

Article

High Value of Information Guided Data Enhancement for Heterogeneous Underwater Wireless Sensor Networks

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Abstract: Ensuring the freshness of high Value of Information (VoI) data has a significant practice meaning for marine observations and emergencies. The traditional forward method with an auv-aid is used to ensure the freshness of high VoI data. However, the methods suffer from two issues: an insufficient high VoI data throughput and random forwarding for cluster heads (CHs). The AUV (Autonomous Underwater Vehicle) with limited energy cannot meet the demand for the random generation of high VoI data. Low VoI data packets compete with high VoI data packets for channels, resulting in an insufficient high VoI data throughput and a low freshness. To address the above issues, we propose the Data Access Channel Scheme based on High Value of Information (DACS-HVOI), which is suitable for prioritizing the transmission packets with a high VoI. First, according to the level of VoI, the packets are divided into K classes, and the packets that are collected and forwarded by the AUV are defined as the highest K+1 class. Second, based on prior knowledge in the network, a Markov chain algorithm-based method is employed to predict which nodes should preferentially use the channel, to avoid conflict between a low and high VoI. Third, based on the stochastic fluid theory, a multilevel queueing system for CHs are constructed to avoid random forwarding. Last, compared with state-of-art protocols, experimental simulation shows that the proposed scheme has a low latency and high network throughput, while improving the throughput of high-VoI packets and ensuring the priority transmission of high-VoI packets.

Keywords: heterogeneous underwater wireless sensor networks (H-UWSNs); value of information (VoI); stochastic fluid model (SFM); Markov chain; autonomous underwater vehicle (AUV)



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1. Introduction

Inspired by the great success of the Internet of Things (IoT) in the interconnected world, expanding the IoT to underwater scenarios to build intelligent ocean systems is a potential trend [1,2]. The Internet of Underwater Things (IoUT) is defined as a broad network that interconnects underwater environments with digital devices and plays an important role in marine science [3]. Underwater wireless sensor networks (UWSNs) have powerful capabilities and are widely utilized in underwater resource exploration, marine geographic meteorological data collection, earthquake and tsunami disaster prevention, water pollution monitoring, and national defense security [4]. In addition, UWSNs can provide ocean information and offer users the ability to detect and predict events in underwater environments [5,6]. The complex underwater environment makes the position of sensor nodes (SNs) uncertain, the propagation delay too long, the acoustic communication transmission power too large, and battery replacement is not easy [7]. To address these challenges, adding autonomous underwater vehicles (AUVs) to UWSNs can increase the

ocean detection range, reduce the propagation delay, and extend the lifespans of SNs [8]. This network structure with AUVs added to UWSNs is referred to as a heterogeneous underwater wireless sensor network (H-UWSN). As shown in Figure 1, H-UWSNs consist of AUVs that collect data along their tracks in water; SNs deployed in water to collect, receive, and forward data; and sinks on the sea surface that receive and process packets. In H-UWSNs, data share channels between AUVs and SNs and then lead to many collisions.

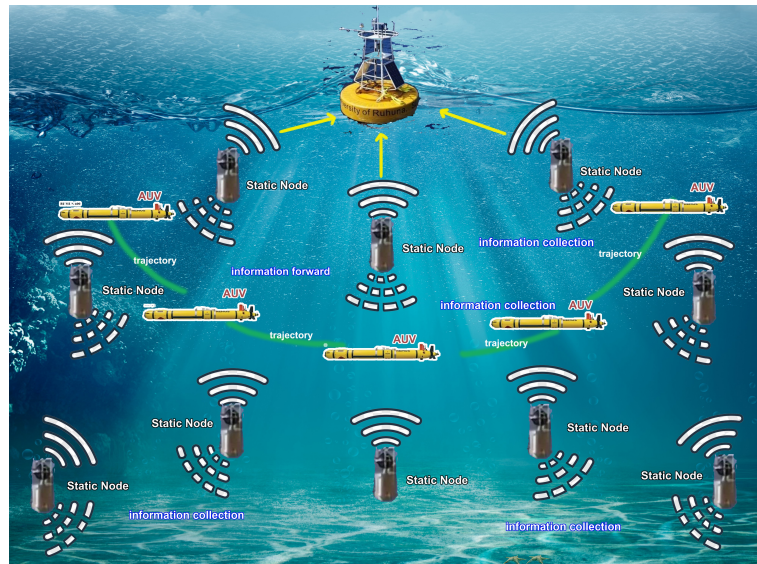


Figure 1. H-UWSNs' architecture.

To meet the needs of large-scale communication and long-term, real-time monitoring, the medium access control (MAC) protocol is crucial in building the IoUT. In H-UWSNs, the MAC protocol provides fair and effective access rules for acoustic channels for AUVs and SNs [9], ensuring the orderly transmission of collected data. However, compared to MAC protocols in terrestrial wireless networks, underwater communication environments are very complex and face many challenges, such as a limited bandwidth, high energy consumption, high transmission loss, multipath effects, high latency, and the Doppler frequency shift [9]. Therefore, many studies have designed various MAC protocols that are suitable for underwater environments to address these challenges. However, most researchers still focus on improving traditional network metrics, such as increasing throughput, reducing energy consumption, and increasing channel utilization and the packet delivery rate, without paying attention to the timeliness of transmitting data with a high value of information (VoI) [10–12]. It is more important to pay attention to data transmission due to the significance of VoI.

Since Qiu et al. [13] proposed the IoUT, researchers have realized that the data transmitted to researchers should have high value and be fresh. For example, Wang and Wu [14] designed a trajectory scheduling algorithm for AUVs in IoUTs and proposed optimized scheduling that minimizes the total time of surfacing for information collection so that the data collected by AUVs can be analyzed and utilized by researchers earlier. Khan et al. [15] considered the time needed for information collected from AUVs to reach ground stations and designed a traversal algorithm to improve the overall data freshness. Fang et al. [16] proposed using the Age of Information (AoI) metric to measure data freshness and established an M/G/1 vacation queueing model to describe and optimize data freshness in the IoUT. Based on the AoI measurement, they determined the optimal upper limit of the number of AUVs serving in the system to balance the timeliness of underwater information with the energy consumption of AUVs. The authors also proposed an algorithm that adaptively adjusts the upper limit of queue length to ensure data freshness. VoI is an indicator that describes the value of information collected in oceanographic surveys. Yan et al. [11] defined VoI as a linear combination of importance and timeliness. Gjanci et al. [17] pro-

posed a greedy adaptive navigation algorithm for identifying AUV paths that considers a heterogeneous model with decaying VoI. Duan et al. [18] analyzed a hierarchical data collection problem for which they optimized AUV paths to maximize participation in VoI scenarios and defined a more realistic enhanced VoI model. Liu et al. [19] established a VoI model that describes the relationship between data importance and timeliness, linking two modes of data collection: AUV collection and multihop routing transmission, based on a classification mechanism that is based on VoI. This paper designs the Data Access Channel Scheme based on the High Value of Information (DACS-HVOI) protocol, which is suitable for H-UWSNs, to transmit data packets with a high value and high freshness.

The main contributions of this article are summarized as follows:

(1) Packets collected and forwarded by the cluster member nodes (CMs) are divided into K classes, and the packets collected and forwarded by the AUV are defined as the highest $K+1$ class. The highest VoI packets in clusters are predicted based on the historical distribution of CMs' collected-forwarded packets, and the channel over the CMs are prioritized with the highest VoI packet. This method effectively schedules the priority use of channels for high VoI packets, improves the throughput of high VoI packets, and ensures the freshness of high VoI packets.

(2) We proposed a multilayer queueing model based on the Stochastic Fluid Model (SFM) for the discrete-continuous feature of packets to collect and forward. Then, we infer the waiting time for different VoI packets to be forwarded. When waiting for CHs to forward high VoI packets, CMs that only forward higher VoI packets can use the channel to forward packets. This method avoids the situation where low VoI packets cannot be forwarded by CHs in time but access the channel, effectively improving the throughput of high VoI packets and ensuring the freshness of high VoI packets.

(3) Many experimental simulations, compared with the state of the art, show that our proposed DACS-HVOI protocol has a high throughput, low latency, and low energy consumption in H-UWSNs and can transmit the packets collected by the AUV and the high VoI packets collected by SNs to the sink node as soon as possible, better preserving the freshness and value of high VoI packets.

The remainder of this article is organized as follows: in Section 2, we introduce some works related to underwater MAC protocols and data collection in recent years. The DACS-HVOI is presented in Section 3. The simulation and performance analyses are shown in Section 4. In Section 5, we conclude this article and provide future research directions. Some important symbols used in this article are given in Table A1.

2. Related Work

The MAC protocol is a sublayer protocol of the link layer. The main purpose of this protocol is to prevent collisions when multiple nodes send packets on the same channel while fully utilizing channel spectrum resources for data transmission. The main function of underwater MAC protocols is to achieve a reasonable distribution of acoustic channels, allowing multiple nodes to share the same channel without conflict [20]. TDMA [21] is a widely utilized, noncompetitive underwater MAC protocol. The idea behind this protocol is to divide time into multiple slots, with each node being assigned a slot for packet transmission. SNs in the network can only transmit data during their assigned slots and enter sleep mode during other slots. However, TDMA requires strict clock synchronization, which is difficult to achieve in large-scale UWSNs, so its use in practical underwater tasks is limited. The ALOHA protocol [22] is a simple, random access-based, competitive MAC protocol and one of the earliest and most typical MAC protocols. In this protocol, all nodes send data immediately after collecting them. As a result, packet collisions are likely to occur when using this protocol, especially when the network load increases. Molins and Stojanovic [23] proposed a handshake-based, competitive FAMA protocol that uses short control packets to compete for channel access before sending data and sends all messages at the beginning of slots. This protocol avoids packet conflicts and improves network performance. However, this protocol only allows one node to send data during

a handshake cycle, so its channel utilization is not high. Chen and Xie [24] proposed a prescheduling-based MAC protocol in which nodes with packets to transmit reserve the channel at the reservation node and the master node schedules packet transmission times based on propagation delays between two nodes. This protocol also considers time and space uncertainty to solve control packet collision problems. Zhuo et al. [25] proposed adaptive scheduling media access control (DQA-MAC) based on delay and queue awareness. This protocol schedules packet transmission times based on propagation delay information and the number of packets waiting in each node's queue. Su et al. [26] proposed a dynamic channel negotiation MAC mechanism (DCN-MAC) for underwater acoustic sensor networks that accepts packets in the queue form initiated by receivers. This mechanism treats multinode conflict problems as Nash equilibrium equations in non-cooperative games with incomplete information. All these protocols have long handshake cycles, which render them inefficient for handshaking and affect the network performance. Dong et al. [27] proposed a UWSN random handshake MAC based on the Nash equilibrium equation. In the RTS stage, this mechanism considers competition behavior among nodes, sending control packets as an incomplete information game for channel access rights using the Nash equilibrium equation.

