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Performance Evaluation of an Improved APIT Localization Algorithm for Underwater Acoustic Sensor Networks

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Abstract. APIT is an approximate point-in triangulation method. The traditional APIT localization algorithm determines where the node is an interior point firstly, and then the Grid-SCAN algorithm is adopted to estimate the coordinates of the unknown node. However, there are large misjudgment probability and severe redundancy error in this method. In this paper, an improved APIT localization algorithm is proposed, which not only limits the selection range of neighbor nodes but also adopts Point-SCAN algorithm to estimation the position. We add TDMA protocol and study the performance of the algorithm by changing the node density and communication range. Simulation results show that our algorithm has better location performance than the traditional APIT algorithm and Centroid algorithm. In addition, it shows that collision has an impact on the location accuracy of the localization algorithm.

Keywords: APIT localization algorithm, TDMA protocol, underwater acoustic sensor network

1 Introduction

With the further development of the ocean, the UWSNs have been widely used in marine resource development, marine exploration, disaster monitoring and national territorial sea protection. However, the UWSNs are facing a totally different environment with terrestrial wireless networks. Radio frequencies that widely used by terrestrial wireless sensor networks do not propagate well in underwater environment, therefore, acoustic channels are employed in UWSNs. The major distinguishing characteristics of the underwater acoustic channel are its low bandwidth and long propagation delay caused by the low speed of sound [1]. In this case, the UWSNs bare additional challenges for localization.

The current localization algorithms can be roughly divided into Range-based localization algorithm and Range-free localization algorithm [2]. Range-based localization algorithm uses the distance or angle information of nodes to locate. In [3], a layered localization algorithm is proposed, which divides the whole localization process into two sub-processes, anchor node localization and ordinary node localization. This method essentially combines Euclidean distance estimation method and recursive positioning. This algorithm can achieve large-scale network positioning, but it has long positioning time, high energy consumption and computational complexity. In [4], a low-cost distributed UWSNs network positioning framework and time synchronization framework are proposed. This algorithm solves the synchronization problem. In localization, it achieves coarse positioning firstly and then fine-grained positioning. The localization algorithm has high location accuracy, wide positioning range, low power consumption and low communication overhead, but the multipath effect will seriously affect the positioning accuracy. In [5], a rough localization algorithm, which is the combination of the trilateration method and the regional optimal solution, is proposed. The algorithm based on consensus estimation is

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designed for the optimal solution of the area. The algorithm not only has higher location accuracy, but the hybrid communication architecture can reduce the number of transmission and communication overhead compared with the egalitarian distributed network.

Range-free localization algorithm mainly includes the Centroid algorithm [6], APIT algorithm [7], DV-Hop algorithm [8], Amorphous algorithm [9] and so on. In [6], an outdoor positioning Centroid algorithm based on network connectivity is proposed. The algorithm is based on the connectivity of the sensor network and had a low complexity of the algorithm. However, the accuracy of the algorithm is closely related to node density and distribution. In [7], an approximate triangle in-point test APIT algorithm is proposed. It uses the high node density of large-scale sensor network to simulate the node movement and utilizes the propagation characteristics of the channel to judge whether it is far or near the anchor node. Compared with the simple Centroid location algorithm, the APIT algorithm has high accuracy and relatively low requirement on the distribution of anchor nodes, and at the same time, it has the characteristics of low hardware requirement of Centroid algorithm and less positioning energy consumption. In [8], a DV-Hop algorithm is proposed, based on the minimum hop number from the anchor nodes to the unknown node. It estimates itself position through triangulation algorithm or maximum likelihood estimators. This algorithm can get better location accuracy only in the uniformly distributed and relatively dense sensor network environment. In [9], an Amorphous algorithm is proposed. The algorithm is improved by the DV-Hop algorithm, but the formula of network average hop distance is different from the DV-Hop algorithm. The Amorphous algorithm is easy to implement, but it requires high node densities and network connectivity.

