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A Collision Avoidance MAC Protocol with Power Control for Adaptive Clustering Underwater Sensor Networks

Libin Xue [1], Hong Lei [1,*] and Rongxin Zhu [2,*]

[1] School of Cyberspace Security, Hainan University, Haikou 570228, China; xuelibin@hainanu.edu.cn
[2] School of Computer Science and Technology, Hainan University, Haikou 570228, China
* Correspondence: leihong@hainanu.edu.cn (H.L.); rongxin914@163.com (R.Z.)

Abstract: Underwater sensor networks (UWSNs) play a vital role in marine exploration and environmental monitoring. However, due to the characteristics of underwater acoustic channels such as high delay, low bandwidth, and energy limitation, the design of an underwater media access control (MAC) protocol has brought great challenges, and existing MAC protocol designs rarely consider the influence of channel interference factors in networking. Therefore, this paper proposes a collision avoidance MAC protocol for clustering underwater sensor networks. The protocol first classifies users by combining the channel characteristics of underwater nodes and the distance measurement between nodes. Then, based on the clustering network, according to the channel correlation distance measurement between nodes and the communication range of the cluster head (CH), the transmit power in clusters is controlled to reduce the lifetime of the network based on the cumulative reduction in node power consumption. Finally, the cluster structure in each cluster is used to schedule the transmission of member nodes in the cluster, and at the same time, the energy consumption of nodes is reduced while multi-node collision-free transmission is realized. The simulation results show that the throughput of the proposed adaptive power control clustering MAC protocol (APCC-MAC) is 26.5% and 19.5% higher than that of packet-level slot scheduling (PLSS) algorithm and Cluster-Based Spatial–Temporal Scheduling (CSS) algorithm, respectively, providing better communication performance and stability for clustered underwater acoustic networks.

Keywords: media access control (MAC); power control; collision avoidance; clustering algorithm; game theory

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1. Introduction

In recent years, with the increase in marine activities and the rapid development of marine industries, underwater acoustic sensor networks (UASNs) [1] have received widespread attention and research in marine exploration, environmental monitoring, and other fields [2,3]. However, marine issues such as ships, waves, ocean noise, and environmental pollution are becoming increasingly serious. Moreover, sound propagation speed is relatively slow, at about 1500 m/s [4], which is five orders of magnitude slower than radio signals [5–7]. This leads to long propagation delays due to the slow signal propagation speed. In addition, the underwater communication bandwidth is limited to less than 15 kHz, which restricts the amount of data that can be transmitted. Furthermore, underwater sensors are powered by batteries that are difficult to replace, posing a critical issue for limited underwater energy consumption.

Moreover, due to significant signal propagation delays underwater, underwater acoustic communication faces the issue of spatiotemporal uncertainty [8], where collisions can

still occur even when data packets are sent in different time slots and locations. The severe access conflicts significantly affect the performance of the network.

In large-scale networks, when the propagation distance is limited, a single node cannot handle the scheduling of the network. Therefore, a clustering network structure is usually adopted. For example, reference [9] constructs a clustered spatiotemporal conflict graph to schedule nodes in the cluster to reduce conflicts. However, due to the high complexity of the graph structure, the utilization of channel time slots is reduced.

Game theory provides an effective means to study the most reasonable energy-efficient scheme among nodes in clusters through competition and cooperation. However, the existing game theory only focuses on the current energy consumption, but ignores the influence of complex underwater channel environments on the energy state between nodes; hence, it cannot accurately reflect the game scenario in actual underwater acoustic networks [10,11].

In addition, the energy consumption during data transmission is closely related to the transmission distance [12]. Therefore, when designing MAC protocols, the transmission power of nodes should be controlled to reduce the energy consumption of nodes, reduce interference between nodes, and avoid collisions.

To address the above issues, this paper proposes a novel underwater MAC protocol. This protocol adopts an adaptive clustering network based on game theory and improves the performance of network concurrent transmission through a transmission scheduling mechanism based on cluster head nodes. Meanwhile, nodes adjust their power to change the communication distance, reducing network energy consumption and further reducing data conflicts.

The main contributions of this paper are summarized as follows:

1. A power control and collision avoidance MAC protocol for UASNs based on adaptive clustering is proposed. It optimizes the power control of nodes on the basis of clustering, thus providing more residual energy for network clustering in the next cycle. After several cycles, the whole network has a longer lifetime than other clustering algorithms.
2. The adaptive clustering algorithm proposed in this paper takes into account the actual distance between nodes and channel correlation in the water-based multi-path channel environment, and designs a penalty mechanism to encourage nodes to make decisions that are more beneficial to the overall income.
3. Based on the above cluster network structure, the protocol combines the channel correlation distance measurement between nodes, and adjusts the transmitting power of nodes inside and outside the cluster to reduce the data conflict and node power consumption between nodes.
4. On the basis of the above power control, the protocol schedules the data transmission order according to the sending priority, considering the CH degree, distance measure, and propagation delay of the nodes, so as to further avoid the collision between the nodes.

The rest of the article is organized as follows: In Section 2 , we will mainly introduce the related research of the proposed MAC protocol. In Section 3, we will introduce the adaptive clustering algorithm proposed in this paper in detail. In Section 4, we will introduce the proposed APCC-MAC protocol in detail. Then, in Section 5, we will conduct a simulation experiment, and in Section 6, we will provide a prospect and summary.

2. Related Work

Currently, traditional MAC protocols include three main categories: scheduling-based MAC protocols, competition-based MAC protocols, and a combination of both.

The ALOHA protocol is the earliest contention-based MAC protocol [13], where nodes choose to send immediately whenever they have data to transmit, leading to severe collisions as the network load increases. Reference [14] analyzed an improved the slotted ALOHA protocol with time slot constraints. Although slotted ALOHA reduces collisions by allocating time slots, collisions still increase with growing traffic load. Therefore, researchers began studying handshake-based contention MAC protocols. Reference [15] proposed a collision avoidance MAC protocol based on game theory under the premise of a node handshake mechanism. This protocol uses non-cooperative games between nodes, allowing the node with the shortest underwater delay to win the competition with the highest probability before starting data transmission, thereby increasing network throughput. However, the protocol adopts a one-handshake-one-send mechanism, which prolongs the overall transmission time of all data in the harsh underwater environment with long delays, reducing the overall efficiency of data transmission.

Scheduling-based MAC protocols are mainly divided into three types: Time Division Multiple Access (TDMA), Frequency Division (OFDM), and Code Division (CDMA). TDMA achieves conflict-free transmission by scheduling nodes to send data in different time slots. Reference [16] designed a TDMA protocol that allocates time slots to different user groups based on slot grouping levels. However, such protocols sacrifice time resources and increase the delay as nodes must wait for their time slots to be allocated. To overcome the above-mentioned latency issues, some experts utilize physical layer frequency division multiplexing modulation technology to improve data transmission rates [17]. Reference [18] proposes an MAC protocol that continuously adjusts transmission power and OFDM subcarriers based on dynamic changes in traffic load, effectively reducing data concurrency conflicts. Reference [19] presents an MAC protocol that combines CDMA and OFDM to achieve concurrent communication in wide-area networks. While these protocols address the long latency issues underwater, they result in sacrificing and wasting spectrum resources.