Recently, the timeliness of high-value information in large-scale underwater communication has attracted increasing research interest. Cheng and Li [28] divided ocean areas into layers and transmitted data to different layers according to their importance. In this way, important information is transmitted to shallower layers and can be collected earlier. Some studies have introduced a concept referred to as the VoI (Value of Information) to describe the performance of submitting time-sensitive data. Yan et al. [11] defined the VoI as a linear combination of importance and timeliness and solved the path planning problem. Gjanci et al. [17] proposed a greedy adaptive navigation algorithm to identify AUV paths that considers heterogeneous models with VoI decay. However, due to inevitable long paths, this method is only suitable for data collection in sparse networks. Han et al. [29] designed a partition-based data collection scheme that divides the area into multiple quality regions using Tyson polygons and deploys AUVs in each partition. Then, the authors added packet concentration to VoI. However, the scheme does not directly reflect the correlation between data importance and VoI decay rate. Duan et al. [18] investigated a hierarchical data collection problem by optimizing AUV paths to maximize the residual VoI while defining a more realistic enhanced VoI; however, it is difficult for a single AUV to complete tasks in large-scale areas. Based on Han et al.'s and Duan et al.'s problems, Liu et al. [19] applied the VoI to measure decaying data values determined by historical abnormal data while using the VoI to describe the relationship between the detection data importance level and its timeliness. The authors also proposed a classification mechanism based on the VoI that connects two underwater data collection modes: multihop routing transmission and AUV-collected data. The multihop routing transmission problem is solved by the routing protocol proposed by their research, while the AUV-collected data problem is modeled as a variant of the traveling salesman problem (TSP). Although this method can effectively transmit data between AUVs and static networks in two communication modes, it is difficult for an already deployed running static network for an AUV to directly join. The limitations of existing underwater MAC protocols are given in Table A2.

To summarize the shortcomings of existing research, this paper proposes a heterogeneous network MAC protocol named DACS-HVOI, which is suitable for the coexistence of AUVs with static nodes that allows AUVs and static nodes to communicate with relay nodes using the same competitive channel rules. The protocol schedules the order of packets sent by different nodes based on the difference in VoI, giving priority to the transmission of high-VoI packets and maximizing the freshness of high-value data.

3. DACS-HVOI Design

3.1. Definition of VoI

Some researchers have applied the relevant criteria of VoI to underwater data transmission research [11,30,31]. However, the relationship between the importance and value decay rate of these research data is not intuitively reflected. Duan et al. [18] proposes a data VoI calculation and decay model. The author uses the tsunami warning system as an example. Tsunamis often occur with submarine earthquakes. If the ground control center receives earthquake warning information within tens of seconds, the damage caused by severe tsunamis will be greatly reduced. Compared with most conventional time-collected wave amplitudes, the wave amplitude collected during an earthquake becomes very large. Therefore, this study concludes that the larger the observed seismic wave amplitude is, the higher the possibility of an earthquake occurrence, and the more important the information. Based on this conclusion, a calculation method of data VoI is extended: data with high anomalies are more valuable than normal data, and their value decays are more severe. Specifically, this study proposes to determine the continuous distribution of VoI data by historical record distribution rather than domain knowledge annotation. The smaller the historical occurrence probability of data is, the greater its VoI and the easier its value decays. We assume that the average value and standard deviation of the data collected by nodes in history are represented by μ_j and σ_j , respectively, and that Q_{ij} is the i th data collected by node j . $E(Q_{ij})$ is used to reveal the expected anomaly of Q_{ij} , as shown in (1).

$$E(Q_{ij}) = \frac{1}{\sigma_j \sqrt{2\pi}} \int_{-\infty}^{\mu_j + Q_{ij} - \mu_j} e^{-\frac{(q - \mu_j)^2}{2\sigma_j^2}} dq, \quad (1)$$

where q is the integral variable. According to the calculation method in (1), the abnormal expectation value domain of Q_{ij} is obtained as [0.5, 1]; the closer its value is to 1, the greater the abnormality and the more important the data.

However, continuous VoI values have problems such as a high computational cost, storage difficulty, and weak robustness, and data are transmitted in the form of discrete packets in H-UWSNs. Therefore, this paper discretizes the VoI methods proposed by [19]. For simple processing, we discretize the VoI of the SN range of $E(Q)$ into K classes. Because AUVs have a limited energy consumption and can detect data in the deep ocean that SNs cannot detect, we define that AUVs always collect and forward high VoI data in the ocean and set the data packets collected and forwarded by AUVs to the highest level of $K+1$. Then, we use $E(E(Q))$ to represent the expected value of the discretization of the VoI. The larger $E(E(Q))$ is, the higher the research value, the lower the frequency of occurrence, and the greater the degree of attenuation. Subsequently, we discretize the value range of $E(Q)$ in (1) into $\sum_{E(E(Q_i))=1}^K E(E(Q_{ij}))$ equal parts on average. The higher the value of $E(E(Q))$, the fewer shares it occupies. The probability of different $E(E(Q))$ categories appearing is calculated as shown in (2).

$$P(E(E(Q_{ij}))) = \frac{K+1-E(Q_{ij})}{\sum_{E(E(Q_{ij}))=1}^K E(E(Q_{ij}))}, \quad (2)$$

$$1 \leq E(E(Q_{ij})) \leq K, E(E(Q_{ij})) \in N + .$$

According to the method of (2), we discretize the continuous distribution of the VoI of SNs, and the result of discretization conforms to the inference that the probability of high VoI data packets being collected is low and that the probability of low VoI data packets being collected is high.

3.2. Predicting the Highest VoI Model Based on the Markov Chain Algorithm

In this subsection, we introduce a model to predict the highest VoI data packet of CMs in the cluster. This model is based on the Markov chain algorithm and constructs a VoI transfer matrix based on the historical packet VoI transfer probability collected by SNs. Using this model, SNs can predict the highest VoI packet in the cluster when competing for the channel and make low VoI packets avoid the channel to give priority to the highest VoI packet transmission. All SNs have the priority to forward the packets with the highest VoI in the queue to be forwarded. X_j^t is defined as the VoI of the t th packet collected by node j , the VoI sequence $X_T^j = X_j^1, X_j^2, \dots, X_j^{t-1}, X_j^t$ of the collected packets is defined by node j , and each element value set in $X_T^j, X_T^j \in [0, K]$. The VoI of the packet sequence collected by all CMs in the cluster is set into matrix C_T ; C_T is shown in (3).

$$C_T = \begin{bmatrix} X_1^1 & X_1^2 & \dots & X_1^j & \dots & X_1^n \\ X_2^1 & X_2^2 & \dots & X_2^j & \dots & X_2^n \\ X_3^1 & X_3^2 & \dots & X_3^j & \dots & X_3^n \\ \dots & \dots & \dots & \dots & \dots & \dots \\ X_t^1 & X_t^2 & \dots & X_t^j & \dots & X_t^n \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix}, X_t^j \in E(E(Q_{ij})), \quad (3)$$

where column vectors in matrix C_T represent VoI sequences of packets collected by CMs. Assume that the VoI sequence X_T^j of packets collected by CMs follows the Markov property, that is, the newly collected packet VoI only depends on the previously collected packet VoI, as shown in (4):

$$P^j(X_t^j | X_1^j X_2^j X_3^j \dots X_{t-1}^j) = P^j(X_t^j | X_{t-1}^j), \\ X_t^j, X_{t-1}^j \in E(E(Q_{ij})), \sum_{X_{t-1}^j=1}^K P^j(X_t^j | X_{t-1}^j) = 1 \quad (4)$$

where $P^j(X_t^j | X_{t-1}^j)$ represents the conditional probability distribution of the t th packet VoI to be collected by node j under the condition of collecting the $(t-1)$ th data packet VoI. The probability of X_t^j occurring only depends on X_{t-1}^j and does not depend on the other previously collected data packets VoI. As (5) shows, we define P_{IJ}^j as the transition probability of collecting the next packet VoI as J by node j when collecting the packet VoI as I .

$$P_{IJ}^j = P(X_t^j = J | X_{t-1}^j = I), \\ I, J \in E(E(Q_{ij})), 1 \geq P_{IJ}^j \geq 0. \quad (5)$$

Then, we calculate all VoI transition probabilities of node j according to (5) and use the VoI transfer matrix $P_{collect}^j$ as shown in (6).

$$P_{collect}^j = \begin{bmatrix} P_{11}^j & P_{12}^j & \dots & P_{1J}^j & \dots & P_{1K}^j \\ P_{21}^j & P_{22}^j & \dots & P_{2J}^j & \dots & P_{2K}^j \\ \dots & \dots & \dots & \dots & \dots & \dots \\ P_{J1}^j & P_{J2}^j & \dots & P_{JJ}^j & \dots & P_{JK}^j \\ \dots & \dots & \dots & \dots & \dots & \dots \\ P_{K1}^j & P_{K2}^j & \dots & P_{KJ}^j & \dots & P_{KK}^j \end{bmatrix}, \quad (6)$$

$j \in [1, 2, \dots, n], J \in E(E(Q_{ij})).$

After calculating the VoI transfer matrix of all nodes in the cluster, these matrices and the VoI initial distribution $P_{initial}$ of the corresponding nodes in each CM in the cluster

are stored, and then they are deployed underwater for data packet collection. $P_{initial}$ is obtained from the occupancy of the historical distribution, as shown in (7).

$$\mathbf{P}_{initial}^j = P\left(\frac{num(X_i^j=1)}{num_{total}}, \frac{num(X_i^j=2)}{num_{total}}, \dots, \frac{num(X_i^j=K)}{num_{total}}\right). \quad (7)$$

To ensure the priority transmission of high VoI packets, nodes need to predict the highest VoI packet to be preforwarded in the cluster when using the channel to avoid collisions caused by simultaneously sending the highest VoI packet. The first prediction method is to predict the maximum VoI packet distribution held by the node based on the initial distribution of the VoI of each node. For example, the probability distribution of the initial distribution $P_{initial}^j$ of node j is used to predict the VoI distribution $P_{initial}^j \rightarrow P_{send}^j$ of the node's first preforwarding packet.

When CMs predict the nonfirst preforwarded packets of other CMs in the cluster, there may be multiple collected packets in the queue to be forwarded by CMs that have not been forwarded. When CMs predict the preforwarding packets of other CMs in the cluster, it can be divided into two parts. One part is the highest VoI packet in the queue to be forwarded after the predicted CMs last sent the packet, and the other part is the highest VoI packet that is newly collected after the CMs last sent the packet.

