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Cross Layer Design for Localization in Large-Scale Underwater Sensor Networks

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Abstract: There are many technical challenges for designing large-scale underwater sensor networks, especially the sensor node localization. Although many papers studied for large-scale sensor node localization, previous studies mainly study the location algorithm without the cross layer design for localization. In this paper, by utilizing the network hierarchical structure of underwater sensor networks, we propose a new large-scale underwater acoustic localization scheme based on cross layer design. In this scheme, localization is performed in a hierarchical way, and the whole localization process focused on the physical layer, data link layer and application layer. We increase the pipeline parameters which matched the acoustic channel, added in MAC protocol to increase the authenticity of the large-scale underwater sensor networks, and made analysis of different location algorithm. We conduct extensive simulations, and our results show that MAC layer protocol and the localization algorithm all would affect the result of localization which can balance the trade-off between localization accuracy, localization coverage, and communication cost. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Large-scale underwater sensor networks, Cross layer design for localization, MAC layer protocol, Localization algorithm.

1. Introduction

The wireless sensor network technology in the land has been improved already, but the development of underwater acoustic sensor networks just begins. Because the underwater acoustic channel is the channel of a very complex space time frequency variant multipath transmission, coupled with the characteristics of its high environmental noise, narrow bandwidth, delay, low applicable carrier frequency and transmission of distance, the underwater acoustic sensor networks faces some special challenges [1, 2]. These challenges require new structures and protocols to improve the performance of underwater acoustic sensor networks. Underwater acoustic sensor network node localization, which is one of the key techniques of underwater acoustic sensor networks, is widely used in data collection, identification and underwater nodes for tracking and detecting the target node location information. Meanwhile, underwater acoustic sensor network node location can also be used to improve the performance of medium access control layer and the routing layer acoustic sensor network. Therefore the underwater acoustic sensor network node positioning technology has a wide application prospect, plays a vital role in improving the performance of underwater acoustic sensor network, and is also the core techniques of underwater acoustic positioning and navigation.

In the research of node localization for underwater acoustic sensor networks, Zhong Zhou [3, 4] proposed effective localization solution in the large-scale sensor network, and adopts the algorithm of 3D Euclidean distance and the recursive method of position. M. Talha Isik [5] proposed a 3DUL network node positioning method, using the two handshake of TOA algorithm as the ranging method, and combined with the projection and the three edge measuring method estimates the target position. But these sensor network localization existing schemes are studied for the localization algorithm, without the cross layer design to the entire sensor network under the cross layer and the research on the MAC protocol in the multi sensor nodes shared channel.

In this paper, a new large-scale underwater acoustic localization scheme based on cross layer design is developed. It should be emphasized that this scheme proposed is based on the analysis of network stratification, and proposed on the research of cross layer, and the physical layer, cross layer which is related to the data link layer and application layer are studied respectively. Then we build the cross layer positioning platform, studying on the positioning results. In large-scale underwater sensor networks positioning platform cross layer has the authenticity and reliability higher than research program on location algorithm.

The remainder of this paper is organized as follows. In Section 2, the architecture of positioning system and cross layer design method of is introduced. In Section 3, we study on cross layer related to the data link layer. The performance of localization is pointed out in Section 4. We present experimental results in detail in Section 5. Finally, this paper is concluded in Section 6.

2. Positioning System Architecture and Cross Layer Design

Large-scale underwater sensor networks consist of a large number of sensor nodes, mainly divided into the underwater master node and sub node. Large scale sensor network node positioning system is mainly for positioning the master node on node through the sensor network has been located, as shown in Fig. 1.

In the positioning system, sensor node underwater nodes that can communicate and surface buoy through the surface buoy. Therefore, in the system that the master node is located, the underwater sensor node is the main and the master node beacon exchanging to estimate its position after positioning the sub nodes and also by threshold decision to transition into "virtual host node", is positioned to assist other sub nodes.

