Value of Information-Based Packet Scheduling Scheme for AUV-Assisted UASNs

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***Abstract*— In this paper, we propose a value of information (VoI)-based packet scheduling scheme (VBPS) in autonomous underwater vehicle (AUV)-assisted underwater acoustic sensor networks (UASNs), where AUVs act as mobile sensor nodes to collect data from areas not accessible to static nodes and then relay data via static nodes. VoI is a performance metric to measure the importance of data packets with different levels of urgency. The proposed scheme aims to avoid collision with the ongoing packet transmission of static nodes without their accurate global information. In specific, the static node localization stage and the topology construction stage are carried out to obtain the local information. Furthermore, the transmission scheduling stage is implemented to avoid packet collision and formulates a combinatorial optimization problem maximizing VoI under the constraint of packet collision avoidance. To solve this complicated problem, a low-complexity distributed search algorithm is proposed, which exploits the spatial-temporal reuse to establish data packet collision constraints and then determines the next-hop node and data transmission time for AUVs. In addition, a collaborative search algorithm is proposed to avoid packet collision among different AUVs by enabling collaboration among AUVs. Extensive simulation results under various scenarios demonstrate the superior performance of the proposed scheme.**

***Index Terms*— Underwater acoustic sensor networks, packet scheduling, autonomous underwater vehicle, value of information.**

I. Introduction

UNDERWATER wireless communications are attracting great attention due to a number of important underwater applications for military and commercial purposes, such as environmental monitoring, marine ranching, and marine resource development [2], [3]. In long-distance underwater wireless communications, sound wave plays a prominent role due to less propagation attenuation than radio wave and less scattering than optical wave [4], [5], [6]. Underwater acoustic sensor networks (UASNs) are expected to be a de-facto technology in underwater wireless communications. Traditional UASNs are mainly static networks, in which data is delivered from static sensor nodes to sink nodes in a multi-hop manner. However, such static networks can only be deployed at fixed areas with limited coverage. As a remedy to these limitations, the autonomous underwater vehicle (AUV) with high maneuverability is considered as promising complement to enhance static UASNs. For the AUV, a plethora of commercial-off-the-shelf products are developed by academia and industry, such as Woods Hole Oceanographic Institution (WHOI) [7], Teledyne Technologies [8], Boston Engineering [9], etc. Equipped with advanced sensing functionalities, AUVs enable a number of applications, such as equipment maintenance, environment monitoring, and disaster prevention [10], [11], [12], [13]. Since AUVs and static UASNs can complement each other, their integration, namely AUV-assisted UASNs, is deemed as a potential underwater communication paradigm, which can expand the coverage as well as enhance the performance of the existing static UASNs.

Generally, in AUV-assisted UASNs, AUVs mainly play two kinds of roles, i.e., data collection nodes and mobile sensor nodes. As *data collection nodes*, AUVs work as data collection centers and move to sensor nodes as close as possible to reduce transmission energy consumption of sensor nodes [14], [15], [16], [17], [18], [19]. As *mobile sensor nodes*, static nodes and AUVs collaboratively sense data in the environment, because AUVs can efficiently expand the network coverage and explore areas that are not accessible by static nodes.

In this paper, we focus on the latter, i.e., AUVs play as mobile sensor nodes to detect abnormal data and forward data to the data center via static nodes. In this scenario, static nodes are pre-deployed to sense the environment for a long time, and then the sensing data is sent to the data center. Once the data center identifies some abnormal data, AUVs are dispatched to the area of interest along the predefined trajectory. Then AUVs sense and deliver abnormal data back to the data center. However, due to the low velocity of AUVs (e.g., 2-10 m/s), delivering data after traveling the whole trajectory cannot satisfy the stringent delay requirement of disseminating abnormal

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data. Therefore, to disseminate data timely and efficiently, AUVs need to schedule data transmission via predeployed static nodes in a collision-free manner.

Designing an effective packet scheduling scheme is challenging due to the following two reasons. Firstly, the *global information* of all static nodes is difficult to be known in advance. Since static nodes have been deployed for a long time, their locations may change due to the fluctuating ocean environment, and the network topology may change because some static nodes may be destroyed or suffer from battery depletion [20], [21]. Secondly, the packet scheduling scheme needs to satisfy *packet collision avoidance* constraints, i.e., data packets from AUVs should not collide with any data packets from static nodes within the communication range of the AUV. Since the propagation delay and communication link between static nodes and AUVs change with the movement of AUVs in AUV-assisted UASNs, the packet collision avoidance constraints vary spatially and temporally.

In this paper, we propose a novel packet scheduling scheme. To transmit data packets via static nodes, AUVs first need to get information about static nodes, such as the node position, network topology, and packet transmission time. Based on such information, AUVs select the optimal next-hop node and schedule the time slot for collision-free packet transmission. To be specific, we propose a value of information (VoI)-based packet scheduling (VBPS) scheme. This scheme first introduces a novel performance metric, VoI, to measure the data packet importance with different levels of urgency. Then, three stages are proposed to avoid collision with the ongoing packet transmission of static nodes without their accurate global information. The static node localization stage adopts a passive time difference of arrival (TDOA)-based localization method to obtain the positions of static nodes and the topology construction stage establishes the topology map and interference map based on the information of data packets listened from static nodes. The transmission scheduling stage formulates a combinatorial optimization problem maximizing the VoI to determine the appropriate next-hop nodes and time slots to transmit data packets under the constraints of packet collision avoidance. Identifying the optimal solution is difficult due to the absence of static nodes' global information which spends additional network resources. Therefore, two low-complexity search algorithms are developed to solve this problem, i.e., the VoI-based distributed packet scheduling algorithm (VBPS-I) and the VoI-based collaborative packet scheduling algorithm (VBPS-C). They exploit the spatial-temporal reuse to construct the data packet collision constraints and determine the next-hop nodes and transmission time for data packets from AUVs. Simulations under various scenarios are carried out to evaluate the performance of the proposed scheme.

The main contributions in this paper are summarized as follows:

- We design a packet scheduling scheme to transmit data packets from AUVs via static nodes without requiring global information while avoiding collision with regular data transmission among static nodes;
- We formulate a combinatorial optimization problem to maximize VoI under the constraint of collision avoidance;
- We develop two low-complexity search algorithms by exploiting spatial-temporal reuse based on the local information, which can achieve close performance to the optimal algorithm as demonstrated by simulation results.

The remainder of this paper is organized as follows. In Section II, the related works on AUV-assisted UASNs are provided. The system model is presented in Section III, and the detailed packet scheduling scheme is proposed in Section IV. Following this, the transmission scheduling problem is formulated in Section V, and the VoI-based packet scheduling algorithms are proposed to solve the problem in Section VI. In Section VII, simulation results are given. Finally, Section VIII concludes this paper.

II. Related Work

In recent years, packet scheduling schemes in AUV-assisted UASNs have attracted much interest and been extensively studied. They can mainly be divided into two categories, i.e., reservation-based packet scheduling schemes and random access-based packet scheduling schemes.

A. Reservation Based Packet Scheduling Schemes

In the reservation-based packet scheduling schemes, reservation packets are transmitted to reserve the channel for AUVs before sending data packets. Some protocols need several rounds of handshaking to reserve data packet transmission time for AUVs. The propagation delay-aware opportunistic MAC protocol named DOTS jointly considered the data packet transmission for both static nodes and AUVs [22]. To avoid packet collision, nodes schedule their packet transmission time and conduct concurrent transmission based on the detected propagation delay among nodes, which requires accurate clock synchronization. Moreover, the AUV-based data delivery protocol named ADDP focused on the data packet transmission among multiple AUVs [23]. In the ADDP, time clock synchronization was required, but the positions of other AUVs were not required. Before data transmission, the control packets were sent to find the next-hop nodes and reserve the time period for each data packet transmission. In some papers, the VoI metric is used to schedule the data transmission considering the event significance and promptness of data to improve the network efficiency [17], [18], [19]. Another solution exploits the flexible time slot to accommodate the dynamic movement of AUVs [24], [25]. Some works leverage the information of propagation delay to improve the efficiency of reservation [26], [27]. The propagation delay between the AUVs and sink node is first estimated by several rounds of handshaking, and then data packet transmission of AUVs is determined and scheduled by the sink node. While feasible, the movement of AUVs in one transmission round is not considered. Different from the above works that require time synchronization and global information of static nodes, our work considers the absence of global information.