For the first part, the highest VoI packet in the queue to be forwarded after the last packet transmission, this paper defines that CMs know all packets' VoI in the queue to be forwarded and carry the preforwarded packets' VoI value VoI ; the VoI value VoI_{next} of the highest VoI packet in the queue to be forwarded in the request frame. For the second part, the request frame also carries the VoI value VoI_{new} of the latest collected packet. Then, the CHs will carry the VoI_{next} and VoI_{new} information of the node when broadcasting the confirmation frame after receiving the packet so that other CMs in the cluster can predict. For example, node j carries VoI_{next} and VoI_{new} when requesting a channel. After the CHs successfully receive the packet, the broadcast confirmation frame informs other CMs in the cluster with information of VoI_{next} and VoI_{new} . Other CMs in the cluster will predict the VoI of the newly collected data packets of node j in the future according to VoI_{new} . The specific prediction method is shown in (8).

$$\begin{aligned} \mathbf{P}_t^j &= [\mathbf{P}_{collect}^j]^T \cdot \mathbf{P}_{New}^j \\ &= \left[\begin{bmatrix} P_{11}^j & \dots & P_{1J}^j & \dots & P_{1K}^j \\ & & \vdots & & \\ P_{I1}^j & \dots & P_{IJ}^j & \dots & P_{IK}^j \\ & & \vdots & & \\ P_{K1}^j & \dots & P_{KJ}^j & \dots & P_{KK}^j \end{bmatrix}^T \right]^M \cdot \begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix}, \end{aligned} \quad (8)$$

where M represents the number of packets collected by j from the time of the node's last successful transmission of data to the time. As shown in (9), P_{New}^j represents the VoI distribution of data packets collected during the node's last successful transmission of data packets, which is determined as:

$$\mathbf{P}_{New}^j = \begin{bmatrix} P^j(E(E(Q_{ij})) = 1) = 0 \\ \vdots \\ P^j(E(E(Q_{ij})) = VoI_{new}) = 1 \\ \vdots \\ P^j(E(E(Q_{ij})) = K) = 0 \end{bmatrix}, \quad (9)$$

After calculating the VoI distribution of the newly collected packets of the node according to (8), the VoI distribution of the new preforwarded packet of the node is calculated according to the method shown in (10).

$$p_{send}^j = \max\{P_t^j, VoI_{next}\}, \quad (10)$$

To avoid channel preemption by low VoI packets and the highest packet, it is stipulated that CMs can compete for channels when preforwarding data packets with the highest VoI in the cluster, otherwise waiting for other CMs to use the channel. The method to predict the highest VoI packet in the cluster is shown in (11):

$$\mathbf{P}_{\max} = \begin{pmatrix} \prod_{j=1}^n p_{send}^j(E(E(Q_{ij})) = 1) \\ \prod_{j=1}^n \left(\sum_{J=1}^2 p_{send}^j(E(E(Q_{ij})) = J) \right) - \\ \prod_{j=1}^n p_{send}^j(E(E(Q_{ij})) = 1) \\ \vdots \\ 1 - \prod_{j=1}^n \left(\sum_{J=1}^{K-1} p_{send}^j(E(E(Q_{ij})) = J) \right) \end{pmatrix}, \quad (11)$$

where the elements in each row in $\mathbf{P}_{\max}$ represent the probability that the maximum preforwarding VoI predicted by the node is its row value. For example, the element in the first row is the maximum preforwarding VoI predicted by the node and is 1, and the element in the last row K is the maximum preforwarding VoI predicted by the node. Because CMs know their own packet VoI, assuming that the preforwarded packet VoI of node k is I , then it can be determined that $p_{send}^k(E(E(Q_{ik})) = I) = 1$. Otherwise, it is determined that $p_{send}^k(E(E(Q_{ik})) = I) = 0$; the value of $p_{send}^k(E(E(Q_{ik})))$ is substituted into (11), and (12) is updated:

$$\mathbf{P}_{\max} = \begin{pmatrix} 0 \\ 0 \\ \prod_{j=1}^{n-1} \left(\sum_{J=1}^I p_{send}^j(E(E(Q_{ij})) = J) \right) \\ \vdots \\ 1 - \prod_{j=1}^{n-1} \left(\sum_{J=1}^{K-1} p_{send}^j(E(E(Q_{ij})) = J) \right) \end{pmatrix}, \quad (12)$$

The preforwarded maximum packet VoI distribution $\mathbf{P}_{\max}$ of all CMs in the cluster is calculated according to (10), and the maximum VoI value of the preforwarded packet is calculated according to the distribution. The specific method is calculated according to the probability value of each row in $\mathbf{P}_{\max}$. For example, $\mathbf{P}_{\max}$ is calculated by node k as shown in (12). At this time, node k predicts the maximum VoI value of the preforwarded packet and compares it with its own preforwarded packet VoI value. If the predicted maximum packet VoI value is equal to its own preforwarded packet VoI value, it competes for the channel. Otherwise, this round of sleep avoids channels. The brief process of predicting the maximum VoI packet in the cluster is presented in Algorithm 1.

Algorithm 1 Predicting the Highest VoI Algorithm

Input: N (number of CMs in clusters), CM i , CM j , K (classification number of VoI), preforwarded packet VoI I of i , VoI_{next} of j , and VoI_{new} of j

Output: Highest VoI

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1: The historical collection VoI of all CMs is initialized;
2: for each CM  $i$  in  $N$  do
3:   for each CM  $j$  in  $N$  do
4:      $\mathbf{C}_T$  is constructed with the historical collection VoI;
5:      $P_{IJ}^j$  and  $\mathbf{P}_{initial}^j$  are calculated with the historical collection VoI;
6:      $\mathbf{P}_{collect}^j$  is constructed by  $P_{IJ}^j$ ;
7:     if  $t == 0$  then
8:        $P_{initial}^j \rightarrow P_{send}^j$ ;
9:     else
10:      The new packets VoI collect by  $j$  are calculated;
11:       $\mathbf{P}_t^j = [\mathbf{P}_{collect}^j]^T \cdot P_{New}^j$ ;
12:       $P_{send}^j = \max\{P_t^j, VoI_{next}\}$ ;
13:    end if
14:  end for
15:   $\mathbf{P}_{max}$  is calculated with  $\mathbf{P}_{send}^j$  and  $I$ ;
16: end for

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3.3. Build Waiting Time Model Based on the Random Fluids Model

As shown in Figure 2, the underwater environment explored in our research is a multi-clustered H-UWSN composed of an AUV and multiple SNs. The AUV moves to collect data in the ocean, and when it reaches a cluster, it forwards packets to the CHs in the cluster. The CMs in the cluster collect data within the collection range and transmit packets to the CHs in the corresponding cluster. Then, the CHs transmit the received packets to the sink node. When the number of clusters increases, the CH packet transmission efficiency decreases due to the joint competition for the receiving channel of the sink node, and the packets received by the CHs accumulate in the queue CH_L to be forwarded. $X(t)$ is defined as the number of packets present in CH_L. When the number of $X(t)$ is large, CMs continue to transmit packets to CHs, only piling up packets in CH_L. When the CHs forward the high VoI packets to the sink node, the high VoI packets have decayed to the low VoI data over time.

To solve the above problem, this subsection proposes a waiting time model based on the stochastic fluid model (SFM) for different VoI packets [32–34]. Specifically, the process of CHs receiving packets is modeled as a finite-state, continuous-time Markov chain (CTMC)

$\varphi(t)$, the state space of $\varphi(t)$ is $\mathbf{S} = \{1, 2, \dots, m\}$, and when $\varphi = i, 1 \leq i \leq m, r_i = \sum_{l=1}^k r_i^l$

indicates the packet flow rate into CH_L, where r_i^l refers to the packet forwarding rate at which the CH forwards packets with the VoI of l in state i . $\mathbf{R} = \text{diag} \langle r_i \rangle$ represents the CH_L input rate matrix, as shown in (12). The generator matrix of $\varphi(t)$ is defined as $\mathbf{Q} = (q_{ij})_{m \times m}$, where $q_{ij} (i \neq j)$ represents the transfer rate from the state i of CHs to the state j .

$$\mathbf{R} = \begin{bmatrix} r_1 & & & \\ & \bullet & & \\ & & \bullet & \\ & & & \bullet \\ & & & & r_m \end{bmatrix}, \quad (13)$$

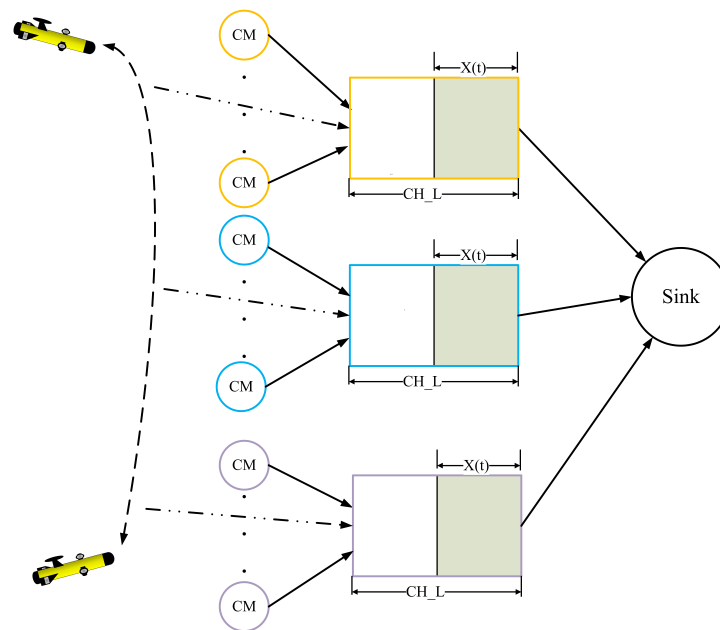


Figure 2. Schematic of CHs queue to be forwarded in H-UWSNs.