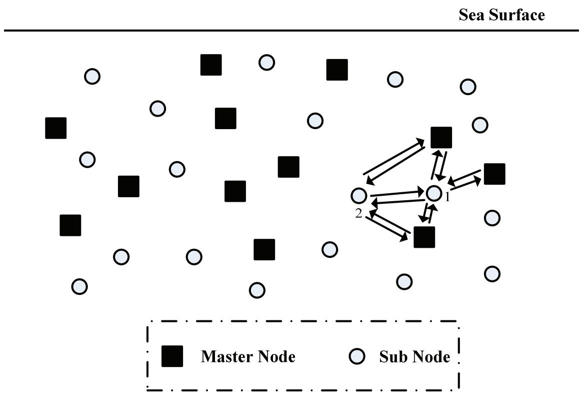

Fig. 1. Large-scale sensor network node positioning system architecture.

In this paper, the architecture of UNA [6], according to the characteristics of node localization in underwater acoustic sensor network, it designs a new cross layer framework, namely in the network node localization mainly involves three layers, respectively, the physical layer, data link layer and application layer, as shown in Fig. 2. Cross layer design is to break the network layer protocol design framework of the original, take the more than two layers of network protocol into consideration. In order to satisfy the requirements of basic function, it can save transmission energy maximization, improve the network throughput.

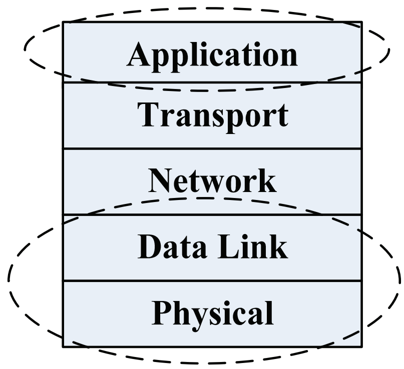

Fig. 2. Cross layer framework.

The whole communication process is, in sending node, layer receives the network node location data in the application layer, data link layer is responsible for the instruction and data encapsulation frame, which sent to physical layer modulation, transmission of data. At the receiving node, in the physical layer detection and demodulation signal, and the signal is converted into a logical information, the data link layer is responsible for logical information from the physical layer to receive re assembled into a frame, and then delivered to the application layer of network node location, node structure system model is shown in Fig. 3.

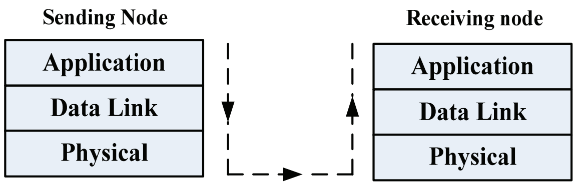

Fig. 3. Node structure system model.

3. Physical Layer, Data Link Layer and Application Layer

To large-scale sensor network node positioning system, we design of a layer three protocols architecture, which mainly is the physical layer, data link layer and application layer, and respectively sets simulation environment in each layer protocol.

3.1. Physical Layer

Modeling of physical layer is the basis of underwater acoustic network simulation. Only accurately describing the physical layer, we can make the network simulation results reliable. Underwater acoustic channel is very complex, which needs to be given full consideration to the characteristics of underwater acoustic channel. According to the characteristics of underwater acoustic channel, this paper models the physical layer, which laid the foundation for the accuracy of the upper layer protocol simulation. In the modeling of physical layer, each node generates a packet rate obeys Poisson distribution, node uses QPSK modulation, sets the wind speed w is 10 m/s, the density is 0.5, the diffusion factor k is 2. We mainly remodel the propagation delay (Propagation Delay), the received power (Receiver Power) and the background noise (Background Noise).

1) In the propagation delay stage, the signal propagation velocity is modified as 1500m/s, simulation assumes acoustic propagation rate remained stable value;
2) In the received power stage, the free space propagation loss model modified [7] for communication power underwater acoustic channel loss model, calculation formula of underwater acoustic channel propagation loss formula (1):

$$A(l,f)=l^k a(f)^l, \tag{1}$$

where k is the diffusion factor, f is the sound frequency, l is for acoustic wave propagation, $a(f)$ is the loss of absorption coefficient of water, the formula (2) numerical calculation:

$$10\log\alpha(f)=0.11\frac{f^2}{1+f^2}+44\frac{f^2}{4100+f^2}+ \\ 2.75\times10^{-4}f^2+0.003 \tag{2}$$

