IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 27, 2018, accepted February 27, 2018, date of publication March 9, 2018, date of current version March 19, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2813082

New Wireless Sensor Network Localization Algorithm for Outdoor Adventure

XUEJIAN ZHAO[1], XINHUI ZHANG[2], ZHIXIN SUN[1], AND PAN WANG[1]
[1]Key Lab of Broadband Wireless Communication and Sensor Network Technology, Ministry of Education, Nanjing University of Posts and Telecommunications, Nanjing 210003, China
[2]College of the Internet of Things, Nanjing University of Posts and Telecommunications, Nanjing 210003, China

Corresponding author: Xuejian Zhao (zhaoxj@njupt.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61373135, Grant 61300240, and Grant 61672299, in part by the Natural Science Foundation of Jiangsu Province of China under Grant BK20140883 and Grant 61572262, in part by the China Postdoctoral Science Foundation funded Project under Grant 2015M581844, in part by the Jiangsu Planned Projects for Postdoctoral Research Funds under Grant 1501125B, and in part by the NUPTSF under Grant NY214101.The work of X. Zhao was supported by the China Scholarship Council.

ABSTRACT For a long time, it has been frequently reported that outdoor adventurers get lost and die. During the course of an outdoor adventure, it is a matter of life and death to locate the lost adventurer and start the emergency rescue after determining that someone was lost. In this paper, a new wireless sensor network localization algorithm for outdoor adventures is proposed. This algorithm is notably easy to implement, with rather low implementation overhead. In the proposed localization algorithm, first, the Fermat point model is used to divide the original triangular pyramid constructed by the neighbor anchor nodes of the unknown node into four smaller sub-triangular pyramids. Next, the available sub-triangular pyramid in which the unknown node is located can be further divided into a set of irregularly shaped subspaces by the mid-perpendicular plane model. Finally, the centroid of the available subspace can be computed and regarded as the location of the unknown node. Simulation results show that the proposed localization algorithm can remarkably improve the localization accuracy.

INDEX TERMS Localization, outdoor adventure, wireless sensor networks, Fermat point model, mid-perpendicular plane model.

I. INTRODUCTION

For a long time, it is frequently reported that outdoor adventurers get lost and die. During the course of an outdoor adventure, it is a matter of life and death to locate the lost adventurer and start the emergency rescue when you find someone who was lost. This problem has increasingly attracted the public's attention. Several GPS-based location devices and remote radio technology based offline tracking devices, such as the Spot satellite communicator and goTele tracker, have been developed and introduced to the market. However, most of these products are used for self-localization and communication. These products will become less useful when the lost adventurer is seriously injured or unconscious. The products cannot help us to easily and quickly locate the lost adventurer in this circumstance. Moreover, the high price of these products may scare many adventurers away. Thus, many outdoor adventurers are still at risk.

In recent years, with further study of IoT (Internet of Things) technologies, a large number of intelligent systems have gradually emerged, such as smart health care, smart homes, and smart grids [1], [2]. To locate the lost adventurers in a fast and low-cost way, a new WSN (Wireless Sensor Network) localization algorithm is proposed in this paper. The proposed algorithm is an approximate point in triangulation test (APIT) -based localization algorithm combining the Fermat point and the mid-perpendicular plane models, and it is named FP-MPP-APIT. It is a distributed range-free localization algorithm for three-dimensional WSNs that possesses the advantages of APIT-based localization algorithms. Moreover, the localization accuracy can be strongly improved by the Fermat point and mid-perpendicular plane model, given that there are only a small number of anchor nodes. The main contributions of this paper are listed as follows.

The first contribution is the mid-perpendicular plane model. The idea of utilizing the perpendicular bisector to divide the triangle containing the unknown node for further analysis to improve the localization accuracy is extended to three-dimensional space. It is favorable for improving the localization accuracy in three-dimensional wireless sensor networks.

Second, a distributed range-free localization algorithm for three-dimensional WSNs, named FP-MPP-APIT, is proposed. This algorithm is a simple, fast and low-cost localization algorithm that can be used in many applications, such as locating lost adventurers in the wild. In the FP-MPP-APIT algorithm, the Fermat point model is combined with the mid-perpendicular plane model to narrow the area in which the unknown node is located. First, the Fermat point is used to divide the original triangular pyramid constructed by the neighbor anchor nodes of the unknown node into four smaller sub-triangular pyramids. Second, the available sub-triangular pyramid in which the unknown node is located can be further divided into a set of irregularly shaped subspaces by the mid-perpendicular plane model. Finally, the centroid of the available subspace can be computed and regarded as the location of the unknown node.

Finally, simulations are conducted to verify the performance of the proposed FP-MPP-APIT algorithm.

The rest of this paper is organized as follows. In Section 2, related works are introduced. In Section 3, the proposed FP-MPP-APIT algorithm is described in detail. In Section 4, we verify and evaluate the performance of the FP-MPP-APIT algorithm, and the simulation results are discussed. Finally, the study's conclusions are presented in Section 5.

II. RELATED WORKS

In recent years, location awareness has become an attractive and critical research issue in wireless sensor networks [3], [4]. The algorithms proposed for dealing with the localization problem in WSNs can be classified into two categories: range-based schemes and range-free schemes [5].

In range-based localization schemes, the range information can be obtained using time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), and received signal strength indicator (RSSI) technologies [6]–[9]. The range-based localization schemes typically have higher location accuracy but usually require additional complex hardware to measure distances or angles. Therefore, range-based schemes do not apply to low-power or low-cost applications due to the inherent characteristics of wireless sensor networks.