To better overcome the drawbacks of scheduling-based MAC protocols, large-scale node scheduling and clustering algorithms have gradually become a research focus for improving network performance [20,21]. The classification and hierarchical ideas in clustering algorithms reduce the complexity of underwater networks and the number of data transmissions for user nodes. Among them, the most representative clustering algorithm is the LEACH protocol [22], which achieves energy balance by periodically re-clustering. However, the setting of random numbers in the algorithm eventually leads to uneven energy consumption.

The authors of [23] proposed an underwater adaptive energy-saving clustering algorithm based on a multi-dimensional game. By establishing a multi-dimensional game model, it increases the chance for historical CH nodes to compete with CH again, and further optimizes the CH election strategy. However, this algorithm rarely considers the state and environmental factors of the nodes themselves, so it is not highly adaptable in real scenarios. Based on clustering, more efficient MAC protocols have been proposed, such as the TDMA-based enhanced MAC protocol in reference [24] and the handshake-based power control MAC protocol in reference [12]. These protocols all use intra-cluster or inter-cluster hierarchical scheduling to achieve network efficiency. However, these algorithms still have many flaws; for example, the clustering process pays little attention to the conditions of the underwater channel, and the overall goals of clustering and MAC protocols are not consistent.

Therefore, an adaptive clustering underwater acoustic network MAC protocol is proposed in this paper. This protocol clusters underwater users while fully considering channel correlation, and adjusts the transmission power range of nodes and the priority

of scheduling users to send data within and between clusters after clustering, in order to combine clustering and MAC protocols to jointly achieve the goal of reducing data conflicts.

3. Adaptive Clustering Algorithm Based on Game Theory

As shown in Figure 1, nodes are randomly distributed in a certain sea area, clustered using the clustering algorithm proposed in this paper to form a single-hop network from member nodes to cluster heads. After ordinary member nodes collect ocean data, they send data packets to the cluster head, which then transmits the received data to the surface base station through multi-hop communication.

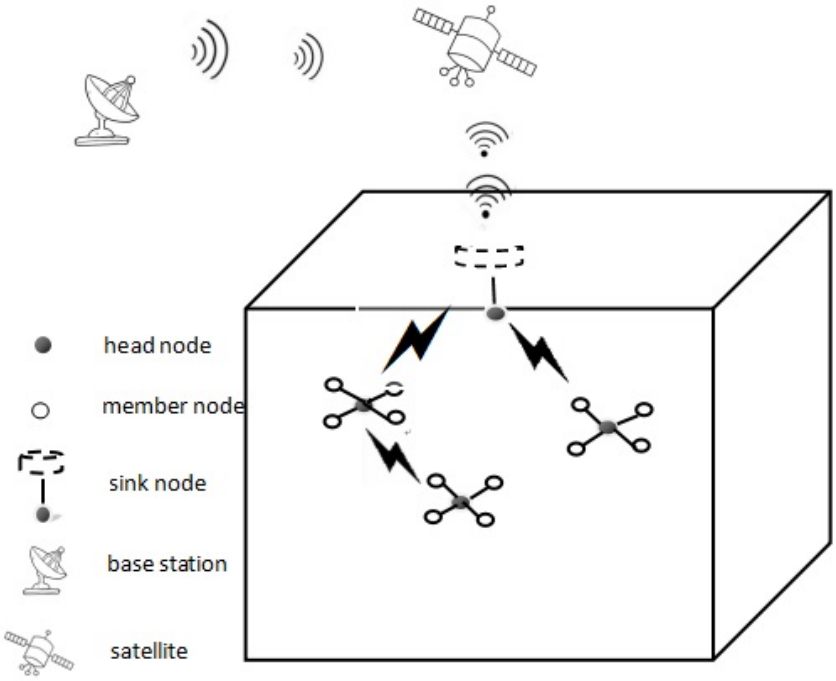


Figure 1. System model.

3.1. Underwater Channel Model and Distance Measurement

There are two main losses when acoustic signals propagate underwater: absorption loss and propagation loss. If $r(m)$ is the transmission radius of the node signal within its communication range, $a_0(f)$ (dB/km) is the absorption factor, and f (kHZ) is the transmission frequency, then the attenuation formula of the acoustic signal can be expressed as follows:

$$\mathrm{a}_0(f) = 0.011\frac{f^2}{f^2+1} + 4.4\frac{f^2}{f^2+4100} + 2.75 * 10^{-4} f^2 + 0.003 \quad (1)$$

Furthermore, the transmission loss of the acoustic signal can be expressed as follows [25]:

$$A(r,f) = L_{sp} + L_{ab} = \quad 10\log\left(r^k a_0(f)^{r\times 10^{-3}}\right) = A_0\left(r^{\mathrm{k}} a_0(f)^{r\times 10^{-3}}\right) \quad (2)$$

In the above formula, the product of coefficient 10 and the *log* function are replaced by the scaling constant A_0. Then, the channel gain H can be further expressed as follows:

$$H = \frac{1}{A_0(A)} \quad (3)$$

In the underwater channel, there are many types of noise, such as wind waves, tides, ship navigation, etc. In this paper, the sum of underwater communication noise is represented as σ^2, and the signal-to-noise ratio can be calculated as follows:

$$\mathrm{SNR_i} = \frac{\mathrm{P_i H}}{\sigma^2} \tag{4}$$

By combining Equations (2)–(4), we obtain the following:

$$\mathrm{P_i} = (\mathrm{SNR})\sigma^2 \frac{1}{A_0\left[r^{\mathrm{k}} a_0(f)^{r\times 10^{-3}}\right]} \tag{5}$$

As can be seen from Formula (5), user i can use the transmission power required for SNR communication, that is, the minimum power necessary to ensure normal communication between network nodes. If the transmission power is too large, interference and communication conflict between communication nodes will be caused.

Therefore, according to the distance between nodes, the power of the control nodes is in a range, which can improve the quality of underwater acoustic communication, and avoid collisions between nodes.

The phenomena of reflection and refraction when sound waves propagate in the seabed will cause the sound signal to form multi-path effects in the way of multi-path superposition at the receiving end, resulting in inter-symbol interference, which seriously affects the quality of underwater acoustic communication.

Therefore, when we consider the channel conditions of node clustering, we must consider the multi-path channel information of node data transmission.

