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An ADAP-MAC Protocol for Medium Access Control in Underwater Sensor Communication Networks

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ABSTRACT

In underwater communication networks, utilizing bandwidth resources and decreasing collisions due to long propagation delays to improve transmission efficiency and extend the operational lifespan of network nodes of network nodes is necessary. The most widely used Medium Access Control (MAC) protocols in these networks include Carrier Sense Multiple Access (CSMA), contention-free, and contention-based MAC protocols, which can operate synchronously or asynchronously. Maximizing channel resource utilization and minimizing collisions remain challenges across these MAC protocol categories. In this study, we propose a MAC protocol that integrates carrier sensing with contention-free and contention-based protocols to leverage the strengths of each approach called ADAP-MAC protocol. An adaptive Automatic Repeat Request (ARQ) algorithm combined with a power optimization method is also used to avoid collisions and save energy. We will simulate and evaluate the performance of the proposed protocol by measuring key parameters such as the successful packet transmission efficiency of network nodes, the number of packet retransmissions due to collisions at the receiving node, transmission distance, and power consumption for packet transmission. The simulation results will be compared with those of traditional protocols to demonstrate the effectiveness of the proposed approach in maximizing channel resource utilization and minimizing collisions.

Keywords: Underwater communication networks, contention-based MAC protocols, contention-free MAC protocols, CSMA MAC protocols

1. INTRODUCTION

Underwater communication networks have various application fields such as environmental monitoring, underwater exploration, scientific data collection, search, and survey (Awan et al., 2019). Each type of application requires a corresponding underwater communication network configuration. In underwater sensor communication networks, there is typically one Master node and several Slave nodes set up to collect data from a specific area on the seabed. The Slave nodes gather data and send it directly to the Master node, which is connected to a Gateway node on the water surface to transmit information to the ground station (Mahfoudh, 2023). The sensor nodes are fixed on the seabed within an area for collecting for specialized missions (Lloret, 2013). Underwater sensor networks encounter challenges such as limited bandwidth, long propagation delays, and power constraints. Due to significant attenuation in the underwater environment, radio and optical waves are impractical for communication throughout the ocean environment (Ayaz et al., 2009). Because of these limitations, the acoustic wave is a good choice for underwater environments. Underwater sensor networks rely exclusively on acoustic signals, which have naturally been used in the ocean since its formation (Khan et al., 2022).

Using acoustic waves in underwater sensor networks presents many research challenges, including limited bandwidth because the current acoustic communication systems can achieve a range-rate product of up to 40 km - 1KBps; long propagation delay, the speed of sound underwater is approximately 1500 m/s, which is about 200,000 times slower than the speed of radio waves; high bit error rate, because underwater acoustic channels are prone to errors due to path loss, noise, and multi-path and Doppler spread; high energy consumption, most existing commercial acoustic modems depend on batteries that are not rechargeable (Liu et al., 2012; Pal et al., 2022).

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These underwater acoustic communication characteristics of acoustic channels pose challenges for designing an efficient MAC protocol for underwater channels. The MAC layer takes charge of the distribution and management of the channel resource and controls the activities of the nodes in the network. The Medium Access Control (MAC) protocol is essential for the functioning of sensor networks. It helps prevent collisions at receiving nodes, allocates acoustic channels, and distributes energy and other resources among competing nodes. Therefore, it is essential to develop an efficient MAC protocol that prioritizes energy efficiency and network throughput to meet the specific requirements of various applications (Yan et al., 2021; Luo et al., 2014).

2. RELATED WORKS

Many MAC protocols dedicated to UWSNs have been proposed in the last decade. These MAC protocols are typically categorized into three primary groups: CSMA, contention-free, and contention-based MAC protocols (Guqhaiman et al., 2021). The earliest traditional MAC protocols used for underwater sensor networks, including FDMA, TDMA, and CDMA, have certain limitations, such as unstable throughput and low transmission efficiency (Sozer et al., 2000; Malumbres et al., 2009). Underwater communication channels have narrow bandwidth, making FDMA unsuitable for underwater communication. TDMA protocols require synchronization between network nodes, which is also a limitation for underwater communication channels due to their low propagation speed. CDMA technology in underwater communication channels often faces issues with near-far packet collisions (Muqattash et al., 2003).