B. Random Access Based Packet Scheduling Schemes

Unlike reservation-based packet transmission schemes, most random access-based packet transmission schemes do not require the global information of the static nodes. However,

TABLE I
SUMMATION OF USED NOTATIONS

Notations	Description	Notations	Description
$\mathcal{N}_A$	Set of AUVs	$m_{i,j}$	Indicator of relay nodes relayed by c_i
N_A	Number of AUVs	M_i	Number of relay nodes relayed by c_i
A	Indicator of AUVs	$\mathcal{M}_i$	Set of relay nodes relayed by c_i
$\mathcal{C}$	Set of sink nodes	$s_{j,k}$	Indicator of sensor nodes relayed by $m_{i,j}$
c_i	Indicator of sink nodes	S_j	Number of sensor nodes relayed by $m_{i,j}$
$\boldsymbol{L}_A$	Locations of AUVs	$\mathcal{S}_j$	Set of sensor nodes relayed by $m_{i,j}$
$\boldsymbol{L}$	Locations of static nodes	r_a^b	Distance between node a and node b
$\boldsymbol{H}_T$	Topology matrix	$\boldsymbol{H}_I$	Interference matrix
$\mathcal{N}'$	Set of next-hop nodes	N'	Indicator of next-hop nodes
$\mathcal{I}$	Set of interference nodes	I	Indicator of interference nodes
Ω	Collision time interval	t_A	Packet transmission time for AUV
$\mu_{i,j}$	Communication time rounds for $m_{i,j}$	$t_{i,j}^{\mu_{i,j}}$	Packet transmission time for $m_{i,j}$ at $\mu_{j,k}$ round

due to the long and dynamic propagation delay, they need to address the issue of high packet collision probability. In the position-aware routing and medium access protocol named P-AUV, before transmitting data packets, nodes need to wait for a random backoff duration adaptively based on the distance between nodes to reduce the collision probability [28]. The traffic-adaptive receiver synchronized named TARS MAC protocol proposed a receiver-synchronized transmission method to handle the spatial uncertainty and align packet receptions [29]. In another line of research, a reinforcement learning-based MAC protocol named UW-ALOHA-QM took advantage of reinforcement learning methods, which allowed nodes to adapt to the dynamic movement of AUVs [30]. In this way, the channel utilization was highly improved while the collision still existed. In addition, some works send a notification packet before data packet transmission to reduce the collision probability caused by random access. In the location-based TDMA MAC protocol (LTM-MAC), since the AUV has holistic information of static nodes' positions, it can select the appropriate time to send the notifying packet under the specific conditions of collision avoidance [31]. Meanwhile, to avoid packet collision with the AUV, static nodes also set a carrier sensing time to hear the transmission of AUVs. Furthermore, in the load-adaptive carrier sense multiple access control (LACCM) protocol, a specific broadcast (BCT) packet was introduced to indicate the joining or leaving of the AUV [32]. When a BCT packet is received, static nodes will transmit data to the AUV. Different from prior random access-based packet transmission schemes interfering with ongoing communications among static nodes, our work considers collision avoidance with regular data transmission among static nodes. Preliminary results of this work have been presented [1], in which collision avoidance between the AUV and the static node is considered. However, the packet transmission collision between AUVs also exists. Therefore, to further improve the network efficiency, this paper proposes a collaborative search algorithm addressing collision avoidance between AUVs.

III. SYSTEM MODEL

In this section, we introduce the network model and the underwater acoustic channel model. Then, we present a two-hop static network with the time division multiple access (TDMA) protocol, which is widely used in UASNs. Table I summarizes the main notations used in this paper.

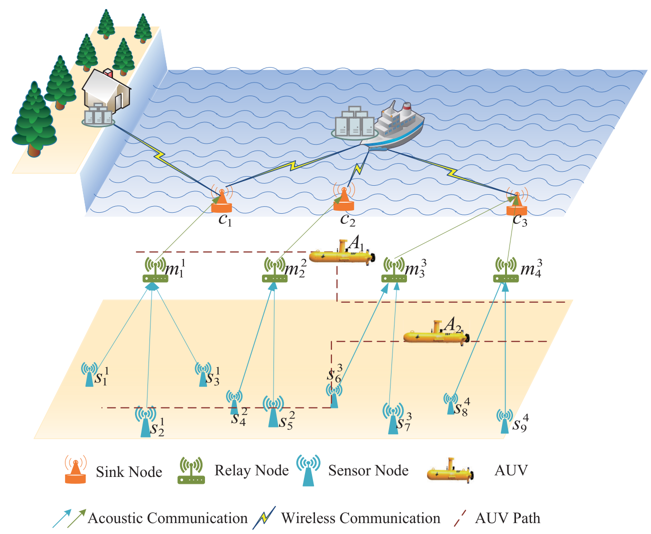

Fig. 1. Considered scenario.

A. Considered Scenario

In this paper, we consider an underwater acoustic network comprising multiple static nodes and AUVs.

- Static nodes: In this network, N number of static nodes are randomly distributed in the area, as illustrated in Fig. 1. In the considered network, static nodes are pre-deployed and organized as a two-hop network. They know the current network topology and transmit their packets with a predefined MAC protocol. Besides, the strategy of the MAC protocol of static network is known to AUVs, but the scheduling time of each node is unknown beforehand. The locations of static nodes and the network topology are also unknown by AUVs. Furthermore, the packet frame structure and method to decode packets are globally known to AUVs so that communication between static nodes and AUVs is possible.
- AUVs: A set of N_A number of AUVs is denoted by $\mathcal{N_A} = \{A_1, A_2, \ldots, A_{N_A}\}$, which can travel to detect the areas that are not accessible to static nodes. Then AUVs send detected data to the data center via static nodes. The trajectories of AUVs are predefined before released according to their task area rather than the accurate locations of static nodes. The coarse locations of static nodes can assist in allocating the task area of AUVs so that the AUVs can cruise in the communication range

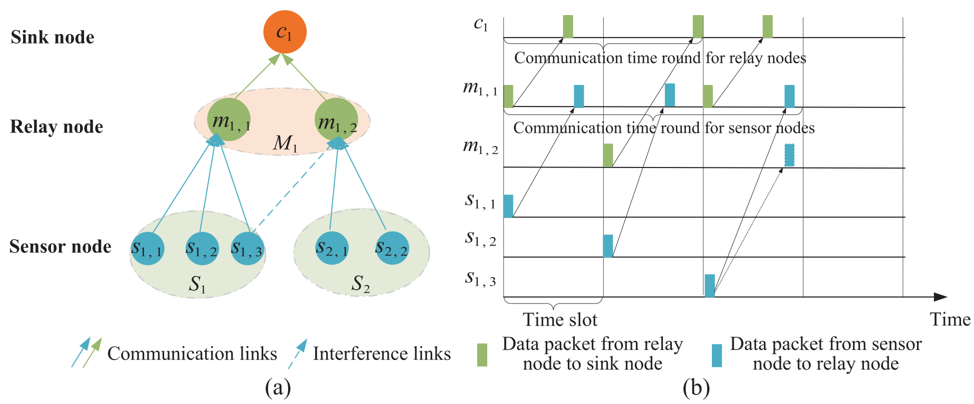

Fig. 2. An example of the static network topology and the TDMA protocol: a) The static network topology; b) The packet scheduling strategy in TDMA protocol.

of static nodes. Therefore, it is unnecessary for AUVs to know the accurate locations of static nodes in advance.

B. Underwater Acoustic Channel Model

In underwater acoustic communications, we assume that the signal-to-noise ratio (SNR) γ of the channel is constant during the transmission time of a data packet. Given transmission power P at the sender a and channel bandwidth B, the SNR at the receiver b with frequency f and distance r_a^b can be expressed as [33]

$$\gamma\left(r_a^b, f\right) = \frac{P \times \left|H\left(r_a^b, f\right)\right|^2}{N(f)B}, \quad (1)$$

where $N(f)$ is the power spectral density of the ambient noise at frequency f. Here, $H(r_a^b, f)$ is the channel response which is given by $H(r_a^b, f) = 1/\sqrt{A\left(r_a^b, f\right)}$. Here, $A\left(r_a^b, f\right)$ is the path loss of the underwater acoustic signal propagation, which suffers from both spreading loss and frequency-dependent absorption loss $\alpha(f)$. The path loss in dB related to transmission distance in meter and frequency in kHz is expressed as

$$10 \log A\left(r_a^b, f\right) = k \times 10 \log r_a^b + r_a^b \times 10^{-3}\alpha(f), \quad (2)$$

where the first term represents the spreading loss, and the second term represents the absorption loss. k is the spreading factor and set to be 1.5 referred to the practical spreading [34]. The absorption loss $\alpha(f)$ is expressed empirically by Thorp's formula, i.e., $\alpha(f) = 0.11 f^2/\left(1+f^2\right) + 44 f^2/\left(4100+f^2\right) + 2.75 \times 10^{-4} f^2 + 0.003$.