Due to the particularity of the limited and unchangeable energy of underwater sensing nodes, energy consumption is an important problem in the design of underwater sensing network node localization algorithms. The range-free localization algorithm has advantages in positioning applications of underwater sensor networks with low cost, low energy consumption and low complexity. In this paper, we propose an improved APIT algorithm that is suitable for underwater acoustic sensor networks and utilize real underwater acoustic environment to analyze the performance of our algorithm in underwater acoustic sensor networks. The algorithm not only reduces the judgment error by limiting the selection range of neighbor nodes, but also reduces the redundancy error of the traditional algorithm by using the point scanning method. Considering the unavoidable errors in the real underwater acoustic environment, we add the TDMA protocol into our algorithm to reduce the collision probability as much as possible. It helps us to more accurately study the positioning performance of the algorithm and the impact of MAC protocol on positioning error. The rest of the paper is organized as follows:

In Section 2, we verify the underwater acoustic channel attenuation model. In Section 3, we describe the principle of traditional APIT algorithm. In Section 4, we analyze the limitations of the traditional APIT algorithm and elaborate the improved APIT algorithm. In Section 5, the performance evaluation is done. Finally, conclusion and some future research directions are provided in Section 6.

2 The Attenuation Model of Underwater Acoustic Channel

Acoustic channel is one of the most complex transmission environments by far. The propagation delay is almost negligible because the radio transmission speed is 3×10^8m/s, however, the speed of sound wave propagation in the underwater is only 1500m/s which mean that the underwater acoustic communication system propagation delay can reach milliseconds. Even worse, compared with the terrestrial communications, there is a serious attenuation of the sound signal underwater because the communications quality in underwater environment will be affected by the ocean temperature, salinity, depth, water flow, season, climate and other factors. And the underwater environment has multipath effects, a variety of noise interference and other propagation loss. Since the APIT algorithm depends on the attenuation characteristics to localization. It is crucial to verify whether the theoretical characteristic of underwater acoustic attenuation is consistent with the attenuation characteristics under real underwater acoustic environment.

Propagation loss, which concludes spreading loss and absorption loss, is that the signal energy appears a certain degree of attenuation with the propagation distance increases. The total transmission loss (Transmitting Lost: TL) can be expressed as [10]:

$$TL = k*10lgl + l*0.01lga(f) \quad \textbf{(1)}$$

Where, the first refers to the spreading loss, the second refers to the absorption loss. And l is the distance of sound signal propagation in meters; k is the diffusion factor, which describes the geometric path of diffusion. In general, when k =2, it means spherical wave propagation. When k =1, it means that the cylindrical wave is diffused. In practice, we take k =1.5. The absorption loss coefficient $a(f)$ can be obtained by the formula (2) when the frequency is higher than a few hundred Hz. The Thorp's expression is as follows [11]:

$$10lga(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75\times10^{-4}f^2 + 0.03 \tag{2}$$

Where, f is the sound signal frequency in kHz.

According to Equation (1), the distance and the frequency both affect the propagation loss TL. We performed a pool experiment to verify the relationship between the signal strength of the received signal and the received distance in real underwater environment. The experimental program is shown in Fig. 1. In the experiment, the transmitting voltage of signal generator is 10V and the transmitting frequency is 30 kHz.

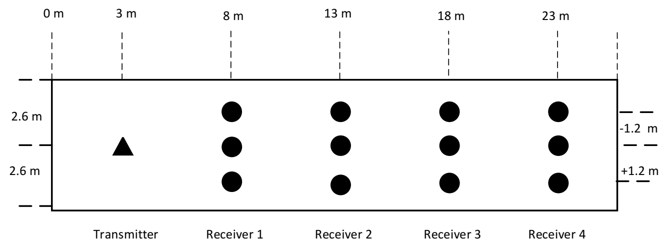


Fig. 1. The program of pool experiment

The experimental results are shown in Fig. 2. We can find that the receiving voltage decreases with the distance between the transmitter and the receiver increases. At the same time, experimental curve in -120cm and 120cm is almost the same because the receiver at -120cm and 120cm is symmetrical. However, the experimental results of the two curves have some slight deviation because there are multipath effects, and the pool is not anechoic.