The forwarding rate of the CH is mainly determined by the channel quality and the SN number of competing sink node channels. To facilitate processing, assuming that the channel quality is unchanged, the forwarding rate of the CH corresponding to the network environment is determined by the number of clusters. The sending packet rate of the CH is defined as μ ; then, the change process of the packets in CH_L is shown in (13). When the quantity in CH_L is not 0, $X(t)$ changes at the rate of $r_i - \mu$; when $X(t) = 0$ and $r_i > \mu$, $X(t)$ increases at the rate of $r_i - \mu$; otherwise, the data amount remains 0. $X(t)$ and $\phi(t)$ constitute a two-dimensional Markov process $\{X^{(I+)}(t), \phi(t), t > 0\}$ to describe the system process of CH forwarding packets.

$$\frac{dX(t)}{dt} = \begin{cases} r_i - \mu & X(t) > 0 \\ \max\{r_i - \mu, 0\} & X(t) = 0 \end{cases} \quad (14)$$

To calculate the waiting time for incoming CH_L packets to be forwarded, the marked liquid drop method is employed to mark the VoI of the packets. We assume that the VoI of packet A newly arriving at the CH is I . When marking the VoI of A, the total number of packets with $I+$ (VoI greater than or equal to A) in CH_L to be forwarded is defined as $X^{(I+)}(t)$. Before A is forwarded by the CH, packets with VoI $I+$ in CH_L must be forwarded by the CH. While A is waiting to be forwarded by the CH, if the CH receives packets with VoI $(I+1)+$, the CH will forward packets with VoI $(I+1)+$. Therefore, the calculation of time A waits to be forwarded can be divided into two parts. The first part is the time of $I+$ packets that exist in CH_L when A arrives at the CH, and the second part is the time required for $(I+1)+$ packets to be forwarded by the CH when A waits to be forwarded.

For the first part, to calculate the amount of $I+$ packets existing in the CH when marking A, the two-dimensional Markov process $\{X^{(I+)}(t), \phi(t), t > 0\}$ of the CH packet forwarding system is defined, where $X^{(I+)}(t)$ represents the number of packets with $I+$ in CH_L when marking A, the background process is $\phi(t)$, and the state space $\mathbf{S}$ and infinitesimal generator $\mathbf{Q}$ are the same as $\mathbf{S}$ and $\mathbf{Q}$ of $\{X(t), \phi(t), t > 0\}$. The difference is that when $\phi = i$, $r_i^{(I+)}$ represents the rate of $I+$ packets reaching CHs, and $R^{(I+)} = \text{diag} \langle r_i^{(I+)} \rangle$ represents the matrix of $I+$ packet rates when CHs forward packets. The net input rate of $I+$ packets in CH_L is defined as $v_{\phi(t)}^{(I+)}$, which is shown in (14):

$$\frac{dX(t)}{dt} = \begin{cases} r_i - \mu & X(t) > 0 \\ \max\{r_i - \mu, 0\} & X(t) = 0 \end{cases} \quad (15)$$

$\{X^{(I+)}(t), \varphi\} = \{X^{(I+)}(t), \varphi(t), t \geq 0\}$ is a CH packet processing system model with VoI as $I+$ based on the SFM. This model is a two-dimensional Markov process. The horizontal process $X^{(I+)}(t)$ describes the change process of the packet quantity in the CH packet processing system with $I+$. The background process $\varphi(t)$ describes the change in the packet state, which affects the change in the number of packets in CH_L. According to the net input rate $v_{\varphi(t)}^{(I+)}$ of the CH_L packet processing system $(X^{(I+)}(t), \varphi)$, the state space is divided into three disjoint subsets $\mathbf{S} = \mathbf{S}_+ \cup \mathbf{S}_- \cup \mathbf{S}_0$, as shown in (16):

$$\begin{aligned} \mathbf{S}_+ &= \{i \in \mathbf{S}, r_i - \mu > 0\}; \\ \mathbf{S}_- &= \{i \in \mathbf{S}, r_i - \mu < 0\}; \\ \mathbf{S}_0 &= \{i \in \mathbf{S}, r_i = \mu\} \end{aligned} \quad (16)$$

where $\mathbf{S}_+$ includes all conditions that make the packet rate of a CH receiving $I+$ greater than that of the sending packets, $\mathbf{S}_-$ includes all conditions that make the packet rate of a CH receiving $I+$ less than that of the sending packets, and $\mathbf{S}_0$ includes all conditions that make the packet rate of a CH receiving $I+$ equal to that of the sending packets. According to the division of $\mathbf{S}$, the transfer rate matrix $\mathbf{Q}$ and the symbol with the net input rate $\mathbf{V}$ of packets with VoI as $I+$ are divided into blocks as shown in (17) and (18):

$$\mathbf{Q} = \begin{pmatrix} \mathbf{Q}_{++} & \mathbf{Q}_{+-} & \mathbf{Q}_{+0} \\ \mathbf{Q}_{-+} & \mathbf{Q}_{--} & \mathbf{Q}_{-0} \\ \mathbf{Q}_{0+} & \mathbf{Q}_{0-} & \mathbf{Q}_{00} \end{pmatrix}, \quad (17)$$

$$\mathbf{V}^{(I+)} = \begin{pmatrix} \mathbf{V}_+^{I+} & & \\ & \mathbf{V}_-^{I+} & \\ & & \mathbf{0} \end{pmatrix}, \quad (18)$$

where matrix $\mathbf{Q}$ is divided into three-order matrices, and the elements in the matrix are the probability of transition in states $\mathbf{S}_+$, $\mathbf{S}_-$, and $\mathbf{S}_0$ defined in Formula (16). The elements in Formula (17) represent the case in which the net flow rate of packets with $I+$ is greater than 0, less than 0, or equal to 0. Matrix $\mathbf{Q}$ is standardized as $\mathbf{L} = \begin{bmatrix} \mathbf{L}_{++} & \mathbf{L}_{+-} \\ \mathbf{L}_{-+} & \mathbf{L}_{--} \end{bmatrix}$ by [30], which means that the number of packets with $I+$ is not 0. The element values in $\mathbf{L}$ are shown in Formula (19):

$$\begin{aligned} \mathbf{L}_{++} &= \mathbf{V}_+^{I+} \left(\mathbf{Q}_{++} + \mathbf{Q}_{+0}(-\mathbf{Q}_{00})^{-1}\mathbf{Q}_{01} \right) \\ \mathbf{L}_{+-} &= \mathbf{V}_+^{I+} \left(\mathbf{Q}_{+-} + \mathbf{Q}_{+0}(-\mathbf{Q}_{00})^{-1}\mathbf{Q}_{0-} \right) \\ \mathbf{L}_{-+} &= |\mathbf{V}_-^{I+}|^{-1} \left(\mathbf{Q}_{-+} + \mathbf{Q}_{-0}(-\mathbf{Q}_{00})^{-1}\mathbf{Q}_{0+} \right) \\ \mathbf{L}_{--} &= |\mathbf{V}_-^{I+}|^{-1} \left(\mathbf{Q}_{--} + \mathbf{Q}_{-0}(-\mathbf{Q}_{00})^{-1}\mathbf{Q}_{0-} \right) \end{aligned} \quad (19)$$

Then, we use $w^{(I+)}(t, x) = [w_i^{I+}(t, x), i \in \mathbf{S}]$ to indicate the joint density function when the VoI is I , the packet volume is x , and the background state is i when A reaches the CHs. Its stationary density is $w_i^{I+} = \lim_{t \rightarrow \infty} w_i^{I+}(t, x)$, and $w_i^{I+}(t, x)$ is shown in (20):

$$w_i^{I+}(t, x) = \frac{d}{dx} P(X^{(I+)}(t) \leq x, \varphi(t) = i), \quad (20)$$

where $w^{(I+)}(t, x)$ is determined by the differential equation shown in Formula (21), and $p^{(I+)}(t) = [p_i^{(I+)}(t)]$ satisfies a set of differential equations in the boundary state. Equations (22) and (23) are part of one comprehensive equation. When $r_i^{(I+)} \leq \mu$, that is, the input rate is less than the output rate, Equation (22) is satisfied. When $r_i^{(I+)} \geq \mu$,

that is, the input rate is greater than the output rate, $p_i^{(I+)}(t) = 0$ is satisfied. $p^{(I+)}(t) = [p_+^{(I+)}, p_-^{(I+)}]$ satisfies (23).

$$\frac{\partial w^{I+}(t, x)}{\partial t} + \frac{\partial w^{I+}(t, x)}{\partial x} (R^{I+} - \mu) = w^{I+}(t, x) \mathbf{Q}, \quad (21)$$

$$\frac{d}{dt} p_i^{I+}(t) = \sum_{i=1}^m p_i^{I+}(t) q_{ij} - w_j^{I+}(t, 0) (r_i^{I+} - \mu), \quad (22)$$

$$\begin{cases} p_-^{(I+)} \mathbf{U}^{(I+)} = 0 \\ p_-^{(I+)} (1 - 2\mathbf{L}_{-+} (\mathbf{K}^{(I+)})^{-1}) = 1 \end{cases}, \quad (23)$$

where $\mathbf{U}$ is the transfer rate of the downward process of the number of $I+$ packets in the CH, as shown in (24). $\mathbf{K}$ is the transfer rate of the upward process of the number of $I+$ packets in the CH, as shown in (25), and the boundary conditions are shown in (26):

$$\mathbf{U}^{(I+)} = \mathbf{L}_{--} + \mathbf{L}_{-+} \Psi, \quad (24)$$

$$\mathbf{K}^{(I+)} = \mathbf{L}_{++} + \Psi \mathbf{L}_{+-}, \quad (25)$$

$$\begin{cases} p_-^{(I+)} \mathbf{U}^{(I+)} = 0 \\ p_-^{(I+)} \left(1 - 2\mathbf{L}_{-+} (\mathbf{K}^{(I+)})^{-1} \right) = 1 \end{cases}, \quad (26)$$

where $\Psi = [[\Psi]_{ik}]$ represents the probability of arriving at $(0, k)$ for the first time in a finite time from $(0, i)$, and Ψ satisfies the Riccati equation [31,35] shown in (27).

$$\Psi \mathbf{Q}_{-+} \Psi + \mathbf{Q}_{++} \Psi + \Psi \mathbf{Q}_{--} + \mathbf{Q}_{+-} = 0, \quad (27)$$

The second part is utilized to calculate the packet forwarding time when VoI is I in the newly entered CH while A is waiting for the CH to forward I . Γ is defined as the random variable of the time when A waits to be forwarded by CHs. Combined with the stationary density calculated in Part 1, the probability distribution of the total waiting time of A is calculated as shown in (28):

$$P(\Gamma < T) = \int_0^\infty \omega^{(I)}(x) G^{((I+1)+)}(T, x) dx, \quad (28)$$

where $G^{((I+1)+)}(T, x)$ is the distribution where the number of incoming CHs of the packets with the VoI in the second part is x and reaches 0 for the first time. The calculation method is expressed as follows (32):

$$\begin{aligned} G^{((I+1)+)}(T, x) = \\ P\left(\tau^{(I+1)+} < T, \varphi(t) = j \mid W^{((I+1)+)}(0) = x, \varphi(0) = i\right), \end{aligned} \quad (29)$$

where $\tau^{((I+1)+)} = \inf(t > 0 : X^{(I+1)+}(t) = 0)$ refers to the time when the number of $(I+1)+$ packets reaches 0 for the first time.