The channel can be regarded as the additive white Gaussian noise (AWGN) channel after adopting channel equalization and inter-symbol interference elimination techniques, which has been demonstrated in existing works [35], [36], [37]. The average BER with binary phase shift keying (BPSK) modulation is represented by $p_e\left(\gamma\left(r_a^b, f\right)\right) = Q\left(\sqrt{2\gamma\left(r_a^b, f\right)}\right)$. Let L denotes the length of a data packet, the packet error rate (PER) with SNR $\gamma\left(r_a^b, f\right)$ and BER $p_e\left(\gamma\left(r_a^b, f\right)\right)$ is expressed as

$$P_e\left(\gamma\left(r_a^b, f\right)\right) = 1 - \left(1 - p_e\left(\gamma\left(r_a^b, f\right)\right)\right)^L. \quad (3)$$

C. Packet Transmission Procedure for Static Nodes

As shown in Fig. 2, for the two-hop static network, static nodes are divided into three layers: (1) the set of C sink nodes is denoted by $\mathcal{C} = \{c_1, c_2, \ldots, c_C\}$ in the upper layer; (2) the set of M relay nodes is denoted by $\mathcal{M} = \{m_1, m_2, \ldots, m_M\}$ in the middle layer; and (3) the set of S sensor nodes is denoted by $\mathcal{S} = \{s_1, s_2, \ldots, s_S\}$ in the lower layer. Here, the total number of static nodes is $N = C + M + S$. As mentioned above, static nodes are all synchronized. Time is divided into multiple time slots whose duration is determined by the communication range d_0, packet length L_{data}, and data rate R, i.e., $T_s = \lceil (t_{\text{data}} + d_0/v_s)/t_{\text{data}} \rceil t_{\text{data}}$, where v_s is the sound speed. Here, t_{data} denotes the packet transmission time by $t_{\text{data}} = L_{\text{data}}/R$. Thus, each time slot consists of $n = \lceil (t_{\text{data}} + d_0/v_s)/t_{\text{data}} \rceil$ packet transmission time.

In the following, we present the data packet transmission procedure for static nodes in detail. The data transmission among static nodes is two-hop, i.e., from sensor nodes to relay nodes and from relay nodes to sink nodes.

1) Transmission From Sensor Nodes to Relay Nodes: Sensor nodes transmit data packets to relay nodes sequentially at the beginning of each time slot. We assume that a relay node $m_{i,j}$ relays data packets for S_j numbers of sensor nodes $s_{j,k} \in \mathcal{S}_j$. Here, k is the ID of the sensor node determined by the sending sequence denoted by $k \in \{1, 2, \ldots, S_j\}$. S_j is the number of sensor nodes transmitting packets to the relay node $m_{i,j}$ and satisfies $S = \sum_{j=1}^{M} S_j$. Then, the time that a sensor node $s_{j,k} \in \mathcal{S}_j$ transmits packets to the relay node $m_{i,j}$ is calculated as follows

$$t_{j,k}^{\mu_{j,k}} = \left((\mu_{j,k} - 1)S_j + k - 1\right) T_s. \quad (4)$$

Here, $\mu_{j,k}$ is the number of communication time rounds for $s_{j,k}$, which means the sensor node $s_{j,k}$ has transmitted $\mu_{j,k} - 1$ data packets. Each communication time round for sensor node $s_{j,k}$ consists of S_j numbers of time slots. $k - 1$ represents the sending sequence for the sensor node related to nodes' ID which has been allocated before sensor nodes are deployed.

2) Transmission From Relay Nodes to Sink Nodes: If relay nodes have received data packets from sensor nodes, they would send data packets to sink nodes. We assume that a sink node c_i receives data packets from M_i numbers of relay nodes $m_{i,j} \in \mathcal{M}_i$. Here, j is the ID of the relay node and determined by the sending sequence, which is denoted by $j \in \{1, 2, \ldots, M_i\}$. M_i is the number of relay nodes that transmit data packets to the sink node c_i and satisfies $M = \sum_{i=1}^{C} M_i$. Then, the time that the relay node $m_{i,j} \in \mathcal{M}_i$

transmits data packets to the sink node c_i is expressed as

$$t_{i,j}^{\mu_{i,j}} = ((\mu_{i,j}-1)M_i + j - 1)\, T_s. \tag{5}$$

Here, $\mu_{i,j}$ is the number of communication time rounds for $m_{i,j}$, which means the relay node $m_{i,j}$ has transmitted $\mu_{i,j}-1$ data packets. Each communication time round for relay node $m_{i,j}$ consists of M_i numbers of time slots. $j-1$ is the sending sequence for the relay node related to nodes' ID which has been allocated before relay nodes are deployed.

Finally, when sink nodes receive data packets, they will forward them to the data center via electromagnetic waves as soon as possible. The propagation delay is ignored due to the characteristics of electromagnetic waves.

IV. VoI-Based Packet Scheduling Scheme

In this section, we first introduce the VoI metric and then present the packet scheduling scheme in detail.

A. Value of Information (VoI) Metric

In this network, AUVs travel around to detect the environment. Different detected data require different transmission urgency. Therefore, to distinguish the different urgency of detected data, two kinds of data, i.e., *the abnormal data and the normal data*, are considered. The abnormal data is detected with a low packet arrival rate and should be scheduled with high urgency, whereas the normal data is in contrast [38]. In addition, the abnormal data and the normal data are generated by the Poisson Process with rates λ_u and λ_m, respectively. Note that $\lambda_u < \lambda_m$ due to the scarcity of the abnormal data.

Since the transmission urgency of data highly depends on the data importance and delivery timeliness, we introduce the VoI metric to measure the event significance and promptness. To be specific, in the proposed scenario, the VoI is influenced by the importance of the detected data as well as the delivery time of detected data. The VoI is defined as [17], [18], and [19]

$$V(t) = \begin{cases} \beta V^0 + (1-\beta)V^0 f(t), & t \le T, \\ 0, & t > T. \end{cases} \tag{6}$$

Here, $V(t)$ is the VoI, V^0 is the initial value, β is the weighting parameter that measures the trade-off between the data importance and delivery timeliness, and $f(t)$ is the decreasing function of t when $t \le T$. We define $f(t) = e^{-[(t-T)/\alpha]}$, where α is the scaling factor and T is the lifetime of the data. For the VoI, the parameters for the abnormal data and the normal data are different due to the different characteristics of two kinds of data, which are indexed by u and m, respectively. In specific, $V_u(t)$, V_u^0, β_u, $f_u(t)$, T_u, and α_u are for the abnormal data, while $V_m(t)$, V_m^0, β_m, $f_m(t)$, T_m, and α_m are for the normal data.

In the network, the AUV may transmit abnormal data packets or normal data packets via the static network at time t_A. Let o_{t_A} denote the transmitting decision for AUV A at time t_A, i.e., $o_{t_A} = 1$ indicates transmitting the abnormal data while $o_{t_A} = 0$ indicates transmitting the normal data. Then the VoI of the data packet transmitted from AUV A to static node N' at time t_A is calculated as follows:

$$V = o_{t_A} V_U + (1 - o_{t_A}) V_M. \tag{7}$$

Here, V_U and V_M are the VoI of abnormal data and normal data that are successfully received considering the packet error rate, respectively, i.e., $V_U = V_u\ (t_A - t'_A)\left(1 - P_e\left(\gamma\left(r_A^{N'}, f\right)\right)\right)$ and $V_M = V_m(t_A - t'_A)\left(1 - P_e\left(\gamma\left(r_A^{N'}, f\right)\right)\right)$.

B. Packet Scheduling Scheme

In this scenario, AUVs are in charge of collecting data from specific interested areas. Before AUVs are dispatched, their trajectories are pre-defined according to the location of tasks. Trajectories of AUVs can be designed via multiple methodologies [39], [40], [41], which is beyond the scope of this paper. When AUVs move along their pre-defined trajectories, they need to determine the next-hop static node to relay data packets as well as the time slot to transmit data packets. Specifically, AUVs need to complete three stages to transmit data efficiently and successfully.

1) Static Node Localization: The positions of static nodes are critical to the calculation of the propagation delay between two nodes, thereby affecting packet collision probability. Since the accurate locations of static nodes are unknown in advance and the communication links between the AUV and the static node will change with the movement of AUVs, AUVs need to obtain the local information of static nodes' positions to calculate the propagation delay between them. The localization stage needs to meet three demands. Firstly, since locations of static nodes are used for calculating the propagation delay with several milliseconds error tolerance, the localization method should be low-complexity instead of very high precision but complex methods to save communication and energy resources for the AUV. Secondly, AUVs do not broadcast any packets to sensor nodes and they just passively listen to the network, through which a passive localization approach is required to estimate locations of sensor nodes. Finally, static nodes are not time synchronized with AUVs due to clock shifts.

There are some existing technologies for underwater localization, including the time of arrival (TOA)-based methods, the time difference of arrival (TDOA)-based methods, and the direction of arrival (DOA)-based methods [42], [43], [44], [45], [46]. However, the TOA-based methods require time synchronization among static nodes and AUV, and the DOA-based methods depend upon precise angular information, which is not suitable for the proposed scenario. Different from the above technologies, the TDOA-based method is a mature multilateration that exploits the time difference of arrival to perform node localization, which can be applied in the proposed network.

