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

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***Abstract*—This paper studies autonomous underwater vehicles (AUV)-assisted underwater acoustic sensor networks (UASNs), where AUVs act as mobile sensor nodes to collect information from areas not accessible to static nodes and then relay data via static nodes. Due to the difficulty of obtaining the accurate global information of all the static nodes, we propose a novel packet scheduling scheme by utilizing local information obtained by AUVs. In the proposed scheme, the localization of static nodes stage and the topology construction stage are carried out beforehand to obtain the local information, based on which the transmission scheduling stage is implemented. Furthermore, in the transmission scheduling stage, we design a value of information (VoI)-based packet transmission scheduling (VBPS) strategy to avoid packet collision. Specifically, we introduce a performance metric, i.e., VoI, to measure the importance of data packets with different levels of urgency. Then, we formulate a combinatorial optimization problem to maximize VoI taking packet collision avoidance into consideration. A low-complexity distributed search algorithm is proposed to solve the problem, 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. Extensive simulations under various scenarios are carried out to evaluate the performance of the proposed algorithm.**

I. Introduction

With the prosperous development of underwater wireless communications, the Internet of underwater Things (IoUT) has become an emerging field and attracted much attention. In long-distance underwater communications, sound wave plays a prominent role due to less propagation attenuation than radio wave and less scattering than optical wave [1]. Underwater acoustic sensor networks (UASNs) are expected to be a defacto technology to meet the tremendous demand of marine exploration, such as environmental monitoring, marine ranching, and marine resource development [2], [3]. Traditional UASNs consisting of several static sensor nodes can only be deployed at fixed areas. As a remedy to the limitation, autonomous underwater vehicles (AUVs) with high maneuverability are considered as a promising complement to static UASNs, which can expand the coverage and enhance the performance of existing UASNs. As such, AUV-assisted UASNs are deemed as a potential paradigm for underwater wireless communications. In AUV-assisted UASNs, AUVs can explore areas that are not accessible to static nodes and forward data via static sensor nodes. In this scenario, static nodes are routinely deployed to monitor the environment for a long period time. When the data center identifies the abnormal information, AUVs are dispatched to the area of interest, and then AUVs can inspect, detect, and report detailed abnormal information. Therefore, to transmit data efficiently, AUVs need to determine the appropriate next-hop node and transmission time to relay and report the detected information, i.e., packet scheduling.

Designing an effective packet scheduling scheme is challenging due to the following two reasons. Firstly, AUVs need to obtain the *global information* of the static network to make optimal data packet transmission decisions. However, global information is not realistic to be known in advance because static nodes have been deployed for a long time and are difficult to be tracked. Secondly, AUVs should transmit data packets *without colliding* with regular data transmissions among static nodes which need to perform their own tasks. However, due to time-varying propagation delay and dynamic network topology in AUV-assisted UASNs, collision avoidance constraints vary spatially and temporally.

In the literature, several research works are devoted to addressing these challenges. The propagation delay-aware opportunistic (DOTS) MAC protocol jointly considered the data packet transmission for both static nodes and mobile nodes [4]. To avoid packet collision, mobile nodes schedule their packet transmission time and conduct concurrent transmission among nodes with the requirement of clock synchronization and global information of the network. In the data-collection-oriented MAC (DCO-MAC) protocol [5], the data transmission time for mobile nodes and static nodes were initiated and scheduled by the sink node sequentially after several rounds of handshaking. In the load-adaptive carrier sense multiple access control MAC (LACCM) protocol, a specific broadcast (BCT) packet was introduced to reserve the channel for AUVs [6]. However, in the above works, reserving transmission resources for AUVs' packets may disturb regular packet transmissions of static nodes. Different from the existing works, our work takes two realistic factors into consideration, i.e., the absence of global information of static networks and the requirement of collision avoidance with regular data transmission among static nodes.

