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The Influence of MAC Protocol on a Non-Synchronous Localization Scheme in Large-Scale UWSNs

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ABSTRACT Localization plays a more and more important role in underwater wireless sensor networks (UWSNs). But in the large-scale UWSNs, the localization algorithm can't be realized for the continuous packet collision. Therefore, we need to consider the impact of MAC protocol on the positioning algorithm. First, this paper proposes a multi-layer positioning model based on the underwater network architecture. Then according to the non-synchronous localization scheme, we analyze the reason of packet collisions and propose the variable interval ALOHA (VI-ALOHA) protocol based on the Poisson distribution. The VI-ALOHA protocol reduces the collision by adding random space–time. Through the comparison of localization coverage, packet loss, and localization time, this paper evaluates the impact on the localization result in equal interval ALOHA (EI-ALOHA) and VI-ALOHA. Our simulation results show that the MAC protocol has a significant influence on localization; besides, the localization coverage and the packet loss of VI-ALOHA protocol are above 20% better than the EI-ALOHA.

INDEX TERMS Localization, UWSNs, packet collision, multi-layer, MAC protocol.

I. INTRODUCTION

Underwater localization as one of the key technologies of UWSNs is widely used in data collection, identification and underwater target detection and tracking node location information. Meanwhile it can also be used to improve the performance of UWSNs medium access control layer and routing protocol, the acoustic positioning technology has witnessed as intense research activities. However, the UWSNs face a totally different environment with terrestrial wireless networks. Radio which is widely used by terrestrial wireless sensor networks doesn't propagate well in underwater environment. Therefore, acoustic channel is 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 large-scale UWSNs bare additional challenges for localization and MAC protocols.

Several localization schemes have been proposed for large-scale UWSNs in the literature [2]. Zhou *et al.* [3] proposed an efficient node localization scheme for large-scale wireless sensor networks, and adopted 3D Euclidean distance estimation algorithm and recursive location method. The work of [4] proposed a 3DUL network node localization method. It uses the two-handshake TOA algorithm as a ranging method, which combines with projection and three-edge measurement method for target position estimation. Ramezani and Leus [5] considered optimal collision-free packet scheduling in UWSNs for the localization task. In this algorithm, the position information of the anchors is used to minimize the localization time. But it requires a fusion center which gathers the positions, and the anchors need to be synchronized. Carroll *et al.* [6] proposed an On-Demand Asynchronous Localization for UWSNs. By taking advantage of a sequential transmission protocol and the broadcasting nature of the acoustic underwater medium, the entire network can be localized simultaneously with small overhead. The DNR positioning scheme in [7] used mobile beacons which learned their coordinates by GPS system when floating over the water surface. While diving into water, these mobile beacons broadcast their coordinates which are used by sensor nodes to localize themselves. The extended DNR scheme proposed in the paper [8] removed the time synchronization feature. This scheme requires only z-coordinate of mobile beacon changing when the anchor nodes dive and rise. But in the large-scale UWSNs, if there are multiple packets arriving on the sensor nodes at the same time, it would cause packet loss by collision, and lead to serious energy consumption for sensor nodes. Meanwhile the underwater sensor node is not easy to be replaced; it will seriously affect the service life of the whole sensor network. For the positioning process of UWSNs, packet collision would cause the failure of localization, because the nodes maybe unable to receive positioning data of the anchor node. So, in the UWSNs localization process, we need to analyze the collision effect on positioning, and use the MAC protocol to solve the problem of collisions.

In UWSNs, MAC protocol has attracted strong attention due to its potentially large impact to the overall network performance [9]. A MAC protocol allows the nodes in a network to share the common broadcast channel. The main task of MAC protocol is to prevent simultaneous transmissions or resolve transmission collisions of data packets while providing energy efficiency, low channel access delays and fairness among the nodes in a network. The underwater acoustic environment poses more severe situation for MAC protocol design compared to MAC design for terrestrial networks. The classification of MAC protocols for UWSNs is Contention-free and Contention-based MAC protocols. The Contention-free MAC protocols mainly adopt fixed allocation mode, such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). However, such a fixed allocation method makes the underwater resource limited channel even less fully utilized. By the Contention-based protocols, the nodes compete for a shared channel resulting in probabilistic coordination. The Contention-based protocols can be classified into random access and handshaking protocols. There are generally two approaches of random access in the classification of Contention-based MAC protocols, which are ALOHA and Carrier Sense Multiple Access (CSMA) with their variances. ALOHA is the simplest random-access MAC protocol to be easily implemented. Its performance for UWSNs has been investigated in real sea experiments [10]. In [11], a receiver synchronized slotted Aloha for UWSNs has been presented. By the Slotted ALOHA, a node can't send its packets at any time, but has to wait for the beginning of a timeslot. In contrast to terrestrial networks, slotted ALOHA operation doesn't yield performance gains for underwater networks in comparison with pure ALOHA due to high propagation delay [12]. CSMA is a representative class of random access protocols, where all nodes have to sense the channel for a certain period of time before the channel access. In [13], a novel CSMA-based protocol with collision avoidance and low energy consumption has been proposed. This protocol works by using the differences of the propagation delay between pairs of incident nodes to avoid collisions. The basic idea of the handshaking or the reservation-based schemes is that a transmitter has to capture the channel before sending any data. In [14], a MAC protocol called propagation-delay- tolerant collision avoidance protocol (PCAP) has been proposed. Besides the requirement of RTS and CTS frames, the protocol allows the transmitting node to perform other actions in the period waiting for the CTS frames returning. However, the current research on MAC protocol mainly focuses on parameters such as throughput, packet loss rate and so on, and doesn't consider the impact of other layers, such as the positioning algorithm of the application layer.