Restricted by the time synchronization, a passive TDOA-based method is introduced for this scenario. Firstly, to get the time difference of arrival, AUVs need to listen to the packet transmission among static nodes while moving to different positions, which is different from the widely used TDOA-based methods. The time difference of arrival is given by

$$t^r(\mu_i) - t^r(\mu_{i-1}) = t(\mu_i) - t(\mu_{i-1}) + (r_{A_i}^a - r_{A_{i-1}}^a)/v_s. \tag{8}$$

Here, i indicates that the AUV has received i numbers of data packets from a specific static node. A_i indicates an AUV A received the ith data packet from the static node a; $t^r(\mu_i)$ and $t^r(\mu_{i-1})$ are the receiving time of data packets which are transmitted at the μ_i round or μ_{i-1} round. $t(\mu_i)$ is the sending time of data packets from the static node a. τ is the time shifting between AUV and static nodes. $r^a_{A_i}$ is the distance between one AUV A receiving ith data packet and the static node a, which is calculated as follows:

$$r^a_{A_i} = ||\boldsymbol{l_a} - \boldsymbol{l_{A_i}}||_2. \tag{9}$$

Let $\boldsymbol{l_a} = [x_a, y_a, z_a]^T$ and $\boldsymbol{l_{A_i}} = [x_{A_i}, y_{A_i}, z_{A_i}]^T$ denote the position of static node a and AUV A, respectively. Therefore, in the 3D area, to get the position of a static node, we need a minimum of three difference equations, which means the AUV has to receive four packets from the static node at four different locations at least, i.e.,

$$\begin{cases} r^a_{A_2} - r^a_{A_1} = v_s(t^r(\mu_2) - t^r(\mu_1) - (t(\mu_2) - t(\mu_1))) \\ r^a_{A_3} - r^a_{A_2} = v_s(t^r(\mu_3) - t^r(\mu_2) - (t(\mu_3) - t(\mu_2))) \\ r^a_{A_4} - r^a_{A_3} = v_s(t^r(\mu_4) - t^r(\mu_3) - (t(\mu_4) - t(\mu_3))) \\ r^a_{A_4} - r^a_{A_1} = v_s(t^r(\mu_4) - t^r(\mu_1) - (t(\mu_4) - t(\mu_1))) \end{cases}. \tag{10}$$

Accordingly, the coordination of the static node can be obtained by solving the nonlinear function. In the field of localization, lots of mature localization methods have been proposed to solve this function, in which the root mean square error (RMSE) is reduced to less than 5 m with SNR $\geq$5 dB [46], [47], [48]. The passive TDOA-based algorithm in this paper can be extended from the underwater acoustical localization of the black box utilizing a single AUV in [46]. Then, each AUV stores the obtained position into a row vector $\boldsymbol{L} = [\boldsymbol{l_1}, \boldsymbol{l_2}, \ldots, \boldsymbol{l_N}]$.

This localization stage also introduces time overhead to this system. Since the localization procedure contains four rounds of data transmission of static nodes, the AUV may not receive four rounds of packets from some static nodes within the communication range. Therefore, the AUV can only obtain local positions of static nodes.

2) Topology Construction: The topology of the network can help AUVs search the possible next-hop nodes and identify the packet scheduling of static nodes. Since AUVs listen to the packet from static nodes, they are able to obtain the source node and the destination node from the packet frame header, which reveals the existence of the communication link. Then AUVs construct a network topology map $\boldsymbol{H}_T$. The elements in $\boldsymbol{H}_T$ represent the communication links in the static network, where $\boldsymbol{H}_T(a, b) = 1$ indicates that a communication link between node a and node b exists, and $\boldsymbol{H}_T(a, b) = 0$, otherwise. Furthermore, based on the sending time of three or more rounds of received packets, the AUV can get the transmission period of static nodes, $T'_{j,k}$ for the sensor node $s_{j,k}$ and $T'_{i,j}$ for the relay node $m_{i,j}$. Then the number of relay nodes or sensor nodes sending data packets to a sink node or relay node is calculated, i.e., $M_i = T'_{i,j}/T_s$ and $S_j = T'_{j,k}/T_s$. Note that since AUV may not receive all packets from the static node, it can only construct the local topology.

In addition, the interference between static nodes should be considered in the packet scheduling scheme. When the distance between nodes r^b_a is larger than d_0 and $\boldsymbol{H}_T(a, b) = 0$, node a and node b will interference with each other, i.e., $\boldsymbol{H}_I(a, b) = 1$, and $\boldsymbol{H}_I(a, b) = 0$, otherwise.

3) Transmission Scheduling: AUVs need to determine the next-hop node and the appropriate time to send data packets without collision. With the information of nodes' positions, network topology map, and interference map, AUVs can calculate the data transmission time of static nodes. Then considering the data transmission time of static nodes, AUVs can identify available time slots to transmit data packets without packet collision. Finally, AUVs can determine the next-hop node and the appropriate time to send data packets. Next, we will give more details about the transmission scheduling stage.

V. Problem Formulation

In the transmission scheduling stage, AUVs need to determine the next-hop node and the sending time for each abnormal data and normal data in accordance with the VoI. To schedule data packets, the VoI maximization problem is formulated.

To schedule data packets successfully, the following constraints should be considered.

1) The data packet should be transmitted before the lifetime reaches, i.e., $t_A - t'_A \leq T$.
2) The next-hop node is expected to be selected from static nodes within the communication range of the AUV, which is denoted by $N' \in \mathcal{N}'$ under the constraint of $r^{N'}_A \leq d_0$. Here, $r^{N'}_A$ is the distance between the AUV A and the next-hop node N'.
3) The sending time t_A should meet the requirement of collision avoidance with the other ongoing transmitted data packets considering the long propagation delay t_p and transmission delay t_{data} in UASNs, i.e., $t_A + t_p + t_{\text{data}} \notin \Omega$, where t_p is expressed as $t_p = r^{N'}_A / v_s$. In addition, Ω is the packet collision time set, at which time data packets from an AUV would collide with data packets from static nodes or other AUVs. The packet collision constraint will be discussed in detail in Section VI-A.

Accordingly, the proposed transmission scheduling problem can be formulated as follows:

$$\max_{t_A \in \mathcal{T}_A,\ N' \in \mathcal{N}'} \quad V, \tag{11a}$$

$$\text{s.t. } t_A - t'_A \leq T, t_A \in \mathcal{T}_A, t'_A \in \mathcal{T}_P, \tag{11b}$$

$$r^{N'}_A \leq d_0, N' \in \mathcal{N}', A \in \mathcal{A}, \tag{11c}$$

$$t_A + t_p + t_{\text{data}} \notin \Omega. \tag{11d}$$

In the above problem, the objective function (11a) maximizes the VoI of data packets that are successfully received, where $\mathcal{T}_A$ is the possible transmission time without collision along the AUV's trajectory. Constraint (11b) limits the waiting time of abnormal data packets and normal data packets, where $\mathcal{T}_P$ is the generation time of data packets along the AUV's trajectory. Constraint (11c) limits the communication distance

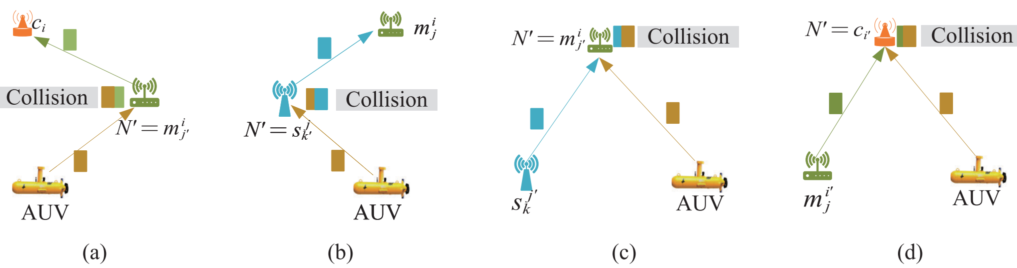

Fig. 3. Packet collision in Case 1 and Case 2: (a) Receiving-sending collision at the next-hop node which is a relay node; (b) Receiving-sending collision at the next-hop node which is a sensor node; (c) Receiving-receiving collision at the next-hop node which is a relay node; (d) Receiving-receiving collision at the next-hop node which is a sink node.

between AUVs and static nodes. Constraint (11d) limits the collision avoidance constraints.

The formulated problem is a combinatorial optimization problem, which can be solved by search algorithms. The search space of this problem depends on the problem constraints and is regarded as spatial and temporal scales. The global information-based search space is the number of static nodes N. To reduce the search space, we proposed the low-complexity algorithm based on the local information. Therefore, the VBPS-I algorithm is proposed to determine the appropriate next-hop nodes and sending time to schedule the normal packets and abnormal data packets based on maximizing the VoI of data packets. Furthermore, to deal with the packet collision among AUVs, we also propose the VBPS-C algorithm.