In contrast, the range-free schemes do not need the distance or angle information for localization. Consequently, the range-free schemes provide an economic approach for localization, although the range-free schemes usually have relatively lower localization accuracy. At present, many classical range-free algorithms have been proposed [10]–[13]. The Centroid algorithm was proposed by Belusu *et al.* [10] to calculate the nodes' locations. Niculescu and Nath [11] proposed the DV-Hop localization method that uses hop counts from each node to specific anchor points for localization. Zhang *et al.* [12] proposed to select the anchor nodes that can meet the condition of hop count threshold and collinearity to participate in the localization procedure to obtain better positioning accuracy in both homogeneous networks and anisotropic networks. He *et al.* [13] proposed a traditional approximate point in triangulation test (APIT) localization algorithm. This algorithm requires low equipped hardware, has relatively high location accuracy and is easy to implement. Therefore, it is widely used for localization in wireless sensor networks. However, there are still defects in the APIT algorithm: 1) it requires high anchor node density, 2) in the process of APIT, the boundary effect and low neighbor node density can easily increase In-To-Out error and Out-To-In error, and 3) the location accuracy of the unknown node in the triangle overlap region should be further improved.

According to the drawbacks of the APIT algorithm, a series of improved algorithms have been proposed [14]–[25]. Yang and Liu [14] proposed a novel algorithm named PB-APIT. In the PB-APIT algorithm, if the unknown node is located in a triangle, we can utilize the perpendicular bisector of each side to divide the triangle into four to six sub-areas for further judgment to improve the localization accuracy. In [15], a thorough analysis of the APIT algorithm was made, and an improvement was proposed to reduce the probabilities of In-To-Out Error and Out-To-In Error. Vivekanandan and Wong [16] suggested that the overlapping area can be divided into a plurality of sub-regions in order to reduce the size of the triangle to improve localization accuracy. In [17], the RSSI-APIT algorithm was proposed to solve the problem that the unknown node with fewer than three neighbor beacon nodes cannot be located. In [18], the MC-APIT algorithm was proposed, which implements random sampling using the Monte Carlo method in the overlap region. Li *et al.* [19] presented an improved APIT algorithm based on the direction searching in. By comparing the received RSSI signal strength of nodes, the node can correctly be judged to be located inside or outside the triangle. In [20], a tetrahedral volume judgment APIT algorithm (VJ-APIT) was proposed. Simulation results show that the proposed algorithm can keep high localization accuracy under different anchor densities and communication radii. Tang *et al.* [21] analyzed the inside and outside triangle cover judgment errors in the APIT algorithm and proposed an improved APIT algorithm named APICT. In [22], a novel virtual nodes-based range-free localization scheme named VN-APIT was proposed. By rationally deploying virtual nodes in the sensor network according to the proposed VN-APIT test theory, the VN-APIT localization scheme can independently determine whether a target node is inside or outside the triangle formed by three certain anchor nodes. The simulation evaluation shows that the proposed VN-APIT scheme is more robust and has a lower average localization error than the conventional APIT scheme. Moreover, considering that wireless sensor networks are often deployed in complex three- dimensional terrains, the APIT algorithm can also be extended up to three-dimensional environments in order to achieve a higher positioning accuracy. Liu and Wang [23] used the concept of the median plane in the APIT-3D algorithm to narrow the positioning range of nodes. In [24], the FM-APIT-3D algorithm based on the Fermat-point division was proposed to address the issue of low localization accuracy. In the FM-APIT-3D algorithm, the original triangular pyramid is divided into four small triangular pyramids using the Fermat-point. Simulation results show that the FM-APIT-3D algorithm can remarkably improve localization accuracy and coverage compared to the APIT-3D. Huang *et al.* [25] presented a localization scheme for wireless sensor networks based on a proposed connectivity-based RF localization strategy called the distributed Fermat-point location estimation algorithm (DFPLE). The DFPLE applies the triangle area of location estimation formed by the intersections of three neighboring beacon nodes. The area of the estimated location is then refined using the Fermat point to achieve the minimum error in estimating sensor node's location.

III. FP-MPP-APIT ALGORITHM

A. FERMAT POINT MODEL

Fermat point is a special point in a three-dimensional space that is similar to the centroid or inside center. In geometry, the Fermat point of a triangular pyramid is the point that makes the total distance from the four vertexes of the triangular pyramid to this minimum point. In any triangular pyramid, the Fermat point must exist and be unique. This point can divide a triangular pyramid into four sub-triangular pyramids. In a three-dimensional coordinate system, the coordinates of the four vertexes of a triangular pyramid are $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, and $D(x_4, y_4, z_4)$. $F(x, y, z)$ is used to represent the coordinates of the Fermat point. Consequently, the sum of distances from the four vertexes A, B, C, and D to the Fermat point F that is denoted by s is calculated by formula (1),

$$s = \sum_{i=1}^{4} \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}. \tag{1}$$

According to the characteristics of the Fermat point, we can assume that the coordinate of the Fermat point $F(x, y, z)$ meets formula (2):

$$\begin{cases} x = \arg \min\limits_{x} s(x, y, z), \\ y = \arg \min\limits_{y} s(x, y, z), \\ z = \arg \min\limits_{z} s(x, y, z). \end{cases} \tag{2}$$

To obtain the minimum value of s, we can strike a partial derivative of formula 1.Thus, we obtain formula (3):

$$\begin{cases} \dfrac{\partial s}{\partial x} = \sum\limits_{i=1}^{4} \dfrac{x - x_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}} = 0, \\ \dfrac{\partial s}{\partial y} = \sum\limits_{i=1}^{4} \dfrac{y - y_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}} = 0, \\ \dfrac{\partial s}{\partial x} = \sum\limits_{i=1}^{4} \dfrac{z - z_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}} = 0. \end{cases} \tag{3}$$

By calculating equation (3), we can thus obtain the coordinates of the Fermat point $F(x, y, z)$.