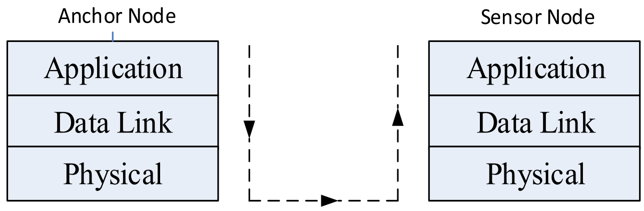


FIGURE 1. Multi-Layer architecture for UWSNs localization.

Most of the existing MAC protocols research on throughput, packet loss rate and other indicators, while the localization schemes mainly research on the positioning accuracy of positioning. But in large scale sensor networks, packet loss of the continuous collision will affect positioning results. And the positioning results can also be used for the MAC protocol. So, it's necessary to study MAC protocols and localization method synthetically.

The rest of the paper is organized as: In Section II, the system model is presented, including Multi-Layer positioning model, the Non-Synchronous Localization Scheme and Medium Access Scheme. In Section III, the performance evaluation of different MAC Protocol schemes is done. Finally, conclusion and some future research directions are provided in Section IV.

II. SYSTEM DESCRIPTION

A. MULTI-LAYER POSITIONING MODEL

Like the terrestrial communication network, UWSNs is organized in accordance with the whole layer. Such a network can reduce the complexity of inter layer protocol design. Each layer undertakes certain network tasks, and provides certain services for the upper layer. Relatively speaking, the layers are not only independent individuals but also interrelated combination. The acoustic localization network is mainly based on node broadcast mode. Because the positioning mode for fixed path isn't used widely, it isn't relatively high requirements for the network layer. Meanwhile the transport layer provides a cushion in the application layer before. In UWSNs, network layer and transport layer are also very important. However, in the network node localization, they will be not as the research focus in order to optimize the network structure. So, based on UNA [15], we design a Multi-Layer positioning framework according to the characteristics of node localization in UWSNs, which involves the physical layer, data link layer and application layer three layers respectively as shown in Fig. 1. The underlying physical layer provides the basic

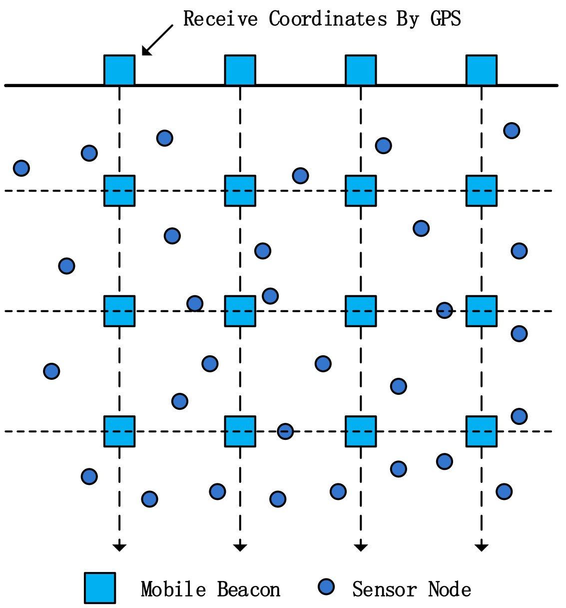


FIGURE 2. Non-synchronous localization scenario.

data communication; data link layer (MAC layer) ensured the collision of multiple nodes is avoided. Meanwhile we set up a Multi-Layer positioning model coupled with the localization algorithm in the application layer. The Multi-Layer is designed to break the original network layer protocol architecture, and provides a positioning performance model which can help the research of underwater acoustic network. We also consider more than two layers of network protocol which aim to save transmission energy and improve the network throughput.