The distance measurement is as follows:

Suppose that the channel information of user i can be marked as follows: $h_i = [h_{i1}, h_{i2}, ...h_{il}]$, then the auto-correlation matrix of user i can be expressed as $R_{ii} = \mathrm{E}\{{h_i}^h h_i\}$, and through the feature decomposition of the auto-correlation matrix, R_{ii} can be expressed as follows:

$$R_{ii} S_i = \Lambda S_i^h \tag{6}$$

If the eigenvalues in Formula (6) are regarded as coefficients, then the multi-path channel information can be represented by the eigenvector r_i as follows:

$$\mathrm{r_i} = \sum_{i=1}^{l} \lambda_{il} S_{il} \tag{7}$$

Next, the channel correlation between the cluster head and the common member node i can be calculated as

$$\mathrm{E_{i,CH}} = \frac{E\left\{r_i^h r_{CH}\right\}}{E\{r_i^h r_i\} \| E\{r_{CH}^h r_{CH}\}} \tag{8}$$

Then, the distance metric that integrates the actual distance from the node to the CH and the channel state is designed as follows:

$$D_{i,CH} = \beta r_{i,CH} + (1-\beta)(-\mathrm{E}_{i,CH}) \tag{9}$$

where $\beta \in (0,1)$ is the weight factor. $r_{i,CH}$ is the actual direct distance between CH and node i. According to the result obtained by Formula (9), any node in the network can be assigned to the cluster with the lowest D value from the other nodes.

3.2. Node Traffic Weight Analysis

Assume that the traffic of node i is x(i), considering the influence of each node on cluster head nodes. Assuming that the weight coefficient of traffic is $\theta \in (0,1)$, and considering the channel distance measurement between nodes, the comprehensive weight generated by member node i on CH nodes is as follows:

$$y_i = \frac{\theta \mathrm{x(i)}}{D_{i,CH}} \tag{10}$$

The weight of the cluster head can be taken as the weight of the cluster head by summing the traffic weight generated by all nodes in the cluster to CH, which is denoted as Z:

$$\mathrm{Z} = \sum_{i=1}^{N} \frac{\theta x(i)}{D_{i,CH}} \tag{11}$$

3.3. Node Energy Consumption Model

According to the underwater channel model formula, the energy consumption for a node to send $l - bit$ data packets is as follows:

$$\mathrm{E_{sent}}\,(\mathrm{l,r}) = \mathrm{P} * \mathrm{A}(\mathrm{r,f}) * \mathrm{T} \tag{12}$$

where P is the received power of node i, T is the transmission delay of i, and Z_i is the traffic weight of i; then, the energy consumption of node i for receiving $l - bit$ data is as follows:

$$\mathrm{E_{received}}(l) = l\mathrm{Z_i}\mathrm{E_1} \tag{13}$$

The energy consumption of the converged $l - bit$ data on node i is as follows:

$$\mathrm{E_{integrated}}(l) = l\mathrm{Z_i}\mathrm{E_2} \tag{14}$$

The energy consumption of data forwarding by CH node i can be expressed as follows:

$$\mathrm{E_{forward}}\,(l) = \eta l \mathrm{Z_i}\mathrm{E_3} + \varepsilon \mathrm{DE_4} \tag{15}$$

Non-cluster head (NCH) node i consumes energy only when forwarding data, which is as follows:

$$E_{\mathrm{forward}}^{NCH}\,(\eta l Z_i, D) = \eta l y_i E_3 + \varepsilon \mathrm{DE_4} \tag{16}$$

3.4. Game Model Between Nodes

Define underwater nodes as a set of competing participants: N = {N_1 , N_2,……,N_n}. The strategy set of each node at the current time of game is as follows: S = {S_1 , S_2,……,S_n}. The revenue function set of game nodes is expressed as follows: U = {U_1 , U_2,……,U_n}.

The proposed adaptive clustering algorithm consists of three steps: Firstly, based on the distance measurement of channel correlation and node traffic analysis, the game model between nodes is established. Secondly, on the basis of setting the penalty factor, according to the Nash equilibrium obtained by the non-cooperative game, a node i is determined to become a CH node and form a cluster. Finally, after a period of cycles, CH nodes are rotated according to the maximum remaining energy of nodes in the cluster to balance the energy consumption. The overall flow chart of the algorithm is shown in Figure 2; as can be seen from the figure, the number of times to judge the income of each node i is n times, and the number of times to further judge whether the residual energy of the node is suitable for CH is also n times. Therefore, the time complexity of the clustering algorithm is $O(n^2)$.