In this paper, we design a novel packet scheduling scheme to tackle these challenges. The scheme includes three steps: (1) localization for static nodes, in which AUVs adopt a modified passive time difference of arrival (TDOA)-based localization method to obtain positions of static nodes; (2) topology construction, in which AUVs establish the topology map and interference map based on the information of data packets listened from static nodes; and (3) transmission scheduling, in which AUVs determine the appropriate next-hop nodes and time to transmit data packets under the constraints of packet collision avoidance. Furthermore, in the transmission scheduling stage, we design a value of information (VoI)-based packet transmission scheduling (VBPS) strategy to avoid packet collisions. Specifically, we introduce a performance metric, value of information (VoI), to measure the importance of data packets with different levels of urgency. Then, we formulate a combinatorial optimization problem to maximize the VoI subject to packet collision avoidance constraints. Obtaining the optimal solution requires global information of static network, which incurs significant signalling overhead. Thus, a low-complexity distributed search algorithm is developed to solve this problem based on local information obtained by each AUV. Besides, the algorithm exploits the spatial-temporal reuse to establish the data packet collision constraints and determines the next-hop nodes and data transmission time for AUVs based on problem constraints. Extensive simulations under various scenarios are carried out, and comprehensive analyses are provided to evaluate the performance of the proposed algorithm.

The main contributions in this paper are summarized as follows:

1) We design a data packet scheduling scheme for AUVs without requiring global information while avoiding collision with regular data transmissions among static nodes;
2) We formulate a combinatorial optimization problem to maximize VoI and develop a low-complexity distributed search algorithm to solve this problem.

The remainder of this paper is organized as follows. In Section II, the packet scheduling scheme is presented. Problem formulation is described in Section III. Following this, the VBPS algorithm is proposed in Section IV. In Section V, performance evaluation is provided. Finally, the conclusion is given in Section VI.

II. Packet Scheduling Scheme

A. System Model

In this paper, we consider a three-dimensional (3D) network consisting of N static nodes that are distributed in the considered area and N_A AUVs denoted by $\mathcal{N}_\mathcal{A} = \{A_1, A_2, ..., A_{N_A}\}$ as illustrated in Fig. 1. AUVs send detected information to the data center located at the boat or the land via static nodes. The trajectories of AUVs are pre-defined before releasing according to their tasks.

For the underwater acoustic communication channel, the average bit error rate (BER) is given by $p_e\left(\gamma\left(r_a^b, f\right)\right) = Q\left(\sqrt{2\gamma\left(r_a^b, f\right)}\right)$ with binary phase shift key (BPSK) modulation, where $\gamma\left(r_a^b, f\right)$ is the SNR at the receiver b at frequency f and distance r_a^b away from the sender a. Then the packet error rate (PER) can be calculated as follows $P_e\left(\gamma\left(r_a^b, f\right)\right) = 1 - \left(1 - p_e\left(\gamma\left(r_a^b, f\right)\right)\right)^L$.

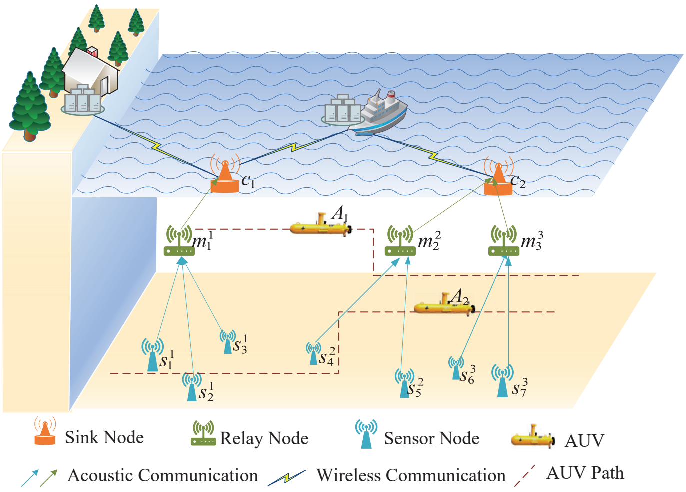


Fig. 1. Network model of the proposed AUV-assisted UASNs.