B. NON-SYNCHRONOUS LOCALIZATION SCHEME

Since our focus is to investigate the impact of MAC protocol on localization, we use the Non-Synchronous Localization Scheme in the paper [8] to place it on the application layer of the Multi-Layer positioning network. Analyzing this kind of localization algorithm is mainly because this method is free from the concept of time synchronization for large scale UWSNs, based on dive and rise mobile beacons floating over the sea surface. It is easy to achieve by the technology development of UUV based on the trajectory of the anchor node.

The Non-Synchronous Localization Scheme can be simplified as shown in Fig. 2. The anchor nodes can dive and rise on vertical direction in sea. They have GPS receiver to receive their coordinates when floating over sea surface. Only z-coordinate of mobile beacon changes when the anchor nodes dive. All anchor nodes have fixed diving speed and communication range in sea. Sensor nodes passively listen to the broadcasting messages sent by mobile beacons and need two messages received from a mobile beacon for measuring distance to that mobile beacon. By lateration, N coordinates can be estimated using the distance estimated from $N + 1$ different mobile beacons.

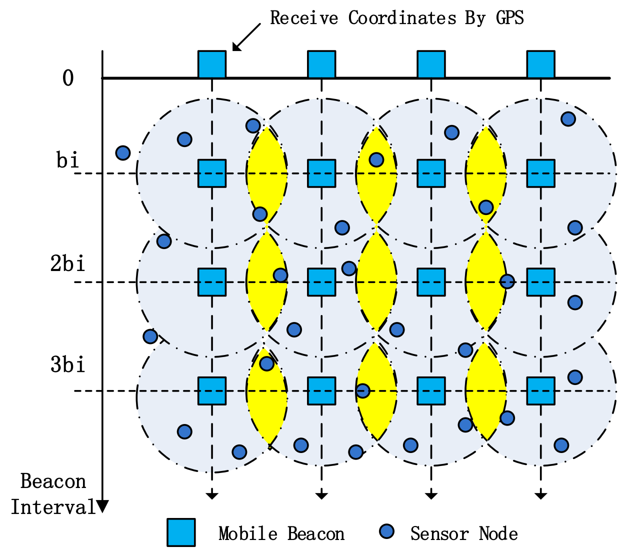


FIGURE 3. Underwater localization collision scenario.

Here, we mainly analyze the problem of packet collision. In the original method, anchor nodes broadcast the beacon with the same time and speed. We believe that the underwater acoustic propagation conforms to the spherical model and has a communication cut-off boundary. As shown in Fig. 3, when the communication range is more than interval between anchor nodes, it will produce the intersection area, such as the yellow area in the Fig. 3. And the intersection area becomes larger as the increase of communication distance. When the sensor nodes are in the intersection area, they maybe can't receive two messages from the different anchor nodes. So, we have to analyze the collision effect of the beacon packet. In this paper, the beacon broadcast of the anchor nodes is programmed into MAC protocol, and the entire Multi-Layer positioning model is constructed to analyze the impact of collision on localization results.

C. MEDIUM ACCESS SCHEME

MAC protocol decides sharing mode of the limited underwater acoustic channel. It's the underlying basis of constructing the system of UWSNs. So, MAC protocol has a significant impact on the performance of large scale sensor network node localization. In the Non-Synchronous Localization Scheme, Anchor nodes broadcast beacon in motion state. Meanwhile the sensor node needs to receive N+1 different mobile beacons, and uses lateration to localization. So, it's necessary to adapt the broadcasting scheme, and CSMA, MACA protocol is not suitable for this model. The earliest Contention-based MAC protocol was ALOHA protocol, and the ALOHA protocol was also applied to UWSNs. In the traditional ALOHA protocol, if a node has data to send, it can transmit directly, which is suitable for broadcasting beacon. The original location method uses the broadcast interval uniform. We summary it as the EI-ALOHA protocol, design a VI-ALOHA protocol on this basis, and make the performance analysis of the location method under the two protocols.