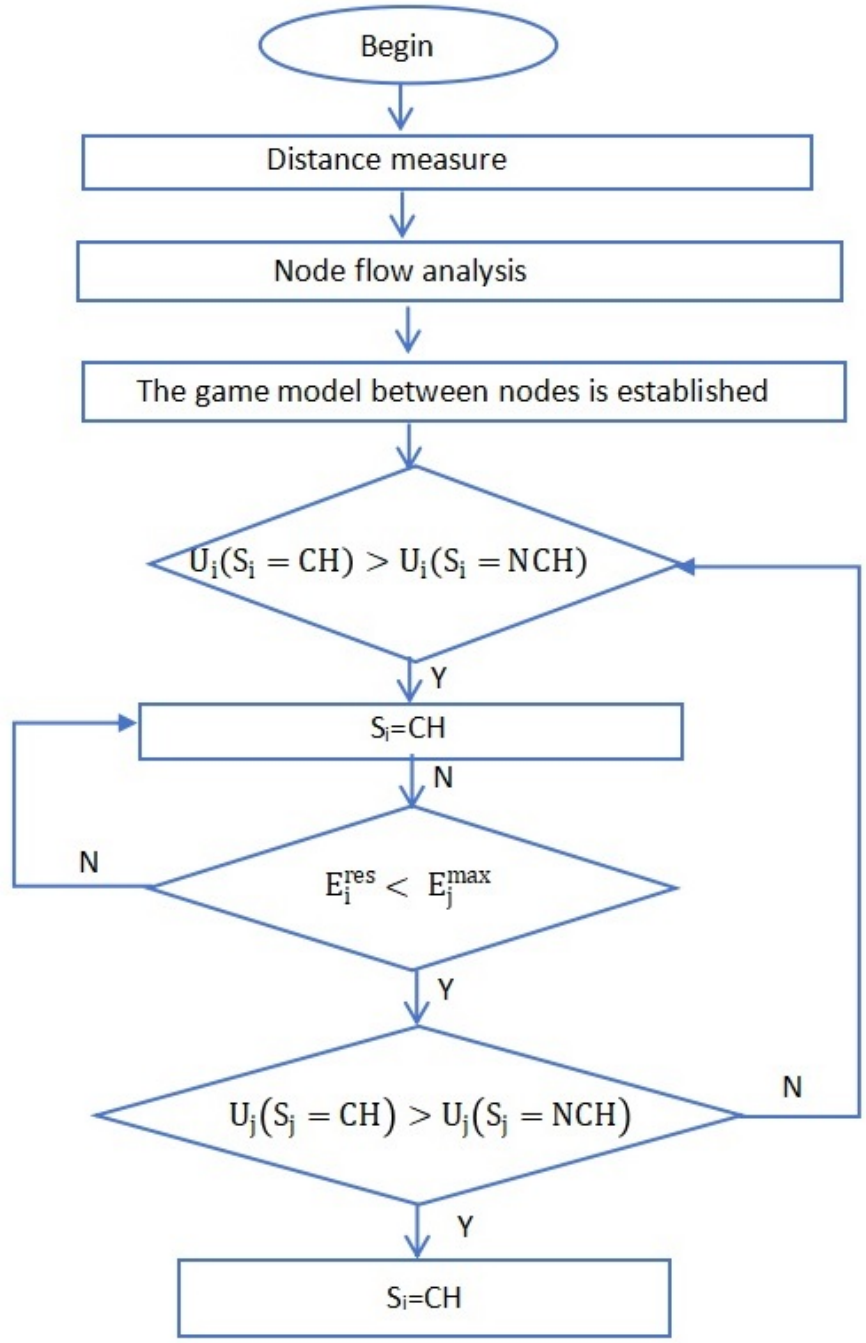


Figure 2. Adaptive clustering algorithm flow.

The detailed steps of the algorithm are as follows:

When node i selects strategy S_i = CH, its return function is as follows:

$$U_i(NCH, S) = aE_i^{residual} - C_i \tag{17}$$

where $a > 0$ is the positive correlation coefficient, C_i is the cost, and $E_{residual}$ is the remaining energy of node I. According to the energy consumption model, cost C_i can be further expressed as follows:

$$\begin{aligned} \mathrm{C}_i &= lZ_iE_1 + lZ_iE_2 + E_{\text{forward}}\left(lZ_i, D\right) \\ &= lZ_i((E_1 + E_2) + \eta lZ_\mathrm{i}\mathrm{E}_3 + \varepsilon \mathrm{DE}_4 \end{aligned} \tag{18}$$

If the node selects NCH, since the non-cluster head node only has the energy consumption of data forwarding, the income of node i can be expressed as follows:

$$\begin{aligned} U_i(NCH, S) &= aE_i^{residual} - E_{\text{forward}}^{NCH}\left(\eta lZ_i, D\right) \\ &= aE_i^{residual} - \eta ly_iE_3 - \varepsilon \mathrm{DE}_4 \end{aligned} \tag{19}$$

Obviously, when the residual energy of node i is the same, the cost of choosing the NCH strategy is far less than the cost of choosing the CH strategy, and the benefit is also far greater. Therefore, it is necessary to impose certain penalties on nodes that choose the NCH strategy, so as to promote more nodes to compete for the cluster head. The penalty r_i can be expressed as follows:

$$r_i = aC_ib\frac{E_i^{residual}}{E_j^{\max}} \tag{20}$$

After penalizing the node, the payoff is as follows:

$$U_i(S_i = NCH) = aE_i^{residual} - \eta ly_iE_3 - \varepsilon \mathrm{DE}_4 - r_i \tag{21}$$

where E_j^{max} is the energy of the node with the largest residual energy among the neighboring nodes. It can be seen from Formula (20) that when the residual energy of node i is closer to the maximum energy of the neighboring node with the largest residual energy, the ratio $E_i^{residual}/E_j^{max}$ of the two is closer to 1, meaning the penalty on node i increases. At this time, node i is more inclined to choose the strategy of becoming a CH node in order to obtain greater benefits for itself. In other words, the function of the penalty r_i is to encourage the nodes with the highest energy in the cluster, as much as possible, to elect the cluster head with the greatest probability in the process of the game.

To sum up, in the course of a round of game, nodes with greater energy tend to become cluster heads and thus obtain the maximum benefits. Nodes with lower energy receive smaller penalty values r_i during the course of the game, and Formula (20) can be used to show that the strategy of choosing NCH has greater benefits. Ultimately, an equilibrium state is reached during the game between the nodes. After a certain period of time, the node that originally chose the CH strategy has a rapid decline in energy due to the excessive load, while other ordinary nodes only send data, and the long-term low energy consumption leads to the energy of an NCH node with the largest residual energy becoming larger than the previous CH, thus replacing the original cluster head and becoming a new cluster head. Through the continuous cycle of this process, finally, the energy consumption of the whole cluster can be balanced.

4. APCC-MAC Protocol Design

4.1. Protocol Overview

The APCC-MAC protocol proposed in this paper adopts a large-scale underwater network as the model, aiming to ultimately avoid packet collision conflicts, reduce node latency, and reduce power consumption. The detailed flow chart of this protocol is shown in Figure 3, with specific steps as follows:

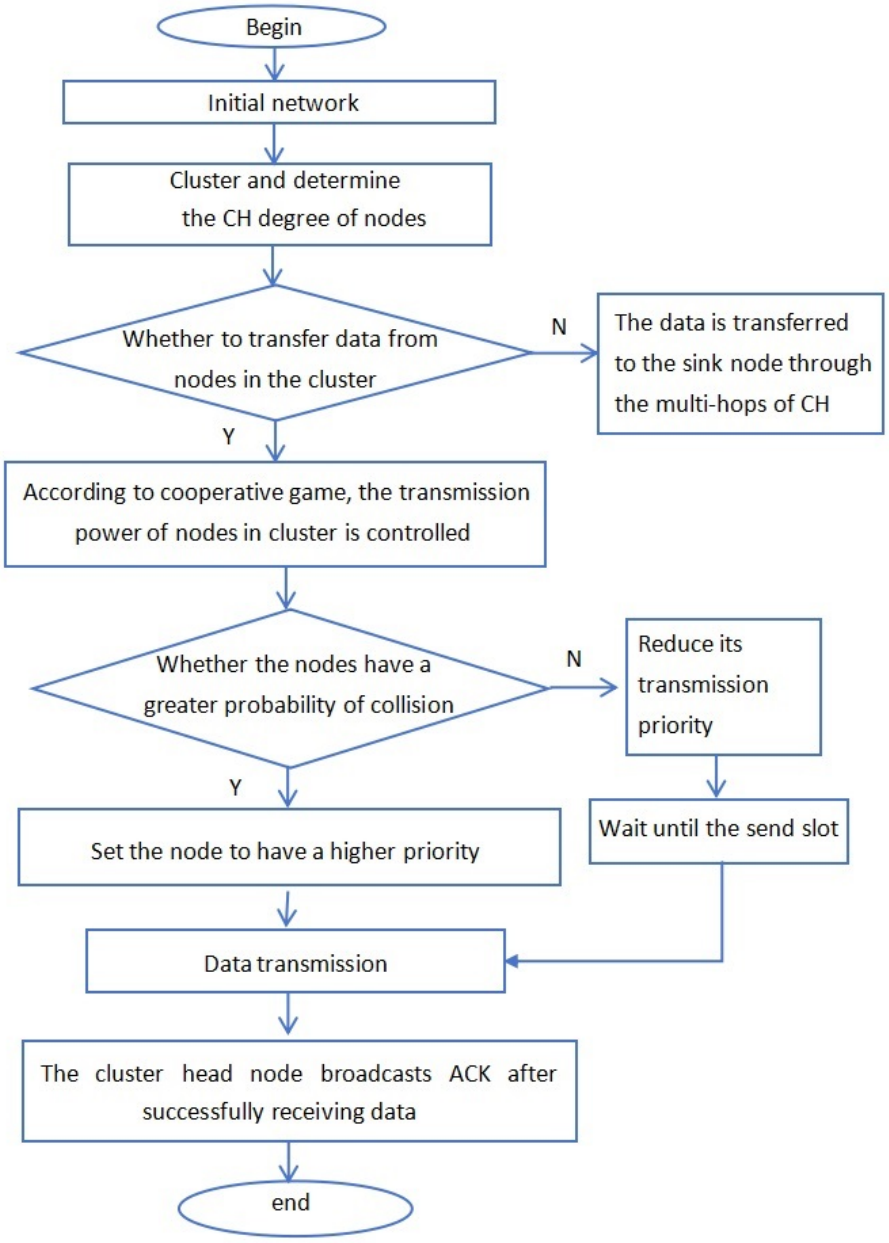


Figure 3. Flow chart of the APCC-MAC protocol.

1. Initial network: In this process, each node collects information about its neighbors within a two-hop range and maintains a delay information table locally through packet switching.

2. Members use the adaptive clustering algorithm based on game theory proposed in this paper to cluster and calculate the CH degree of each node.

3. Determine whether the communication at this moment involves the data transmission of nodes in the cluster. If not, the data will be transmitted to the sink node through multi-hop communication via CHs. If it does, the transmit power of nodes in the cluster will be controlled according to the cooperative game algorithm proposed in the literature [26], so as to reduce the power consumption of nodes and allocate optimal power resources for the subsequent scheduling of the MAC protocol.

4. The packet structure of the algorithm in this paper adopts the data frame structure shown in Figure 2 in the literature [27]. After the CH node allocates transmission power to all its members, the priority of transmission scheduling is determined according to the

CH degree, distance measure, and propagation delay of the node, and the scheduling information is encapsulated in a short packet for broadcast.

5. After the completion of scheduling, the data enter the transmission phase. After the transmission is completed, CH broadcasts an ACK confirmation packet of the data transmission results and continues to the next round of transmission.

4.2. Power Control in the Protocol

The power control of the protocol can be divided into the power control of the cluster head node and the power control of the common member nodes; furthermore, the power control of the cluster head nodes can be divided into intra-cluster communication and inter-cluster communication.

As shown in Figure 4a, H_1, B, and H_2, C are two clusters, where H_1 and H_2 are cluster heads. When H_1 sends signals to B and H_2 to C, respectively, collisions may occur between nodes H_1 and H_2, and between H_2 and B. If the transmitting power of cluster head nodes H_1 and H_2 is within a certain range, as shown in Figure 4b, collisions between nodes H_1 and H_2, as well as between nodes H_2 and B, can be avoided, thus avoiding collisions between clusters through power control.

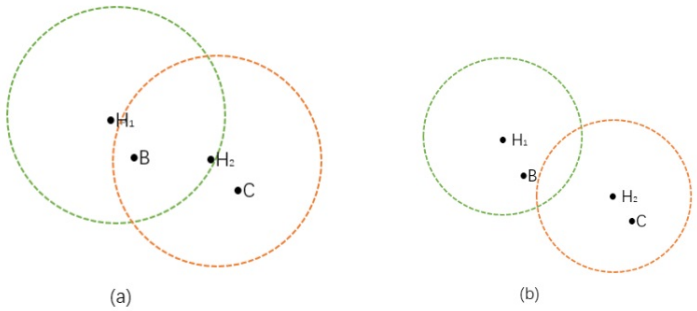


Figure 4. Power control and collision avoidance between clusters.

The power control between nodes in the cluster is shown in Figure 5a, where H is the cluster head, and member nodes $N_{1,1}$ and $N_{1,2}$ in the same cluster are all in the collision area with each other. After controlling the power, as shown in Figure 5b, nodes $N_{1,1}$ and $N_{1,2}$ reduce their transmit power without affecting their normal communication with cluster head node H. Thus, collisions with each other are avoided, and the power consumption of nodes is also reduced.

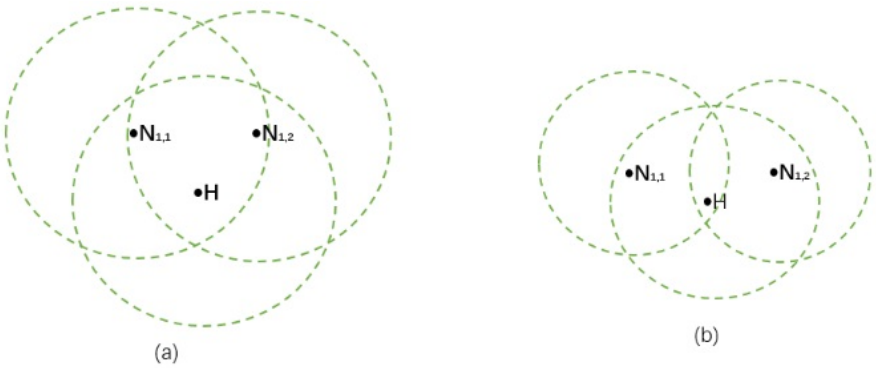


Figure 5. Power control and collision avoidance in clusters.

When cluster head node H performs intra-cluster communication, combined with the distance metric D, it is assumed that the minimum power that can normally communicate with the farthest node in the cluster is P_{min}; in this cluster, for more specific power control

of each node, the power control algorithm in my recently published work [26] is further adopted. When H performs inter-cluster communication, the maximum power that it can use to communicate with the furthest cluster head is P_{max}; then, the range of intra-cluster and inter-cluster transmitting power should be adjusted as follows:

$$P_{min} < P_{th}(1 - \beta) < P_{max} \quad (22)$$

4.3. Node Scheduling

When the power of the nodes in the protocol is controlled, the protocol uses the cluster head nodes in each cluster to complete the scheduling of its cluster member nodes. Before scheduling, it is necessary to confirm the priority of the node to be scheduled. Here, the three factors of CH degree, distance measurement, and traffic weight of the node are mainly considered to determine the priority. The detailed process is as follows:

1. CH degree: As shown in Figure 6, nodes $N_{2,1}$ have collision relations with cluster heads H_1, H_2, and H_3 of the three clusters, so their CH degree is 3; nodes $N_{1,1}$, within their propagation range, only have conflict relations with H_1 and H_2, so its CH degree is 2. Therefore, a node with a higher CH degree has the highest probability of collision and should have a higher priority.