For the network, static nodes are already pre-deployed and running with two hops with the time division multiple access (TDMA) protocol. Static nodes can be divided into three layers: (1) sink nodes denoted by $\mathcal{C} = \{c_1, c_2, ..., c_C\}$; (2) relay nodes denoted by $\mathcal{M} = \{m_1, m_2, ..., m_M\}$; (3) sensor nodes denoted by $\mathcal{S} = \{s_1, s_2, ..., s_S\}$. Here, we have $N = C + M + S$. Time is divided into time slots, whose duration is decided by the communication range d_0, sound speed v_s and packet length, i.e., $T_s = \left\lceil \frac{t_{\text{data}} + d_0/v_s}{t_{\text{data}}} \right\rceil t_{\text{data}}$. Here, t_{data} denotes the data transmission time, i.e., $t_{\text{data}} = L_{\text{data}}/R$, where L_{data} is the data packet length and R is the transmission data rate of the underwater acoustic modem. We assume that a relay node m_j relays data packets for S_j number of sensor nodes s_k^j, which is denoted by $s_k^j \in \mathcal{S}_j$ $(k = \sum_{j'=1}^{j-1} S_{j'} + (1, 2, ..., S_j))$. Note that the number of sensor nodes satisfy $S = \sum_{j=1}^{M} S_j$. Similarly, we assume that a sink node c_i receives data packets from M_i number of relay nodes m_j^i, which is denoted by $m_j^i \in \mathcal{M}_i$ $(j = \sum_{j'=1}^{i-1} M_{j'} + (1, 2, ..., M_i))$. Note that the number of relay nodes satisfy $M = \sum_{i=1}^{C} M_i$. The strategy of the MAC protocol is known to AUVs, but the scheduling time of each node is not revealed. In addition, the locations of static nodes and the network topology are unknown by AUVs. What's more, static nodes are all time synchronized while AUVs may not be synchronized with them.

B. Scheme Design

In this paper, we propose the packet scheduling scheme to help AUVs transmit data packets via static nodes efficiently. In this scenario, AUVs are in charge of collecting data from specific interested areas with pre-defined trajectory. Trajectory of AUVs can be designed via multiple methods [7], [8], which is beyond the scope of this paper. When AUVs move along their pre-defined trajectories, they need to determine the static node to relay data packets as well as the time to send data packets. In the proposed scheme, the following three steps are conducted to transmit data efficiently and successfully.

1) Localization for Static Nodes: In this network, AUVs need to obtain the locations of nodes to calculate the propagation delay between them, which is used for the packet collision avoidance strategy. Restricted with the time synchronization, the modified TDOA-based method is proposed for this scenario [9]–[11]. To get the time difference of arrival, AUVs need to listen to the data packet transmissions from static nodes while moving to different positions. In the 3D area, to get the position of a static node denoted by $l = [x, y, z]$, AUVs need to listen four packets from the static node at four different locations at least, which can be modeled as $\boldsymbol{r} \approx \hat{\boldsymbol{r}}$, where $\boldsymbol{r}$ is the Euclidean distance difference of nodes, $\hat{\boldsymbol{r}}$ is the vector of estimated Euclidean distance difference of static node and AUV based on TDOA during the time of four rounds packet transmissions listened by AUV.

2) Topology Construction: AUVs should know the topology of the network, which helps AUVs select the next-hop nodes and identify the MAC protocol of static networks. When AUVs listen packet transmission among static nodes, the source and the destination address can be gotten from the packet frame head and further transferred into the topology map $\boldsymbol{H}_T$. The elements in $\boldsymbol{H}_T$ represent the topology links of the static network, where $\boldsymbol{H}_T(a, b) = 1$ indicates that there is a communication link between node a and node b, and $\boldsymbol{H}_T(a, b) = 0$, otherwise.

Then based on the positions calculated by AUVs, the interference map $\boldsymbol{H}_I$ can be defined as the relationship between the nodes' distance r_a^b and the communication distance d_0. When $r_a^b > d_0$ and $\boldsymbol{H}_T(a, b) \neq 1$, node a and node b would cause interference with each other, i.e, $\boldsymbol{H}_I(a, b) = 1$; $\boldsymbol{H}_I(a, b) = 0$, otherwise.

3) Transmission Scheduling: With the information of localization and topology, AUVs can calculate the collision probability with other static nodes for possible transmission. Then AUVs can determine the next-hop node and appropriate time to send data packets.