VI. Proposed Algorithms

In this section, we first present the packet collision constraint of AUVs' data transmission and then propose two algorithms to solve the problem.

A. Packet Collision Constraint

Due to the inherent characteristic of long propagation delay in UASNs, the spatial-temporal reuse is exploited by allowing multiple nodes to transmit data packets concurrently without packet collisions. Specifically, to schedule data transmission for AUVs without affecting the data transmission of static nodes, data packets from AUVs should not collide with any data packets from static nodes within the communication range of the AUV. The data packet collision constraints are constructed based on the transmission time of data packets and the propagation delay between nodes. Nodes within the communication range are divided into two categories, the next-hop node $N' \in \mathcal{N}'$, where $\mathcal{N}' = \{N' \mid \boldsymbol{H}_T(N', A) = 1\}$ and interference node $I \in \mathcal{I}$, where $\mathcal{I} = \{I \mid \boldsymbol{H}_I(I, A) = 1, \boldsymbol{H}_T(I, A) = 0\}$. In UASNs, due to the half-duplex communications, collision will happen when a node either receives or receives and sends two or more data packets simultaneously. As such, the packet collision scenario is divided into the following four cases. The detailed procedures of the packet collision constraint are shown in Algorithm 1.

1) Case 1: Receiving-Sending Collision at the Next-Hop Node: Due to the half-duplex underwater acoustic communications, the receiving time of the data packet from AUV should not collide with the sending time of the static node. So when an AUV wants to send a data packet to the next-hop node, it needs to justify when the next-hop node sends the data packet, at which time data packets from the AUV cannot be received simultaneously. As shown in Fig. 3(a), if the next-hop node N' of the AUV is a relay node $m_{i,j'} \in \{m_{i,j'} \mid \boldsymbol{H}_T(m_{i,j'}, c_i) = 1\}$, the condition is that when the node $m_{i,j'}$ is sending a data packet to the sink node c_i, it cannot receive the data packet from the AUV, which is expressed as

$$t_A + r^A_{m_{i,j'}}/v_s + t_{\text{data}} \notin \Omega_1, \tag{12}$$

where t_A is the sending time of the data packet from the AUV, Ω_1 is the collision time interval, denoted by $\Omega_1 = \left[t^{\mu_{i,j'}}_{i,j'} - t_g, t^{\mu_{i,j'}}_{i,j'} + 2t_{\text{data}} + t_g\right]$. Here, $\mu_{i,j'}$ is the number of communication time rounds for $m_{i,j'}$ when the AUV wants to send the data packet, which is calculated as follows $\mu_{i,j'} = \left\lfloor \frac{t_A}{T_s} \right\rfloor / M_i + 1$. t_g is the guard time. Similarly, as shown in Fig. 3(b), if the sensor node $s_{j,k'}$ is the next-hop node

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Algorithm 1 Collision Condition Calculation Subroutine

Input: $\boldsymbol{L}$, t_A, T_s, $\mathcal{S}$, $\mathcal{M}$, $\mathcal{C}$, $\boldsymbol{L}_A$, t_{data}, $\boldsymbol{H}_T$, r^A_N, $\boldsymbol{H}_I$, N', $\mathcal{N}'$;
Output: t_A;

```
Ω = ∅;
Put N' \ N' into I; //The interference node set;
if N' ∈ C then
    Calculate Ω ← Ω_4 based on (15);
else if N' ∈ M then
    Calculate Ω ← Ω_1 ∪ Ω_3 based on (12) and (14);
else if N' ∈ S then
    Calculate Ω ← Ω_2 based on (13);
end if
for N' ∈ I do
    Calculate Ω ← Ω_5 ∪ Ω_6 based on (16) and (17);
end for
if t_A + r^A_{N'}/v_s + t_data ∉ Ω then
    t_A = t_A;
    The AUV transmits data packets to node N' at time t_A;
else
    while t_A + r^A_{N'}/v_s + t_data ∈ Ω do
        t_A = t_A + t_i;
    end while
    The AUV transmits data packets to node N' at time t_A;
end if
return t_A.
```

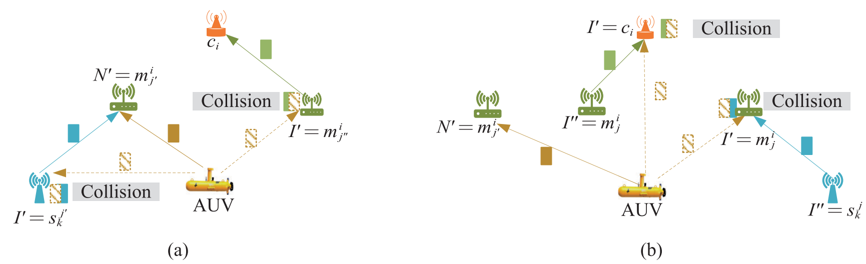


Fig. 4. Packet collision in Case 3 and Case 4: (a) Receiving-sending collision at the interference nodes; (b) Receiving-receiving collision at the interference nodes.

of the AUV, it cannot send the data packet to node $m_j \in \{m_j \mid \boldsymbol{H}_T(s_{j,k'}, m_j) = 1\}$ while receiving the data packet from the AUV. So the collision avoidance condition is given by

$$t_A + r^A_{s_{j,k'}}/v_s + t_{\text{data}} \notin \Omega_2, \tag{13}$$

where Ω_2 is the collision time interval for the sensor node and is denoted by $\Omega_2 = \left[t_{j,k'}^{\mu_{j,k'}} - t_g, t_{j,k'}^{\mu_{j,k'}} + 2t_{\text{data}} + t_g\right]$. Here, $\mu_{j,k'}$ is the number of communication round for $s_{j,k'}$ when the AUV wants to send data packet, which is given by $\mu_{j,k'} = \left\lfloor \frac{t_A}{T_s} \right\rfloor / S_j + 1$.

Since sink nodes do not need to send data via the acoustic communication link, they will not suffer from receiving-sending collision when they serve as the next-hop node.

2) Case 2: Receiving-Receiving Collision at the Next-Hop Node: The collision occurs when multiple data packets are received simultaneously at the next-hop node. That is to say, when an AUV wants to send a data packet to the next-hop node, it should consider the receiving data packet collision with other nodes. As shown in Fig. 3(c), if the next-hop node of AUV is a relay node $m_{i,j'}$, it cannot receive the data packets from other nodes simultaneously. So the AUV firstly needs to find the sensor node $s_{j',k} \in \mathcal{S}^{j'}$, where $\mathcal{S}^{j'} = \{s_{j',k} \mid \boldsymbol{H}_T(m_{i,j'}, s_{j',k}) = 1\}$, who is sending data packet to the relay node $m_{i,j'}$. At time t_A, the sequence k is calculated as follows $k = \left\lfloor \frac{t_A}{T_s} \right\rfloor - (\mu_{j',k} - 1) S_{j'} + 1$. So the collision avoidance time is given by

$$t_A + r^A_{m_{i,j'}}/v_s + t_{\text{data}} \notin \Omega_3, \tag{14}$$

where Ω_3 is the collision time interval for the relay node and is denoted by $\Omega_3 = \left[t_{j',k}^{\mu_{j',k}} + r_{m_{i,j'}}^{s_{j',k}}/v_s - t_g, t_{j',k}^{\mu_{j',k}} + r_{m_{i,j'}}^{s_{j',k}}/v_s + 2t_{\text{data}} + t_g\right]$. Similarly, as shown in Fig. 3(d), if the next-hop node of AUV is a sink node $c_{i'}$, it cannot receive the data packets from the AUV and the relay node $m_{i',j} \in \mathcal{M}^{i'}$ simultaneously, where $\mathcal{M}^{i'} = \{m_{i',j} \mid \boldsymbol{H}_T(c_{i'}, m_{i',j}) = 1\}$. The sequence number j is calculated as follows $j = \left\lfloor \frac{t_A}{T_s} \right\rfloor - (\mu_{i',j} - 1) M_{i'} + 1$. So the collision avoidance condition is expressed as

$$t_A + r^A_{c_{i'}}/v_s + t_{\text{data}} \notin \Omega_4, \tag{15}$$

where Ω_4 is the collision time interval for the sink node and is denoted by $\Omega_4 = \left[t_{i',j}^{\mu_{i',j}} + r_{c_{i'}}^{m_{i',j}}/v_s - t_g, t_{i',j}^{\mu_{i',j}} + r_{c_{i'}}^{m_{i',j}}/v_s + 2t_{\text{data}} + t_g\right]$.

Since the sensor nodes do not receive any data packets from others, they will not cause the receiving-receiving collision when they serve as the next-hop node.