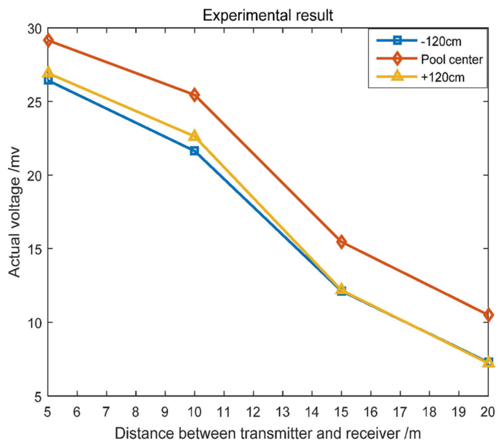


Fig. 2. Error curve between theory and experiment

We adopt the relative attenuation to calculate the voltages obtained by empirical formulas at the receiver, which is:

$$TL_i - TL_j = 10lg\left(\frac{v_j^2}{I^2}\right) - 10lg\left(\frac{v_i^2}{I^2}\right) = 10lg\left(\frac{v_j^2}{v_i^2}\right) = 10lg\left(\frac{v_j}{v_i}\right) \tag{3}$$

Taking the voltage at the transmitter i as a reference, then (3) can be transformed into:

$$V_j = V_i 10 \frac{TL_i - TL_j}{20} \quad \textbf{(4)}$$

In our experiment, we take the voltage at the receiver (the voltage at 8 meters) as the reference, which is denoted as V8, and then the theoretical voltage value at the other positions is calculated by the equation (4). And the theoretical voltage and experimental voltage value subtracted to get the error between them.

The error curve is shown in Fig. 3. We can find the error range between the theoretical value and the experimental value is from -7mv to 3 mv, which is an acceptable error.

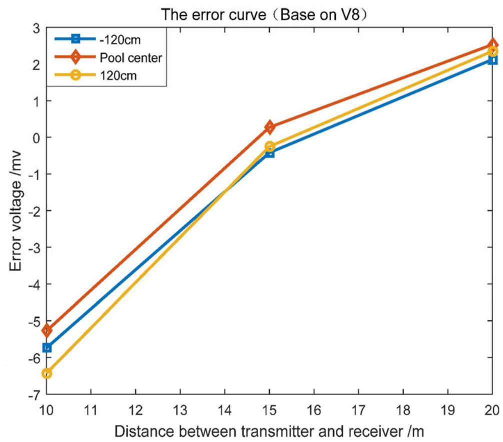


Fig. 3. The result of pool experiment

3 The Traditional APIT Algorithm

The approximate point-in triangulation (APIT) algorithm is a typical rang-free localization algorithm. The basic principle is that if there is a neighbor node which approaches or is away from the three vertices of the triangle at the same time compared with the unknown node, the unknown node is determined to be outside the triangle. Whereas inside the triangle [7]. The APIT principle is shown in Fig. 4.

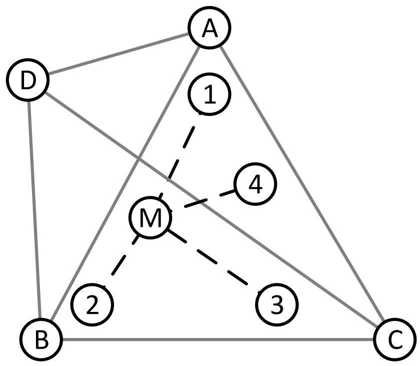


Fig. 4. The principle of the traditional APIT

In Fig. 4, M is the unknown node, the point A, B, C and D are four anchor nodes which are received by M, and point 1, 2, 3 and 4 are the neighbor nodes which received by M. The point A, B, C and D form four triangles, namely △ABC, △ACD, △ABD, and △DBC. In △ABD, the unknown node M has the neighbor node 3 is away from the vertices A, B and D of the triangle at the same time compared with the unknown node M. Therefore, according to the principle of APIT, the unknown node M is judged to be outside of △ABD. Similarly, the unknown node M is located inside of △ABC, △DBC and outside of △ACD.

According to Section 2, the receiving power of node decreases with the propagation distance increases. Therefore, when node M finds that the signal strength of neighboring node received from an anchor node is greater than the signal strength it received. It indicates that the node M is farther away from the anchor node than the neighbor node, and otherwise is close to the anchor node.

The basic idea of Grid SCAN algorithm is that dividing the entire network into several grids according to certain steps, and using the APIT algorithm to determine the relationship between the unknown nodes and the triangles. If the unknown node is inside the triangle, the value of all the grids in the triangle is added by 1; and if the unknown node is outside the triangle, the value of all the grids in the triangle is decreased by 1. After traversing all the triangles, the area with the maximum value is the area where the node is most likely to appear.