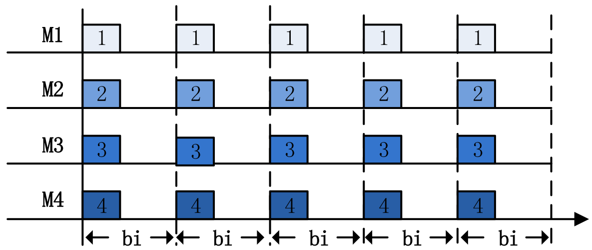
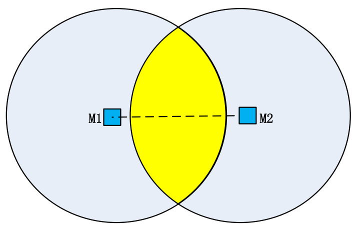
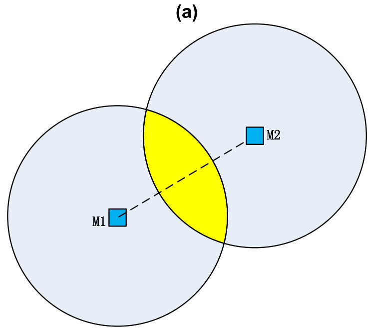


FIGURE 4. Equal Interval ALOHA.



(a)



(b)

FIGURE 5. Anchor nodes communication intersection. (a) Same depth intersection, (b) Different depth intersection.

S-ALOHA is proposed to reduce the packet collision probability [11]. S-ALOHA protocol requires dividing the channel into a long slot. When the data packet of anchor nodes has to be transmitted, it must be sent at the start of the slot. For the broadcast characteristic of Non-Synchronous Localization Scheme interval, we design the slot length for beacon interval longer than the beacon packet length, as shown in Fig. 4, and call it an EI-ALOHA. Because the anchor nodes are in the broadcast beacon state, there is no need to consider the back off problem of the conflict. However, when the communication range is larger than the distance interval between anchor nodes in equal interval beacon transmitting, the intersection collision occurs. When the interval is equal, the area of intersection is the largest, as shown in Fig. 5(a).

Considering the moving anchor nodes are prone to collision in equal interval slot broadcast beacon, we propose a VI-ALOHA protocol with random change of interval time slot, which can reduce the collision by increasing the randomness of Space-Time. The proposed protocol is mainly based on two factors: Firstly, variable beacon interval can reduce the intersection of beacon coverage. As shown in Fig. 5(b). When the anchor nodes broadcast the beacon in the equal interval

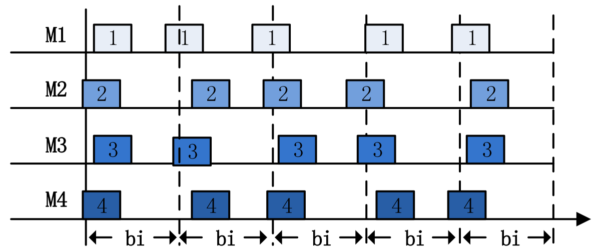


FIGURE 6. Variable Interval ALOHA.

slots, their depth is the same. So the intersection region is the largest. When variable slot is adopted, the distance between two anchor nodes can be increased, and the range of intersection area can be reduced. So it can reduce the collision. Secondly, it adopts a random Poisson distribution method to randomly generate beacon interval, which increases the randomness of each beacon broadcast, and reduces the collision due to equal interval. Poisson distribution is a discrete probability distribution, which characterizes the number of random events occurring in unit time. A large number of events are fixed frequency. When the Poisson distribution is near the frequency, there is the highest probability of occurrence of events, which is symmetrical down to both sides. It is unlikely to be bigger and smaller. This is in line with beacon interval that we design, which is integer and is generated near the equal interval, otherwise the location time can't be guaranteed.

The probability function of Poisson distribution is:

$$P(X = k) = \frac{\lambda^k}{k!} e^{-\lambda}, \quad k = 0, 1, \cdots \tag{1}$$

Among them, P denotes probability, X denotes some function relation, K denotes quantity, and λ denotes the expectation and variance of event. Its characteristic function is:

$$\psi(t) = \exp\{\lambda(e^{jt} - 1)\} \tag{2}$$

As shown in Fig. 6, the next broadcast beacon of anchor nodes is randomly generated, and the protocol can avoid collision to some extent. The specific comparison with equal interval will be shown in the simulation.

III. PERFORMANCE EVALUATION

In this section, the performance of proposed scheme has been evaluated using OPNET simulation. The distribution range of the UWSNs is 1000m∗1000m∗1000m. Two different numbers of 50 and 100 sensor nodes are randomly distributed in this area. The sensor nodes are fixed. The anchor nodes are average placement, and the trajectory of coordinate XYZ is respectively (250,250,0) −(250,250,1000), (250,750,0) −(250,750, 1000), (750,250,0) −(750,250,1000), (750,750,0) −(750,750, 1000). Anchor node speed is 1m/s. Beacon interval changes from 50 to 350 per 100. The transmission range for anchor nodes varies from 500 to 1500 m per 100. Underwater sound propagation speed is 1500m/s. Propagation loss which is calculated by underwater acoustic transmission

TABLE 1. The multi-layer network parameter settings.