In the FP-MPP-APIT algorithm, the Fermat point is used to divide the triangular pyramid composed of four neighbor anchor nodes of the unknown node into four smaller triangular pyramids. Then, we can determine in which smaller triangular pyramid the unknown node is located by the RSSI.As is shown in Fig.1,node M is the unknown node, and nodes A, B, C and D are the four neighbor nodes of node M that form the triangular pyramid $ABCD$. F is the Fermat point of the triangular pyramid $ABCD$. Next, the triangular pyramid $ABCD$ can be divided into four smaller sub-triangular pyramids $FABC$, $FACD$, $FABD$ and $FBCD$ using the Fermat point F. Thus, the APIT-3D algorithm [23] can be used to determine in which sub-triangular pyramid the unknown node M is located. The sub-triangular pyramid that contains the unknown node is called the available sub-triangular pyramid.

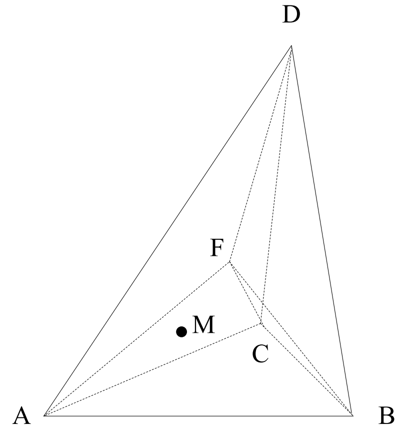

FIGURE 1. Dividing the triangular pyramid by the Fermat-point model.

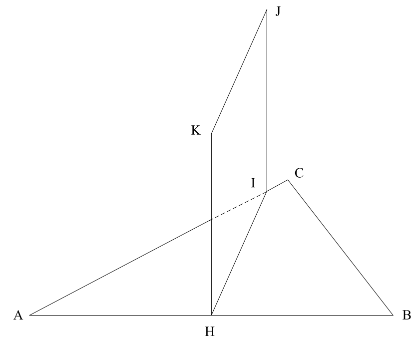

FIGURE 2. Mid-perpendicular plane model.

B. MID-PERPENDICULAR PLANE MODEL

As is shown in Fig.2,H is the midpoint of the edge AB in triangle ABC. KH, HI and AB are mutually perpendicular. This finding implies that the plane $HIJK$ is the mid-perpendicular plane of AB. Thus, any node located in plane $HIJK$ is equidistant from node A and node B. If an unknown node is located in the left side of the mid-perpendicular plane $HIJK$, node A is more likely to have a higher RSSI value. In the FP-MPP-APIT algorithm, the mid-perpendicular plane model is used to divide the sub-triangular pyramids obtained from the Fermat point model. Consequently, the area in which the unknown node is located can be narrowed further. To estimate the

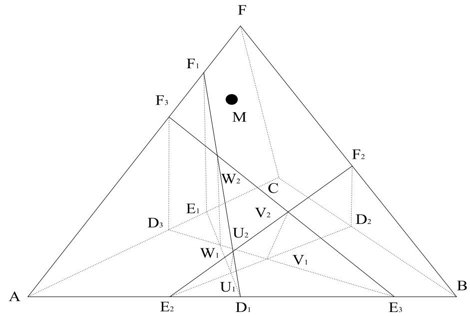

FIGURE 3. Dividing the available triangular pyramid using the mid-perpendicular plane model.

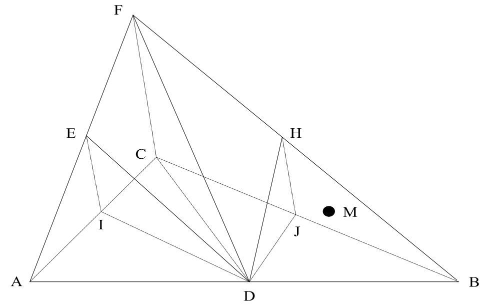

FIGURE 4. Dividing the available triangular pyramid by the mid-perpendicular plane model.

location of the unknown node, the range of the area must be defined. Accordingly, the equation of the mid-perpendicular plane $HIJK$ should be given firstly. Suppose the coordinates of the three vertexes of triangle ABC are $A(x_1,\ y_1,\ z_1)$, $B(x_2,\ y_2, z_2)$, and $C(x_3, y_3, z_3)$,and the coordinates of H is (x_0, y_0, z_0). We can easily get the following formula:

$$\begin{cases} x_0 = \dfrac{x_1 + x_2}{2}, \\ y_0 = \dfrac{y_1 + y_2}{2}, \\ z_0 = \dfrac{z_1 + z_2}{2}. \end{cases} \tag{4}$$

Suppose $N(x, y, z)$ is an arbitrary point on plane $HIJK$. Then, we can deduce that $\overrightarrow{AB} \cdot \overrightarrow{HN} = 0$. The equation of the mid-perpendicular plane $HIJK$ is:

$$(x_2 - x_1)(x - x_0) + (y_2 - y_1)(y - y_0) + (z_2 - z_1)(z - z_0) = 0. \tag{5}$$

If the values of x_0, y_0 and z_0 are substituted into formula (5), formula (5)will be converted to formula (6):

$$(x_2 - x_1)x + (y_2 - y_1)y + (z_2 - z_1)z + \frac{x_1^2 - x_2^2}{2} + \frac{y_1^2 - y_2^2}{2} + \frac{z_1^2 - z_2^2}{2} = 0. \tag{6}$$

In the FP-MPP-APIT algorithm, the mid-perpendicular plane model is used to divide the available sub-triangular pyramid(such as the sub-triangular pyramid $FABC$ in Figure 4) further. As is shown in Fig. 3, the pyramid $FABC$ is an available sub-triangular pyramid in which the unknown node M is located. Planes $D_1E_1F_1$, $D_2E_2F_2$ and $D_3E_3F_3$ are the mid-perpendicular planes of edges AB, BC and AC in triangle ABC, respectively. Points U_1, V_1 and W_1 are the intersection points of planes $D_1E_1F_1$, $D_2E_2F_2$ and $D_3E_3F_3$ on plane ABC. Similarly, points U_2, V_2 and W_2 are the intersection points of planes $D_1E_1F_1$, $D_2E_2F_2$ and $D_3E_3F_3$ on plane ABF. Next, the available sub-triangular pyramid $FABC$ can be divided into a set of irregularly shaped subspaces, such as tetrahedron $U_2 - D_1U_1E_2$, pentahedrons $F_1F_3W_2{-}E_1D_3W_1$, $D_2F_2B{-}V_1V_2E_3$ and $D_1U_1U_2{-}E_3V_2V_1$, hexahedron $AE_2U_1W_1D_3 - AE_2U_2W_2F_3$ and heptahedron $E_1W_1V_1D_2C - F_1W_2V_2F_2F$.

