

FRAB-MAC: A Reliable Adaptive Broadcast MAC protocol for Mobile UACNs

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Abstract—The rapid development of Autonomous Underwater Vehicles (AUVs) enables AUV formations to execute complex tasks such as ocean exploration and remote surveillance. Information exchange within AUV formations relies on Underwater Acoustic Communication Networks (UACNs), where MAC protocol design is crucial for collision-free transmission and high network throughput. As a representative MAC protocol for mobile UACNs, AB-MAC enables collision-free broadcast communication among AUVs and improves network throughput through genetic algorithm-based optimization of transmission sequences. Moreover, we propose FRAB-MAC, a reliable extension that incorporates reliability into the scheduling objective. By jointly optimizing the minimal frame length and a scoring-based reliability factor that accounts for the packet delivery probability between nodes, FRAB-MAC enhances the probability for AUVs to successfully receive control information, thereby significantly mitigating the likelihood of remaining silent. Meanwhile, FRAB-MAC employs a optimization algorithm based on the fire hawk optimizer (FHO), which effectively improves network throughput by generating optimal transmission sequences with minimal frame length. MATLAB simulation results demonstrate that FRAB-MAC shortens average frame length, reduces the number of silent nodes, and improves network throughput by an average of 15.06% compared with AB-MAC.

Index Terms—AUV, MAC protocol, TDMA, fire hawk optimizer (FHO), Underwater acoustic communication networks (UACNs).

I. INTRODUCTION

As core underwater communication infrastructures, Underwater Acoustic Communication Networks (UACNs) are essential for applications such as oceanic environmental monitoring, underwater navigation, and resource exploration. The medium access control (MAC) protocol, defining how nodes access the limited underwater acoustic channel, is critical for optimizing UACNs performance [1]. Many underwater acoustic MAC protocols have been developed recently, and they can generally be grouped into two categories: contention-based and contention-free MAC protocols. Contention-based protocols, such as ALOHA [2] and CSMA [3], rely on random channel access, which inevitably results in packet collisions degraded network throughput in highly dynamic underwater environments. In contention-free MAC protocols, channel resources are multiplexed through various schemes including FDMA [4], CDMA [5], and TDMA [6], [7]. Among these, TDMA achieves collision-free transmission by dividing time into

distinct slots. Due to its simplicity, ease of implementation, and inherent collision avoidance characteristics, TDMA has been widely adopted in underwater acoustic communication networks.

TDMA-based MAC protocols can be further categorized into two classes. Distributed TDMA protocols, such as GC-MAC [8] and PGGC-MAC [9], are primarily designed for data transmission in AUV-aided UACNs. On the other hand, centralized TDMA protocols, such as OBS [10] and AB-MAC [11], which are mainly designed for broadcast communication within a AUV formation. In such formations, all AUVs fall within each other's communication range, forming a fully connected network. This paper also focuses on centralized TDMA-based MAC protocols in fully connected networks.

In centralized TDMA-based MAC protocols, the control node determines the transmission sequence and the corresponding time slot duration for each node, which is the so-called frame optimization problem, and broadcasts the results to all nodes. Ordinary nodes then transmit data in their assigned slots. Network throughput is influenced by two factors: First, nodes that fail to receive the control packet remain silent, reducing overall data transmission volume; Second, different transmission sequences yield varying frame lengths, i.e., the sum of all time slot duration. AB-MAC introduces an adaptive adjustment mechanism that enables nodes to recover control information from data packets of ordinary nodes, and employs a genetic algorithm (GA) for frame optimization to minimize frame length, thereby ensuring network throughput.

In AB-MAC, as illustrated in Fig. 1, the control node broadcasts a control packet at the beginning of each frame, which specifies the transmission sequence and time slots of all nodes derived from the genetic algorithm. To ensure fairness and balanced energy consumption, nodes take turns serving as the control node. During data transmission, ordinary nodes embed the ID of the next sending node in their data packets. This design prevents nodes from remaining silent when they fails to receive the control packet due to propagation loss or burst noise. It should be noted that the “next sending node” here refers specifically to the subsequent node in the transmission sequence, rather than to a neighboring node or one with a larger ID.