Settings	Simulation Setting Value
underwater acoustic transmission model	$k \cdot 10\log l + l \cdot 10\log a(f)$
underwater sound propagation speed	1500m/s
available bandwidth	3kHz-25kHz
modulation mode	QPSK
data rate	1024bit/s
beacon packet size	68bit

model is shown in Formula (3). The size of the beacon packet is 68bit. The modulation mode is QPSK. Available bandwidth is 3 kHz-25 kHz. Data rate is 1024bit/s. Simulation time is 1000s. The Multi-Layer network parameter settings are shown in Table 1.

$$TL = k \cdot 10\log 1 + 1 \cdot 10\log a(f) \quad (3)$$

Among them, k denotes diffusion factor, $a(f)$ denotes absorption loss coefficient, f denotes acoustic frequency, and l denotes sound propagation distance.

Performance of the proposed scheme is analyzed in terms of transmission range and beacon interval. A discussion regarding the evaluation parameters and the obtained results are given in this section as below:

1) LOCALIZATION COVERAGE

Localization coverage refers to the range of large-scale sensor network localization system and the unknown node positioning proportion. Different positioning system or algorithm may locate different unknown sensor nodes in certain nodes density or within a period of time. Location coverage is an important evaluation index for node localization in large-scale UWSNs. Assuming that there are $N_{sen-node}$ nodes to be located in the sensor network, the number of nodes which are successfully positioned is $L_{sen-node}$, and then we can define the location coverage rate K as:

$$K = (L_{sen-node}/N_{sen-node}) \times 100\% \quad (4)$$

2) PACKET LOSS

Packet loss rate is the phenomenon of packet loss during packet transmission. In large scale sensor networks, packet loss has an important impact on the positioning results.

Assuming that the total number of transmitting packets is P_a, the number of packets successfully received is P_r, we can define the packet loss rate P as:

$$P = [(P_a - P_r)/P_a] \times 100\% \quad (5)$$

3) LOCALIZATION TIME

The location time describes the speed of the positioning, which we can define the average time of the successful locating nodes. Assuming the number of successful nodes is $L_{sen-node}$, the simulation time when the number of locations is no longer increasing is T_s, the location time T can be defined as:

$$T = T_s/L_{sen-node} \quad (6)$$

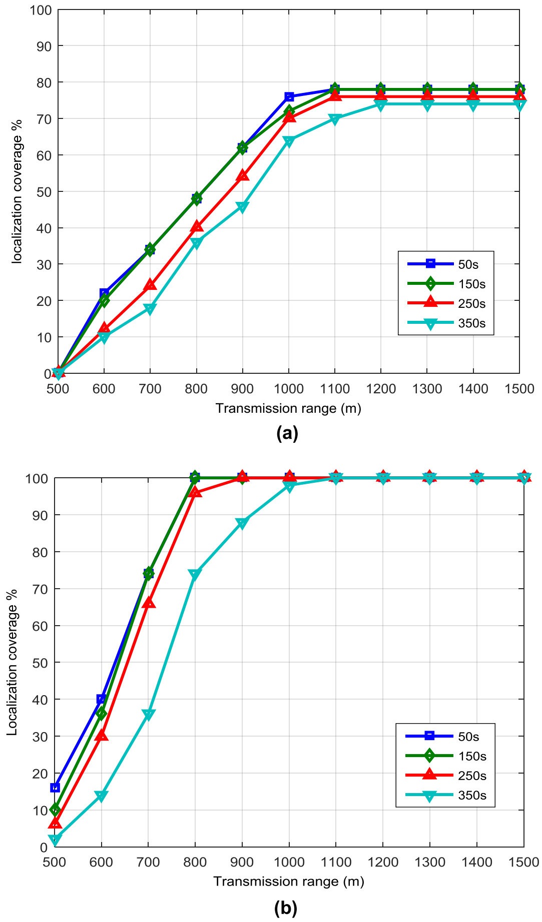


FIGURE 7. Localization coverage versus transmission range. (a) EI-ALOHA, (b) VI-ALOHA.