If expressed in dB form, propagation loss TL formula (3):

$$TL=10\log A(l,f)=k\cdot10\log l+ \\ l\cdot10\log a(f) \tag{3}$$

3) In the background noise in the original stage concludes background noise, thermal noise and environmental noise. In this paper, the background noise model for underwater acoustic channel noise model [8], calculation formula of reference formula of underwater acoustic channel noise model (4):

$$NL_{total}(f)=NL_{turbulence}(f)+NL_{shipping}(f)+ \\ NL_{wind}(f)+NL_{thermal}(f) \tag{4}$$

3.2. Data Link Layer

In this paper, we propose a location three layer framework for large-scale sensor networks using the MAC protocol, the classical S-ALOHA in the data link layer.

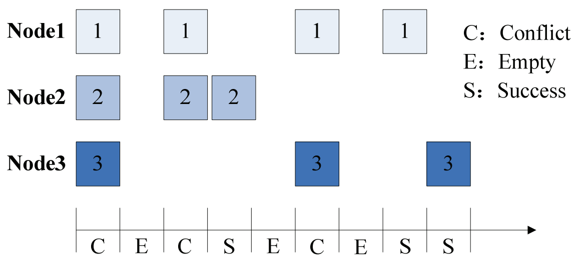

Fig. 4. S-ALOHA.

S-ALOHA is a modified ALOHA protocol, which reduces the probability of packet collision [9], requiring in the S-ALOHA channel into a long slot, and the node can only transmit provisions at the beginning of each time slot. When the conflict happens, conflict node will random wait some time slots and then send, as shown in Fig. 4, the data packets are sent in the time slot head, so the probability of conflict is greatly reduced.

3.3. Application Layer

The core algorithm of modeling builds the modeling the application layer of network, including positioning algorithm and iterative threshold method. The comparison and analysis of the Range-Free based Centroid, APIT algorithm and TOA algorithm based on TOA algorithm Range-Based, analyzing the performance index of different location algorithm.

3.3.1. Centroid Algorithm

Centroid algorithm [10] is the outdoor localization algorithm for network connectivity proposed by Nirupama Bulusu of the University of Southern California. The basic idea of the algorithm is: the main node every once in a while, broadcasting a beacon signals, including their own and position information signal, sub node receives the beacon signals from different host node on the duration, then the definition of connectivity (Connectivity Metric) is:

$$CM_i = \frac{N_{recv}(i,t)}{N_{sent}(i,t)} \times 100\%, \quad (5)$$

where $N_{sent}(i,t)$ means the R_i signal is transmitted in time T, $N_{recv}(i,t)$ means signals R_i received at T time.

The estimated coordinate expression for the (X_{est}, Y_{est}):

$$(X_{est}, Y_{est}) = (\frac{X_{i1} + ... + X_{ik}}{k}, \frac{Y_{i1} + ... + Y_{ik}}{k}), \quad (6)$$

where $(X_{i1}, Y_{i1})...(X_{ik}, Y_{ik})$ identified as sub node type in the collection.

3.3.2. The APIT Algorithm

APIT (Approximate Point-In-Triangulation) is a kind of approximate test algorithm [11], the theoretical basis of the algorithm is the best test method in PIT. The basic idea of approximate test is unknown nodes listens nearby anchor node information, then select any three nodes. Calculation of overlap region contains the unknown node all triangles, the centroid overlap region as the location of the unknown nodes, as shown in Fig. 5.

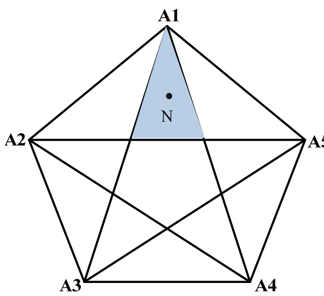

Fig. 5. APIT.