After dividing the available triangular pyramid using the mid-perpendicular plane model, the subspace in which the unknown node is located can be determined according to the following rules in formula (7):

$$In \begin{cases} AE_2U_1W_1D_3 - AE_2U_2W_2F_3, \\ \quad if\ RSSI(A) > RSSI(C) > RSSI(B); \\ U_2 - D_1U_1E_2, \\ \quad if\ RSSI(A) > RSSI(B) > RSSI(C); \\ D_1U_1U_2 - E_3V_2V_1, \\ \quad if\ RSSI(B) > RSSI(A) > RSSI(C); \\ D_2F_2B - V_1V_2E_3, \\ \quad if\ RSSI(B) > RSSI(C) > RSSI(A); \\ E_1W_1V_1D_2C - F_1W_2V_2F_2F, \\ \quad if\ RSSI(C) > RSSI(B) > RSSI(A) \\ F_1F_3W_2 - E_1D_3W_1, \\ \quad if\ RSSI(C) > RSSI(A) > RSSI(B). \end{cases} \tag{7}$$

In formula (7), $RSSI(A)$ is the RSSI value of the signal received by node A from node M. $RSSI(B)$ and $RSSI(C)$ have similar meanings. The first line of formula (7) means that if $if\ RSSI(A) > RSSI(C) > RSSI(B)$, the unknown node is more likely to be located in hexahedron $AE_2U_1W_1D_3 - AE_2U_2W_2F_3$. Furthermore, the other lines of formula (7) can be explained in the same way. Similarly, the irregularly shaped subspace in which the unknown node is located is called the available subspace.

However, it should be noted that the specific number and shapes of irregular subspaces depend on the shape of the available sub-triangular pyramid. For example, as is shown in Fig.4, $AC \perp BC$, $AC \perp FC$, $BC \perp FC$, $AC = BC$, and planes DEI, DFC and DJH are the mid-perpendicular planes of edges AB, BC and AC in triangle ABC, respectively. Next, the available sub-triangular pyramid $FABC$ is only divided into four irregularly shaped subspaces. In another example, as is shown in Fig.5, the available sub-triangular pyramid $FABC$ is a regular triangular pyramid. Thus, the six irregularly shaped subspaces are all triangular pyramids. Although the number and shapes of irregular subspaces may be different, we can estimate the location of the unknown node M in the same way.

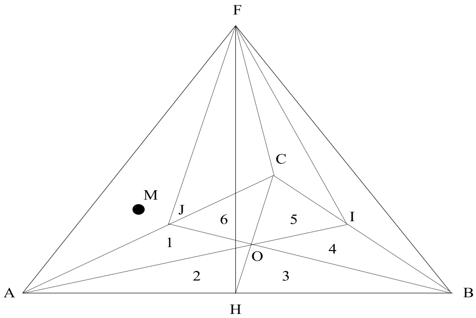

FIGURE 5. Dividing the available triangular pyramid by the mid-perpendicular plane model.

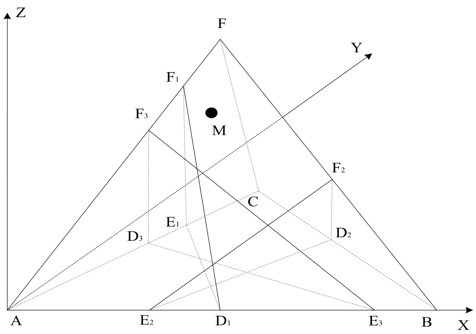

FIGURE 6. Schematic diagram of computing the location of the unknown node.

C. COMPUTING THE LOCATION OF THE UNKNOWN NODE

In this subsection, the method of computing the location of the unknown node will be described in detail.

As is shown in Fig. 6, $FABC$ is an available sub-triangular pyramid, planes $D_1E_1F_1$, $D_2E_2F_2$ and $D_3E_3F_3$ are the respective mid-perpendicular planes of edges AB, BC and AC in triangle ABC, and M is the unknown node to be located.

To compute the location of the unknown node, first a coordinate system is established. In the coordinate system, as is shown in Fig. 9, point A is the coordinate origin, line segment AB is on the X coordinate axis, the Z coordinate axis is perpendicular to the plane ABC, and the triangle ABC is in the first quadrant. Since points A, B and C are three neighbor anchor nodes of the unknown node M and point F is the Fermat point, the coordinates of these points can be easily obtained in the established coordinate system. For convenience, we denote the coordinates of points A, B, C and F as (x_A, y_A, z_A), (x_B, y_B, z_B), (x_C, y_C, z_C) and (x_F, y_F, z_F), respectively. Then, we can easily get the equation of plane ABF as:

$$f_{ABF}(x, y, z) = \begin{bmatrix} (y_F - y_A)\cdot(z_B - z_A) - (y_B - y_A)\cdot(z_F - z_A) \\ (z_F - z_A)\cdot(x_B - x_A) - (z_B - z_A)\cdot(x_F - x_A) \\ (x_F - x_A)\cdot(y_B - y_A) - (x_B - x_A)\cdot(y_F - y_A) \end{bmatrix} \cdot [x\ y\ z] = 0 \tag{8}$$