In underwater acoustic communication channels, due to the propagation delay characteristic of sound waves, the probability of packet collisions at the receiving node is typically high. The earliest MAC protocol used in underwater communication channels is the Aloha protocol. In this protocol, nodes send packets immediately upon having data. As a result, packets arriving at the receiving node simultaneously, within the packet length time frame, will cause collisions at the receiver. Nodes that do not receive an acknowledgment packet for a successful transmission will have to retransmit the packet. This lowers network transmission efficiency and drains the battery power of sensor nodes, which cannot be replaced in underwater communication channels (Chirdcho et al., 2007).

Due to these limitations, enhanced versions of the Aloha protocol, such as Aloha-CS and Aloha-AN, have been proposed. In the Aloha-CS protocol, sensor nodes optimize collision probability by gathering network status information and scheduling packet transmissions accordingly to avoid collisions. However, this protocol only benefits nodes with a fixed packet transmission schedule and is ineffective in sensor networks where nodes have a random transmission schedule. Another enhancement of the Pure Aloha protocol is known as Aloha-AN. In this protocol, each sensor node has data to transmit, it first sends a Notification Packet (NTF) to other network nodes before the actual packet transmission. This increases the energy cost due to NTF transmissions, and the potential collisions of NTF packets add to the sensor network's burden.

Other medium access methods are the Carrier Sense Multiple Access (CSMA) protocols (Awan et al., 2019; Yang et al., 2012; Luo et al., 2012; Liao et a., 2012). In these protocols, sensor nodes listen to the channel before transmitting. If a carrier signal is detected on the channel, the node delays its transmission until the channel is free, at which point it sends the packet. These approachs are unsuitable for underwater acoustic communication channels because of the high propagation delay. Additionally, packet collisions at the receiving node can still occur due to hidden-terminal and exposed-terminal issues.

Other methods for medium access are known as the handshake-based access methods (Guo et al., 2009; Chirdchoo et al., 2007; Hai et al., 2013; Pal et al., 2022; Fullmer et al., 1995). In these protocols, a handshake process takes place before the actual data transmission. The sender node transmits a Request-To-Send (RTS) packet to the receiving node. If the receiver is idle, it responds with a Clear-To-Send (CTS) packet, establishing the transmission session, and the sender sends the data packet. If the sender does not receive an RTS within a specified time, it enters a waiting state and retries sending the RTS after a designated period. If other nodes have a packet to send that receives the RTS packet, they delay their own transmissions. In underwater communication channels, conserving channel resources and preserving sensor node battery life is critical as it directly impacts node lifespan. However, handshake-based

MAC protocols consume extra channel resources and reduce sensor node operational time due to the handshake process prior to data transmission.

Other MAC protocol enhancements include UCMAC (Kim et al., 2018), a cooperative MAC protocol. This protocol is designed for relay-based networks and operates by identifying neighboring nodes. During the transmission process, neighboring nodes near the receiver store a copy of the transmitted packet. If a transmission collision occurs, the neighboring nodes retransmit the stored packet using a closest-one-first approach.

A study on optimization based on reinforcement learning is proposed in (Wang et al., 2019). The reinforcement learning process enables network configuration to adapt to changes in underwater communication channels. The protocol focuses on identifying transmission channel characteristics to optimally select data transmission parameters.

In underwater communication channels, when data transmission fails, the sender node must enter a sleep state for a certain period before waking up to attempt retransmission. The timing of this wake-up and retry process is crucial, as it helps reduce the probability of collisions during packet retransmission. In research conducted by Andrej, the impact of ARQ (Automatic Repeat reQuest) on the distortion performance of underwater acoustic mobile networks was examined. The findings indicate that in underwater communication networks utilizing sensors, the operational lifetime of a sensor node is significantly affected by its energy consumption (Stefanov, 2021). When network nodes are designed to be intelligent and possess large memory and high operating frequency, it may result in increased energy consumption and a reduced lifespan (Kalman et al., 2020; Radwan et al., 2021; Rahman et al., 2019; Pan et al., 2024; Khan et al., 2022; Guqhaiman et al., 2021; Molins et al., 2006). An important point to note is that sensor nodes will enter a sleep state after a failed packet transmission. In the studies mentioned earlier, when a node tries to send data and encounters a collision, it schedules the retransmission of the packet for a random time. However, this randomness can result in multiple packets selecting the same time to resend, causing them from different nodes to arrive at the receiving node simultaneously. This ongoing overlap leads to further packet collisions (Molins et al., 2006). A reasonable wake-up algorithm after transitioning to the sleep state helps improve transmission performance, reduces the number of retransmissions, saves energy, and enhances the operational lifespan of the sensor node.