III. Problem Formulation

In this section, the transmission scheduling problem is formulated. We first introduce the value of information metric, and then the transmission scheduling problem is formulated as a combination problem.

A. Value of Information (VoI) Metric

To meet the requirement of diversified detected data from AUVs, the VoI metric is introduced to evaluate the event significance and promptness. To be specific, two types of data with different levels of urgency, the urgent data and the moderate data, are expected to be detected, which are assumed to be generated following the Poisson distribution with average rate λ_u and λ_m packets per second, respectively. Then the VoI at time t may decay with time following [12]–[14]:

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

Here, $V(t)$ is the VoI for the urgent data $V_u(t)$ and the moderate data $V_m(t)$, V^0 is the initial value, β is the weighting parameters that measure the trade-off between the information importance and the time delay, $f(t)$ is decreasing function with respect to t when $t \leq T$. Here, we define $f(t) = e^{-[(t-T)/\alpha]}$, where α is the scaling factor. Note that parameters V^0, β, α, and T depend on the types of the data packet.

B. VoI Maximization Problem

We assume that the arriving time for the urgent data and the moderate data are t'_u and t'_m, respectively meanwhile the sending time are t_u and t_m. The VoI of data packets that are successfully received by the static node N' at the distance of $r_A^{N'}$ away from AUV A can be measured as follows

$$V_U = V_u\left(t_u - t'_u\right)\left(1 - P_e\left(\gamma\left(r_{A_{t_u}}^{N'_{t_u}}, f\right)\right)\right), \tag{2}$$

$$V_M = V_m(t_m - t'_m)\left(1 - P_e\left(\gamma\left(r_{A_{t_m}}^{N'_{t_m}}, f\right)\right)\right), \tag{3}$$

Our objective is to maximize VoI, and hence the optimization problem can be formulated as follows:

$$\max_{\{t_u,\, t_m\} \in \mathcal{T_A}} \max\{V_U, V_M\} \tag{4a}$$

$$\text{s.t.} \quad t_u - t'_u \leq T_u, t_u \in \mathcal{T_A}, t'_u \in \mathcal{T_P}, \tag{4b}$$

$$t_m - t'_m \leq T_m, t_m \in \mathcal{T_A}, t'_m \in \mathcal{T_P}, \tag{4c}$$

$$r_{A_{t_u}, N'_{t_u}} \leq d_0, t_u \in \mathcal{T_A}, N'_{t_u} \in \mathcal{N}', A \in \mathcal{A}, \tag{4d}$$

$$r_{A_{t_m}, N'_{t_m}} \leq d_0, t_m \in \mathcal{T_A}, N'_{t_m} \in \mathcal{N}', A \in \mathcal{A}, \tag{4e}$$

$$t_A + r_A^a + t_{\text{data}} \notin \varOmega. \tag{4f}$$

In the above problem, objective function (4a) maximizes the VoI of data packets that successfully received, where $\mathcal{T_A}$ is the possible transmission time without collision along the AUV's trajectory. Constraints (4b) and (4c) limit the waiting time of urgent data packets and moderate data packets respectively. Constraints (4d) and (4e) limit the communication distance between AUVs and possible next-hop node $N' \in \mathcal{N}'$. Constraints (4f) limits the collision avoidance constraints, where t_A is denoted by t_u or t_m for the urgent data packets or the moderate data packets, respectively. In addition, $\varOmega$ is the collision time set, at which time data packets from an AUV would be collided with data packets from static nodes or other AUVs. The packet collision constraint will be discussed in detail in Section IV-A.

The above problem is a combinatorial optimization problem, which can be solved by search algorithms. However, the search space depends on the problem constraints and can be regarded as spatial and temporal scales. To solve this problem, we propose a low-complexity VBPS algorithm to determine the optimal next-hop node and transmission time.

IV. Proposed VoI-based Packet Transmission Scheduling (VBPS) Algorithm

In this section, the VBPS algorithm is proposed. Firstly, the packet collision constraint is analysed in detail in both the spatial and temporal scales. Then a distributed search algorithm is presented to determine the optimal next-hop node and transmission time for AUVs.