However, this chain-based recovery strategy also has limi-

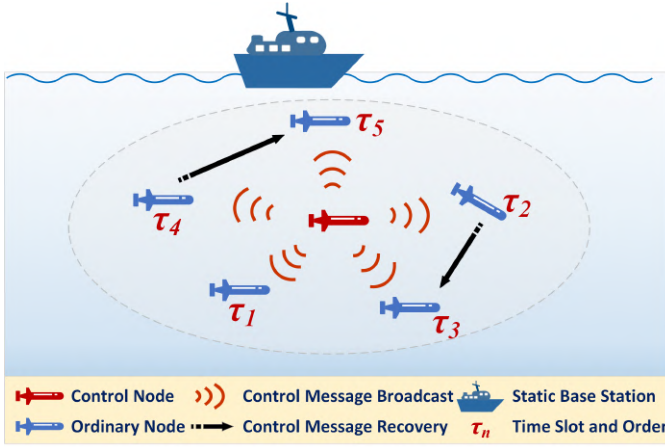


Fig. 1. Architecture of UACNs with AUVs and example of AB-MAC.

tations. The genetic algorithm formulates its optimization objective exclusively around minimizing frame length, ignoring the packet delivery success rate between arbitrary pairs of adjacent nodes in the transmission sequence. Consequently, certain nodes may be forced to recover control information from nodes that are spatially distant, thereby reducing the robustness of recovery processes. In addition, as the number of AUV increases, the genetic algorithm suffers from slower convergence and weaker global search performance. To overcome the limitations discussed above, this paper makes the following contributions:

- 1) We design a new objective function that integrates a scoring-based reliability factor into the evaluation of transmission sequences, guiding heuristic algorithms to derive reliable scheduling results that enhance the robustness of recovery strategies.
- 2) FRAB-MAC introduces an FHO-based frame optimization algorithm that determines reliable transmission sequences and slot lengths, addressing the joint optimization problem of minimum frame length and network reliability. Simulation results demonstrate that FRAB-MAC significantly reduces the number of silent nodes and effectively improves network throughput.

II. DETAIL DESIGN OF FRAB-MAC

A. Topology Discovery

Before the initialization phase, nodes have no prior knowledge of the positions of their peers and thus lack awareness of the overall topology. To address this, we adopt the same initialization strategy as AB-MAC: nodes broadcast their position information using a conventional TDMA protocol with random transmission order, where the slot length is deliberately set long enough to avoid packet collisions.

Upon obtaining the location of each node, the control node estimates the signal-to-noise ratio (SNR) of the received signals between any pair of nodes by applying the empirical transmission path loss model [13]. The path loss is modeled

as a function of transmission distance d in km and frequency f in kHz, and is formulated as:

$$A(d, f) = 10 \times k \times \log d + a(f) \times d. \quad (1)$$

where $k = 2$ is typically used to reflect spherical spreading. The absorption coefficient $a(f)$ in dB/km is given by the Thorp equation as follows:

$$10 \log a(f) = \frac{0.11f^2}{1 + f^2} + \frac{44f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003. \quad (2)$$

The SNR can then be calculated as:

$$SNR_{dB} = P - A(d, f) - N_{am}. \quad (3)$$

$$\gamma = 10^{SNR_{dB}/10}. \quad (4)$$

where N_{am} represents the ambient noise, which follows Urlick's classical formulation [14]. To analyze the bit error rate (BER), the SNR should be converted from the logarithmic scale to the linear scale, represented as γ .

Assuming that the acoustic communication modem employs Binary Phase Shift Keying (BPSK) modulation, the average BER $P_{i,j}^e$ between node i and node j under additive white Gaussian noise (AWGN) channel can be calculated as a function of their linear SNR $\gamma_{i,j}$ using the Q-function:

$$P_{i,j}^e = Q(\sqrt{2 \cdot \gamma_{i,j}}). \quad (5)$$

where Q -function is defined as follows:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt. \quad (6)$$

For a packet with m bits, the packet success rate (PSR) between node i and node j , denoted by $P_{i,j}$, can be computed as:

$$P_{i,j}^s = (1 - P_{i,j}^e)^m. \quad (7)$$

$$\mathcal{P} = \{P_{i,j}^s \mid 1 \leq i, j \leq N\}. \quad (8)$$

where N is the total number of nodes. By estimating the PSR for each pair of nodes, a success probability matrix $\mathcal{P}$ can be obtained.