3.3.3. The TOA Algorithm

A location algorithm based on bidirectional beacon exchange [12], the algorithm is Range-Based, which gets the distance of the beacon two exchanges through the master node and transmission delay, and position using three sided measurement.

$$t_{prop} = [(T_2 - T_1) + (T_4 - T_3)] / 2 \quad (7)$$

4. Performance Index of Positioning

The distribution range of underwater acoustic sensor network in the simulation is 5000 m×5000 m×1000 m. In the 100 sensor nodes that random distributing in the distribution range, the main node density is respectively 10 %, 15 %, 20 %, 25 %, 30 %, 35 % and 40 %. The maximum transmission distance of the nodes is 500 m. The performance indexes of localization respectively are:

4.1. Localization Error

The positioning accuracy is the primary evaluation index system, which can be expressed with the proportion of node maximum communication distance between the error value and the nodes. The communication radius of the Common nodes is normalized. For the whole network, positioning error refers to the average error of all unknown nodes in the network; the positioning accuracy is expressed as:

$$error = \frac{\sum_{i=1}^{N_{sub-node}} \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2}}{N_{sub-node} R}, \quad (8)$$

where $N_{sub-node}$ is an unknown number of sub nodes, (x_i, y_i) is the actual coordinates of the unknown nodes, $(\hat{x}_i, \hat{y}_i)$ is estimated coordinates of node i, R is the node communication radius.

4.2. Localization Coverage

The localization coverage rate is the positioning proportion of the unknown nodes in the large-scale sensor network localization systems. Supposed there are $N_{sub-node}$ sub nodes in the sensor network, in which the number of successful positioning of the sub node is $L_{sub-node}$, K can define as the positioning coverage rate:

$$K = \frac{L_{sub-node}}{N_{sub-node}} \times 100\% \quad (9)$$

4.3. Master-node Density

Large-scale sensor network nodes can be divided into master node and sub nodes according to the position. The master node is the reference scale to the child nodes in the network node location, which plays a crucial role in the process of locating. Supposed there are N nodes in a sensor network, the number of master nodes is $N_{master-node}$, then the principal node density can be expressed as the number of master nodes in a sensor network node which is represented as a percentage of ϕ :

$$\varphi = \frac{N_{master-node}}{N} \times 100\% \qquad (10)$$

4.4. Communication Cost

As the energy of underwater acoustic sensor node Battery is limited, the communication loss in sensor network is an important index. Therefore, under the precondition of ensuring accuracy, the power consumption of the communication overhead, storage overhead, the time complexity and distributed computing are key indexes. In large scale sensor networks, nodes exchange information will appear phenomena of collisions and retransmissions, so we mainly define the average communication loss C:

$$C = \frac{M}{L_{sub-node}}, \qquad (11)$$

where M is the number of sending all the nodes of type, $L_{sub-node}$ for the successful positioning of the sub nodes.

5. Experimental Results

Fig. 6 shows the relationship between the location error and the master node density. From Fig. 6, we can see that when the node density is low, the localization accuracy of TOA algorithm is higher than Centroid and APIT. This is because the Centroid algorithm and APIT algorithm are as the same as the Range-Free localization algorithm, which mainly carries on the localization by the connectivity of the network. So when the master node density is low, the TOA algorithm based on Range-Based in the positioning still had distance on the accuracy. With the increase of the master node density, the positioning accuracy of two kinds of Range-Free algorithms has been improved significantly. This phenomenon is just because that the Range-Free algorithm is the use of multiple nodes to locate, when the master node beacon receiving more, the unknown the target area is further constrained. On the other hand, the TOA algorithm which is based on the master node beacon number can locate the target by calculation. Seen from Fig. 6, we can also find that when the main node density of >30 %, APIT gradually close to the accuracy of the TOA algorithm.

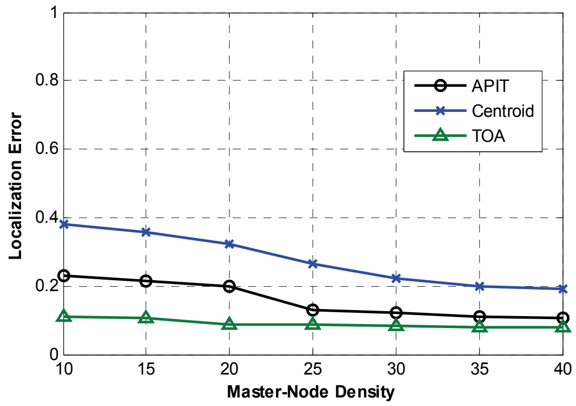

Fig. 6. Localization error.