A. Packet Collision Constraint Analysis

In UASNs, when two or more data packets arrive at a node simultaneously, they will collide. However, due to the inherent characteristic of long and dynamic propagation delay in AUV-assisted UASNs, the spatial-temporal reuse can be exploited to schedule data transmissions for AUVs without affecting the data transmissions of static nodes. Data packets from the AUV have the probability of collision with any data packets from nodes within the communication range of the AUV. Nodes within the communication range can be 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 $\mathcal{I} = \{I \mid \boldsymbol{H}_I(A, I) = 1, \boldsymbol{H}_T(A, I) \neq 1\}$. In this network, the packet collision constraint can be divided into four cases. Next, we analyse these four cases in detail as follows.

1) Case 1: Receiving-Sending Collisions at the Next-hop Node: When an AUV wants to send a data packet to the next-hop node, it needs to determine when the next-hop node sends the data packet, at which time data packets from the AUV can not be received simultaneously. 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 can not receive the data packet from the AUV, which can be expressed as

$$t_A + r^A_{m^i_{j'}}/v_s + t_{\text{data}} \notin \Omega_1, \tag{5}$$

where t_A is the sending time of the data packet from the AUV, Ω_1 is the collision time interval, denoted by $\Omega_1 = \left[t^i_{j'}(\mu^i_{j'}), t^i_{j'}(\mu^i_{j'}) + 2t_{\text{data}}\right]$, $\mu^i_{j'}$ is the number of communication time round for $m^i_{j'}$ when the AUV want to send data packet, which can be calculated as follows $\mu^i_{j'} = \left\lfloor \frac{t_A}{T_s} \right\rfloor / M_i + 1$. Similarly, if the sensor node $s^j_{k'}$ is the next-hop node of the AUV, it can not send the data packet to node $m_j \in \left\{ m_j \mid \boldsymbol{H}_T(s^j_{k'}, m_j) = 1 \right\}$ while receiving the data packet from the AUV. So the collision avoidance condition is given by

$$t_A + r^A_{s^j_{k'}}/v_s + t_{\text{data}} \notin \Omega_2, \tag{6}$$

where Ω_2 is the collision time interval for the sensor node and is denoted by $\Omega_2 = \left[t^j_{k'}(\mu^j_{k'}), t^j_{k'}(\mu^j_{k'}) + 2t_{\text{data}}\right]$, where $\mu^j_{k'}$ is the number of communication round for $s^j_{k'}$ when the AUV want to send data packet, which can be 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 do not need to consider the receiving-sending collisions when they serve as the next-hop node.

2) Case 2: Receiving-Receiving Collisions at the Next-hop Node: When an AUV wants to send a data packet to the next-hop node, it should consider the conflicts caused by the simultaneous arriving data packet from the other nodes. If the next-hop node of AUV is a relay node $m^i_{j'}$, it can not receive the data packets from other nodes simultaneously. So AUV firstly need to find the sensor node $s^{j'}_k \in \mathcal{S}^{j'}$, where $\mathcal{S}^{j'} = \left\{ s^{j'}_k \mid \boldsymbol{H}_T(m^i_{j'}, s^{j'}_k) = 1 \right\}$, who is sending data packet to the relay node $m^i_{j'}$. At time t_A, the sequence k can be calculated as follows $k = \left\lfloor \frac{t_A}{T_s} \right\rfloor - \left(\mu^{j'}_k - 1 \right) S_{j'} + \sum_{j=1}^{j'} S_j + 1$. So the collision avoidance time can be given by

$$t_A + r^A_{m^i_{j'}}/v_s + t_{\text{data}} \notin \Omega_3, \tag{7}$$

where Ω_3 is the collision time interval for the relay node and is denoted by $\Omega_3 = \left[t^{j'}_k(\mu^{j'}_k) + r^{s^{j'}_k}_{m^i_{j'}}/v_s, t^{j'}_k(\mu^{j'}_k) + r^{s^{j'}_k}_{m^i_{j'}}/v_s + 2t_{\text{data}}\right]$. Similarly, if the next-hop node of AUV is a sink node $c_{i'}$, it can not receive the data packets from the AUV and the relay node $m^{i'}_j \in \mathcal{M}^{i'}$ simultaneously, where $\mathcal{M}^{i'} = \left\{ m^{i'}_j \mid \boldsymbol{H}_T(c_{i'}, m^{i'}_j) = 1 \right\}$. The sequence number j can be calculated as follows $j = \left\lfloor \frac{t_A}{T_s} \right\rfloor - (\mu^{i'}_j - 1) M_{i'} + \sum_{i=1}^{i'} M_i + 1$. So the collision avoidance condition can be expressed as