B. Optimization of Transmission Sequence

To jointly optimize frame length and ensure network reliability, we extend AB-MAC by reformulating the optimization objective. Rather than minimizing frame length alone, the heuristic algorithm is guided by a new objective function that additionally accounts for a reliability factor R_s , which is defined as the cumulative score of a transmission sequence, calculated based on the estimated PSR between nodes. Its detailed definition is as follows:

$$R_s = \sum_{i=1}^N r_i. \quad (9)$$

$$r_i = \begin{cases} 1, & P_{c,i} > P_{thc} \text{ or } P_{i,i-1} > P_{thd} \\ 0, & P_{c,i} < P_{thc} \text{ and } P_{i,i-1} < P_{thd}. \end{cases} \quad (10)$$

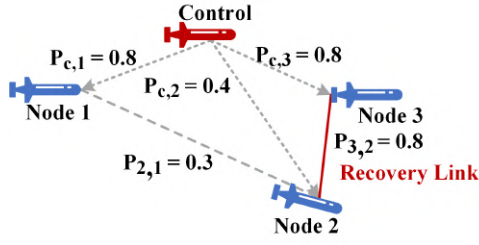


Fig. 2. Estimated PSR between nodes.

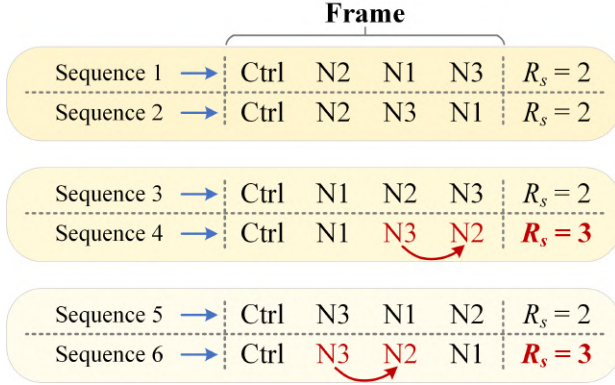


Fig. 3. Transmission sequence optimization of FRAB-MAC.

where $P_{c,i}$ denotes the PSR between current control node and the i -th node in the transmission sequence S , while $P_{i,i-1}$ represents the PSR between the i -th node and its immediate predecessor in S , with P_{thc} and P_{thd} denoting the PSR thresholds for control–ordinary node links and ordinary–ordinary node links, respectively. In general, control nodes in the formation possess higher transmission signal power. However, since nodes take turns serving as the control node in our scheme, we assume $P_{thc} = P_{thd} = 0.5$ in this study.

When either $P_{c,i} > P_{thc}$ or $P_{i,i-1} > P_{thc}$, the node is able to acquire or reconstruct its slot information from the control node or its predecessor, thereby avoiding silence. If both fall below their respective threshold, the node is very likely to lose control information and remain silent. By including the reliability factor in the objective function, the heuristic algorithm is prevented from generating unreliable transmission sequences.

Fig. 2 illustrates a formation of four AUVs, where the control node broadcasts the transmission sequence and assigned time slots to all members at the beginning of each TDMA round. During data transmission, each node appends the ID and time slot of the next sending node to its packet header, ensuring that the recovery mechanism aligns with the strategy adopted in AB-MAC. Node 2, due to specific task or ocean currents, drifts relatively farther away from other nodes. The estimated PSR between nodes are also shown in Fig. 2, and the potential transmission sequences derived by the control node are illustrated in Fig. 3. Evaluation of the reliability factor for each candidate sequence reveals that the

maximum reliability is achieved when Node 3 precedes Node 2 in the transmission order. This can be explained by the fact that Nodes 1 and 3 are both located near the control node, and thus the reliability of overall sequence primarily depends on whether Node 2 can obtain the control information. Given Node 2's greater distance from the control node, it is more dependent on its predecessor for recovering scheduling information. Consequently, when Node 3 directly precedes Node 2, the control information can be effectively recovered, yielding the most reliable transmission sequence.

The new objective function is described as follows:

$$Obj = \alpha \times (N - 1 - R_s) + \beta \times F, \quad \alpha, \beta \in (0, 1). \quad (11)$$

where α and β are weight coefficient and we assume that $\alpha = \beta = 0.5$, F denotes the frame length. Here, $N - 1$ represents the ideal scenario where every node in the transmission sequence successfully receives the control packet, thus defining the maximum achievable reliability factor. Consequently, the term $N - 1 - R_s$ quantifies the sequence's unreliability. Since the original objective function is to minimize the frame length, it is inherently a minimization problem. Minimizing $N - 1 - R_s$ reflects improving reliability, while still maintaining the new objective as a minimization problem.

In calculating the frame length, we adopt the theorem and formulations from the AB-MAC protocol. To avoid packet collisions during broadcast in fully connected networks, AB-MAC establishes and proves the following theorem:

Theorem: As long as a node sends after completely receiving the packet of the previous transmitting node, the packets sent by these two nodes will not collide at any node.