As shown in Fig. 5, the black triangle is the unknown node, and the shaded area is the largest polygon area where the node is most likely to appear.

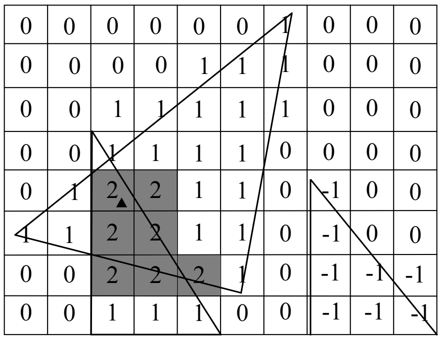


Fig. 5. The grid SCAN algorithm

4 An Improved APIT Algorithm

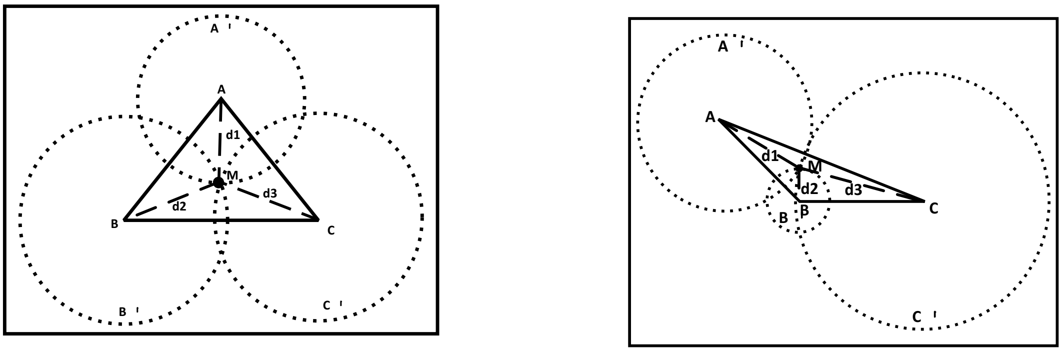
4.1 The Analysis of Traditional APIT Algorithm

The error of remote neighbor nodes. According to the traditional APIT algorithm, if there is a neighbor node which is closer to or further away from the anchor nodes A, B and C with the unknown node M, the unknown node is located outside the triangle ABC, otherwise inside the triangle ABC. Obviously, the selection of neighbor nodes plays a key role. However, when the neighbor node is far away from the unknown node, in other words, when the distance between the neighbor node and the vertexes A, B, C is much larger than the distance between the unknown node M and the three vertices, the unknown node M must be judged to be inside the triangle, which brings about a great error. Therefore, we hope to limit the selection range of neighbor nodes to reduce this error.

According to the principle of the traditional APIT algorithm, it is easy to obtain the distribution range of neighbor nodes where the algorithm can correctly determine the relationship between unknown nodes and triangles under ideal conditions when the neighbors exist. For the triangle ABC, if the distance between the unknown node M and the three vertices A, B and C is respectively d1, d2 and d3, then the circles A', B', C' are respectively drawn with A, B and C as the centers and d1, d2 and d3 as the radius respectively.

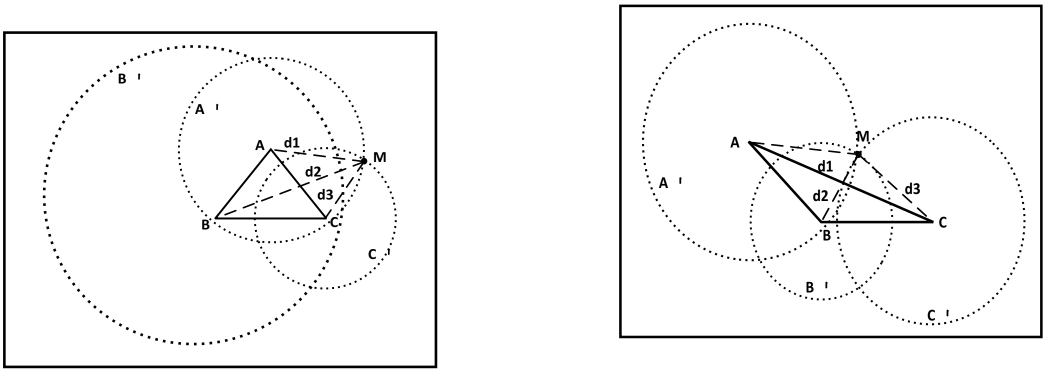
As shown in Fig. 6 and Fig. 7, the intersection of the circles A', B' and C', named NEAR area, is the area where the neighbor node is closer to anchor node A, B and C simultaneously than the unknown node M. And the complement of the union of the circles A ', B' and C', named FAR area, is the area where the neighbor node is far away from anchor node A, B and C simultaneously than the unknown node M.