$$t_A + r^A_{c_{i'}}/v_s + t_{\text{data}} \notin \Omega_4, \tag{8}$$

where Ω_4 is the collision time interval for the sink node and is denoted by $\Omega_4 = \left[t^{i'}_j(\mu^{i'}_j) + r^{m^{i'}_j}_{c_{i'}}/v_s, t^{i'}_j(\mu^{i'}_j) + r^{m^{i'}_j}_{c_{i'}}/v_s + 2t_{\text{data}}\right]$.

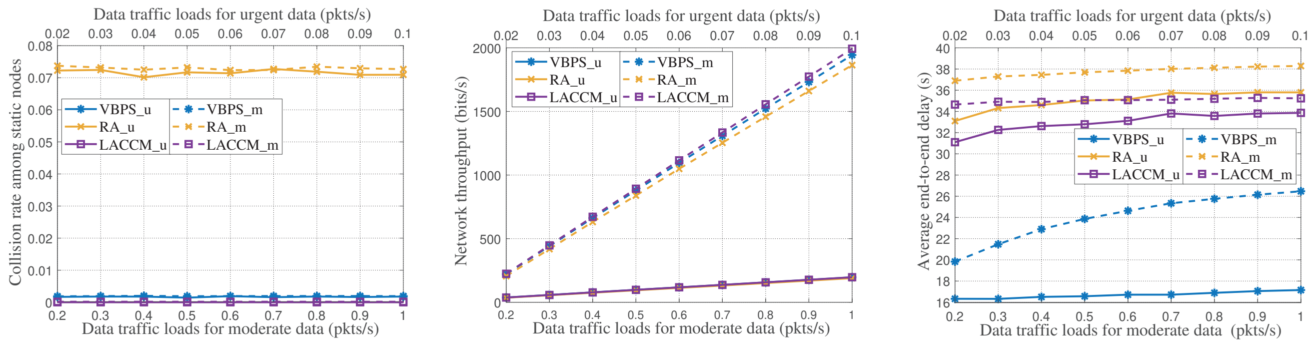
Since the sensor nodes do not receive any data packets from others, they do not need to consider the receiving-receiving collisions when they serve as the next-hop node.

3) Case 3: Receiving-Sending Collisions at the Interference Nodes: When an AUV wants to transmit a data packet, it needs to consider the collisions 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 can not overlap, which can be denoted by

$$t_A + r^A_{I'}/v_s + t_{\text{data}} \notin \Omega_5, \tag{9}$$

where Ω_5 is the collision time interval for the interference node and is denoted by $\Omega_5 = \left\{ \left[t^{j'}_k(\mu^{j'}_k), t^{j'}_k(\mu^{j'}_k) + 2t_{\text{data}}\right] \mid I' \in \mathcal{S}^{j'} \right\} \cup \left\{ \left[t^{i'}_j(\mu^{i'}_j), t^{i'}_j(\mu^{i'}_j) + 2t_{\text{data}}\right] \mid I' \in \mathcal{M}^{i'} \right\}$.

4) Case 4: Receiving-Receiving Collisions at the Interference Nodes: When a data packet is transmitted from the AUV, it may cause a non-neglected receiving-receiving collisions at the interference node $I' \in \mathcal{I}$. That is, the interference node I' can not 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 can not overlap with the arriving time of the data



(a) Collision rate among static nodes
(b) Network throughput
(c) Average end-to-end delay

Fig. 2. Network performance with different traffic loads.

packet from the corresponding interference node I'', which can be calculated as follows

$$t_A + r^A_{I'}/v_s + t_{\text{data}} \notin \Omega_6, \tag{10}$$

where Ω_6 is the collision time interval for the interference node and is denoted by $\Omega_6 = \left\{ \left[t^{j'}_k(\mu^{j'}_k) + r^{I''}_{I'}/v_s, t^{j'}_k(\mu^{j'}_k) + r^{I''}_{I'}/v_s + 2t_{\text{data}} \right] \mid I'' \in \mathcal{S}^{j'} \right\} \cup \left\{ \left[t^{i'}_j(\mu^{i'}_j) + r^{I''}_{I'}/v_s, t^{i'}_j(\mu^{i'}_j) + r^{I''}_{I'}/v_s + 2t_{\text{data}} \right] \mid I'' \in \mathcal{M}^{i'} \right\}$.