Moreover, AB-MAC specifies the formula for frame length F and each time slot in centralized TDMA scheduling under the assumption of this theorem. Given the transmission sequence S of N nodes, the duration of the l -th time slot can be expressed as:

$$F = \sum_{l=1}^N \tau_l. \quad (12)$$

$$\tau_l = \begin{cases} \frac{d_{O_c, s_2}}{c} + \frac{M_c + M_d}{B} + t_g, & l = 1 \\ \frac{d_{s_l, s_{l+1}}}{c} + \frac{M_d}{B} + t_g, & 2 \leq l \leq N - 1 \\ \frac{d_{s_N, O_n}}{c} + \frac{M_d}{B} + t_g, & l = N. \end{cases} \quad (13)$$

where $d_{s_l, s_{l+1}}$ is the distance between the node at the l -th position and the node at the $l + 1$ -th position in the transmission sequence S , c represents the acoustic speed in underwater environments, O_c and O_n denote the current and the next control node, M_c represents the length of the control packet, M_d indicates the length of data packets, B refers to the data rate, and t_g is the guarding time between consecutive transmissions.

Finally, we employ a FHO-based [15] frame optimization algorithm to solve this combinatorial optimization problem, since it offers advantages such as simplicity, fast convergence,

and strong global search capability. Compared with other metaheuristics such as particle swarm optimization (PSO), the generation of new populations in FHO—i.e., position updates—depends on the global optimum and locally superior solutions, helping the algorithm avoid local optima [12]. In terms of computational complexity, for instance, genetic algorithms require execute a sequence of operations including crossover, mutation, and recombination, along with extensive random number generation and condition checking. In contrast, FHO updates positions through relatively simple vector operations, resulting in a shorter computational path and lower complexity. In this algorithm, the distance matrix $\mathcal{D}$, success probability matrix $\mathcal{P}$ and the list of node IDs within the formation serve as inputs. The FHO outputs an optimized permutation of node IDs and the corresponding time-slot duration for each node, jointly satisfying the objectives of minimizing frame length and enhancing reliability. The procedure of FHO is illustrated in Algorithm 1.

III. SIMULATION AND RESULTS

We evaluate the performance of proposed FRAB-MAC, AB-MAC and conventional centralized TDMA (C-TDMA) protocols with MATLAB in this section. The AUV nodes are randomly deployed within a 3-D underwater area of $4 \times 4 \times 4$ km³ and maintain the initial random formation while moving linearly at a speed of 5 knots. In addition to ambient noise, burst noise is also considered in the simulation to evaluate its impact on data packet transmission and reception. Burst noise is assumed to obey a Poisson distribution with parameter λ , which indicates the frequency of noise events. We assume that if burst noise occurs during the reception of a packet, the reception is considered unsuccessful. For a fair comparison, both the genetic algorithm and the FHO are initialized with a population size of 100 and run for up to 100 generations. To ensure the robustness of the results, 40 independent trials were conducted for each network size and node density. The detailed simulation settings are summarized in Table I.

Three key metrics are considered in the simulations to compare the performance of different MAC protocols. The first metric is the average frame length, defined as the mean duration of a TDMA cycle, i.e., the sum of all node time slots, measured in seconds. The second metric is the average throughput per node, defined as the ratio of the total amount of data received by all nodes to the product of the simulation duration and the number of nodes. This metric is considered the most critical indicator of MAC protocol performance in UACNs. Third, the average number of silent nodes per frame, which reflects whether the optimized transmission sequence can reliably guarantee that every node has successfully received the broadcast control packet.

As shown in Fig. 4a and Fig. 4b, the performance comparison of the FHO and GA algorithms was evaluated under ideal conditions with uniformly distributed nodes. It can be observed that, for the same number of iterations, FHO converges faster than the genetic algorithm when solving the frame optimization problems, as reflected by its consistently

Algorithm 1: FHO-based Optimization Algorithm

Input:

Control node: O_c, O_n ; Packet length: M_c, M_d ;

Node set: $\mathcal{N} = \{x_1, \dots, x_i, \dots, x_N\}$;

Distance matrix $\mathcal{D}$; Success probability matrix $\mathcal{P}$;

Population size: P ; Number of fire hawks: N_{hawk} ;

Output:

Transmission sequence: $\mathcal{S} = \{s_1, \dots, s_l, \dots, s_N\}$;

begin

Initialization: generate P random sequences with O_c as first element as the initial population $\mathcal{C}$;