In short, if the unknown node M is located outside the triangle, it can correctly determine the relationship of unknown node M and the triangular when the unknown node M is distributed in the NEAR area and the FAR area. And if the unknown node M is located inside the triangle, the relationship between the unknown node and the triangle can be correctly judged when the neighbor node of the unknown node M is outside of these two regions.



(a) Acute triangle (b) Obtuse triangle

Fig. 6. The unknown node is inside the triangle



(a) Acute triangle **(b)** Obtuse triangle

Fig. 7. The unknown node is outside the triangle

From the above analysis, if we choose the NEAR area and the FAR area as the selecting area of the neighbor nodes, we can judge completely correctly when the unknown node is located outside the triangle. However, if the unknown node is inside a triangle, our judgment will be completely wrong. This is an extreme choice. Obviously, these two kinds of errors are contradictory and can't be eliminated completely. So, we will find a compromise range to improve the location accuracy.

The limitation of the gird SCAN algorithm. The basic idea of the gird SCAN algorithm is using the centroid of the polygons where the unknown nodes are most likely to appear in as the coordinates of the unknown nodes. The polygon area is made up of several grids. As shown in the Fig. 8, the yellow area is the real area where the unknown node may exist, and the shaded area is the polygon area obtained by using the grid SCAN algorithm.

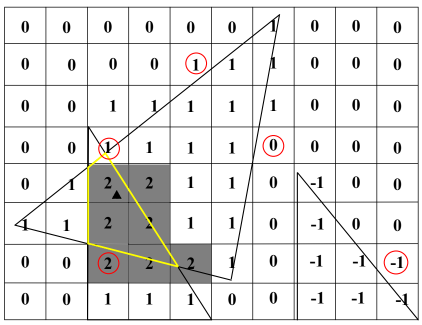
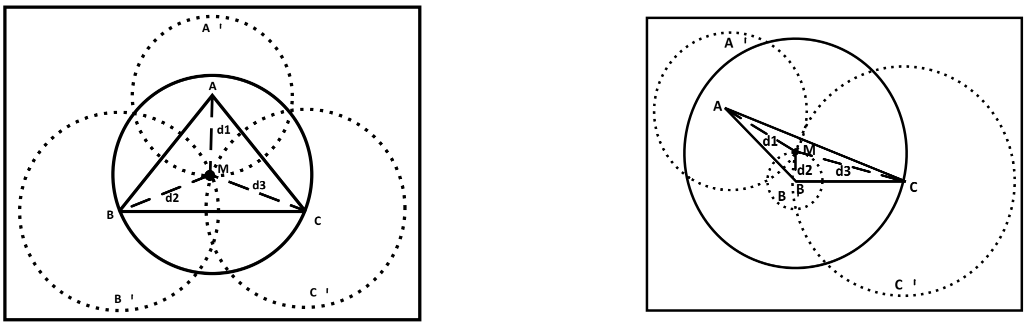


Fig. 8. The limitation of the grid SCAN algorithm

As shown by the red circle in the Fig. 8 [12], some redundancy will be introduced because the fact that there is no clear criterion for determining whether the grid is inside a triangle and the grid may be not small enough. In the implementation of the algorithm, the algorithm firstly divides the network by points, and then it forms a grid by every four neighboring points, however, the grids need to be restored into the form of points when calculating the center of gravity of the overlapping regions in the computer. Therefore, it makes the complexity of the algorithm greatly increased, and it is not suitable for underwater acoustic environment.