The equation of plane ACF is

$$f_{ACF}(x, y, z) = \begin{bmatrix} (y_C - y_A)\cdot(z_F - z_A) - (y_F - y_A)\cdot(z_C - z_A) \\ (z_C - z_A)\cdot(x_F - x_A) - (z_F - z_A)\cdot(x_C - x_A) \\ (x_C - x_A)\cdot(y_F - y_A) - (x_F - x_A)\cdot(y_C - y_A) \end{bmatrix} \cdot [x\ y\ z] = 0 \tag{9}$$

The equation of plane BFC is

$$f_{BFC}(x, y, z) = \begin{bmatrix} (y_F - y_B)\cdot(z_C - z_B) - (y_C - y_B)\cdot(z_F - z_B) \\ (z_F - z_B)\cdot(x_C - x_B) - (z_C - z_B)\cdot(x_F - x_B) \\ (x_F - x_B)\cdot(y_C - y_B) - (x_C - x_B)\cdot(y_F - y_B) \end{bmatrix} \cdot [x\ y\ z] = 0 \tag{10}$$

The equation of plane $D_1E_1F_1$ is

$$f_{D_1E_1F_1}(x, y, z) = \begin{bmatrix} x_B - x_A \\ y_B - y_A \\ z_B - z_A \end{bmatrix} \cdot [x\ y\ z] + \frac{x_A^2 - x_B^2}{2} + \frac{y_A^2 - y_B^2}{2} + \frac{z_A^2 - z_B^2}{2} = 0 \tag{11}$$

Since plane $D_1E_1F_1$ is parallel to the Z coordinate axis, the equation of plane $D_1E_1F_1$ can be simplified to

$$f_{D_1E_1F_1}(x, y, z) = \begin{bmatrix} x_B - x_A \\ y_B - y_A \end{bmatrix} \cdot [x\ y\ ] + \frac{x_A^2 - x_B^2}{2} + \frac{y_A^2 - y_B^2}{2} = 0 \tag{12}$$

Similarly, the simplified equation of plane $D_2E_2F_2$ is

$$f_{D_2E_2F_2}(x, y, z) = \begin{bmatrix} x_C - x_B \\ y_C - y_B \end{bmatrix} \cdot [x\ y\ ] + \frac{x_B^2 - x_C^2}{2} + \frac{y_B^2 - y_C^2}{2} = 0 \tag{13}$$

The simplified equation of plane $D_3E_3F_3$ is

$$f_{D_3E_3F_3}(x, y, z) = \begin{bmatrix} x_A - x_C \\ y_A - y_C \end{bmatrix} \cdot [x\ y\ ] + \frac{x_C^2 - x_A^2}{2} + \frac{y_C^2 - y_A^2}{2} = 0 \tag{14}$$

When the irregularly shaped subspace in which the unknown node is located on the basis of RSSI information according to formula (7), the range of the available irregularly shaped subspace can be described by the six planes given above. Furthermore, the centroid of the available irregularly shaped subspace can be regarded as the location of the unknown node. The pseudo-code of computing the location of the unknown node M is as follows.

D. FP-MPP-APIT ALGORITHM

In the FP-MPP-APIT algorithm, the Fermat point model is used to divide the triangular pyramid formed by the anchor nodes of the unknown node into four smaller triangular pyramids. Then, the smaller triangular pyramid can be further divided by the model of the mid-perpendicular plane. Thus, the area in which the unknown node is located can be further

Algorithm 1 Computing the Location of the Unknown Node M

Input: (x_A, y_A, z_A) : the coordinates of points A, (x_B, y_B, z_B): the coordinates of points B, (x_C, y_C, z_C): the coordinates of points C, (x_F, y_F, z_F): the coordinates of points F, $RSSI(A)$: the RSSI value of the signal received by node A from node M, $RSSI(B)$: the RSSI value of the signal received by node B from node M, $RSSI(C)$: the RSSI value of the signal received by node C from node M.

Output:
the location of unknown node M.

1. let $x_{\min} = \min\{x_A, x_B, x_C, x_F\}$, $x_{\max} = \max\{x_A, x_B, x_C, x_F\}$, $y_{\min} = \min\{y_A, y_B, y_C, y_F\}$, $y_{\max} = \max\{y_A, y_B, y_C, y_F\}$, $z_{\min} = \min\{z_A, z_B, z_C, z_F\}$, $z_{\max} = \max\{z_A, z_B, z_C, z_F\}$, $PS = \emptyset$.
2. for a point (x, y, z),x,$y$and z are all integers, $x_{\min} \le x \le x_{\max}$, $y_{\min} \le y \le y_{\max}$, $z_{\min} \le z \le z_{\max}$ do
3. if $RSSI(A) > RSSI(B) > RSSI(C)$ then
4. if $f_{ABF}(x, y, z)$>0 & $f_{ACF}(x, y, z) > 0$ & $f_{BFC}(x, y, z) > 0$ & $f_{D_1E_1F_1}(x, y, z) < 0$ & $f_{D_2E_2F_2}(x, y, z) < 0$&$f_{D_3E_3F_3}(x, y, z) < 0$ then
5. $PS \to PS \cup \{(x, y, z)\}$
6. end if
7. else if $RSSI(A) > RSSI(C) > RSSI(B)$ then
8. if $f_{ABF}(x, y, z) > 0$ & $f_{ACF}(x, y, z) > 0$&$f_{BFC}(x, y, z) > 0$ & $f_{D_1E_1F_1}(x, y, z) < 0$ & $f_{D_2E_2F_2}(x, y, z) > 0$ & $f_{D_3E_3F_3}(x, y, z) < 0$ then
9. $PS \to PS \cup \{(x, y, z)\}$
10. end if
11. else if $RSSI(B) > RSSI(A) > RSSI(C)$ then
12. if $f_{ABF}(x, y, z) > 0$ & $f_{ACF}(x, y, z) > 0$ & $f_{BFC}(x, y, z) > 0$ & $f_{D_1E_1F_1}(x, y, z) > 0$ & $f_{D_2E_2F_2}(x, y, z) < 0$ & $f_{D_3E_3F_3}(x, y, z) < 0$ then
13. $PS \to PS \cup \{(x, y, z)\}$
14. end if
15. else if $RSSI(B) > RSSI(C) > RSSI(A)$ then
16. if $f_{ABF}(x, y, z) > 0$ & $f_{ACF}(x, y, z) > 0$ & $f_{BFC}(x, y, z) > 0$ & $f_{D_1E_1F_1}(x, y, z) > 0$ & $f_{D_2E_2F_2}(x, y, z) < 0$ & $f_{D_3E_3F_3}(x, y, z) > 0$ then
17. $PS \to PS \cup \{(x, y, z)\}$
18.end if
19. else if $RSSI(C) > RSSI(A) > RSSI(B)$ then
20. if $f_{ABF}(x, y, z)$>0 & $f_{ACF}(x, y, z) > 0$ & $f_{BFC}(x, y, z) > 0$ & $f_{D_1E_1F_1}(x, y, z) < 0$ & $f_{D_2E_2F_2}(x, y, z) > 0$ & $f_{D_3E_3F_3}(x, y, z) > 0$ then
21. $PS \to PS \cup \{(x, y, z)\}$
22. end if
23. else if $RSSI(C) > RSSI(B) > RSSI(A)$ then
24. if $f_{ABF}(x, y, z) > 0$ & $f_{ACF}(x, y, z) > 0$ & $f_{BFC}(x, y, z) > 0$ & $f_{D_1E_1F_1}(x, y, z) > 0$ & $f_{D_2E_2F_2}(x, y, z) > 0$ & $f_{D_3E_3F_3}(x, y, z) > 0$ then
25. $PS \to PS \cup \{(x, y, z)\}$
26.end if
27. end if