3) Case 3: Receiving-Sending Collision at the Interference Node: Interference nodes are in the communication range of the AUV and will receive data packets transmitted from the AUV. Since the underwater acoustic communication modem is in half-duplex mode, the interference nodes can not send data packets when it is receiving the data packets. As shown in Fig. 4(a), when an AUV wants to transmit a data packet, it needs to consider the collision not only at the next-hop node but also at the other interference node $I' \in \mathcal{I}$. That is, the arriving time of data packets from the AUV and the sending time of data packets at the interference node cannot overlap, which is denoted by

$$t_A + r^A_{I'}/v_s + t_{\text{data}} \notin \Omega_5, \tag{16}$$

where Ω_5 is the collision time interval for the interference node and is denoted by $\Omega_5 = \left\{\left[t_{j',k}^{\mu_{j',k}} - t_g, t_{j',k}^{\mu_{j',k}} + 2t_{\text{data}} + t_g\right] \mid I' \in \mathcal{S}^{j'}\right\} \cup \left\{\left[t_{i',j}^{\mu_{i',j}} - t_g, t_{i',j}^{\mu_{i',j}} + 2t_{\text{data}} + t_g\right] \mid I' \in \mathcal{M}^{i'}\right\}$.

4) Case 4: Receiving-Receiving Collision at the Interference Node: The collision occurs when multiple data packets are received overlapping at interference nodes. As shown in Fig. 4(b), when a data packet is transmitted from the AUV, it may cause a non-neglected receiving-receiving collision at the interference node $I' \in \mathcal{I}$. That is, the interference node I' cannot receive data packets from the AUV, and the corresponding interference node $I'' \in \{I'' \mid \boldsymbol{H}_I(I', I'') = 1\}$, simultaneously. So the arriving time of the data packet from the AUV A cannot overlap with that of the packet from the corresponding interference node I'', which is expressed as

$$t_A + r^A_{I'}/v_s + t_{\text{data}} \notin \Omega_6, \tag{17}$$

where Ω_6 is the collision time interval for the interference node and is denoted by $\Omega_6 = \left\{\left[t_{j',k}^{\mu_{j',k}} + r_{I'}^{I''}/v_s - t_g, t_{j',k}^{\mu_{j',k}} + r_{I'}^{I''}/v_s + 2t_{\text{data}} + t_g\right] \mid I'' \in \mathcal{S}^{j'}\right\} \cup \left\{\left[t_{i',j}^{\mu_{i',j}} + r_{I'}^{I''}/v_s - t_g, t_{i',j}^{\mu_{i',j}} + r_{I'}^{I''}/v_s + 2t_{\text{data}} + t_g\right] \mid I'' \in \mathcal{M}^{i'}\right\}$.

According to (12)-(17), the collision avoidance conditions is summarized as follows

$$t_A + r^A_{N'}/v_s + t_{\text{data}} \notin \Omega, \tag{18}$$

where $\Omega = \{\{\Omega_1 \cup \Omega_3 \mid N' \in \mathcal{M}\} \cup \{\Omega_2 \mid N' \in \mathcal{S}\} \cup \{\Omega_4 \mid N' \in \mathcal{C}\} \cup \{\Omega_5 \cup \Omega_6 \mid N' \in \mathcal{I}\}\}$.

B. VBPS-I Algorithm

To transmit the abnormal data and the normal data, we should select a next-hop node from static nodes and determine the transmission time with the least collision and minimum delay. Based on the network topology and positions of static nodes, AUVs first find out all possible next-hop nodes within the AUVs' communication range and calculate the transmission time based on packet collision constraints. Then AUVs can determine the optimal next-hop nodes and transmission time for the abnormal data and the normal data. Finally, data packets are transmitted to the selected nodes at the scheduled time. The details are shown as follows and the detailed procedures of the VBPS-I algorithm are presented in Algorithm 2.

1) **Search possible next-hop nodes**. As AUVs move, they can obtain the locations of static nodes based on Section IV-B.1. When data packets arrive, AUVs take the static nodes within AUVs' communication range as candidate next-hop nodes. Note that an AUV can only select the static nodes whose locations are obtained by it. Actually, since AUVs do not obtain the global information of static nodes, they will be not aware of some static nodes within their communication range. Note that the probability of no possible next-hop nodes is determined by the distance between the static node and the AUV at the AUV's data packet arrival time and the static node's data packet departure time. If the trajectory of AUV is carefully designed, the probability can be greatly reduced. In addition, if there are no possible next-hop nodes when a data packet arrives, the AUV will delay the data packet sending time to find the next-hop node until the next packet is generated.
2) **Search possible transmission time**. As illustrated in Section VI-A, AUVs calculate the possible transmission time based on the packet collision constraints. As the data packets arrive, AUVs search all the possible earliest sending time for each candidate next-hop node $N' \in \mathcal{N}'$. When the data packets arrive at AUVs, AUVs check the collision constraint based on (18). If the transmission time does not satisfy the collision constraint, it will be delayed until the earliest collision-free time. Specifically, in the VBPS-I, AUVs do not cooperate with each other, and packet collision among AUVs cannot be avoided.
3) **Avoid collision between abnormal data and normal data**. Although the abnormal data and normal data arrive following different packet arrival rates, they may arrive at the same time slot. Therefore, we need to select different next-hop nodes and transmission times to avoid collision among them. For these two kinds of data, the abnormal data requires less waiting delay, so the abnormal data should be transmitted before the normal data when their arrivals meet at the AUV.
4) **Determine optimal next-hop node and transmission time**. Based on the above possible transmission time and collision avoidance constraint, AUVs can calculate the VoI of data packets. Then AUVs select the optimal next-hop node and transmission time from all the possible search spaces for abnormal data and normal data.

Algorithm 2 VBPS-I

Input: $\boldsymbol{L}$, T_s, $\mathcal{S}$, $\mathcal{M}$, $\mathcal{C}$, $\boldsymbol{L}_A$, t_{data}, $\boldsymbol{H}_T$, $\boldsymbol{H}_I$, t'_{Au}, t'_{Am};
Output: N'_u, t_{Au}, N'_m, t_{Am};
1: // Search possible next-hop nodes;
2: $\mathcal{N}' = \emptyset$;
3: **while** $\mathcal{N}' = \emptyset$ **do**
4:   **for** $N \in \mathcal{C} \cup \mathcal{M} \cup \mathcal{S}$ **do**
5:     $r_N^A = ||\boldsymbol{l}_N - \boldsymbol{l}_A(t)||_2$;
6:     **if** $r_N^A \leq d_0$ **then**
7:       $\boldsymbol{H}_T(A,N) = 1$, $\boldsymbol{H}_I(A,N) = 1$;
8:       Put N into $\mathcal{N}'$;
9:     **end if**
10:   **end for**
11:   $\boldsymbol{l}_A(t) = \boldsymbol{l}_A(t + t_i)$;
12: **end while**
13: // Search possible transmission time
14: // For the abnormal data packet
15: $V'_U = 0$, $V'_M = 0$;
16: **for** $N' \in \mathcal{N}'$ **do**
17:   $t_A = t'_{Au}$;
18:   Execute Collision Condition Calculation Subroutine;
19:   Calculate V_U;
20:   **if** $V_U \geq V'_U$ **then**
21:     $N'_u = N'$, $t_{Au} = t_A$;
22:   **end if**
23: **end for**
24: // For the normal data packet
25: **for** $N' \in \mathcal{N}'$ **do**
26:   $t_A = t'_{Am}$;
27:   **if** $N' \neq {N_u}'$ **then**
28:     Execute Collision Condition Calculation Subroutine;
29:   **else**
30:     **repeat**
31:       Execute Collision Condition Calculation Subroutine;
32:     **until** $|t_A - t_{Au}| > t_{\text{data}} + t_g$;
33:   **end if**
34:   Calculate V_M;
35:   **if** $V_M \geq V'_M$ **then**
36:     $N'_m = N'$, $t_{Am} = t_A$;
37:   **end if**
38: **end for**
39: Send the abnormal data packet to ${N_u}'$ at time t_{Au};
40: Send the normal data packet to ${N_m}'$ at time t_{Am};

Computational Complexity Analysis: Let the number of nodes in $\mathcal{N}'$ is denoted by $|\mathcal{N}'|$, which is much smaller than N. The subroutine executes the loop $|t_A|$ times. In Algorithm 2, the process is divided into three phases. Firstly, for the calculation of distance in Lines 1-8, the loop is executed N times. Secondly, for each abnormal data packet in Lines 9-18, the loop is executed $|\mathcal{N}'|$ times, and the subroutine is executed once. Finally, for each normal data packet in Lines 19-28, the loop is executed $|\mathcal{N}'|$ times. As a result, the computational complexity of the VBPS-I algorithm is quadratic $O(|\mathcal{N}'||t_A|)$.

C. VBPS-C Algorithm

The VBPS-I algorithm only considers packet collisions between static nodes and AUVs but it does not consider packet collisions between AUVs. Therefore, we propose another algorithm named VBPS-C to address the problem of packet collisions between AUVs.