Now, on the basis of all discussed parameters, the analysis of various results is given as below. Firstly, we analyze the random distribution of 50 sensor nodes:

Fig. 7 shows the variation in localization coverage as a function of transmission range in terms of beacon interval variation. Initially, the transmission range is considered as 500m and it varies up to 1500 m with an increment of 100m at each level. In Fig. 7(a) beacon interval is taken as 50s and it varies regularly with a fixed interval of 100 up to 350s. It can be clearly observed that as the transmission range increases, coverage increases from 0 to 78%. However, when the transmission range is bigger than 1200m, the coverage can be constant and no longer increase which can't reach 100%. This can be attributed to the fact that when the transmission range is more than 1200m, all nodes can be covered by communication. However, the continuous packet collision makes some sensor nodes can't receive two or more messages. As the beacon interval is increased from 50 to 350 s, coverage decreases to some extent. If the beacon interval is increased, it will cause some sensor nodes can't be covered by a communication beacon. However, the problem of

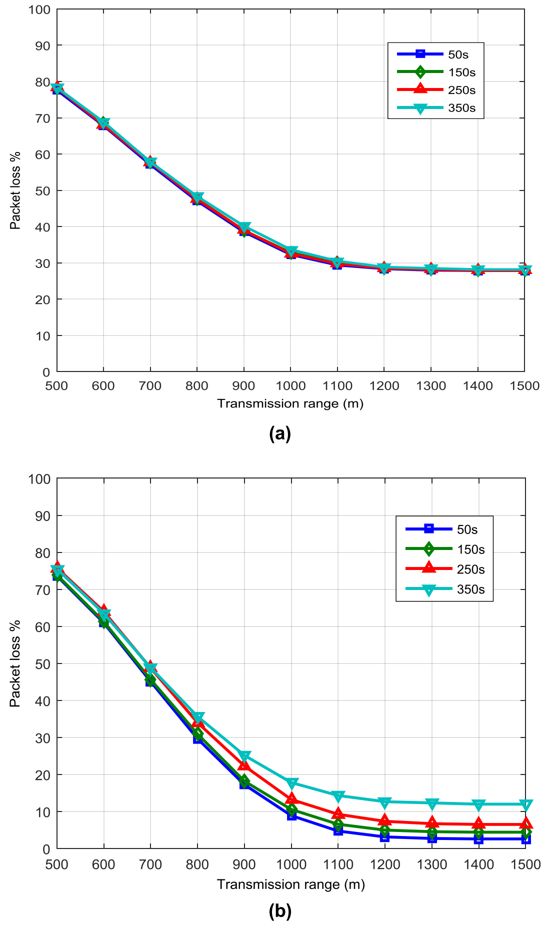


FIGURE 8. Packet loss versus transmission range. (a) EI-ALOHA, (b) VI-ALOHA.

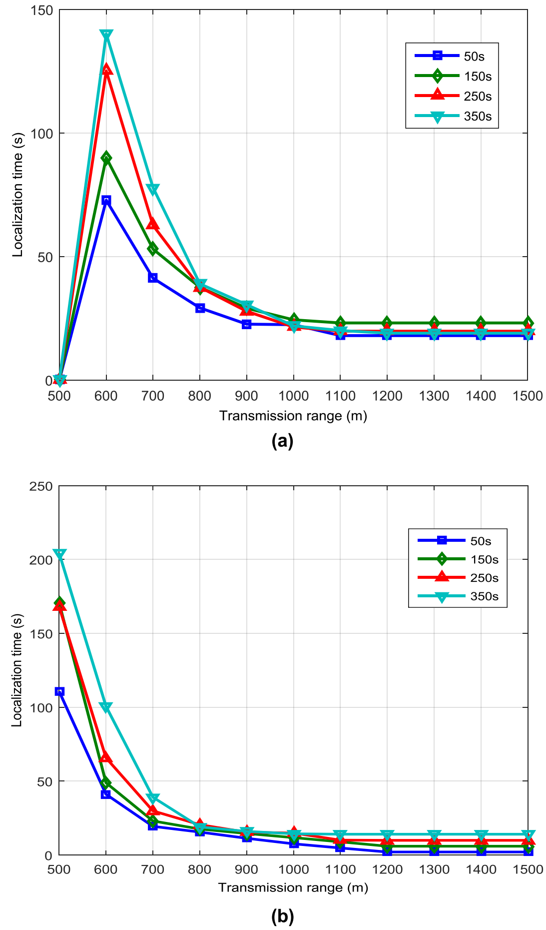


FIGURE 9. Localization time versus transmission range. (a) EI-ALOHA, (b) VI-ALOHA.

communication coverage caused by the increase of beacon interval can be compensated by increasing the transmission range. In Fig. 7(b) the beacon interval is random, and the variable interval is in accordance with the Poisson distribution. It can be clearly observed that as the transmission range increases, coverage can reach to 100%. The main reason is that the random Poisson distribution slot can avoid packet collision, so all nodes can receive two or more messages. As the beacon interval is increased from 50 to 350 s, like Fig. 7(a), the coverage is going to decline. When the communication distance is less than 1000m, the decrease is obvious. When more than 1000m, coverage reaches 100%. The increase of communication distance makes up for the problem of beacon interval.