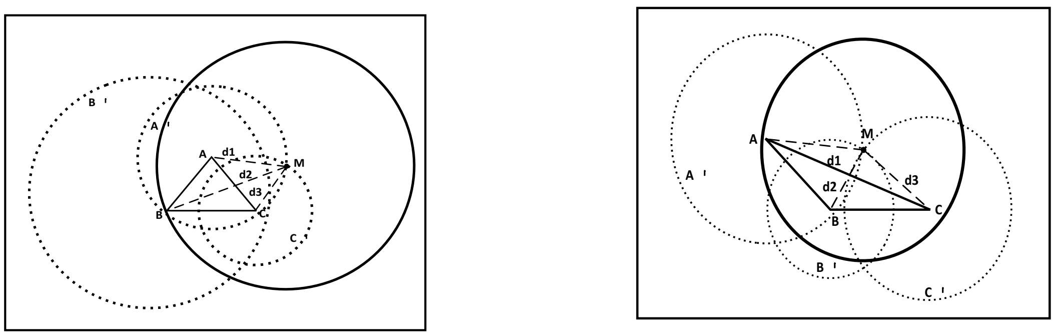
4.2 An Improved APIT Algorithm

The selection of the distribution range of neighbor nodes. In order to reduce the error caused by the neighboring nodes, we draw a circle with taking the longest distance between the unknown node and the vertices of triangle as the radius and the position of unknown node as the center (as shown in Fig. 9 and 10). In this paper, we specify that the area within the circle is the selection range of the neighbor node.



(a) Acute triangle (b) Obtuse triangle

Fig. 9. The unknown node is inside the triangle



(a) Acute triangle (b) Obtuse triangle

Fig. 10. The unknown node is outside the triangle

Observe that the area not only contains most of the areas that can be correctly judged, but also greatly reduces the misjudgment area. Theoretically speaking, using this region as a neighbor node selection range avoids the errors brought by remote neighbor nodes. Besides, it also improves the location accuracy to a certain extent.

The point SCAN algorithm. We proposed a point SCAN algorithm. This algorithm divides the network into several points uniformly in a certain step, and then it uses the APIT algorithm to determine the position relationship between the unknown node and the triangle. If the unknown node is inside the triangle, the values of all points in the triangle add 1, otherwise decrease it by 1. After traversing all the triangles, the arithmetic average of the coordinates of the point with the largest value is taken as the coordinates of the unknown node. As shown in Fig. 11, the black triangle is the unknown node, and the black point is the point with the maximum value.

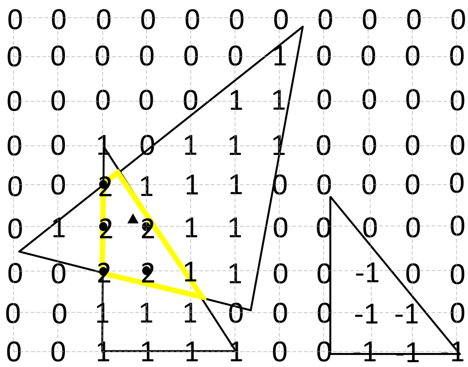


Fig. 11. The point SCAN algorithm

The algorithm not only has a clear standard in judging whether a point is within a triangle, but also narrows the intersection area, which solves the redundancy problem that may occur in the traditional APIT algorithm. In addition, the algorithm does not require the process of dimensionality reduction and dimension elevation in the concrete implementation. Thus, the algorithm complexity is greatly reduced compared with the traditional APIT algorithm.

5 Simulation Results

5.1 Simulation Setting

In this section, the performance of proposed scheme has been evaluated using OPNET simulation. We compare the performance of our algorithm, the traditional APIT algorithm and the Centroid algorithm by changing the node density, node communication range and adding MAC protocol to observe their location accuracy and the packet loss rate respectively. The simulation settings are shown in Table 1.