In summary, we can calculate the probability distribution of waiting time when a packet with VoI enters the CH. After receiving the packet, the CH broadcasts the confirmation frame to inform the CMs in the cluster. The CMs calculate the waiting time according to the probability distribution of the waiting time of the packet. During the waiting time, data cannot be transmitted to the CHs. Algorithm 2 details the implementation process of this part.

Algorithm 2 Waiting time of CHs forward packets time algorithm

Input: N (number of CMs in clusters), M (number of clusters in H-UWSNs), CM_j , A (packet received by CHs), I (VoI of A), K (classification number of VoI), $NUM_{(I+)}$ (number of packets in C_T when A arrives at CHs)

Output: waiting time T

```

1: Initialize  $\lambda$  (Packet transfer rate of CMs),  $\lambda_{AUV}$  (Packet transfer rate of AUV),  $\mu$  (Packet
   transfer rate of CHs);
2: for each  $j$  in  $N$ : do
3:   while packets with  $I$  received by CHs do
4:      $\{X^{(I+)}(t), \varphi\} = \{X^{(I+)}(t), \varphi(t), t \geq 0\}$  is constructed;
5:      $v_{\varphi(t)}^{(I+)}$  as  $\lambda$ ,  $\lambda_{AUV}$ , and  $\mu$  is calculated;
6:      $S$  is divided into  $S_+ \cup S_- \cup S_0$ ;
7:     Rate matrix  $Q$  and the symbol with net input rate  $V^{(I+)}$  are transferred;
8:     if  $V^{(I+)} > 0$  then
9:        $U^{(I+)} = L_{--} + L_{-+}\Psi$ ;
10:    else
11:       $K^{(I+)} = L_{++} + \Psi L_{+-}$ ;
12:    end if
13:     $p^{(I+)}(t)$  as (21)–(23) are calculated;
14:     $G^{((I+1)+)}(T, x)$  are calculated as (29);
15:    Distribution of waiting time  $P(\Gamma < T)$  is calculated as (28);
16:     $T$  is returned as  $P(\Gamma < T)$ ;
17:   end while
18: end for

```

3.4. Complete Process of the DACS HVOI Protocol

This subsection introduces the complete process of the DACS-HVOI protocol, as shown in Figure 3. This paper defines that all SNs in the network have priority in forwarding packets with the highest VoI in the queue to be forwarded and that packets with the same VoI are forwarded in the order of FCFS (First Come First Send). According to the classification method of VoI introduced in III, B, the data packets collected by SNs are divided into Class K VoIs, and the data collected by AUVs are defined as the highest $K+1$. After the node is successfully deployed underwater, the SNs collect data at an acquisition rate of λ at a fixed location, and the AUV moves along the track and collects data at an acquisition rate of λ_{AUV} . After SNs collect the data packets, it is necessary to predict whether the preforwarded data packet is the highest VoI value packet in the cluster. If the packet is the highest, it sends the UW-REQ frame to the CH to request the channel; otherwise, it sleeps and gives way to CMs with high VoI data in the cluster.

After the CHs receive the first UW-REQ frame, to ensure channel utilization, fairness, and high VoI packet priority transmission, the CH does not temporarily reply to the UW-REQ frame but enters phase $UW - REP_SD$, as shown in (30). In phase $UW - REP_SD$, the CHs continuously receive the UW-REQ frames that propagate in the channel. After the end of phase $UW - REP_SD$, the CHs broadcast a scheduling frame, which carries the reply to all UW-REQ frames received in phase $UW - REP_SD$ and the transmission order of the corresponding CMs. The sending order is sorted according to the VoI. If there are multiple packets with the same VoI, they are sorted according to the FCFS principle.

$$UW - REP_SD = 2PD_{MAX} - PD_{first} + 2T_{contr}, \quad (30)$$

where PD_{MAX} is the maximum propagation delay of the CHs and $2PD_{MAX}$ is the sum of the maximum propagation delay of the UW-ACK frame sent by the CH and the maximum propagation delay of the UW-REQ frame received by the CHs. PD_{first} is the propagation delay of the first UW-REQ frame received by the CHs in the channel, T_{contr} is the transmission delay of the control frame, and $2T_{contr}$ is the sum of the transmission delays of the

UW-ACK frame sent by the CH and the UW-REQ frame sent by the CMs. According to the calculation method of $UW - REP_SD$, all CMs in the cluster have the opportunity to compete for the channel within the propagation range of CHs.

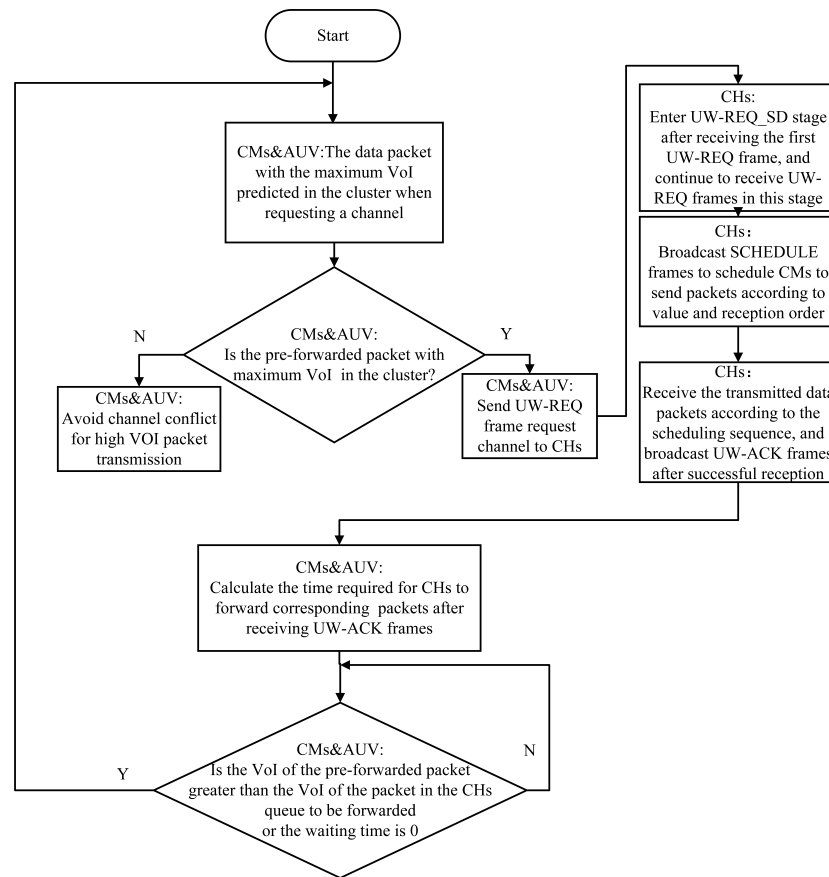


Figure 3. DACS-HOVI working flow chart.

After receiving the scheduling frame, the CM in the first order sends the data packets to the CHs, the CM in the second order waits for the CHs to receive the first packet and returns the confirmation frame UW-ACK to send the packets, etc., until all the packets are sent according to the transmission order. A complete transmission process is shown in Figure 4.

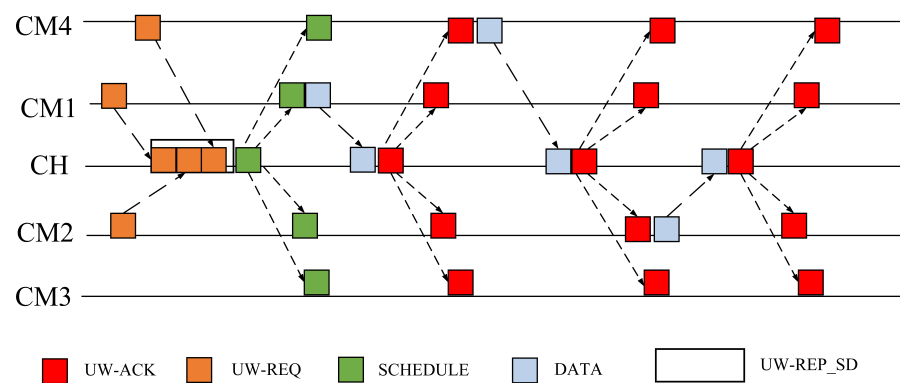


Figure 4. Schematic of request scheduling sending confirmation process.

CM1, CM2, and CM3 send the UW-REQ frame request channel to the CH in the competition round. Because CM1 is closest to the CH, the UW-REQ frame sent by CM1 first reaches the CH, and the CH enters $UW - REP_SD$ after receiving the UW-REQ frame sent

In this section, we use simulation experiments to evaluate the performance of different MAC protocols underwater. The simulation experiments are based on the Aqua-sim [11]

underwater sensor network extension package for the NS2 network simulation simulator. Table A3 lists the experimental simulation parameters and their default values.

Each SN in this paper has a unique ID and limited energy. The AUV collects and forwards data packets along its trajectory and transmits the collected data packets to the CHs in each cluster when it passes through. The simulation ends when the sink successfully receives 1000 data packets. We assume an ideal channel with no data errors caused by the channel environment during data transmission. We simulate and analyze our proposed DACS-HVOI protocol with three other protocols, TDMA [21], UW-ALOHA [22], and RHNE-MAC [28], in simulation environments with different numbers of nodes or clusters and compare the effects of these four protocols on the throughput, average end-to-end delay, average energy consumption, throughput of high VoI packets, and the residual value of packet VoI.

(1) Throughput

Throughput refers to the total amount of data that the network can transmit in a unit of time, reflecting the data load capacity of the entire network, calculated as shown in (31).

$$\text{Throughput} = \frac{\text{Packets}_{\text{num}}}{T_{\text{total}}}, \quad (31)$$

where $\text{Packets}_{\text{num}}$ refers to the total number of data packets received by the sink node and T_{total} refers to the total running time of the network.

(2) Average end-to-end delay

Delay refers to the average time that it takes for data packets successfully received by the sink node to travel from the sending node to the receiving node. The calculation method is shown in Formulas (32) and (33).

$$\text{Delay}_{\text{total}} = \sum_{i=1}^{1000} (\text{Delay}_{\text{tran}}^i + \text{Delay}_{\text{prop}}^i + \text{Delay}_{\text{queue}}^i + \text{Delay}_{\text{proc}}^i), \quad (32)$$

$$\text{Delay} = \frac{\text{Delay}_{\text{total}}}{\text{Packets}_{\text{num}}}, \quad (33)$$

where $\text{Delay}_{\text{tran}}^i$, $\text{Delay}_{\text{prop}}^i$, $\text{Delay}_{\text{queue}}^i$, and $\text{Delay}_{\text{proc}}^i$ refer to the transmission delay, propagation delay, queuing delay, and processing delay, respectively, of the data packet received by the sink node. $\text{Delay}_{\text{total}}$ is the total delay of all data packets received by the sink node, and $\text{Packets}_{\text{num}}$ is the total number of data packets received by the sink node.