Fig. 7 shows the relationship between the main node coverage and density of positioning. We can see that the localization coverage of TOA algorithm is better than Centroid and APIT algorithm from Fig. 7. This is mainly because the TOA algorithm had higher positioning conditions and precision, the positioning coverage rate is larger. From the whole, three algorithms for positioning coverage rate is increased with the master node density, but when the master node density reaches a certain value, the coverage rate of positioning was slowing. For example, for the TOA algorithm, when the node density is 25 %, positioning coverage rate is 0.84, then the master node density increases, the coverage rate of positioning did not significantly increase, so the network node localization, coverage and node density can be balanced in location selection.

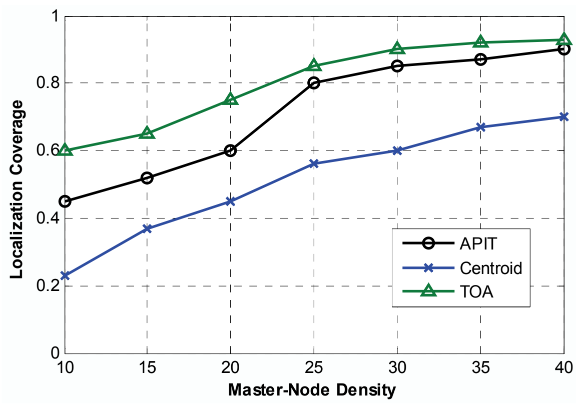

Fig. 7. Localization coverage.

Fig. 8 shows the relationship between the communication loss and the master node density. As can be seen from Fig. 8, the loss of these two kinds of Range-Free algorithm of Centroid and APIT communication is lower than that of TOA algorithm, because the positioning based on exchange two handshake beacons which increased the transmission loss. Meanwhile in the two kind of Range-Free localization algorithms, node localization is mainly focused on listening, not beacon exchange. From the overall trend, three algorithms all have a turning point. For example, in the APIT algorithm, when the master node density >25 %, communication loss turned to gradually rising instead of decreasing, which mainly because our simulation in MAC layer is added with the S-ALOHA protocol. So when the master node reached a certain density, it will produce a data packet collision with reducing the channel utilization rate. In the comparison of Centroid and APIT algorithm, the communication loss of the Centroid algorithm is mainly due to the smaller positioning sub coverage and fewer nodes which can avoid colliding packets.

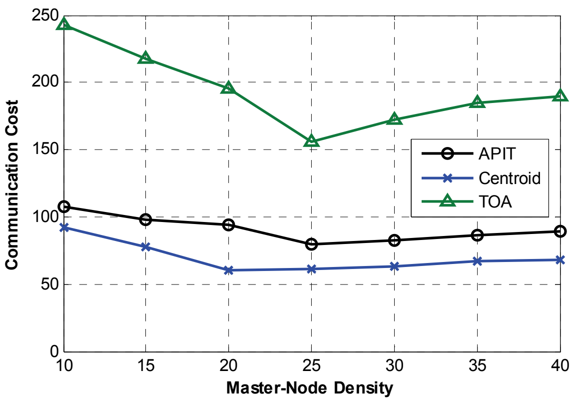

Fig. 8. Communication cost.

6. Conclusion

In this study, the cross layer design for localization in large-scale underwater sensor networks is proposed. The goal is to achieve cross layer positioning platform and comparative analysis of various localization algorithms for underwater acoustic environment. It should be emphasized that, for the physical layer, data link layer and application layer, we constructed the simulation framework of the positioning platform, which increased the authenticity of the entire large-scale sensor network node positioning simulation. Our results show that it should meet the needs of different localization algorithm in Localization Error, Localization Coverage, Communication Cost and Master-Node Density, which had to make the trade-off in the research of large-scale sensor network node location. That is to say, this study is workable in the future development of localization in large-scale underwater sensor networks.

In the future, we plan to extend our work in two directions: 1) to improve the contrast large scale sensor positioning platform, and compare with more MAC protocols and localization algorithms, and 2) on the base of balancing the positioning performance factors, design new localization algorithms. The algorithm we design should robust on more scenarios.

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