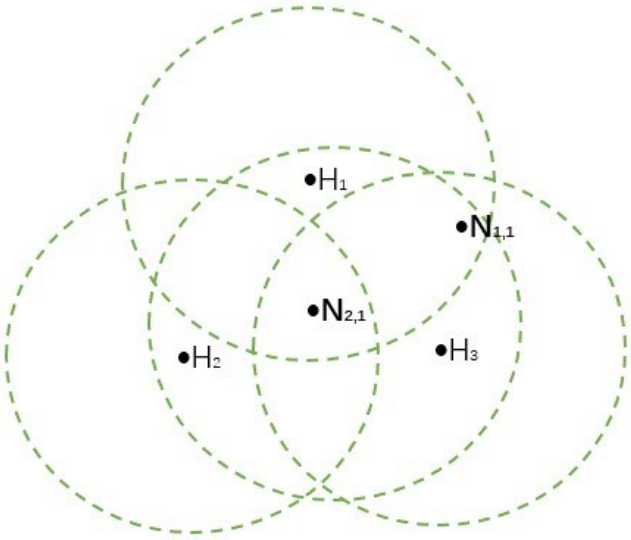


Figure 6. Calculation of the CH degree of nodes.

2. Distance measurement: If nodes have the same cluster head degree, it is necessary to further determine the priority of nodes to be scheduled by using distance measurement D in Formula (9) in Section 3. Because of the smaller $D_{i,CH}$ of the node i, which represents the minimum compromise between channel correlation and the actual distance between nodes and cluster heads, we hope that such nodes can obtain greater priority.

3. Node delay: After the network is clustered, each node collects delay information within its propagation range and broadcasts its position and cluster head information to the network. After receiving the information, the CH creates a general table of the delay information of nodes in its cluster, adjusts its own transmission power based on the farthest location of nodes in the cluster, and broadcasts the delay information table. After receiving the broadcast, all member nodes in the cluster maintain the information state table containing the delay information of all nodes in the cluster locally.

It can be seen from Figure 7 that the CH node schedules the node transmission process according to priority. Suppose that from Node1 to Node4, the CH degrees of the four nodes are 1, 2, 1, and 1. The size relationship of the four nodes in the delay information

table is $T_{Node2,h} < T_{Node1,h} < T_{Node4,h} < T_{Node3,h}$; the size relationship of the four distance measures is $D_{node1,CH} = D_{node2,CH} < D_{node3,CH} = D_{node4,CH}$. At this time, as Node2 has the largest cluster head degree, it obtains the highest sending priority. Node1 and Node4 have the same cluster head degree, but Node1 has a smaller distance metric than Node4. Therefore, Node1 has a higher priority than Node4. Compared with Node3 and Node4, although the cluster head and distance measurements are the same, Node4 is given higher scheduling priority than Node3 because its delay is smaller than that of Node3. In summary, the scheduling priorities of these nodes are in the following order: Node2, Node1, Node4, and Node3. When the cluster head completes the scheduling sequence of nodes through the control package, it enters the data transmission stage.

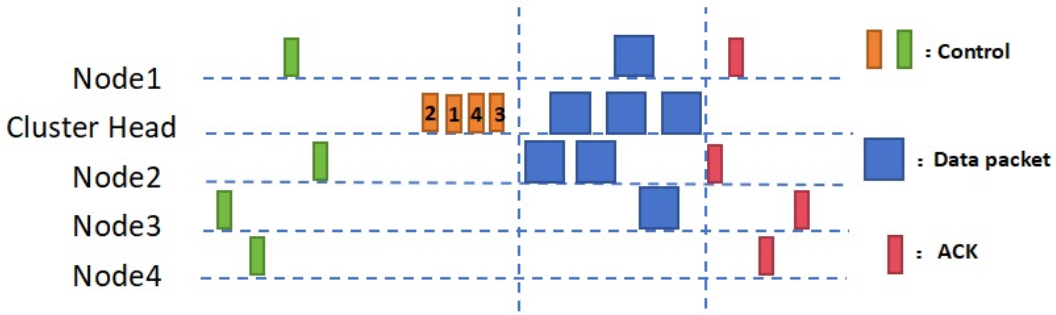


Figure 7. Scheduling priority of the nodes.

5. Simulation and Performance

In this chapter, we use the Aqua-sim-tg simulator based on ns-3, combined with real ocean data, to simulate real ocean scenarios. The specific scenario settings are shown in Figure 8. A random and uniform deployment of nodes is carried out within a 3D cubic area measuring 5*5*6, with the network consisting of a total of 30 to 50 nodes. Each node is equipped with its own location information and a unique id identifier. An energy-unconstrained sink node is strategically deployed on the surface of this area. The weight factor α for the channel correlation distance metric is assumed to be 0.6, the maximum power P_{max} of inter-node communication is 90w, and the node traffic weight is adjustable within the range of $\theta \in (0,1)$. The length of control packets is set at 180 bits, while data packets are 1024 bits in length, and the scheduling period of the cluster head node is 0.07 s. Transmission power can be adjusted to meet the requirements of communication distance. The duration of a single simulation run is established at 12,000 s. The complete parameter settings are presented in Table 1.

Table 1. Simulation parameter.

Parameter	Value
Network size	6000 × 6000 × 6000 (m)
Sink location	(2500, 2500, 6000)
Node size	30 to 50
Data packet size	1024 bits
Control packet size	180 bits
Modulation mode	bpsk
Transmission rate	1 kbps
Transmission bandwidth	10 kHZ

Table 1. *Cont.*

Parameter	Value
Carrier frequency	20 kHZ
E_1	80 nJ/bit
Transmitter power	2 to 90 w
E_2	30 nJ/bit
η	0.65
α	0.6
θ	0 to 1
Simulation time	12,000 s