Algorithm 1 *(Continued.)* Computing the Location of the Unknown Node M

28.end for
29. Compute the location of the unknown node M, $x_M = \frac{\sum_{T\in PS} x_T}{N_{PS}}$, $y_M = \frac{\sum_{T\in PS} y_T}{N_{PS}}$, $z_M = \frac{\sum_{T\in PS} z_T}{N_{PS}}$, N_{PS} is the number of points in point set PS.

narrowed. Consequently, the accumulative errors of localization can be further minimized. It is favorable for improving the localization accuracy in large scale three-dimensional WSNs, especially when the number of anchor nodes is insufficient.

The procedures of the FP-MPP-APIT algorithm can be summarized as follows:

1) Each anchor node in the network broadcasts a Hello message that includes its ID and coordinates using the maximum transmitting power.

2) Each unknown node in the network maintains a counter k, and the initial value of k is set to 0. Upon receiving a Hello message from an anchor node, the counter k adds one and the ID and coordinates of the anchor node are recorded.

3) If an unknown node has four or more anchor nodes, it randomly chooses four anchor nodes to construct a triangular pyramid. Next, the APIT-3D algorithm is used to determine whether the unknown node is located in the constructed triangular pyramid. If so, proceed with step 4. Otherwise, choose another group of four anchor nodes and repeat the process. If there are not enough anchor nodes, the unknown node should wait for a new HELLO message.

4) For the unknown node that is located in the constructed triangular pyramid, the Fermat point model is adopted to divide the constructed triangular pyramid into four sub-triangular pyramids. First, the coordinates of the Fermat point of the constructed triangular pyramid are computed according to formula (3).Then, theAPIT-3D algorithm is used to determine in which sub-triangular pyramid the unknown node is located.

5) For the unknown node that is located in the available sub-triangular pyramid, the mid-perpendicular plane model is used to divide the available sub-triangular pyramid into a set of irregularly shaped subspaces. The unknown node selects an anchor node that is a vertex of the sub-triangle as the coordinate origin and establishes a coordinate system, as Figure 9 shows. The location of the unknown node is computed by algorithm 1.

6) The unknown node that is successfully located broadcasts a Hello message that includes its ID and coordinates using the maximum transmitting power.

It should be noted that the FP-MPP-APIT algorithm is a completely distributed range-free localization algorithm. For each unknown node, the time complexity is very low. It depends on the space size of the available sub-triangular pyramid. Additionally, in the FP-MPP-APIT algorithm, the localization accuracy can also be significantly improved when the unknown node has four and only four anchor nodes. Moreover, the located unknown nodes can be regarded as anchor nodes to locate the unknown nodes that do not have enough anchor nodes. Consequently, we have reasons to believe that the FP-MPP-APIT algorithm can perform well in large scale three-dimensional WSNs, especially when the number of anchor nodes is insufficient.

IV. PERFORMANCE ANALYSIS

In this section, we evaluate the performance of the FP-MPP-APIT algorithm using the Matlab 2014a platform. The performance of the FP-MPP-APIT algorithm are analyzed and compared with the PB-APIT-3D algorithm, the FM-APIT-3D algorithm and the DFPLE algorithm. The localization accuracy and coverage are selected as performance indicators.

A. PERFORMANCE ANALYSIS: LOCALIZATION ACCURACY

In this subsection, the localization accuracy of the FP-MPP-APIT algorithm is evaluated. The localization accuracy is the most significant indicator for evaluating localization algorithms in wireless sensor networks. The localization accuracy can be described by the localization error that is calculated by the following formula:

$$LE(\mathrm{i}) = \frac{\sqrt{(x_{i-act} - x_{i-est})^2 + (y_{i-act} - y_{i-est})^2}}{R} \tag{15}$$

where $LE(\mathrm{i})$ is the localization error of node i, (x_{i-act}, x_{i-act}) is the actual location of node i, (x_{i-est}, y_{i-est}) is the estimated location of node i and R is the communication radius of node i. The average localization error AE for all unknown nodes is calculated as follows:

$$AE = \frac{\sum_{i=1}^{N_u} LE(i)}{N_u} \tag{16}$$

where N_u is the number of unknown nodes.