Evaluation: calculate objective of each sequence using (11) and sort in ascending order to get $\mathcal{C}'$;

Grouping:

$GB \leftarrow \mathcal{C}'[1], FHs \leftarrow \{\mathcal{C}'[1], \dots, \mathcal{C}'[N_{\text{hawk}}]\}$;

$Preys \leftarrow$ remainings of $\mathcal{C}'$;

Calculate territory: compute the distance between FHs and $Preys$ and assign preys to nearest FHs ;

while $iter < MaxIter$ do

for $FH_l \in FHs$ do

calculate new position and obtain FH_l^{new} ;

$\mathcal{C}_{\text{new}} \leftarrow \mathcal{C}_{\text{new}} \cup \{FH_l^{\text{new}}\}$;

end

for $PR_q \in Preys$ do

calculate new position and obtain $PR_q^{\text{new1}}, PR_q^{\text{new2}}$;

$\mathcal{C}_{\text{new}} \leftarrow \mathcal{C}_{\text{new}} \cup \{PR_q^{\text{new1}}, PR_q^{\text{new2}}\}$;

end

Repeat **Evaluation** of $\mathcal{C}_{\text{new}}$ and get $\mathcal{C}'_{\text{new}}$;

if $\mathcal{C}'_{\text{new}}[1].objective < GB.objective$ **then**

$GB \leftarrow \mathcal{C}'_{\text{new}}[1]$;

end

$FHs \leftarrow \{\mathcal{C}'_{\text{new}}[1], \dots, \mathcal{C}'_{\text{new}}[N_{\text{hawk}}]\}$;

$Preys \leftarrow \{\mathcal{C}'_{\text{new}}[N_{\text{hawk}} + 1], \dots, \mathcal{C}'_{\text{new}}[P]\}$;

Repeat **Grouping** and **Calculate territory**;

$iter = iter + 1$;

end

$\mathcal{S} \leftarrow GB.sequence$;

end

TABLE I
SIMULATION SETTINGS

Parameters	Value	Unit
Network field	$4 \times 4 \times 4$	km ³
Modem frequency	25	kHz
Data packet size	800	bits
Data rate	1700 / 3070	bps
AUV speed	5	knot
Number of nodes	10-50	-
Poisson(λ)	0.1	-
Duration of burst noise	0.1 / 0.3 / 0.5	s
Population size	100	-
Number of fire hawks	5	-
Max generation	100	-
Number of experiments	40	-

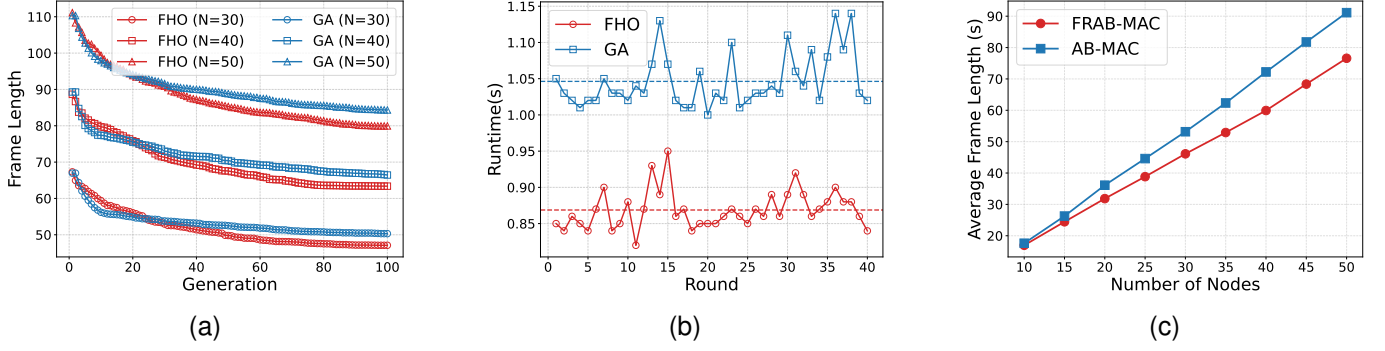


Fig. 4. Performance Comparison of (a) Convergence speed of FHO and GA. (b) Per-round execution time for FHO and GA when number of nodes is 50. (c) different MAC protocols on Average frame length.