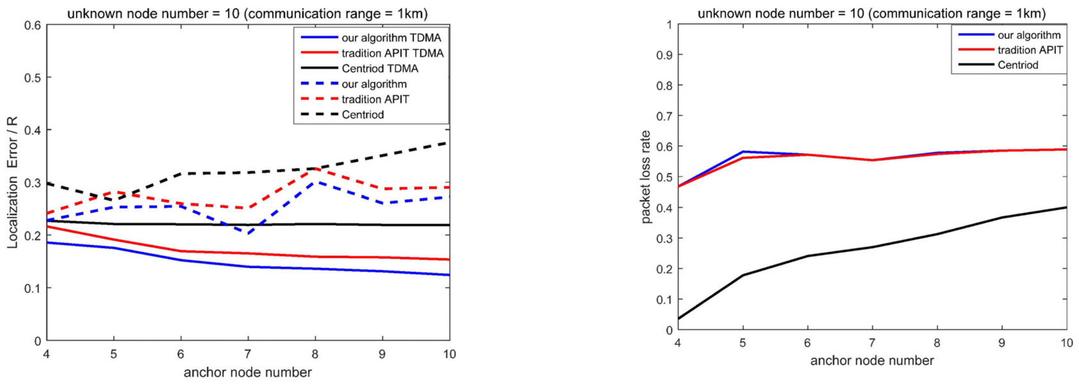
Table 1. Simulation setting

Attribute	Value
Network size (m)	1000×1000
Distribution	Random
Data rate (bps)	1024
Modulation	QPSK
Sound speed (m/s)	1500
Bandwidth (kHz)	2.0
Min frequency (MHz)	0.03
Power (W)	100

5.2 Anchor Node Density

In this simulation, the communication range is 1 km, and the number of unknown nodes is 10. We can observe the location accuracy and packet loss rate of these algorithms at different anchor node densities, and analyze the impact of the MAC protocol on the location performance.

As shown in Fig. 12 (a), under the TDMA protocol, the location error of our improved algorithm and the traditional APIT algorithm decreases with the increase of the anchor node density. That is because the area of the possible unknown node location narrows when the anchor node density increases, in other word, the overlapping area is reduced. When the density of anchor nodes increases, however, the location accuracy of Centroid algorithm is not obviously improved as the APIT algorithm. This is because the Centroid algorithm is not sensitive to the deployment density and topology of sensor nodes. In the absence of MAC protocol environment, the location accuracy of our algorithm is still better than the traditional APIT algorithm and the centroid algorithm. However, their location error curves are not decrease monotonously as the TDMA protocol. Their location accuracy fluctuates something worse. This is because the network load increases when the number of anchor nodes increases. As we can be seen from Fig. 12 (b), the packet loss rate continues to increase. Therefore, the information of many anchor nodes in the network collides with each other and can't be used effectively enough. Our algorithm performs better than the traditional APIT algorithm and the Centroid algorithm. This indicates our algorithm further narrows the area where unknown nodes may exist.



(a) The location error at different anchor node density

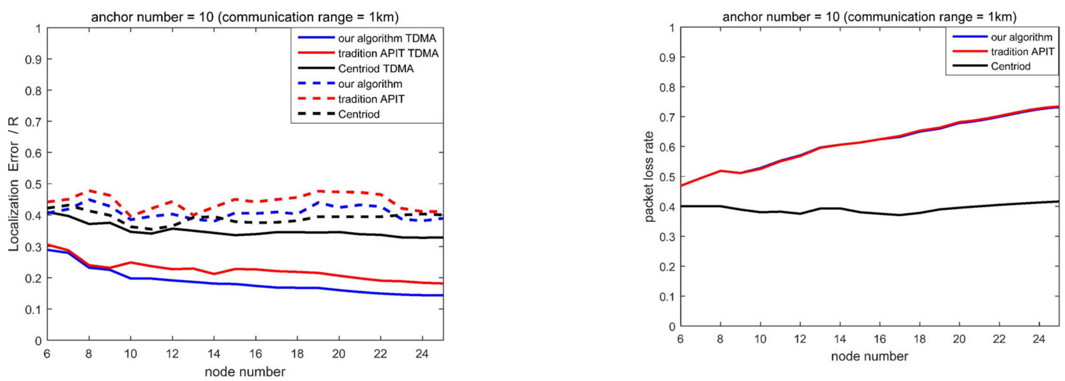
(b) The packet loss rate at different anchor node density

Fig. 12. Execution results of the anchor node density

5.3 Unknown Node Density

In this simulation, the communication range is 1 km, and the number of anchor nodes is 10. We can observe the location accuracy and packet loss rate of these algorithms at different unknown node densities, and analyze the impact of the MAC protocol on the location performance.