(3) Average energy consumption

Energy refers to the average energy consumption of packets successfully received by the sink node, which reflects the energy consumption of the network to successfully transmit and send unit packets. The calculation method is shown in (34).

$$\text{Energy} = \frac{\text{Energy}_{\text{total}}}{\text{Packets}_{\text{num}}}, \quad (34)$$

where $\text{Energy}_{\text{total}}$ refers to the total energy spent by the network to receive data packets and $\text{Packets}_{\text{num}}$ is the total number of data packets received by the sink node.

(4) Throughput of high VoI data

We use $\text{Throughput}_{\text{VoI}}$ to reflect the throughput of high VoI data. The calculation method is shown in (35) and (36).

$$\text{VoIRank} = \frac{\text{VoI}_{\text{total}}}{\text{Packets}_{\text{num}}}, \quad (35)$$

$$\text{Throughput}_{\text{VoI}} = \text{Throughput} \times \text{VoIRank}, \quad (36)$$

where $\text{VoI}_{\text{total}}$ refers to the total VoI of data packets sent by SNs and $\text{Packets}_{\text{num}}$ is the total number of packets received by the sink node. *VoI Rank* refers to the average VoI of packets received by the sink node.

(5) Residual Value of Information

We use $V_{residual}$ to represent the remaining value of information, as shown in (37) and (38), which refers to the remaining value of the initial data value collected by the AUV and SNs after being transmitted to the sink node. $V_{residual}$ reflects the degree of attenuation of different value data after being collected in H-UWSNs.

$$V(Q) = 2E(Q) - 1, Q \in [0, 1], \quad (37)$$

$$V_{residual} = V(Q)(1 - \xi E(Q))^{t_{col}}, \xi \in (0, 1), \quad (38)$$

where $E(Q)$ represents the value of the data packet transmission information collected by SNs, which indicates the importance of the data packet. $V(Q)$ is the initial value of the VoI of the data packet collected by the node, ξ is an adjustable parameter, and t_{col} is the time needed for the information to be collected from the initial node to the sink node to receive it.

4.2. Results and Analysis

Figure 6 shows the comparison of the impact of four MAC protocols on the network throughput. The basic principle of the UW-ALOHA protocol is to send the packet immediately after it is collected. The protocol should have the maximum throughput. However, in the actual process, as the number of nodes increases, the collision rates increase, and the number of retransmissions increases, resulting in an increase in time consumption and a decrease in throughput. Therefore, the performance in the two experiments is the worst. The TDMA protocol allocates fixed time slots for nodes, so with an increase in the number of nodes, the number of packets sent per unit time is similar. However, if the nodes do not send data in the allocated time slots, the time slots will be wasted. Therefore, the throughput under both experimental conditions is relatively poor, only compared with the UW-ALOHA protocol. In contrast, the throughputs of RHNE-MAC and DACS-HVOI proposed in this paper are better. These two protocols are based on handshaking; although they increase the number of control packets, they use scheduling mechanisms to better utilize the channel during transmission. In particular, they consider reducing the occurrence of request frame collisions in the handshake phase, thereby reducing the retransmission of control packets in the channel and improving the channel utilization compared to the traditional handshake protocol. The simulation results show that when the number of CMs in the clusters is small, the throughput of the RHNE-MAC protocol is higher because the protocol competes for the channel by avoiding control packet collisions. When the number of CMs is small, the probability of control frame collisions is very low, so using this protocol does not have to consider the problem of control frame collisions and can fully utilize the channel. However, when there are more nodes in the network, the probability of control packet collisions increases. The CMs in the RHNE-MAC protocol consider the problem of control frame collisions, and the throughput is similar to that of DACS-HVOI proposed in this paper. Therefore, we conclude that DACS-HVOI not only can forward high VoI packets with priority but also has a close throughput compared with the current advanced MAC protocols in networks with more nodes and can efficiently use the channel.

Figure 7 shows the comparison of four MAC protocols affecting the average end-to-end delay. UW-ALOHA does not need to send control packets, and the collected packets are directly transmitted. Therefore, this protocol performs best under both experimental conditions. TDMA allocates fixed time slots for nodes. With an increase in the number of nodes, each node needs more delay to send packets to the receiving nodes. Therefore, the average end-to-end delay of the protocol is the longest under both experimental conditions. Both RHNE-MAC and DACS-HVOI are handshake-based protocols, which will cause an increase in control packets; thus, they have a higher delay than the UW-ALOHA protocol. However, in the transmission process, these two protocols efficiently use the channel, and the delay is significantly lower than TDMA without the use of control frames. RHNE-MAC has a slightly lower delay than the DACS-HVOI protocol in both simulation

environments because the RHNE-MAC protocol has a shorter waiting time for forwarding data packets to CHs, and while using the DACS-HVOI protocol, low VoI packets wait for a long time at CHs to be forwarded, which makes the average delay higher than that of the RHNE-MAC protocol. Overall, the DACS-HVOI protocol has a slightly higher average end-to-end delay than RHNE-MAC, but the slightly higher end-to-end delay is mainly caused by prioritizing the transmission of high VoI packets, which leads to an increased delay for low VoI packets.

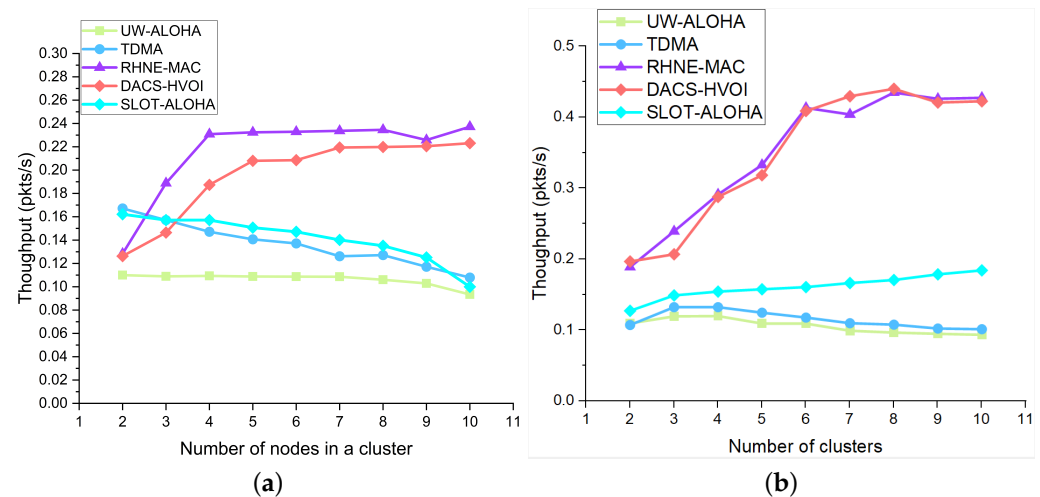


Figure 6. Comparison chart of four protocols affecting throughput. (a) Comparison chart of throughput affected by different numbers of CMs in clusters. (b) Comparison chart of throughput affected by different clusters' numbers.

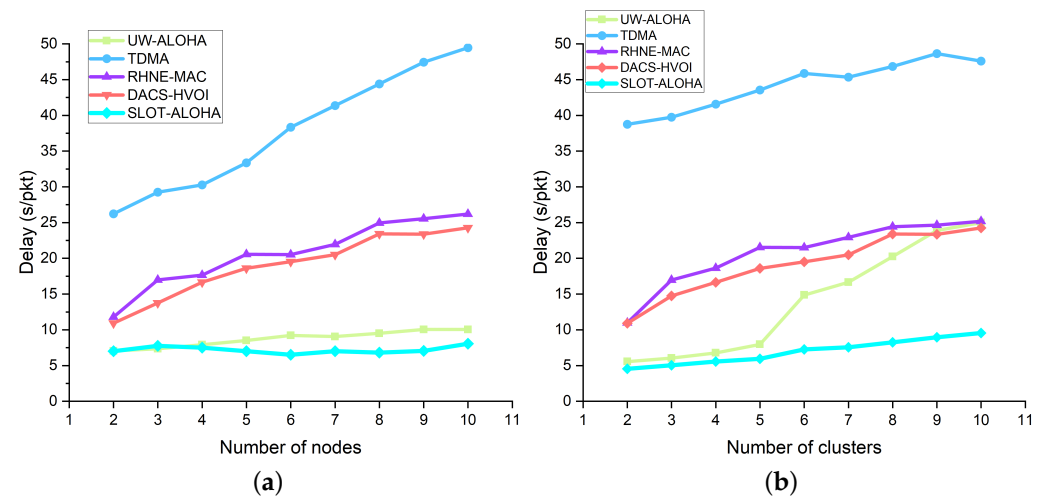


Figure 7. Comparison chart of four protocols affecting delay. (a) Comparison chart of delay affected by different numbers of CMs in clusters. (b) Comparison chart of delay affected by different clusters' numbers.

Figure 8 shows a comparison of four MAC protocols that affect the average energy consumption. When the UW-ALOHA protocol is utilized, the packet collision rates increase with an increase in the number of CMs in the cluster. Therefore, the energy consumption of multiple retransmission data is the largest. The TDMA protocol uses fixed channel allocation for data transmission, without packet collision, and does not need to use additional control packets to reserve the channel and schedule the transmission order. Thus, the average energy consumption of each packet is the smallest. The RHNE-MAC and DACS-HVOI protocols are competitive MAC protocols based on reservation channels,

which need to generate additional energy to send control packets. Therefore, the energy consumption of using these two protocols is slightly higher than that of using the TDMA protocol. Although they consume more energy than TDMA, these protocols have a higher throughput and lower delay, and data packets can be transmitted to the sink node at a faster rate. Therefore, overall, the RHNE-MAC and DACS-HVOI protocols are more suitable for underwater networks that focus on timeliness.