According to (5)-(10), the collision avoidance conditions can be summarized as follows

$$t_A + r^A_{N'}/v_s + t_{\text{data}} \notin \Omega, \tag{11}$$

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 Algorithm Design

To transmit the urgent data and the moderate data, we should select a next-hop node from static networks and the transmission time with least collisions and minimum delay. The detailed VBPS algorithm is shown as follows.

1) Searching Possible Next-Hop Nodes: When data packet arrives, AUVs take static nodes within AUVs' communication range as candidate next-hop nodes. Note that an AUV can only select static nodes whose locations are obtained by it. Actually, since AUVs do not obtain the global information of all the static nodes, they will miss some static nodes within their communication range.

2) Searching the Possible Transmission Time: As illustrated in Section IV-A, AUVs calculate the possible transmission time based on packet collision constraint. As data packets arrive, AUVs search all the possible earliest sending time for each candidate next-hop node $N' \in \mathcal{N}'$. When data packets arrive at AUVs, AUVs check the collision constraint based on (11), where $t_A = t'_u$ for urgent data or $t_A = t'_m$ for moderate data. If the transmission time does not satisfy the collision constraint, it would be delayed until the earliest collision-free time.

3) Avoiding Collisions between Urgent Data and Moderate Data: Although the urgent data and moderate data arrive following different traffic loads, they may arrives at the same time interval. Therefore, we need to select different next-hop node and transmission time to avoid collisions among them. For these two kinds of data, the urgent data requires less waiting delay, so the urgent data should be transmitted before the moderate data when they arrive in conflict at the AUV.

4) Selecting the Optimal Next-Hop Node and Transmission Time: Based on the above possible transmission time and next-hop node, AUVs can calculate the VoI of data packets. Then AUVs select the optimal next-hop node and transmission time from all the possible search space for the urgent data and the moderate data.

We assume that the number of possible next-hop nodes in $\mathcal{N}'$ is $|\mathcal{N}'|$, which is much smaller than N_n. And we assume that the number of possible transmission time is $|t_A|$. The computational complexity of VBPS algorithm is quadratic $O(|\mathcal{N}'||t_A|)$.

V. Performance Evaluation

Simulations are carried out to evaluate the performance of the proposed VBPS algorithm. Two protocols are used for comparison, i.e., random access protocol (RA) and load adaptive carrier sense multiple access control MAC protocol (LACCM) [6]. In the RA protocol, AUVs send data packets randomly following a random distribution. And in the LACCM, AUVs send a beacon packet before sending the data packets, which stops all the ongoing transmissions to avoid packet collisions.

A. Simulation Setup

In this simulation, we use the commercial underwater acoustic communication modem specifications of S2CR18/34 from Evologics [15]. For this modem, the frequency f, the data rate R, the communication range d_0, and the transmission power Pt are set to be 18 kHz to 34 kHz, 13.9 kbps, 3,500 m, and 65 W. The velocity of AUVs is set to be 10 m/s. In terms of the VoI, the initial values, V^0_u and V^0_m, are the same as the data packet size; the weighting parameters β_u and β_m are set to be 0.5 and 0.3, respectively; the scaling factor is 3 for both

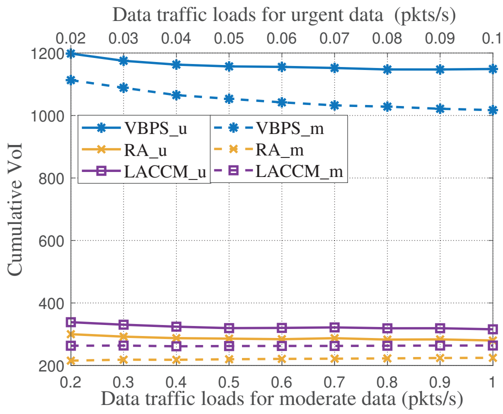


Fig. 3. Cumulative VoI with different traffic loads.