Fig. 8 compares packet loss as a function of transmission range in terms of beacon interval variation. Initially, the transmission range is taken as 500 m, and it varies regularly with a fixed interval of 100 up to 1500 m. In Fig. 8(a) the beacon interval is set to the 50, 150, 250 and 350 s. It is observed that packet loss has little change with the different beacon interval, and decreases with an increase in transmission range. The minimum packet loss rate occurs when the transmission range is greater than 1200m, which is maintained at about 30%. This is mainly because the packet loss is determined by beacon packets to fail to reach the sensor node and collision loss. When the communication distance is less than 1200m, the failed beacon packets are the main cause of packet loss, and decreases as the increase of the transmission range. While the transmission range is more than 1200m, it is mainly due to packet loss of collision. At the same time, because of the equal interval broadcast beacon, the packet loss of four different beacon intervals is basically the same. The beacon interval in Fig. 8(b) is random and the time interval is accordance with Poisson distribution, which has the same trend in Fig. 8 (a). When it's less than 1200m, because broadcast beacon didn't reach the sensor node which mainly caused of the loss, it's obviously decreasing with the increase of the communication distance. When it's greater than 1200m, it gradually becomes stable. Meanwhile, when the beacon interval is 50s, the packet loss rate can reach 2.6%. From the comparison of packet loss rate in Fig. 8, the VI-ALOHA protocol can avoid collision effectively. In the case of small packet loss rate in Fig. 8 (b), the results of location coverage in Fig. 7 (b) can be guaranteed. When the packet loss rate of 30% occurs in Fig. 8(a), it would cause the failure of 100% coverage.