As shown in Fig. 13 (a), under the TDMA protocol, our algorithm has the improvement compared with the traditional APIT algorithm when the unknown node density increases. This is because the accuracy rate of judging the position relationship between triangles and unknown nodes improves when the number of neighbor nodes increases and the selection of the range of the neighbors' range effectively reduce the error caused by the remote neighbor nodes. In addition, we find that, unlike the APIT algorithm, the increase in the unknown node density has no significant change in the location accuracy and the packet loss rate for the Centroid algorithm. This is because the unknown nodes of the centroid algorithm do not communicate with each other, whereas the APIT algorithm not only communicates between anchor nodes and unknown nodes, but also communicates between neighboring nodes. As shown in Fig. 13 (b), with the increase of the number of unknown nodes, the packet loss rate of our algorithm and the traditional APIT algorithm are significantly increased, while the packet loss rate of the centroid algorithm is almost constant. This is because both the anchor node and the neighbor node send packets in our algorithm, while only the anchor node generates the packet in the Centroid algorithm. In other word, the APIT algorithm has a much larger network load than the Centroid algorithm. Thus, in the absence of MAC protocol environment, our algorithm is no obvious advantage in location accuracy.



(a) The location error at different unknown node density

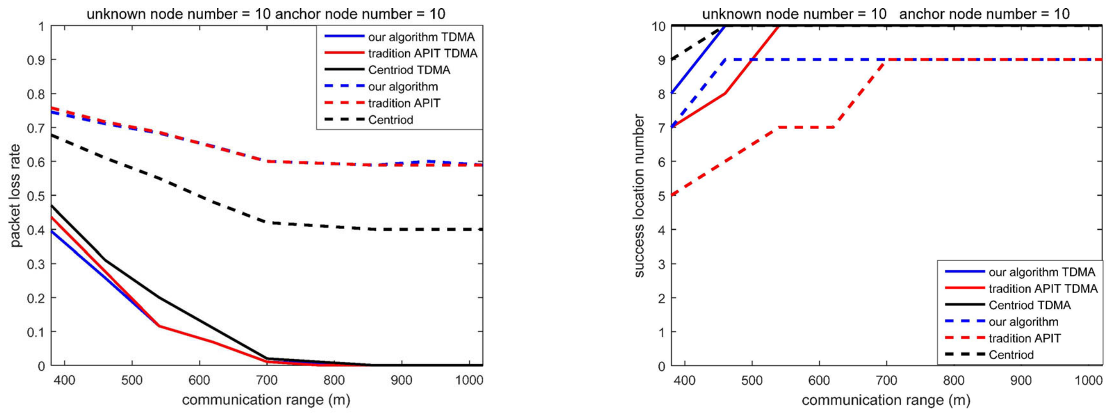
(b) The packet loss rate at different unknown node density

Fig. 13. Execution results of the unknown node density

5.4 Communication Range

In this simulation, the number of anchor nodes is 10, and the number of unknown nodes is 10. We can observe the location accuracy and packet loss rate of these algorithms at different communication ranges, and analyze the impact of the MAC protocol on the packet loss rate and the number of node located successfully.

As shown in Fig. 14, the packet loss rate of our algorithm, the traditional APIT algorithm and the Centroid algorithm decreases monotonously with the increase of the communication range, and the number of nodes located successfully increases. This is because the increase of communication distance allows more nodes to communicate successfully. Therefore, there are more nodes to be located. Notably, our algorithm allows more nodes to be located under the same conditions when the communication range is small. This is because the limited range of neighbor nodes discards some interference nodes, so that the probability of misjudging the external nodes as internal nodes is greatly reduced.



(a) The location error varying communication range

(b) The number of node located varying communication range

Fig. 14. Execution results of the communication range

6 Conclusions

In the paper, we analyze the disadvantage of the traditional APIT algorithm. After that, we propose an improved APIT localization algorithm for underwater acoustic sensor network. Simulation result shows that location performance of our algorithm is better than the traditional APIT algorithm and the Centroid algorithm. This is because the selection range of neighbor nodes we proposed effectively reduces the errors caused by remote neighbor nodes and the point SCAN algorithm also reduces the redundancy error. In addition, since the MAC protocol has the function of allocating channel resources, the TDMA protocol can make the channel completely collision-free when the appropriate communication distance is selected. Therefore, the addition of TDMA protocol not only enables to analyze the performance of the algorithm in a certain environment more accurately, but also greatly improves the algorithm's location accuracy and packet loss rate. However, the TDMA protocol will have a high latency, resulting in low location efficiency, which is contrary to the efficiency. In future, we will continue to study the MAC protocol to obtain high positioning accuracy at the expense of low latency.

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