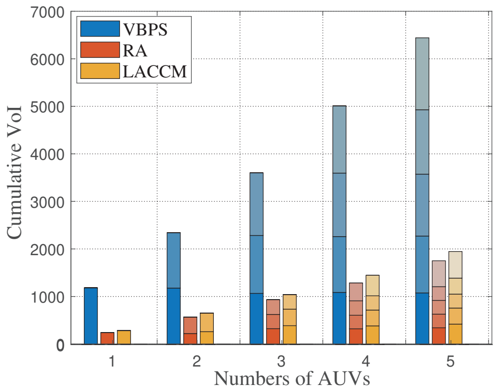


Fig. 4. Cumulative VoI with different number of AUVs.

α_u and α_m; and T_u and T_m are five and ten times as long as the time slot.

To verify the performance of the proposed algorithm, we carry out simulations with different scenarios. The performances are compared with different data traffic loads λ varying from 0.01 to 0.1 packets/s for the urgent data and from 0.1 to 1 packets/s for the moderate data, and different number of AUVs varying from 1 to 5. The performances of these algorithms are all evaluated in terms of collision rate among static nodes, network throughput, average end-to-end delay, and cumulative VoI.

B. Simulation Results

Figure 2 displays the performance of proposed algorithms with different data traffic loads. The collision rate among static nodes is shown in Fig. 2(a). It shows that with the increasing of data traffic load, the collision rate among static nodes of all algorithms is stable. This is because, the collision rate among static nodes is mainly related to the global information of static network when data packets arrive at the AUV while it is not influenced by the number of generated data packets. The collision rate among static nodes of VBPS is larger than that of LACCM while it is greatly smaller than that of RA. This is because, in VBPS, we take actions to calculate the packet collision constraints to avoid collisions, which is not considered in RA. However, due to the imperfect knowledge of the static network, the possibility of collisions among static nodes still exists. Fig. 2(b) shows how the data traffic load influences the network throughput. The results show that the network throughput increases linearly as data traffic load increases. The network throughput of these algorithms is very similar. The average end-to-end delay is illustrated in Fig. 2(c) and that of these protocols increases slightly as data traffic load increases. In addition, the average end-to-end delay of VBPS is greatly shorter than that of RA and LACCM. Due to the VBPS calculates all possible receivers and select the best candidate of next-hop node based on VoI. Thus, the end-to-end delay is shorter compared with RA and LACCM which select the next-hop nodes randomly.

In terms of the cumulative VoI, the influence of data traffic load and number of AUVs are shown in Fig. 3 and Fig. 4, respectively. Results show that VBPS performs better than RA and LACCM. The reason is that the next-hop node for AUVs is selected to maximize VoI in VBPS while it is selected randomly in RA and LACCM. Results prove that the strategy of data packet transmission based on VoI is effective. Besides, the cumulative VoI of all of them decreases slightly as the data traffic load increases. This is because, the relative end-to-end delay increases slightly with the increasing of the data traffic load, which results in the decreasing of VoI. In addition, when the number of AUVs increases, the cumulative VoI increases linearly while that for each node is slightly decreased. The cumulative VoI for each AUV in each algorithm is roughly similar.

VI. Conclusion

In this paper, we have presented a novel packet scheduling scheme for the AUV-assisted network without requiring global information while avoiding collision with regular data transmissions among static nodes. Furthermore, we have formulated a combinatorial optimization problem to maximize the VoI and proposed a distributed search algorithm to solve it, 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. Extensive simulation results have shown that the proposed scheme performs better than the benchmarks in terms of collision rate, network throughput, average end-to-end delay, and cumulative VoI. The significant of this research is to make AUVs perform monitoring tasks in a dynamic and scalable manner, without interfering with activities carried out by existing static nodes. For the future work, we will study the joint optimization of mobile nodes' deployment and data transmission strategies.

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