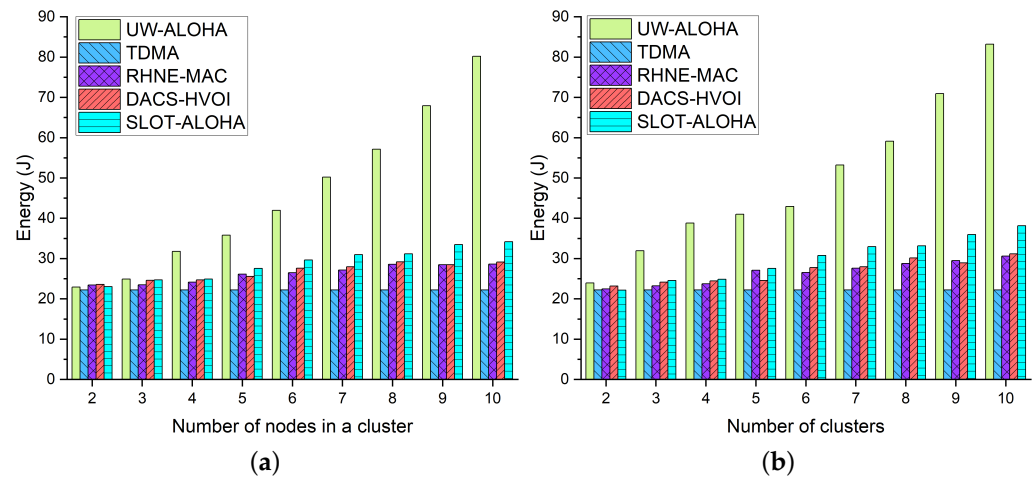


Figure 8. Comparison chart of four protocols affecting energy. (a) Comparison chart of energy affected by different numbers of CMs in clusters. (b) Comparison chart of energy affected by different numbers of clusters.

Figure 9 shows a comparison of the throughput of high VoI packets in the network for four MAC protocols in two simulation environments. In both experiments, the throughput of high VoI packets for the UW-ALOHA and TDMA protocols was very low because the network throughput of these two protocols is poor and high VoI packets were not separated from low VoI packets. Compared with traditional UW-ALOHA and TDMA protocols, the RHNE-MAC protocol has a slightly higher throughput of high VoI packets when there are fewer nodes in the network. When the number of nodes in the network increases, the network throughput is significantly higher, so the throughput of high VoI packets is significantly higher. The DACS-HVOI protocol proposed in this paper has a higher throughput of high VoI packets than the RHNE-MAC protocol when the network throughput is lower than that of the RHNE-MAC protocol. Especially for a larger number of nodes, the throughput of high VoI packets is approximately 200% higher than that of the RHNE-MAC protocol. Therefore, the simulation results verify that DACS-HVOI mainly transmits high VoI packets and has the highest network throughput of high VoI packets among the four protocols.

Figure 10 shows the impact of the four MAC protocols on the information value. In this simulation experiment, there are five clusters, with five CMs in each cluster. As shown in the figure, when the TDMA protocol is applied, the value of information shows the largest decreases because the TDMA protocol's strategy is to transmit packets via fixed channel allocation. Thus, several times the time to transmit the data packet to the next hop node is needed. Although the average time for the packet to be delivered to the next hop is the smallest, each packet consumes more time, and especially, sometimes the node that has no packet to be forwarded needs to be allocated a time slot. ALOHA, RHNE-MAC, and DACS-HVOI are competition-based protocols. Because DACS-HVOI considers the priority transmission of high VoI packets, the attenuation of high value information is minimal. For the packets collected by the AUV and the high value information collected by static nodes, the residual value after being transmitted to the sink node is 250% of the RHNE-MAC protocol, which is 340% of the ALOHA protocol. For low-value information,

RHNE-MAC does not consider the VoI of packets. Therefore, this protocol has more residual value than DACS-HVOI.

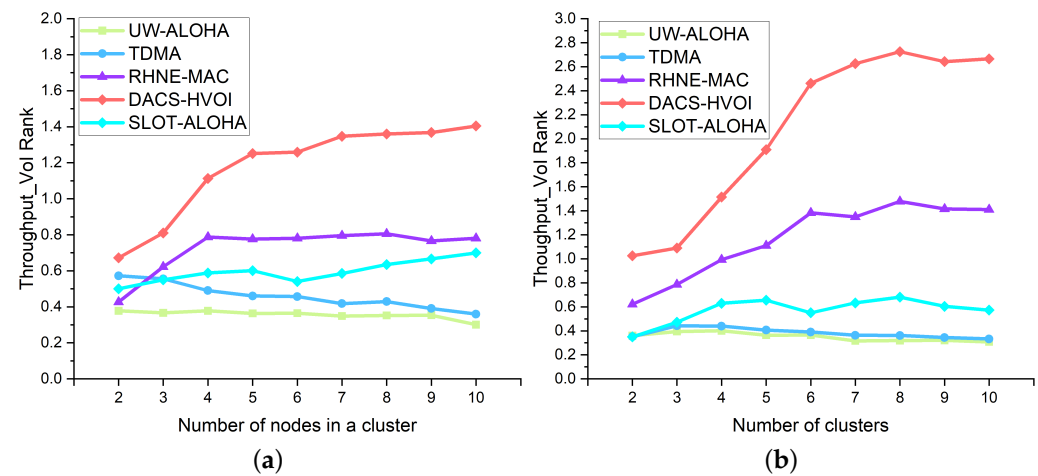


Figure 9. Comparison chart of four protocols affecting throughput of high VoI data in the network. (a) Comparison chart of throughput of high VoI data affected by different numbers of CMs in clusters. (b) Comparison chart of throughput of high VoI data affected by different numbers of clusters.

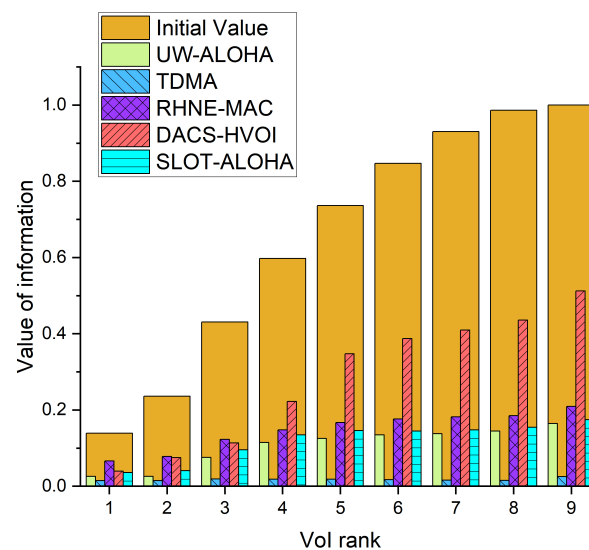


Figure 10. Comparison chart of four protocols that affect residual value of information.

5. Conclusions

In this paper, we propose the DACS-HVOI protocol for H-UWSNs. This protocol allows an AUV and SNs that have collected high VoI data packets to prioritize channel access. We analyze the problems of channel competition between low VoI packets and high VoI packets, the value decay of high VoI packets, the limited forwarding capabilities of CHs, and channel contention among SNs and the AUV. Based on this analysis, we use the Markov chain algorithm to predict the highest VoI packet that is preforwarded in the competitive channel and use a stochastic fluid model to predict the time needed for CHs' pending forwarding queue to complete the forwarding of high VoI packets. Combining these two methods, we designed a complete MAC protocol process that sends high VoI packets as soon as possible to avoid excessive value decay. Simulation experiments show that the DACS-HVOI can achieve high network throughput, low latency, and low energy consumption while maximizing the preservation of high VoI data value. In future work, we

will further explore methods for multiple AUVs and static nodes to cooperate in completing data tasks, providing more practical solutions for IoUT.

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Appendix A

Table A1. Notation and explanation.

Notation	Full Name	Explanation
CM/CMs	Cluster Member nodes	Collect and transfer packets to CHs
CH/CHs	Cluster Head nodes	Receive packets of CMs and AUV
SNs	Static Nodes	Static Nodes
AUV	Autonomous Underwater Vehicle	Underwater mobile node that collects and transfers packets to CHs
VoI	Value of Information	Describes the value of collected data packets
VoI_{next}	\	VoI of the node's next pre-forwarded packet
VoI_{new}	\	VoI of the node's latest pre-forwarded packet
P_{send}	\	Distribution of the VoI of packets to be forwarded
P_{max}	\	Distribution of maximum VoI of packets in the cluster
C_T	\	CHs' queue to be forwarded
$I+$	\	Packets with VoI greater than or equal to I in C_T
$(I+1)+$	\	Packets with VoI greater than or equal to $I+1$ in C_T
$X^{(I+)}(t)$	\	When the packets with received by CHs, the number of packets with VoI greater than or equal to I in C_T
Q	\	Transfer rate matrix of packets with VoI of C_T
S	\	State space of CTMC
U	\	Transfer rate of the number of packets with VoI as I in C_T to the downward process
K	\	Transfer rate of the number of packets with VoI as I in C_T to the upward process
Γ	\	Random variable of packet waiting time to be forwarded by CH

Table A2. Limitations of existing underwater MAC protocols.

Protocol	Full Name	Application	Limitation
TDMA	Tandem Differential Mobility Analyzer	This protocol is to divide time into multiple slots, with each node being assigned a slot for packet transmission.	TDMA requires strict clock synchronization, which is difficult to achieve in large-scale UWSNs, so its use in practical underwater tasks is limited.
ALOHA	\	In this protocol, all nodes send data immediately after collecting them.	Packet collisions are likely to occur when using this protocol, especially when the network load increases.
FAMA	Floor Acquisition Multiple Access	This protocol uses short control packets to compete for channel access before sending data and sends all messages at the beginning of slots.	This protocol only allows one node to send data during a handshake cycle, so its channel utilization is not high.
UWASN	Underwater Acoustic Sensor Network	This protocol nodes with packets to transmit reserve the channel at the reservation node and the master node schedules packet transmission times based on propagation delays between two nodes	\
DQA-MAC	Delay and Queue Aware Adaptive Scheduling-based Medium Access Control	This protocol schedules packet transmission times based on propagation delay information and the number of packets waiting in each node's queue.	\
DCN-MAC	Dynamic Channel Negotiation MAC Mechanism based on Spatial-temporal Mapping of Receiving queue	This mechanism treats multinode conflict problems as Nash equilibrium equations in non-cooperative games with incomplete information.	All these protocols have long handshake cycles, which render them inefficient for handshaking and affect network performance.
RHNE-MAC	Random Handshake MAC Protocol based on Nash Equilibrium	In the RTS stage, this mechanism considers competition behavior among nodes sending control packets as an incomplete information game for channel access rights using the Nash equilibrium equation.	\
UWSNs	Underwater Multi-modal Wireless Sensor Networks	This protocol considers heterogeneous models with VoI decay.	Due to inevitable long paths, this method is only suitable for data collection in sparse networks.
UASNs	Underwater Acoustic Sensor Networks	This protocol divides the area into multiple quality regions using Tyson polygons and deploys AUVs in each partition. Then, the authors added packet concentration to the VoI.	The scheme does not directly reflect the correlation between data importance and VoI decay rate.

Table A2. Cont.