In this study, we optimize and integrate solutions from CSMA (Carrier Sense Multiple Access), contention-free protocols, and contention-based protocols to create a hybrid MAC (Medium Access Control) protocol called ADAP_MAC. Our protocol aims to leverage the strengths of each method, allowing nodes to flexibly select the appropriate transmission protocol and power levels based on network conditions. This approach helps to minimize packet collisions and conserve battery energy for network nodes.

3. MATERIALS AND METHODS

In our proposed protocol, when a collision occurs or when a node learns of a recent collision at the receiving end by monitoring the channel and receiving a NACK (Negative Acknowledgment) packet, all nodes switch to a synchronized active state with allocated time slots. These time slots are optimized based on the distance between each node and the identified receiving node. After a synchronized period without collisions at the receiving node, the nodes will revert to a contention-free active state.

The operation of the network following the ADAP_MAC protocol algorithm includes the following steps:

3.1. Network initialization step.

In this step, the sensor nodes will determine their distance to the Master node as follows: The Master node initiates the network by sending an RCV (recover packet) to all the sensor nodes in the network while activating a timer. The sensor nodes that receive the RCV packet from the Master node respond with a REPi packet containing their own ID

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information. Based on the time of receipt of the REPi packet, the Master node determines the corresponding reception time for each sensor node and calculates the distance from the Master node to each sensor node, assuming a propagation speed of 1500 m/s (Liu et al., 2012). The Master node will then send a DISi packet containing information about the required distance/transmission time to the sensor nodes. Assume that the propagation time of the packet from each sensor node to the Master node is t_{di}. The transmission time for the maximum distance to the farthest sensor node is t_{d_max}.

Based on the t_{di} information, when the nodes transmit packets, they will optimize the transmission power corresponding to the distance to the Master node. The transmission power is calculated based on the distance, which is determined by the propagation time as follows:

$$t_{di} = timer_i/2. \quad (1)$$

The energy consumption model used in this research is the reference from (Rodoplu et al., 2005) is given as follows:

$$E_T = P_0 T_p A(r) = P_0 T_p r^k a^r \quad (2)$$

In Formula (2), E_T is the transmit energy, the power P_0 is the reference received energy which can decode information in the received packet correctly, the packet duration is T_p, the distance between the source and destination node is r, and k is the spreading factor which usually sets 1 for cylindrical, 1.5 for practical, and 2 for spherical spreading. In Formula (1), $a = 10^{(\alpha(f))}$ is the frequency dependent term obtained from the absorption coefficient α(f). By Thorp's expression (Berkhovskikh et al., 1982) in [dB/km] as follows:

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 * 10^{-4} f^2 + 0.03 \quad (3)$$

In Formula (3), f is in kHz. For the simulations in this research, we chose parameters as f = 10 kHz, k = 2 for the spherical spreading case, and the maximum transmission distance is d.

The total acoustic power loss (in dB) can be calculated using as follows:

$$TL = \text{Spreading Loss} + \text{Absorption Loss}$$

$$TL = k * \log10 * r + \alpha(f) * r \quad (4)$$

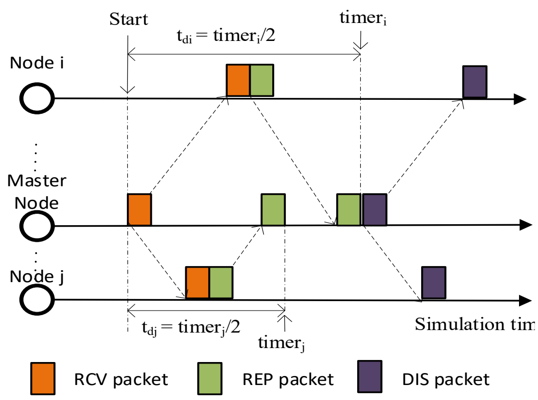

Figure 1. Network Initialization Step

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3.2. Asynchronous operation of the nodes in the network.

Each sensor node, when it has data to send to the Master node, will perform carrier sensing on the communication channel and there are two possible cases as follows:

If no carrier is detected on the communication channel, the nodes in the network will operate asynchronously (in a contention-free manner). The sending node will immediately transmit the packet and then wait for an acknowledgment (ACK) packet to confirm successful transmission. If the node receives a negative acknowledgment (NACK) indicating that the transmission was unsuccessful, it will switch to synchronous operation mode.

If a carrier is detected on the communication channel, the sending node will listen to determine if an ACK or NACK packet is being transmitted. If an ACK packet is detected, the node will wait until the channel is clear of the carrier before sending its packet. If a NACK packet is detected on the channel, the node will switch to synchronous operation mode.