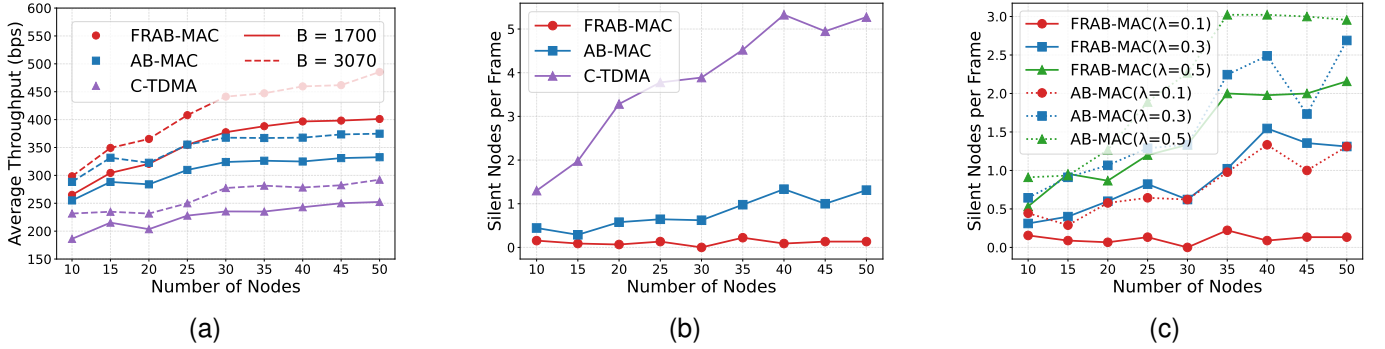


Fig. 5. Performance evaluation of different MAC protocols on (a) Average throughput per node. (b) Average silent nodes per frame ($\lambda = 0.1$). (c) Average silent nodes per frame ($\lambda = 0.3$ and $\lambda = 0.5$).

lower frame lengths. To provide a simple measure of computational complexity, we further compare the runtime of a single execution of each algorithm. As shown in Figure 4b, FHO also requires less computation time than GA. The dashed lines indicate the average runtime, which is 1.05 seconds for GA and 0.87 seconds for FHO under our experimental settings. Therefore, the proposed FHO-based frame optimization algorithm outperforms the GA-based one in terms of both convergence speed and computational efficiency.

Fig. 4c presents the average frame length under random network topologies as the network size and node density increase. The results indicate that FRAB-MAC achieves a shorter average frame length compared to AB-MAC, with an average reduction of 12.57%. As shown in Fig. 5a, FRAB-MAC consistently achieves the highest throughput, followed by AB-MAC and C-TDMA exhibits the lowest, regardless of whether the data rate B is 1700 bps or 3070 bps. On average, FRAB-MAC improves throughput by 15.06% compared with AB-MAC. This improvement is mainly attributed to the fact that C-TDMA relies on fixed time slot allocation without a control packet recovery mechanism. Although AB-MAC employs an improved genetic algorithm to derive the transmission sequence, its optimization capability declines as the network size and number of nodes increase, making it difficult to obtain a near-optimal solution within the same

number of iterations. In contrast, FRAB-MAC, guided by the FHO and the scoring-based reliability factor, exhibits stronger global search capability under the same iteration conditions, generating shorter and more reliable transmission sequences that lead to the highest network throughput.

As shown in Fig. 5b and Fig. 5c, by introducing a new objective function that jointly optimizes throughput and reliability, FRAB-MAC significantly enhances the success rate of the chain-based recovery mechanism, thereby reducing the number of silent nodes. Under $\lambda = 0.1$, the average number of silent nodes per frame is approximately 0.11, compared to 0.79 for AB-MAC and substantially lower than that of C-TDMA. Even under higher burst noise levels, FRAB-MAC consistently maintains fewer silent nodes—for instance, when $\lambda = 0.3$ and $\lambda = 0.5$, the averages are 0.89 and 1.45, respectively, both markedly lower than AB-MAC's 1.60 and 2.14.

IV. CONCLUSION

This paper proposed FRAB-MAC, a FHO-based reliable adaptive broadcast MAC protocol for underwater AUV formations. By redefining the FHO objective function, FRAB-MAC incorporates a scoring-based reliability factor to ensure that all nodes successfully receive the broadcast schedule from the control node, effectively overcoming the limitations of AB-MAC's control message recovery strategy. Simulation

results demonstrate that FRAB-MAC outperforms AB-MAC and conventional centralized TDMA by achieving shorter average frame length, reducing the number of silent nodes, and significantly improving the network throughput.

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