{2k_y} - \dfrac{k_x u_x}{k_y} + \dfrac{k_y}{2} \end{cases} \tag{5}$$

At this point, the position of node u is known, and it acts as anchors, the relative coordinates of other unknown nodes are obtained according to the binding process based on the proposed algorithm in this paper.

3. **Simulation Analysis.** In the sensor network, different application environments have different requirements for nodes to form a network, and all the localization algorithms are not universal, so it is difficult to determine which localization algorithm is better. The algorithm proposed in this paper mainly focused on the network environment which is not suitable for deploying anchors but requires precise positioning. At the same time, the transmission of position information among nodes is realized in the process of node topology formation to reduce the global energy and time overhead. So it can be used to verify the applicability of this algorithm from the aspects of node localization probability, isolated nodes localization and localization error source. The default simulation parameters are as follows, in the $100m \times 100m$ two-dimensional square area, the n nodes are randomly deployed, and the node communication radius is R.

3.1. **Analysis of nodes localization Probability.** The parameters that affect node localization probability are mainly the communication radius R and the number of deployed nodes n. By selecting the sizes of n and R, the probability distribution of nodes in different conditions can be obtained. First, 50 nodes were randomly deployed in a square area with a length of $100m$, and the average number of simulations was more than 100 times. According to the algorithm, we get the localization probability distribution of different R, as is shown in Fig. 4.

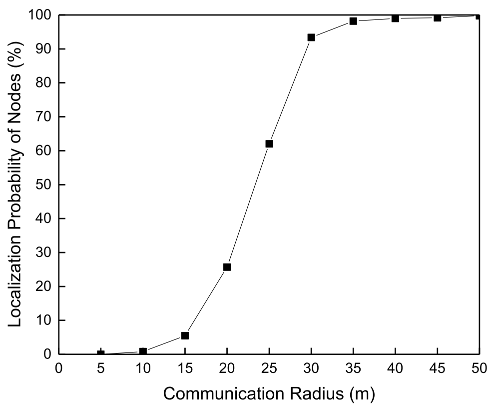

FIGURE 4. The Relationship between R and Localization Probability

It can be seen from the Fig. 4, when $R \leq 20$, the localization probability is very low, or even less than 1/3. The main reason is that the node deployment process is random, local network may be sparse, after the establishment of RCS_i, unknown nodes limited by R cannot communicate with other three nodes simultaneously, resulting in isolated points cannot locate. However, the probability is improved as R increases. When $R = 30$, the probability is over 90%. When $R \geq 35$, the probability is close to 100%.

Another parameter that affects the probability is the number of nodes n. In a square area with a length of $100m$, n nodes are randomly deployed, set $R = 35$, and the average number of simulations is more than 100 times. According to the algorithm in this paper, it can be seen from Fig. 5 that the probability distribution of the nodes with different network density.

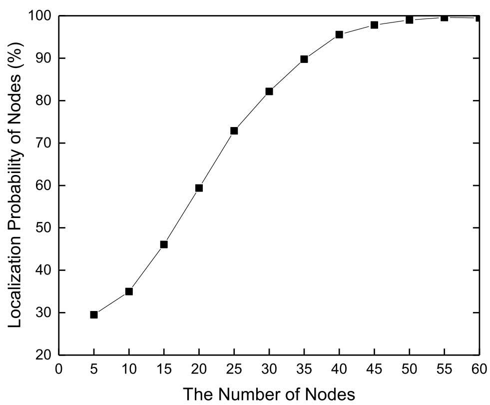

FIGURE 5. The Relationship between n and Localization Probability

3.2. **Analysis of Isolated Nodes.** In the process of establishing RCS_i, message information for the discovery of neighbor nodes is sent by any node, and nodes location is realized according to the above algorithm. As shown in Fig. 6, where $\times$ represents the first responded nodes, $\Box$ indicates the localized nodes, and $\bigcirc$ stands for isolated node. It is not difficult to find that the nodes in the network boundary may be far apart from the neighbor nodes or the number of neighbors is small, resulting in the localization accuracy is not high, and even only the direction and angle range of the nodes can be determined due to the random topology structure.