When AUVs move within each others' communication range, they can share information, such as known locations of nodes and the topology of the static network. Then to avoid packet collision among AUVs, AUVs send a short frame before transmitting packets to inform the other AUVs. If other AUVs receive this frame, they will take these packets into consideration when scheduling their packet transmission. The packet collision probability of short frames is considered to be negligible due to the following two reasons. Firstly, the length of the short frame is short, such that the collision probability is low. Secondly, the packet error rate of the short frame is lower than that of long data packets with the same BER.

When two or more AUVs want to send data packets, they need to consider the collision they cause at the same node. Therefore, for node $N' \in \mathcal{N}'$, where $\mathcal{N}' = \{N' \mid \exists A' \in \mathcal{N}_A, A \in \mathcal{N}_A, A \neq A', \boldsymbol{H}_I(A, N') = 1, \boldsymbol{H}_I(A', N') = 1\}$, which is located in the communication range of two or more AUVs, the collision avoidance condition is calculated as follows:

$$t_A + r_{N'}^{A}/v_s + t_{\text{data}} \notin \Omega_7, \tag{19}$$

where $\Omega_7 = \left[t_{A'} + r_{N'}^{A'}/v_s - t_g, t_{A'} + r_{N'}^{A'}/v_s + 2t_{\text{data}} + t_g\right]$. Since the computation of the cooperation among AUVs is linear, the computation complexity of the VBPS-C algorithm is the same as the VBPS-I algorithm, i.e., $O(|\mathcal{N}'||t_A|)$.

VII. Performance Evaluation

Extensive simulations are carried out to demonstrate the performance of the proposed VBPS-I and VBPS-C algorithms.[1]

A. Simulation Setup

In this simulation, we use the commercial underwater acoustic communication modem specifications of S2CR18/34 from Evologics [49]. For this modem, the frequency f is set to be 18 kHz to 34 kHz, the data rate R is 13.9 kbps, and the transmission power P is 65 W. The static network is a two-hop network, where N nodes are randomly deployed in a 3D area of 10,000 m $\times$ 6,000 m $\times$ 5,000 m. The velocity of AUVs is set to be 10 m/s. The packet generation follows a Poisson arrival with packet arrival rate λ_u for the abnormal data and λ_m for the normal data. Regarding the VoI, the initial value V^0 is the same as the data packet size; the weighting parameters β_u and β_m are set to be 0.3 and 0.5, respectively; the scaling factor α is 3; and T_u and T_m are five and ten times of the time slot T_s.

To evaluate the performance of the proposed algorithms, three benchmarks are compared:

- Random access strategy (RA): When the data packet arrives at the AUV, the data packet will be sent after a random back-off time.
- Load adaptive CSMA/CA MAC protocol (LACCM): AUVs send a beacon packet before sending data, which stops all the ongoing transmission to avoid packet collision [32].
- Optimal strategy: In the optimal strategy, AUV possesses the global information of static nodes. So the data transmission is scheduled based on the global information.

B. Performance Metrics

In this simulation, some performance metrics are evaluated.

1) Collision Probability: We define the collision probability to measure the deterioration of transmission efficiency, which contains two parts, i.e., the collision probability between AUV and static nodes and the collision probability among AUVs. The first part indicates the effectiveness of packet collision avoidance in the proposed VBPS-I algorithm and the second part verifies the packet collision avoidance strategy among AUVs in the VBPS-C algorithm.

2) Congestion Ratio: If the packet has not been released promptly before the next packet is generated, it will congested in the queue. The congestion ratio is used to measure the congestion of the packet queue and indicates the promptness of the transmission, which is defined as

$$\eta = \sum_{a=1}^{N_A} \frac{\sum_{n=1}^{n_a} W_a(n)}{n_a}, \tag{20}$$

Here, $W_a(n) = 1$ indicates that the data packet n from an AUV A needs to wait in the queue and $W_a(n) = 0$, otherwise. Note that if the next-hop node can not be found, the data packet will be congested. Therefore, the network congestion ratio can also be defined as the probability of no possible next-hop nodes.

3) Network Throughput: The network throughput is defined as the average number of bits per second that static nodes receive from AUVs successfully during the time of AUV's trajectories.

4) Average End-to-End Delay: The average end-to-end delay is the average time delay of all data packets from the time generated at the AUV to the time received by the sink node. In other words, the end-to-end delay consists of the waiting time at the AUV, the transmission time, the propagation delay transmitted from the AUV to the next-hop node, and the time delay from the next-hop node to the sink node. Therefore, the average end-to-end delay can reflect the promptness of the data packet transmission.

5) Cumulative VoI: The cumulative VoI is the sum of VoI for all AUVs during their trajectory T_a and is calculated as follows

$$V_c = \sum_{a=1}^{N_A} \sum_{T_a} V. \tag{21}$$

C. Simulation Results

To verify the performance of the proposed VBPS-I and VBPS-C algorithms, we conduct simulations in different

[1]The codes to reproduce the simulation results are available on https://github.com/zhuoxx/code-for-VBPS-UASNs

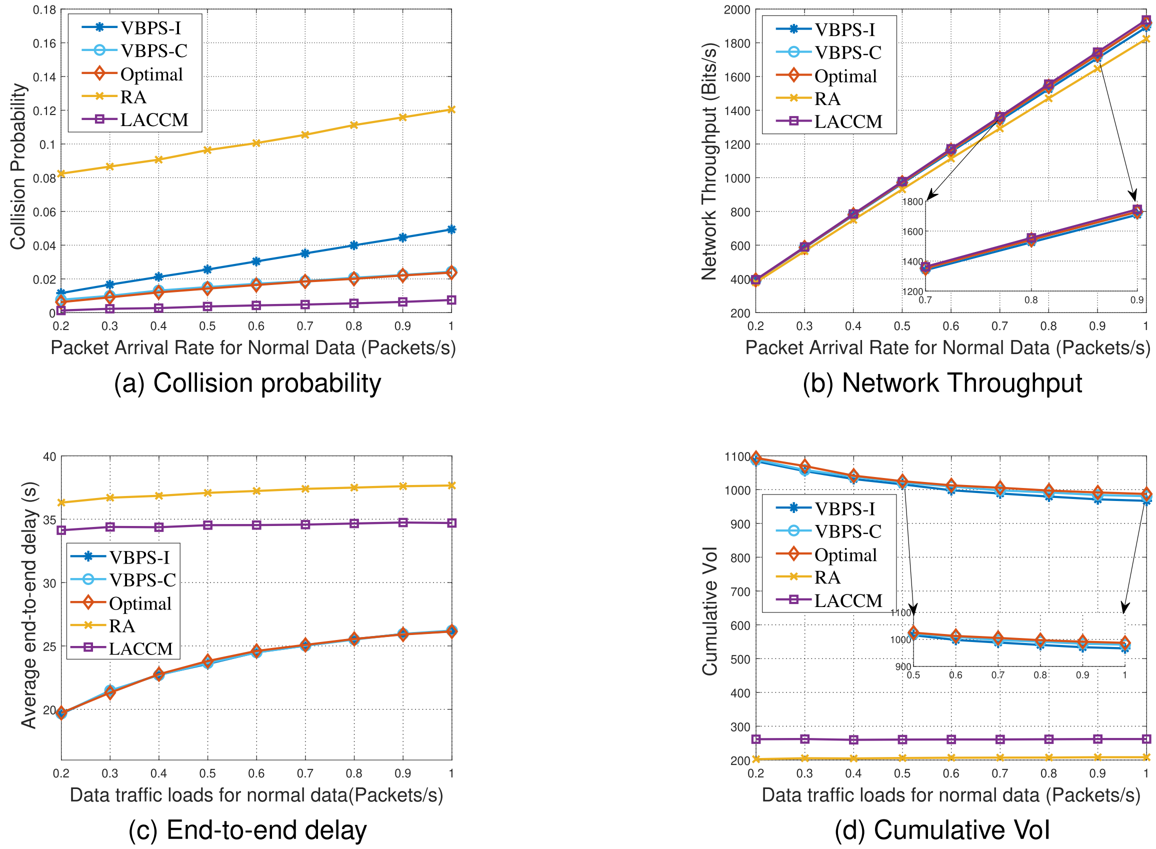


Fig. 5. Network performance with different packet arrival rates.

scenarios, i.e., different packet arrival rates λ varying from 0.01 to 0.1 packets/s for the abnormal data and from 0.1 to 1 packets/s for the normal data, different numbers of AUVs varying from 1 to 5, and different packet sizes varying from 500 to 5,000 bits.