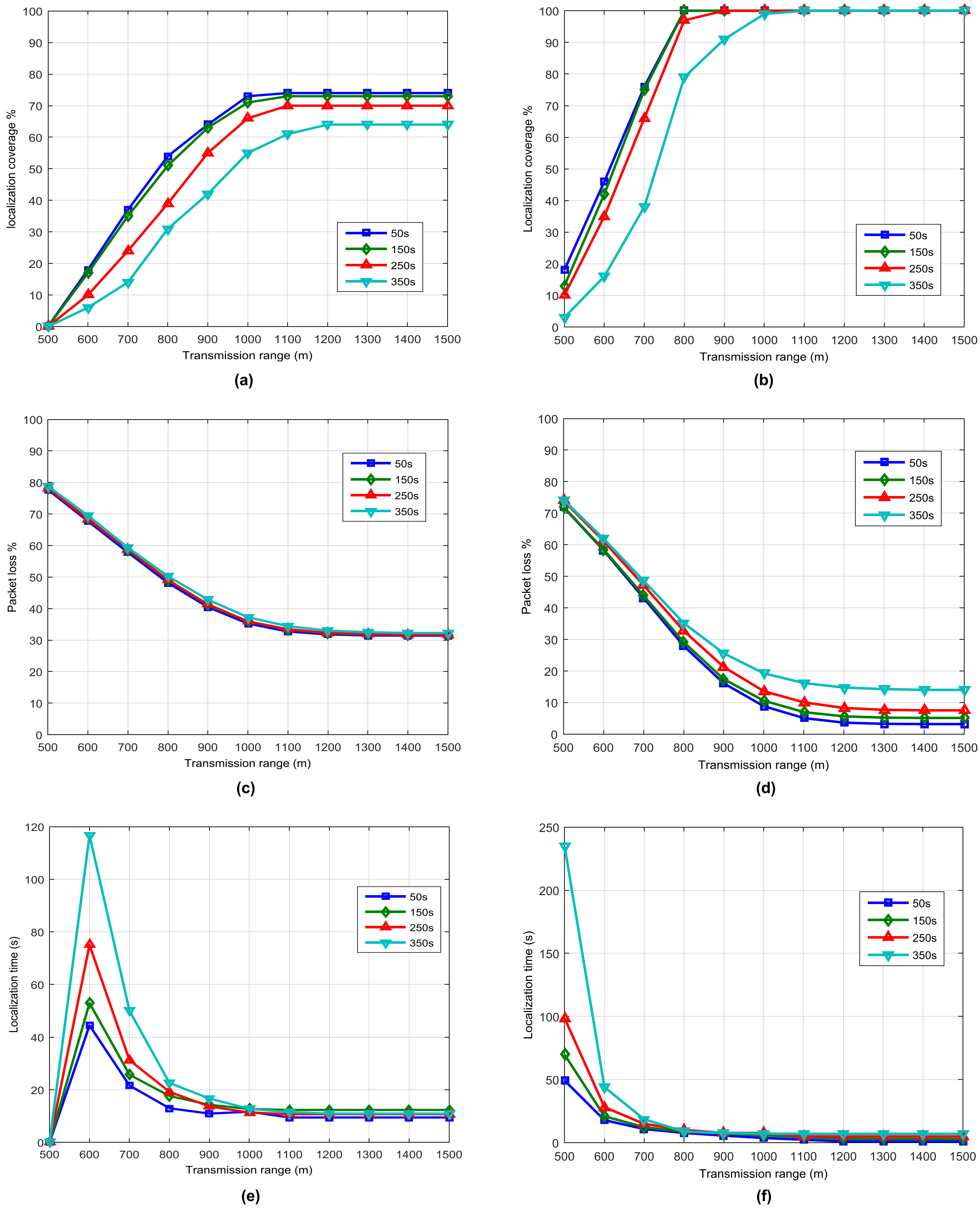


FIGURE 10. Localization coverage, Packet loss, Localization time versus transmission range. (a, c, e) EI-ALOHA, (b, d, f) VI-ALOHA.

Fig. 9 determines the localization time function of transmission range in terms of beacon interval. The transmission range is also from 500 to 1500m with a fixed interval of 100m. In Fig. 9(a) the beacon interval is set to 50, 150,250 and 350 s. It can be seen that the transmission range starts from 600m. The localization time decreases with the increase of the transmission range, and gradually becomes stable after 1200m. The minimum positioning time is about 20s. This is mainly because of the increase of transmission range, the location coverage is the higher, and the average sensor node positioning time will be reduced. Meanwhile, when there is no sensor node which can achieve the positioning, the positioning time is 0, as in the Fig. 9(a) transmission range is 500m. As the beacon interval is increased from 50 to 350 s, localization time increases to some extent. And the change is not obvious after it is greater than 1000m, it can be seen that the increase of transmission range can also be a good complement to beacon interval. The beacon interval of Fig. 9(b) is random accordance with Poisson distribution. It can be seen that the localization time decreases with the increase of transmission range. After 1000m, it gradually approaches the stable state, and the minimum average positioning time is about 2s. The location coverage increases with the increase of transmission range, which causes the decreases of average positioning time. Compared with the equal interval, the coverage is greater and the minimum localization time is much smaller by using variable interval.

Then we analyze the random distribution of 100 sensor nodes:

Fig. 10 shows the change of localization coverage, packet loss, localization time in different beacon interval as the transmission range. Firstly Fig. 10 (a) and (b) show the difference between equal interval and variable interval on localization coverage. Similar with the results in Fig. 7, when the random Poisson beacon interval is used and the transmission range reaches 1000m, 100% of the coverage can be achieved, while the maximum localization coverage of equal interval is about 75%. Fig. 10(c) and (d) show the contrast of packet loss rate at different beacon interval. When equal interval is used in Fig. 10(c), packet loss rate has little difference in different beacon interval, and the minimum packet loss rate is about 30%. In the Fig. 10(d), the packet loss rate can be reduced to about 5% by using the variable interval with random Poisson distribution, which can ensure the results of localization coverage. Fig. 10(e) and (f) contrast the change of localization time. Fig. 10(e) shows the basic change rule which decreases with the increase of transmission range, and the minimum localization time is about 15s. Fig. 10(f) shows obvious decreasing trend after the beacon interval adopts Poisson distribution, and the minimum can reach about 1s.

By comparing the random placement of 50 and 100 sensor nodes, VI-ALOHA can get higher localization coverage, lower packet loss, and shorter localization time than EI-ALOHA, which has obvious advantages. Localization coverage and other indicators are basically improved with the transmission range increased. However, the increase of the transmission range causes more power consumption, the transmission range is about 1000-1200m for optimal selection; beacon interval size has little impact on the results, which can be compensated by the transmission range, so it can be appropriate to select a larger interval.

IV. CONCLUSION

In large-scale UWSNs, persistent packet collisions may have a serious impact on the localization results. Therefore, in the study of positioning algorithm, we need to consider the impact of MAC Protocol on the localization algorithm. In order to analyze the influence of MAC Protocol on localization algorithm more intuitively, firstly we construct a Multi-Layer localization model, and put the localization algorithm on the application layer. According to a Non-Synchronous Localization Scheme, we analyze the reason of packet collisions, and propose a VI-ALOHA protocol based on random variation of Poisson distribution. It aims to reduce the collision by adding random Space-Time. In simulation, the results of localization coverage, packet loss, localization time under different protocols are compared. It can be concluded that VI-ALOHA has obvious advantages in these indicators, and the impact on the localization coverage and localization time can be seen through packet loss. In future, we will continue to analyze the impact of collision under different localization algorithms, and study the packet loss rate and the specific numerical relationship between the localization algorithm model.

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