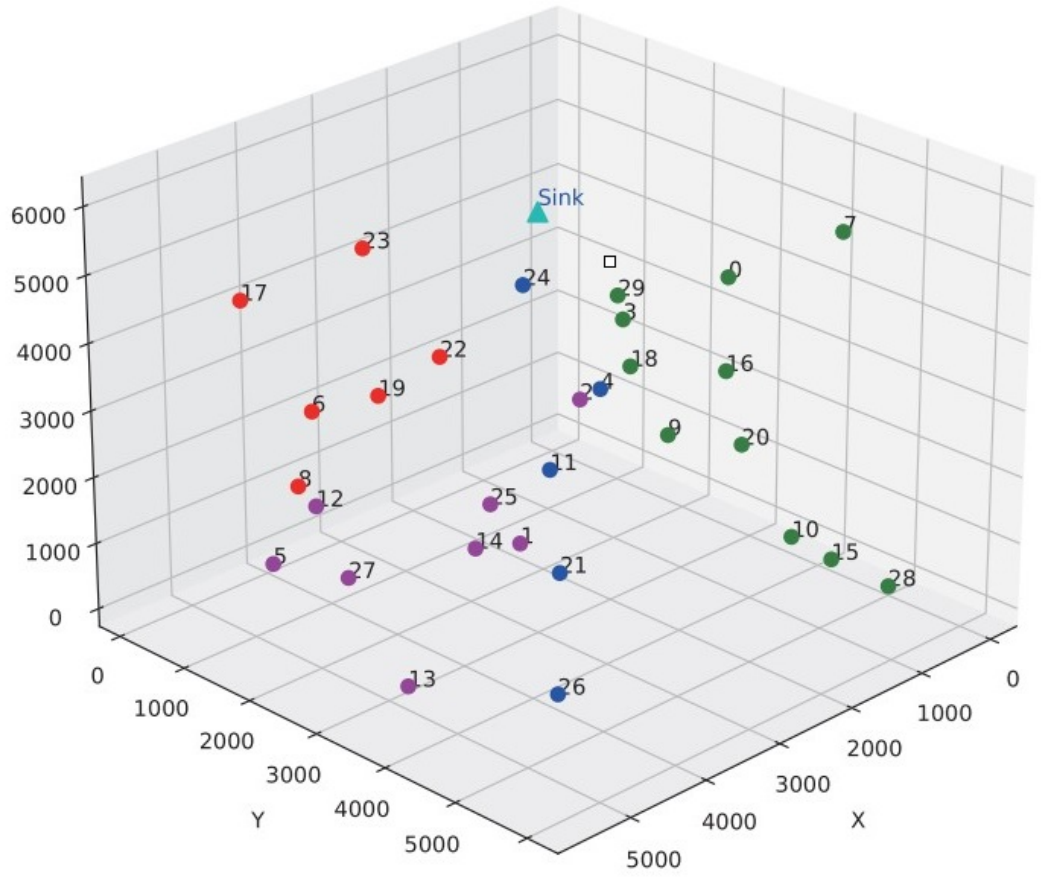


Figure 8. Network topology scenario.

5.1. Comparison of User Clustering Algorithms

Here, we first verify the effectiveness of the proposed clustering algorithm in terms of performance indicators such as throughput and power consumption, and compare and analyze three algorithms: elbow method clustering (EC) [28] based on distance measurement, the random clustering algorithm (RC) [29], and the APCC clustering algorithm proposed in this paper. The throughput in Figures 9 and 10 below is normalized.

As shown in Figure 9, at the beginning, due to the very low traffic in the network, the three protocols show almost the same throughput. However, as the network load increases, the throughput of the EC algorithm gradually exceeds that of the RC algorithm. This is because the RC algorithm only clusters randomly without considering the impact of the underwater channel environment on the nodes between clusters, requiring higher transmission power to avoid interference caused by the lack of correlation in channel classification. The EC algorithm classifies user nodes using distance measurement, effectively

reducing intra-cluster interference. However, the EC algorithm does not further control the transmission power of the nodes in the cluster, so the communication quality needs to be improved by sacrificing the transmission rate to avoid the interference between nodes.

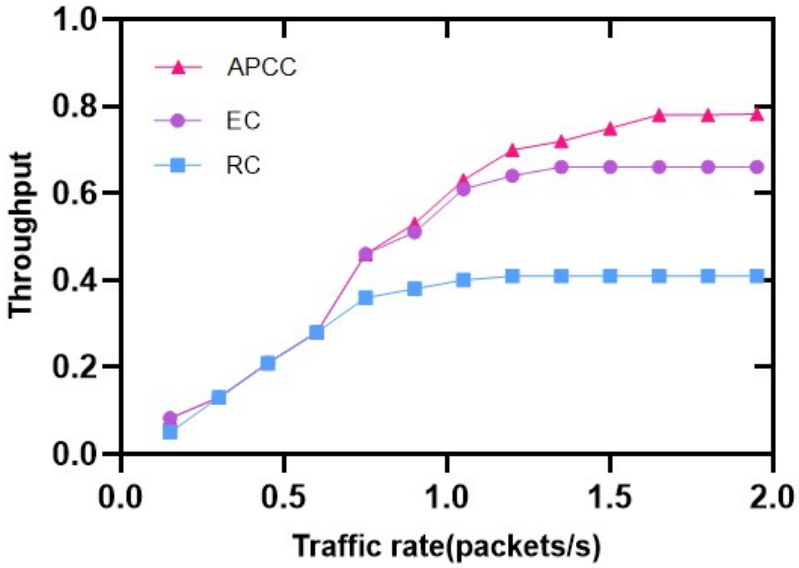


Figure 9. Throughput of users under different clustering protocols.

In the APCC algorithm, the node energy consumption of the whole network is balanced by clustering through an inter-node game. Based on the clustering network and the distance measurement of channel correlation, the cooperative game algorithm proposed in the literature [26] is used in each cluster to control the power of the member nodes in the cluster, thus further reducing the power consumption of the nodes. Therefore, as shown in Figures 9 and 10, with the increase in network traffic, the performance of the clustering algorithm proposed in this paper, such as throughput and energy consumption, is superior to the other two algorithms.

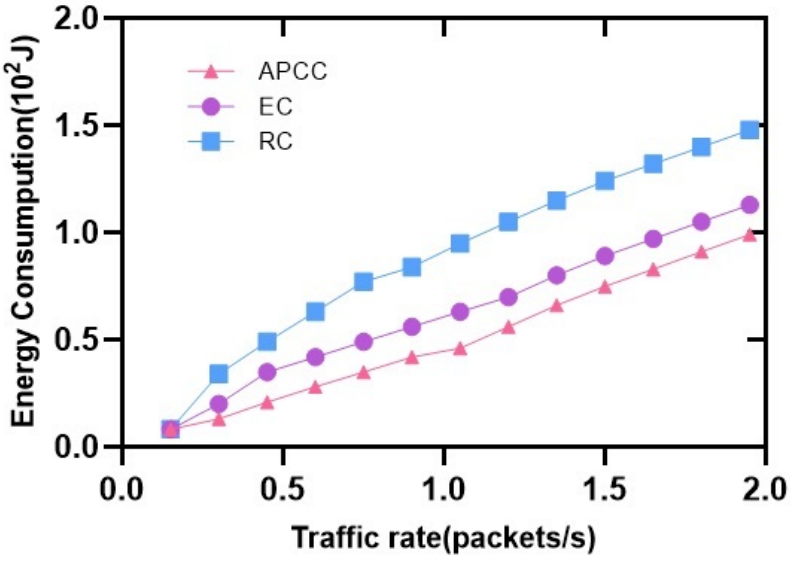


Figure 10. Energy consumption of users under different clustering protocols.