In this group of experiments, 200 nodes are randomly distributed in a $100m \times 100m \times 100m$ cubic space. Among 200 nodes, 20 nodes are anchor nodes, and the rest is unknown nodes. Additionally, the communication radius R is set to 15. The network topology before localization is as Fig.7 shows. Fig.8 depicts the network topology after localization using the FP-MPP-APIT algorithm. In Fig.8, there is an error distance line at each unknown node. The end points of the error distance line are the actual location and estimated location of the unknown node, respectively. Consequently, the error distance line can intuitively and naturally display the localization accuracy.

Fig.9 shows the localization accuracy of the PB-APIT-3D algorithm, the FM-APIT-3D algorithm, the DFPLE algorithm and the FP-MPP-APIT algorithm with the number of anchor nodes varying from 5 to 50. As observed from the figure, the curves show that the average localization

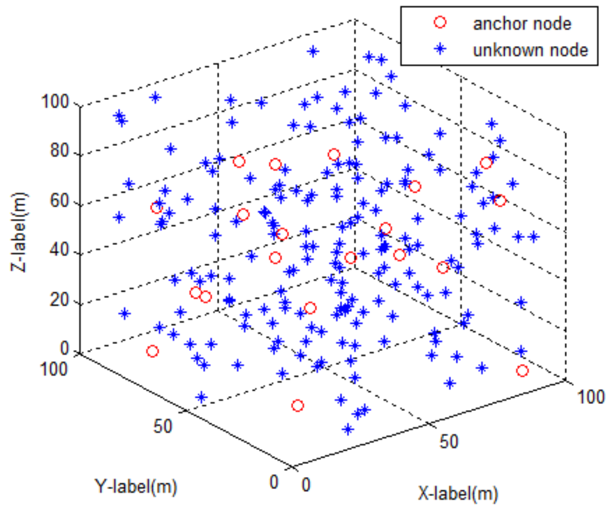

FIGURE 7. Network topology before localization.

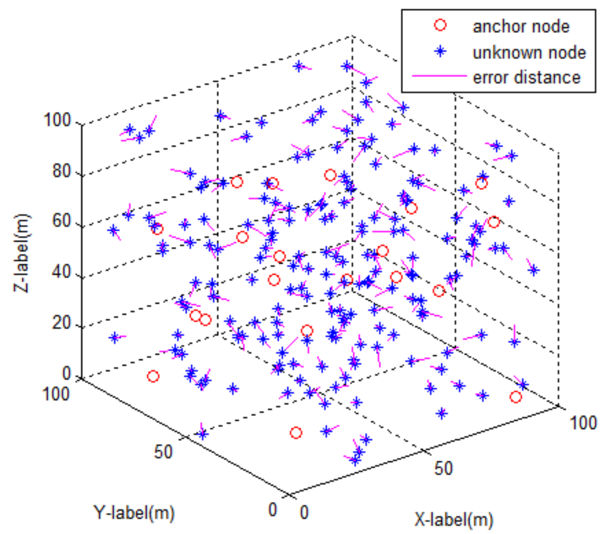

FIGURE 8. Network topology after localization.

error of the abovementioned algorithms gradually decreases with the increase of the anchor nodes. This point makes perfect sense since more anchor nodes results in more information to improve localization accuracy of the unknown nodes. Specifically, in comparison with the PB-APIT-3D algorithm, the FM-APIT-3D algorithm and the DFPLE algorithm, the FP-MPP-APIT algorithm has a smaller localization error when possessing the same number of anchor nodes. The primary reason for this situation is that the FP-MPP-APIT algorithm adopts the Fermat point model and mid-perpendicular plane model to narrow the estimated range of unknown nodes.

As shown in Fig.10, when the number of anchor nodes N_a is set to 18, the curves show that the localization error of all four algorithms rapidly decline with the gradual increase of the communication radius R. This decline is observed because when the communication radius R increases, the unknown

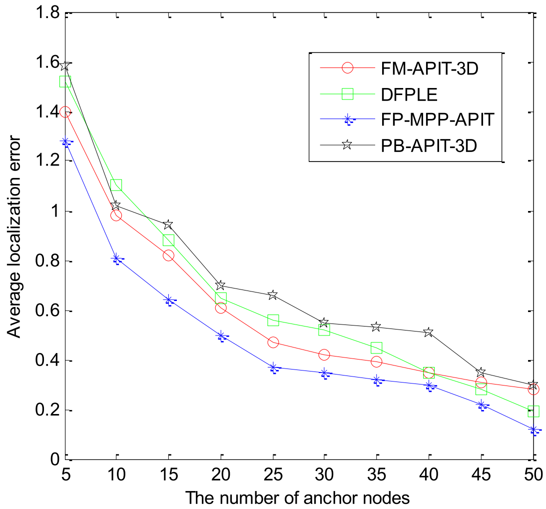

FIGURE 9. Average localization error Vs. number of anchor nodes ($R = 16$).