Protocol	Full Name	Application	Limitation
UWASNs	Underwater Acoustic Sensor Networks	This protocol is a hierarchical data collection problem by optimizing AUV paths to maximize residual VoI while defining a more realistic enhanced VoI; however, it is difficult for a single AUV to complete tasks in large-scale areas.	It is difficult for a single AUV to complete tasks in large-scale areas.
HDCS	Hybrid Data Collection Scheme	This protocol applied the VoI to measure decaying data values determined by historical abnormal data while using VoI to describe the relationship between the detection data importance level and its timeliness.	Although this method can effectively transmit data between AUVs and static networks in two communication modes, it is difficult for an already deployed running static network for an AUV to directly join.

Table A3. Simulation Parameters.

Simulation Parameters	Value
Radio propagation Channel	Underwater Propagation Underwater Channel
Data rate	1 Kbps
Network Size	2000 m × 2000 m × 1000 m
Number of clusters	2–10
Number of nodes in the cluster	2–10
Control packet size	20 Bytes
Packet generation rate	0.1
Transmitting power	3.13 w
Receiving power	0.13 w
Maximum transmission radius	500 m
Number of AUVs	1
Speed of AUV	5 m/s

References

1. Khan, M.T.R.; Ahmed, S.H.; Kim, D. AUV-aided energy-efficient clustering in the Internet of underwater things. *IEEE Trans. Green Commun. Netw.* **2019**, *3*, 1132–1141. [\[CrossRef\]](#)
2. Saeed, N.; Alouini, M.S.; Al-Naffouri, T.Y. Accurate 3-D localization of selected smart objects in optical internet of underwater things. *IEEE Internet Things J.* **2019**, *7*, 937–947. [\[CrossRef\]](#)
3. Bai, L.; Han, R.; Liu, J.; Choi, J.; Zhang, W. Random access and detection performance of Internet of Things for smart ocean. *IEEE Internet Things J.* **2020**, *7*, 9858–9869. [\[CrossRef\]](#)
4. Zhang, Q.; Wang, H.; Zhao, R.; Shen, X.; He, K.; Zhang, H. The Design of Clustering Algorithm and MAC Protocol for Low Delay Underwater Acoustic Sensor Networks. *IEEE Sens. J.* **2022**, *23*, 3251–3261. [\[CrossRef\]](#)
5. Berlian, M.H.; Sahputra, T.E.R.; Ardi, B.J.W.; Dzatmika, L.W.; Besari, A.R.A.; Sudibyo, R.W.; Sukaridhoto, S. Design and implementation of smart environment monitoring and analytics in real-time system framework based on internet of underwater things and big data. In Proceedings of the 2016 International Electronics Symposium (IES), Denpasar, Indonesia, 29–30 September 2016; pp. 403–408.
6. Zhao, Z.; Liu, C.; Li, Z.; Wu, B.; Ma, M.; Zhao, Z.; Liu, L. EBTOR: An Energy-Balanced 3D Topology Control Algorithm Based on Optimally Rigid Graph in UWSNs. *Adhoc Sens. Wirel. Netw.* **2018**, *42*, 295–315.
7. Han, G.; Long, X.; Zhu, C.; Guizani, M.; Bi, Y.; Zhang, W. An AUV location prediction-based data collection scheme for underwater wireless sensor networks. *IEEE Trans. Veh. Technol.* **2019**, *68*, 6037–6049. [\[CrossRef\]](#)

8. Su, R.; Zhang, D.; Li, C.; Gong, Z.; Venkatesan, R.; Jiang, F. Localization and Data Collection in AUV-Aided Underwater Sensor Networks: Challenges and Opportunities. *IEEE Netw.* **2019**, *33*, 86–93. [\[CrossRef\]](#)
9. Su, Y.; Zuo, Y.; Jin, Z.; Fu, X. OSPG-MAC: An OFDMA-based subcarrier pregrouping MAC protocol for underwater acoustic wireless sensor networks. *J. Sens.* **2019**, *2019*, 4965231. [\[CrossRef\]](#)
10. Xi, Z.; Kan, X.; Cao, L.; Liu, H.; Manogaran, G.; Mastorakis, G.; Mavromoustakis, C.X. Research on underwater wireless sensor network and MAC protocol and location algorithm. *IEEE Access* **2019**, *7*, 56606–56616. [\[CrossRef\]](#)
11. Yan, J.; Yang, X.; Luo, X.; Chen, C. Energy-efficient data collection over AUV-assisted underwater acoustic sensor network. *IEEE Syst. J.* **2018**, *12*, 3519–3530. [\[CrossRef\]](#)
12. Talak, R.; Karaman, S.; Modiano, E. Optimizing information freshness in wireless networks under general interference constraints. In Proceedings of the Eighteenth ACM International Symposium on Mobile Ad Hoc Networking and Computing, Los Angeles, CA, USA, 26–29 June 2018; pp. 61–70.
13. Qiu, T.; Zhao, Z.; Zhang, T.; Chen, C.; Chen, C.P. Underwater Internet of Things in smart ocean: System architecture and open issues. *IEEE Trans. Ind. Inform.* **2019**, *16*, 4297–4307. [\[CrossRef\]](#)
14. Wang, N.; Wu, J. Trajectory scheduling for timely data report in underwater wireless sensor networks. In Proceedings of the 2015 IEEE Global Communications Conference (GLOBECOM), San Diego, CA, USA, 6–10 December 2015; pp. 1–6.
15. Khan, M.T.R.; Jembre, Y.Z.; Ahmed, S.H.; Seo, J.; Kim, D. Data freshness based AUV path planning for UWSN in the internet of underwater things. In Proceedings of the 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 9–13 December 2019; pp. 1–6.
16. Fang, Z.; Wang, J.; Jiang, C.; Zhang, Q.; Ren, Y. AoI-inspired collaborative information collection for AUV-assisted internet of underwater things. *IEEE Internet Things J.* **2021**, *8*, 14559–14571. [\[CrossRef\]](#)
17. Gjanci, P.; Petrioli, C.; Basagni, S.; Phillips, C.A.; Bölöni, L.; Turgut, D. Path finding for maximum value of information in multi-modal underwater wireless sensor networks. *IEEE Trans. Mob. Comput.* **2017**, *17*, 404–418. [\[CrossRef\]](#)
18. Duan, R.; Du, J.; Jiang, C.; Ren, Y. Value-based hierarchical information collection for AUV-enabled Internet of Underwater Things. *IEEE Internet Things J.* **2020**, *7*, 9870–9883. [\[CrossRef\]](#)
19. Liu, Z.; Meng, X.; Liu, Y.; Yang, Y.; Wang, Y. AUV-aided hybrid data collection scheme based on value of information for internet of underwater things. *IEEE Internet Things J.* **2021**, *9*, 6944–6955. [\[CrossRef\]](#)
20. Han, G.; Shen, S.; Song, H.; Yang, T.; Zhang, W. A stratification-based data collection scheme in underwater acoustic sensor networks. *IEEE Trans. Veh. Technol.* **2018**, *67*, 10671–10682. [\[CrossRef\]](#)
21. Latif, M.B.; Liu, F.; Liu, K. A TDMA-based MAC protocol for mitigating mobility-caused packet collisions in vehicular ad hoc networks. *Sensors* **2022**, *22*, 643. [\[CrossRef\]](#)
22. Clazzer, F.; Grec, M. Analytical Model of ALOHA and Time-and Frequency-Asynchronous ALOHA with Forward Error Correction for IoT Systems. *Sensors* **2022**, *22*, 3741. [\[CrossRef\]](#)
23. Molins, M.; Stojanovic, M. Slotted FAMA: A MAC protocol for underwater acoustic networks. In Proceedings of the OCEANS 2006-Asia Pacific, Singapore, 16–19 May 2006; pp. 1–7.
24. Chen, H.; Xie, L. A pre-scheduling-based MAC protocol for underwater acoustic sensor network. In Proceedings of the OCEANS 2017-Aberdeen, Aberdeen, UK, 19–22 June 2017; pp. 1–6.
25. Zhuo, X.; Qu, F.; Yang, H.; Wei, Y.; Wu, Y.; Li, J. Delay and queue aware adaptive scheduling-based MAC protocol for underwater acoustic sensor networks. *IEEE Access* **2019**, *7*, 56263–56275. [\[CrossRef\]](#)
26. Su, Y.; Dong, L.; Yang, Q. DCN-MAC: A dynamic channel negotiation MAC mechanism for underwater acoustic sensor networks. *Sensors* **2020**, *20*, 406. [\[CrossRef\]](#)
27. Wei, D.; Qiuling, Y.; Yanxia, C.; Shijie, S.; Xiangdang, H. RHNE-MAC: Random Handshake MAC protocol based on Nash equilibrium for underwater wireless sensor networks. *IEEE Sens. J.* **2021**, *21*, 21090–21098. [\[CrossRef\]](#)
28. Cheng, C.F.; Li, L.H. Data gathering problem with the data importance consideration in underwater wireless sensor networks. *J. Netw. Comput. Appl.* **2017**, *78*, 300–312. [\[CrossRef\]](#)
29. Han, G.; Tang, Z.; He, Y.; Jiang, J.; Ansere, J.A. District partition-based data collection algorithm with event dynamic competition in underwater acoustic sensor networks. *IEEE Trans. Ind. Inform.* **2019**, *15*, 5755–5764. [\[CrossRef\]](#)
30. Horváth, G. Waiting time and queue length analysis of Markov-modulated fluid priority queues. *Queueing Syst.* **2020**, *95*, 69–95. [\[CrossRef\]](#)
31. Ramaswami, V. Matrix analytic methods for stochastic fluid flows. In Proceedings of the 16th International Teletraffic Congress, Edinburgh, UK, 7–11 June 1999.
32. Anick, D.; Mitra, D.; Sondhi, M.M. Stochastic theory of a data-handling system with multiple sources. *Bell Syst. Tech. J.* **1982**, *61*, 1871–1894. [\[CrossRef\]](#)
33. Bean, N.G.; O'Reilly, M.M.; Sargison, J.E. A stochastic fluid flow model of the operation and maintenance of power generation systems. *IEEE Trans. Power Syst.* **2010**, *25*, 1361–1374. [\[CrossRef\]](#)

34. Jones, G.L.; Harrison, P.G.; Harder, U.; Field, T. Fluid queue models of battery life. In Proceedings of the 2011 IEEE 19th Annual International Symposium on Modelling, Analysis, and Simulation of Computer and Telecommunication Systems, Singapore, 25–27 July 2011; pp. 278–285.
35. da Silva Soares, A.; Latouche, G. Further results on the similarity between fluid queues and QBDs. In *Matrix-Analytic Methods: Theory and Applications*; World Scientific: Singapore, 2002; pp. 89–106.

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