The timing of each sensor node after receiving a NACK packet need to start its transmission time slot during the synchronous operation phase is determined according to Formula (6) and the timing diagram illustrating the precise moment a node transitions into the synchronized state is shown in Figure 2.

3.3. Synchronous operation and optimization of transmission power of the nodes.

In the synchronous operation state, each node will carry out the transmission process according to the time slot allocation for each node, where the order of the time slots corresponds to the ID of each node. The width of the time slot is equal to the time required to transmit to the Master node, denoted as t_{di}. In this state, since the transmission channel is entirely allocated to each sensor node during the corresponding time slot, the transmission efficiency is one hundred percent (Molins et al., 2006). Therefore, during this phase, the node only sends packets and does not require acknowledgment packets (ACK/NACK).

The nodes will operate synchronously during a period (Figure 3) equal to the total number of time slots (n) allocated for each network node as follows:

$$t_{Syn} = n\sum_{1}^{n} t_{di} \tag{5}$$

In Formula (5), t_{Syn} represents the time at which node i begins transitioning into the synchronized state, and n denotes both the number of nodes and the number of time slots allocated to the sensor nodes.

When receiving a NACK packet, the nodes need to determine the start time of the first time slot for the synchronization process, which is defined by Δt_i according to Formula (6). The node will enter a sleep state and time its wake-up for the allocated time slot to transmit the packet. The timing duration is calculated according to Formula (7).

$$\Delta t_i = t_{d\_max} - t_{di} \tag{6}$$

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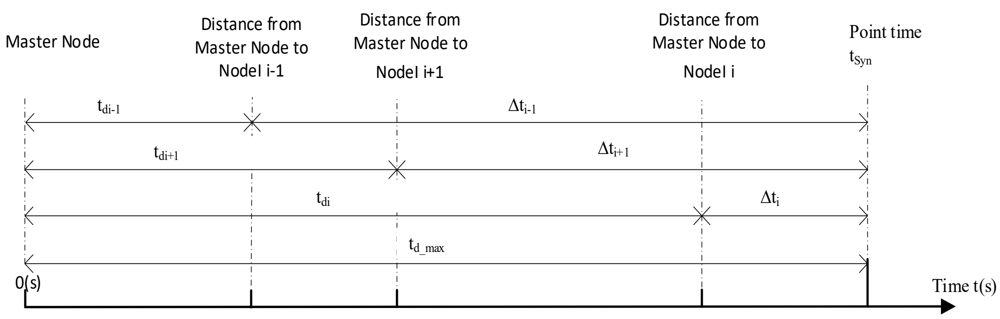

Figure 2. Transmittion time beetween Master node and other Sensor note

$$t_{timer\_i} = \Delta t_i + i * \sum_1^i t_{dj} \tag{7}$$

After sending the packet, the network node will transition back to the sleep state in order to wait before transitioning to the asynchronous operation state. The timing for a node to transition back to the asynchronous state is determined based on Formula (8).

$$t_{WaitForAsyn} = t_{Syn} - t_{timer\_i} + 1 \tag{8}$$

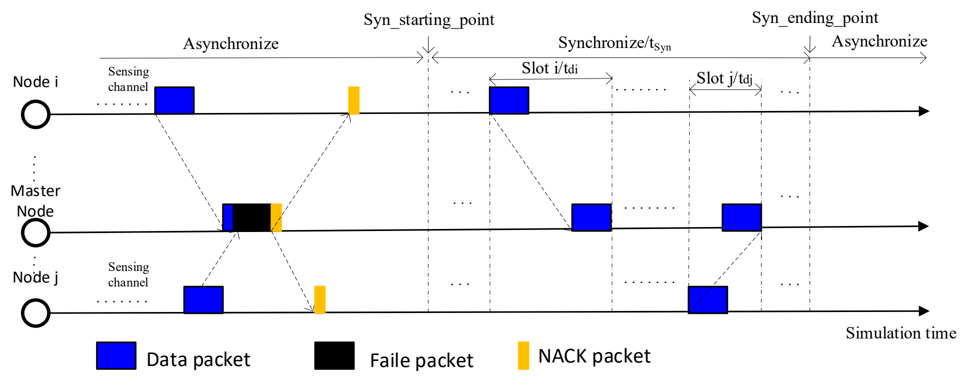

Figure 3. A transmission operation phase of nodes

4. CALCULATING NETWORK THROUGHPUT

To analyze the throughput S of the transmission channel in the ADAP-MAC protocol, we denote Δt as the ratio of propagation delay to packet transmission time and $\overline{\Delta t}$ as the average of Δt, t_d is the time required to send a data packet with a value of 1, and $\overline{t_d}$ as the average value of t_d, G is the offered traffic rate.

$$\overline{\Delta t} = \Delta t_i + \frac{1}{n} * \sum_1^n \Delta t_i \tag{9}$$

$$\overline{t_d} = t_{d\_max} - \overline{\Delta t} \tag{10}$$

A transmission operation phase of a node is illustrated in Figure 4.