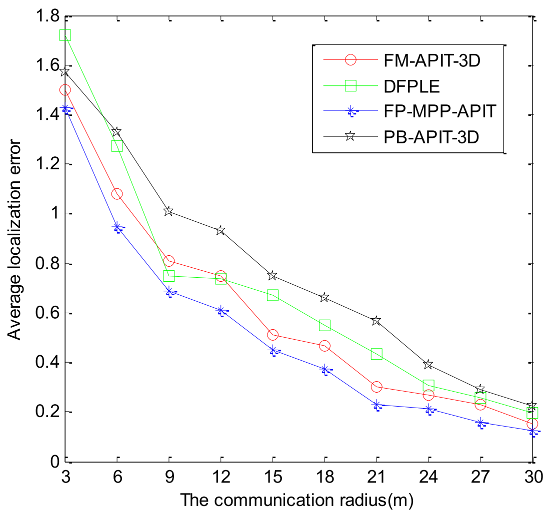

FIGURE 10. Average localization error Vs. communication radius ($N = 18$).

nodes can communicate with more anchor nodes. Consequently, the number of test triangular pyramids increases and the estimated range of the node can be further narrowed. Similarly, in comparison with the PB-APIT-3D algorithm, the FM-APIT-3D algorithm and the DFPLE algorithm, the FP-MPP-APIT algorithm has a smaller localization error when having the same communication radius. When $R = 15$, the average localization error of the FP-MPP-APIT algorithm is decreased by 40%, 11.8% and 33.2% compared with the PB-APIT-3D algorithm, the FM-APIT-3D algorithm and the DFPLE algorithm, respectively. Combining Fig. 9 and Fig. 10, the FP-MPP-APIT algorithm has a better performance on localization accuracy than the PB-APIT-3D algorithm, the FM-APIT-3D algorithm and the DFPLE algorithm when the number of anchor nodes is the same and all nodes have identical communication radii.

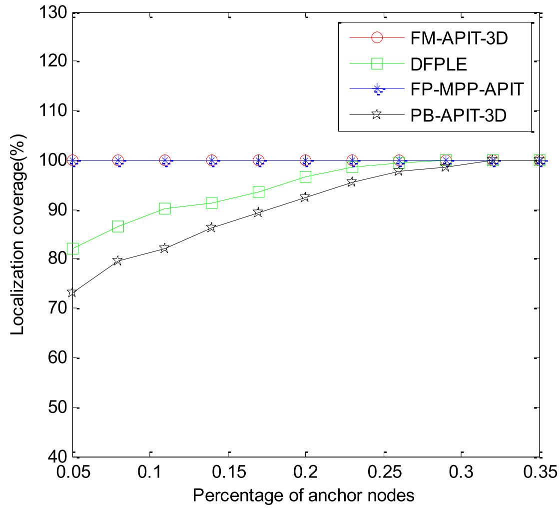

FIGURE 11. Localization coverage Vs. percentage of anchor nodes ($R = 16$).

B. PERFORMANCE ANALYSIS: LOCALIZATION COVERAGE

Localization coverage is also a critical performance indicator for localization in wireless sensor networks. Localization coverage LC can be calculated by the following formula:

$$LC = \frac{N_{ul}}{N_u} \tag{17}$$

where N_{ul} is the number of unknown nodes whose location can be calculated by a specific algorithm, and N_u is the number of unknown nodes.

In this group of experiments, there are also 200 nodes randomly deployed in a $100m \times 100m \times 100m$ cubic space. The communication radius R is set to 16. Fig.11depicts the relationship between localization coverage and the percentage of anchor nodes. It can be observed from the figure that the localization coverages of the FM-APIT-3D algorithm and the FP-MPP-APIT algorithm are always 100%. This is because the unknown nodes that do not have enough anchor nodes can also be located with the aid of located unknown nodes in the FP-MPP-APIT algorithm. For the FM-APIT-3D algorithm, it also has an appropriate method to calculate the location of the unknown nodes whose neighbor anchor nodes is less than four. However, the localization coverages of the PB-APIT-3D algorithm and the DFPLE algorithm are just 73% and 82% respectively when the portion of anchor nodes is 5%. The localization coverage gradually increased with the increase of the percentage of anchor nodes. When the percentage of anchor nodes reaches 28%, the localization coverage of the DFPLE algorithm reaches up to100%. Similarly, when the percentage of anchor nodes reaches approximately 32%, the localization coverage of the PB-APIT-3D algorithm also reaches up to100%. In conclusion, compared with the DFPLE algorithm and the PB-APIT-3D algorithm, if the percentage of anchor nodes is not high enough, the FP-MPP-APIT algorithm has a good performance in localization coverage.

V. CONCLUSIONS

In this paper, the FP-MPP-APIT algorithm is proposed to improve the localization accuracy in three-dimensional WSNs. In the FP-MPP-APIT algorithm, first, the Fermat point is used to divide the original triangular pyramid constructed by the neighbor anchor nodes of the unknown node into four smaller sub-triangular pyramids. Second, the available sub-triangular pyramid in which the unknown node is located can be further divided into a set of irregularly shaped subspaces by the mid-perpendicular plane model. Finally, the centroid of the available subspace can be computed and regarded as the location of the unknown node. Simulation results show that the proposed FP-MPP-APIT algorithm can perform well in large scale three-dimensional WSNs, especially when the number of anchor nodes is insufficient.

The proposed FP-MPP-APIT algorithm is a completely distributed range-free and low-cost localization algorithm. For each unknown node, the time complexity is notably low. The algorithm is expected to be used for emergency events, such as emergency rescue of lost adventurers in the wild.

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XUEJIAN ZHAO received the M.Sc. and Ph.D. degrees in computer application technology from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2007 and 2011, respectively. He is currently an Associate Professor with the School of Modern Posts, Nanjing University of Posts and Telecommunications. His current research interests include wireless sensor networks, ad hoc networks, and big data.

XINHUI ZHANG is currently pursuing the master's degree with the College of Internet of Things, Nanjing University of Posts and Telecommunications, Nanjing, China. Her current research interests include wireless sensor networks.

ZHIXIN SUN received the Ph.D. degree from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1998. He finished his post-doctoral research work in Seoul National University in 2002. He is currently a Professor with the School of Modern Posts, Nanjing University of Posts and Telecommunications. His current research interests include computer network and security, network multimedia communications, and network management and protocol.

PAN WANG received the Ph.D. degree from the College of Computer Science, Nanjing University of Posts and Telecommunications, Nanjing, China, in 2013. He is currently an Associate Professor with the School of Modern Posts, Nanjing University of Posts and Telecommunications. His current research interests include information security, ubiquitous computing, and wireless communications technologies.