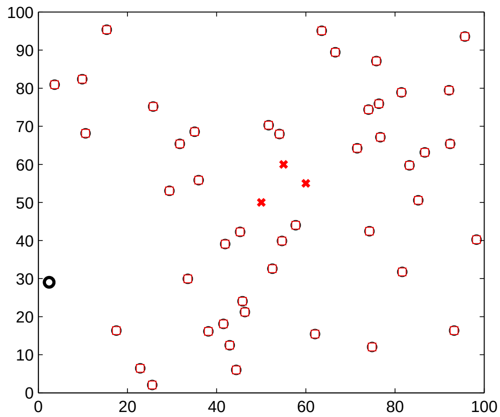

FIGURE 6. Node Localization

The initial topology generated during node localization is shown in Fig. 7. It can be seen that the isolated node has only one neighbor node and cannot be pinpointed. It is necessary to use the angle information for the node to determine the approximate range of its position to ensure that the point will not be lost.

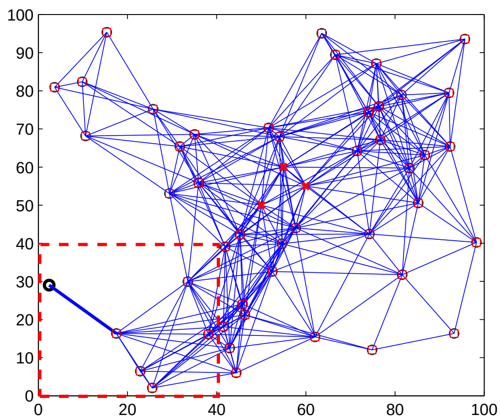

FIGURE 7. Initial Topology

Fig. 8 is an enlarged view of the dotted line area in Fig. 7. Since isolated node A cannot communicate with other nodes except the node B, the position area of A can be calculated by the following method, B is the neighbor node of A, so A will be on the circle B; since C and D are the two nodes closest to A except B, the circle C and circle D is in addition to B points, the distance from the A point of the two nodes, respectively, C, D as

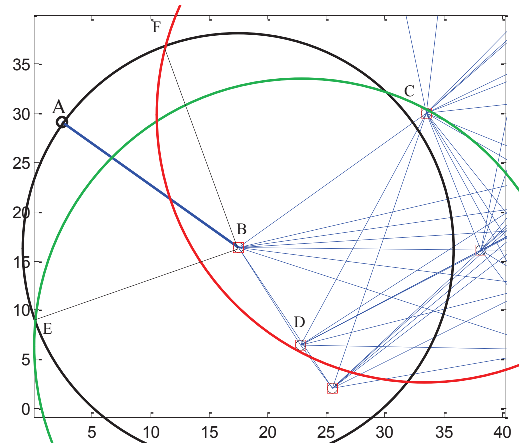

FIGURE 8. Isolated Node Localization

the center, R as the radius of the circle, its intersection point with circle B is E, F. If A is located below F, then node A will communicate with node C, become the neighbor of C, which contraries to the actual situation. When A is located above E, A will communicate with node D, become the neighbor D, the same contradiction, so we can determine the range of node A on $\widehat{EF}$.

3.3. **Localization Error Source.** At the beginning of the network topology formation without anchors introduced, the distance information transmitted among the nodes is based on the parameter measurement, so the localization accuracy is related to the measurement. On the one hand, the wireless channel transmission environment is complex and varied, such as noise, path loss, multi-path interference, etc., which leads to the distance error. On the other hand, the processing time of the relevant processor has a certain influence on the localization accuracy. When the network environment is more complicated, the nodes waiting in the network beyond the load of the network nodes, which causes network congestion. The phenomenon will increase the processing time, resulting in localization error.

4. **Conclusions.** A relative coordinate localization algorithm based on topology control without anchors introduced is proposed. The localization algorithm can control the cluster and channel management from the global control. At the beginning of the formation of the node topology, the distance information is added during the message exchange process. According to the principle of relative coordinate system, the relative coordinates of each node are obtained by recursive way. On the one hand, a feasible algorithm is proposed for node localization in the monitoring area where the number of anchors is less. It provides new thinking for the cross-layer design of topology control and node localization. On the other hand, the algorithm can cover positioning technology with anchors, more suitable for dynamic tracking of the whole network node, which will be studied in the future work.

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