5.2. Throughput Comparison with Other MAC Protocols

Then, we combine the proposed APCC-MAC protocol with a new time slot ALOHA (SA) [14], the PLSS algorithm [16], and the CSS algorithm [9]. Three advanced MAC protocols are compared. As can be seen from Figure 11, the throughput of the SA protocol shows a trend of first increasing and then decreasing. This is because when the network load is low, nodes can efficiently and freely compete to send data, thereby obtaining increasing throughput. However, when the network load increases, more and more nodes compete under the time slot mechanism. This can still lead to increased data conflicts and decreased throughput. PLSS performs better than SA in the process of increasing load due to the time difference field added to the packet. Through the construction of a space–time conflict graph, CSS achieves a throughput slightly higher than the PLSS protocol; however, it does not consider the interference caused by the power size to the node like the APCC protocol, so its throughput is much smaller than the APCC protocol.

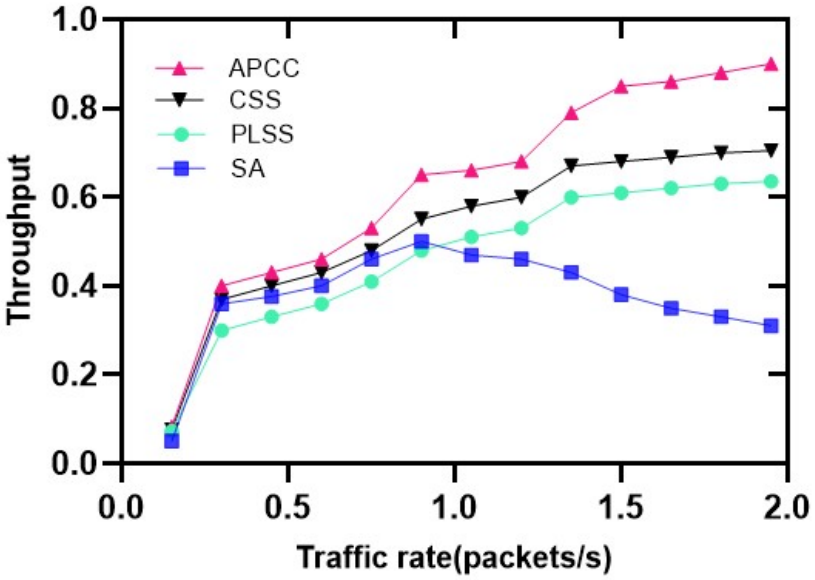


Figure 11. Throughput of different protocols with different number of nodes.

5.3. End-to-End Delay

As shown in Figure 12, PLSS is essentially a scheduling MAC protocol with fixed slot allocation, and the delay increases with the increase in network load. When the network traffic is small, the delay of the SA protocol is also small, but with the increase in network traffic, its delay increases faster than that of the PLSS protocol. This is due to its competition-based mechanism, which causes sending conflicts between packets to increase dramatically as the network load increases. The end-to-end delay changes in the APCC protocol and the CSS protocol are similar, both of which decrease with the increase in the number of nodes. This is because both of them adopt the method of intra-cluster node scheduling and transmission, which results in a decrease in transmission time as network data packets increase. In the case of a small traffic load, the CSS protocol can make every node in the network obtain a conflict-free continuous allocation scheme by constructing a space–time conflict graph to fix the time slot, so its transmission delay is slightly lower than that of APCC-MAC proposed in this paper. However, with the increase in network load, the CSS protocol can reduce the traffic load. This fixed allocation scheme, which has a high degree of correlation with node location, cannot adapt to the dynamic network topology, so its delay is gradually longer than that of the proposed protocol. On the other hand, the priority scheduling algorithm adopted by the APCC-MAC protocol can prioritize the scheduling

and transmission of nodes that are more prone to conflicts on the basis of controlling power, thus reducing the collision of nodes in the cluster to a greater extent, and thus obtaining better performance than the CSS protocol.

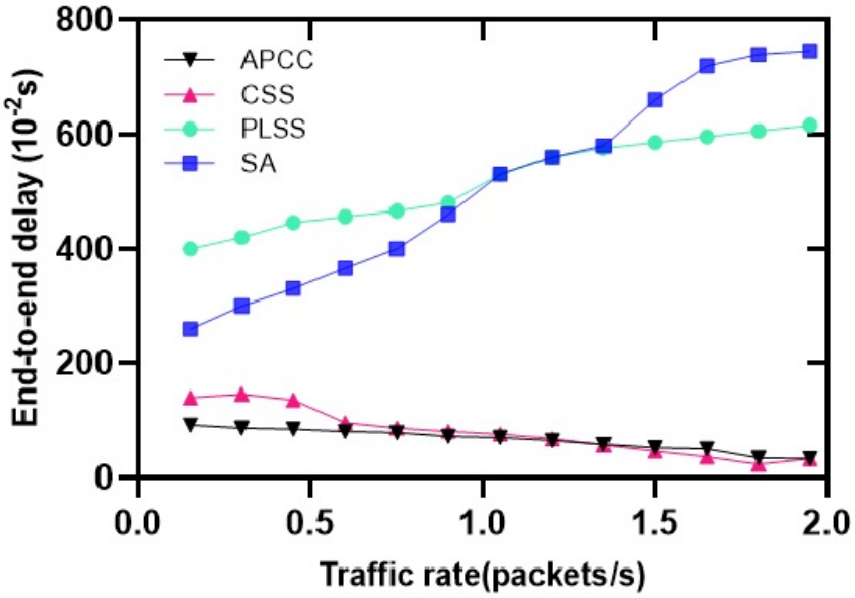


Figure 12. End-to-end delay changes under different loads.

6. Conclusions

UWSNs have limited bandwidth and long delays, which bring great challenges to underwater acoustic networks. To solve the problems of energy limitation and node conflict in underwater acoustic networks, a new APCC-MAC protocol is proposed in this paper. Firstly, an adaptive clustering algorithm based on a non-cooperative game is designed to establish a clustering network that is more suitable for lower-channel communication. Secondly, based on the clustering underwater acoustic network, the transmitting power of nodes under different distance measures is controlled to reduce power consumption and extend the lifetime of the whole network. Finally, on the basis of clustering and power control, the cluster head node dispatches the member nodes to avoid data conflict and reduce the energy consumption of the whole network. Simulation results show that the proposed APCC-MAC protocol has higher throughput, lower energy consumption, and lower latency than existing protocols. However, this paper only verifies the validity of the proposed protocol in a simulation environment.

In future work, the efficiency of the protocol will be further verified by real underwater environment experiments, and the low-level implementation of the protocols will be explained in more detail. Furthermore, more specific presentations of node distance proximity will be considered.

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