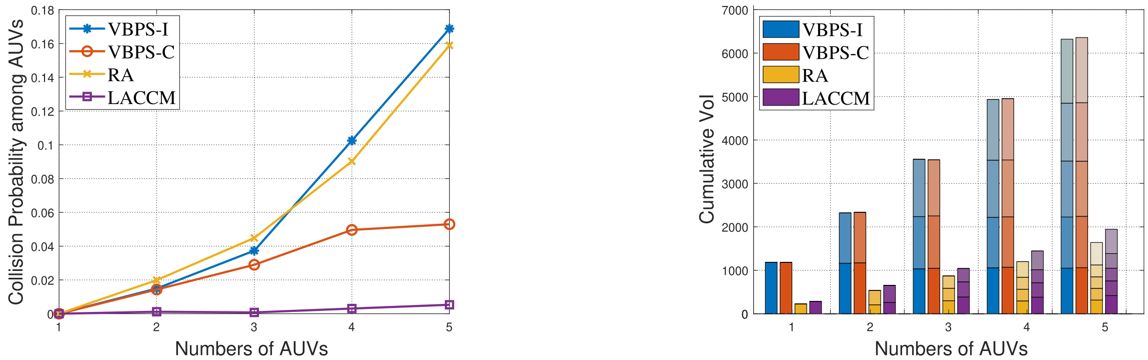
1) Performance With Different Packet Arrival Rates: In the simulation, all data packets arrive at AUVs following the Poisson process with different packet arrival rates λ varying from 0.01 to 0.1 packets/s for the abnormal data and from 0.1 to 1 packets/s for the normal data. In the scenario, the number of AUVs is set to be 2, the number of static nodes is 42, and the packet size is 1,000 bits. In addition, once data packets arrive, AUVs add them into the waiting queue and send them at scheduled time.

Figure 5 displays the performance of proposed algorithms with different packet arrival rates. The collision probability is shown in Fig. 5(a). It shows that with the increase of packet arrival rate, the collision probability of all algorithms increases. To be specific, the collision probability of the VBPS-I is larger than that of the VBPS-C while it is greatly smaller than that of the RA. This is because, the proposed VBPS-C and VBPS-I both calculate the packet collision constraints to avoid collision, while the RA does not. In addition, in the VBPS-C, AUVs cooperate with each other and share the information of static nodes, which is not applied in the VBPS-I. Furthermore, due to the absence of global information of static nodes, the collision probability of VBPS-C is slightly larger than that of the optimal strategy. The collision probability of the LACCM strategy is negligible due to stopping all the ongoing packet transmission before transmitting packets.

Figure 5(b) shows how the packet arrival rate affects the network throughput. The results show that the network throughput increases linearly as the packet arrival rate increases. The network throughput of these algorithms is influenced by the collision probability and end-to-end delay. The higher collision probability leads to lower network throughput.

Figure 5(c) displays the average end-to-end delay. The average end-to-end delay of these protocols increases slightly with the increase of packet arrival rate. The reason is that with the increase of packet arrival rate, the waiting queue increases, which results in the increase of the average end-to-end delay. In addition, the average end-to-end delay of the VBPS-I, the VBPS-C, and the optimal strategy is greatly shorter than that of the RA and the LACCM. This is because the VBPS-I and the VBPS-C calculate the end-to-end delay of all possible receivers and select the best candidate of the next-hop node based on VoI. Thus, the end-to-end delay is shorter compared with that of the RA and the LACCM which select the next-hop nodes randomly.

Regarding cumulative VoI, the VBPS-I, the VBPS-C, and the optimal strategy perform closely and better than the RA and the LACCM as shown in Fig. 5(d). The reason is that the next-hop nodes are selected to maximize VoI in the VBPS-I and the VBPS-C, while they are selected randomly in the RA and the LACCM. Results demonstrate that the strategy of data



(a) Collision probability among AUVs (b) Cumulative VoI

Fig. 6. Collision probability among AUVs and cumulative VoI performance with different numbers of AUVs.

packet transmission based on VoI is effective. In addition, the cumulative VoI of all the algorithms decreases slightly as the packet arrival rate increases. This is because, the relative end-to-end delay increases with the increase of the packet arrival rate, which results in the decrease of VoI.

2) Performance With Different Numbers of AUVs: Network performance is closely related to the number of AUVs, so the collision ratio among AUVs and cumulative VoI are evaluated with different numbers of AUVs varying from 1 to 5. The packet arrival rates of abnormal and normal data are set to 0.05 packets/s and 0.5 packets/s, respectively.

Figure 6(a) demonstrates that with the increase of AUVs' number, the collision probability among AUVs increases. In addition, the collision probability among AUVs of VBPS-I is close to that of RA while larger than that of VBPS-C and the LACCM. This is because the VBPS-I has not considered collision avoidance among AUVs. Furthermore, the collision probability among AUVs of the VBPS-C is larger than that of the LACCM. This is because the collaboration among AUVs in the VBPS-C can reduce the packet collision among AUVs but the hidden terminal problem leads to packet collision when the number of AUVs is large. As shown in Fig. 6(b), the cumulative VoI of the VBPS-I and the VBPS-C is larger than that of the RA and the LACCM as illustrated above. When the number of AUVs increases, the cumulative VoI increases linearly while the cumulative VoI for each node is slightly decreased. In addition, the cumulative VoI for each AUV in each algorithm is roughly close.

3) Performance With Different Types of Data: Since the abnormal data and normal data arrive with different packet arrival rates and with different VoI, they would be scheduled with different levels of urgency. Therefore, to show the performance of abnormal data and normal data accurately and clearly, the congestion ratio defined in (20) is verified to show the different network performances of different kinds of data.

The congestion ratio is displayed in Fig. 7. Note that the packet arrival rate in the horizontal coordinate is for both abnormal data from 0.01 to 0.1 packets/s with the interval of 0.01 packets/s and normal data from 0.1 to 1 packets/s with the interval of 0.1 packets/s. In general, it shows that the congestion ratio of the VBPS-I, the VBPS-C, and the optimal strategy increases greatly with the increase of packet arrival rate while that of the RA and the LACCM decreases for abnormal

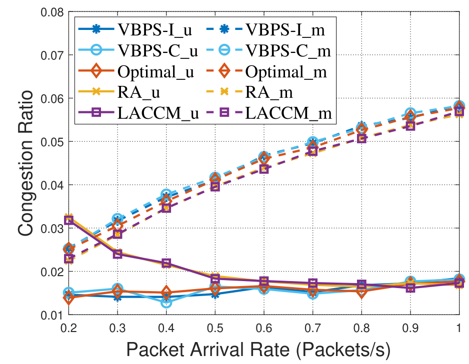


Fig. 7. Congestion ratio for abnormal data and normal data.

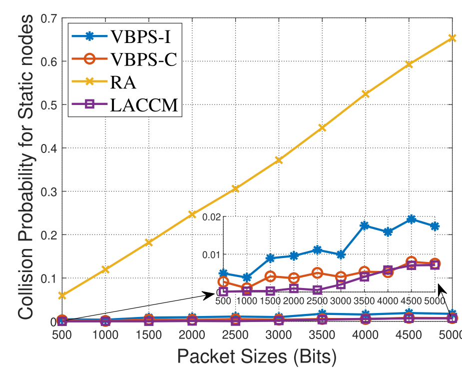


Fig. 8. Collision probability with vary packet sizes.

data and increases for normal data. More specifically, the congestion ratio of the proposed VBPS-I, the VBPS-C, and the optimal strategy is lower than that of the RA and the LACCM with packet arrival rate for abnormal data while it is larger with packet arrival rate for normal data. This is because, in the VBPS-I, the VBPS-C, and the optimal strategy, when the packet arrival rate is low, AUVs can easily identify a proper static node as the next-hop node under packet collision constraints. However, as the packet arrival rate increases, a number of packets are not sent promptly, so the length of the queue increases. In the RA and the LACCM, AUVs select a random node as the next-hop node, regardless of collision constraints, such that the congestion ratio is lower than that of the VBPS-I, the VBPS-C, and the optimal strategy.

4) Performance With Different Packet Sizes: The packet sizes affect the collision probability among static nodes. In this simulation, we evaluate the performance with different packet sizes varying from 500 to 5000 bits. In this case, the number of static nodes and AUVs is 63 and 2, respectively. In addition, the packet arrival rate is 0.05 packets/s for the abnormal data and 0.5 packets/s for the normal data. As shown in Fig. 8, the collision probability among static nodes of the VBPS-I, the VBPS-C, and the LACCM increases slightly with the increase of packet size while that of the RA increases linearly. This verifies that the performance of the VBPS-I and the VBPS-C is robust with the change of packet length, benefiting from the consideration of packet collision constraints.

VIII. Conclusion

In this paper, we have proposed a VoI-based packet scheduling scheme for AUVs via static networks to address challenges of the absence of static nodes' global information and collision avoidance with the ongoing transmission of static nodes. The proposed scheme can enable AUVs to promptly deliver abnormal data packets while avoiding packet collision. Extensive simulation results show that the proposed scheme can perform closely to the optimal one. For future work, we will study the joint design of AUV trajectory and packet scheduling.

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