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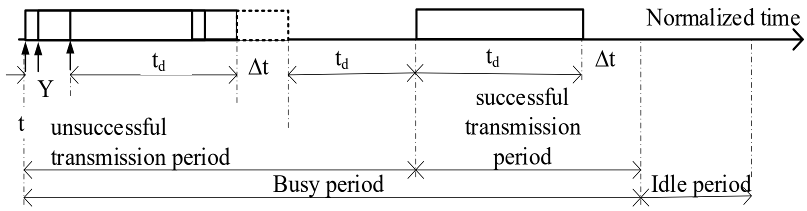

Figure 4. Transmission operation phases of a node

The network throughput is calculated:

$$S = \frac{\overline{U}}{\overline{B}+\overline{I}} \tag{11}$$

where $\overline{U}$ is the probability that no terminal transmits during the first Δt seconds of period

$$\overline{U} = e^{-\overline{\Delta t}G} \tag{12}$$

$\overline{B}$ is the average duration of a busy interval

$$\overline{B} = 2 + \overline{Y} + \overline{\Delta t} \tag{13}$$

$\overline{Y}$ is the expected value of Y

$\overline{I}$ is the average duration of an idle period

$$\overline{I} = \frac{1}{G} \tag{14}$$

Applying the expression for $\overline{U}$, $\overline{B}$, $\overline{I}$ we get S as follow:

$$S = \frac{Ge^{-\overline{\Delta t}G}}{2G(1+2\overline{\Delta t})+e^{-\overline{\Delta t}G}} \tag{15}$$

5. SIMULATION AND RESULTS

We conduct simulations to evaluate network performance, comparing the proposed ADAP-MAC protocol with Pure Aloha, Aloha with CSMA, Slotted Aloha, and Slotted Aloha with CSMA, as referenced in (Pal et al., 2022; Molins., et al 2006). The simulation program models the activities of each node, as illustrated in Figure 5. Unless specified otherwise, we will use typical parameter values commonly found in the literature (Awan et al., 2019; Yang et al., 2012; Luo et al., 2012; Liao et al., 2012).

Our network simulation model consists of 10 sensor nodes and one Master node. The sensor nodes and the Master node are randomly fixed on the seabed within a range of 500x500 square meters. The master node gathers data from ten sensor nodes, which send information at random intervals. The time interval for generating each packet at each node is a random moment within the interval of simulation times/λ, where λ is the total number of packets each node will generate throughout the simulation time. We will simulate the network with varying values of λ, starting from 10 packets generated per sensor node until the network throughput reaches a saturated state.

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For each value of λ, we will conduct five simulations, with each lasting 1,800 seconds. We will collect statistics on parameters such as the number of success packets, the packet transmission success rate, the number of retransmission packets, the total transmission distance of each node, and the total transmission power loss of each node for each simulation run. The size of each data packet is set to 1,000 bits long, while each control packet has 100 bits long. The bit rate is 10 Kbps, and the maximum transmission range extends to 500 meters within an area measuring 500 by 500 square meters. The frequency of the acoustic waves is 10 kHz. We apply spherical spreading to the waves, meaning they propagate equally in all directions, which gives us a coefficient (k) of 2.

6. DISCUSSION

The simulation results for successfully transmitted packets for each λ case are illustrated in Figure 5. The results indicate that at the beginning of situations, when the number of packets generated by each sensor node is still low, ranging from 10 to 30 packets per node, the number of successful packets corresponds to the number of packets generated. The number of packet retransmissions during these situations also varies across different protocols (Figure 6), depending on the randomness of packet generation. In these situations, the number of retransmissions is low, and the success rate is quite high, as shown in Figure 9. Other parameters, such as the total transmission distance (Figure 7) and the total power consumption (Figure 8), also remain low. This is due to the relatively small number of generated packets, and the ADAP-MAC protocol maintains a lower number of retransmissions compared to the Pure Aloha, Aloha with CSMA, Slotted Aloha, and Slotted Aloha with CSMA protocols.

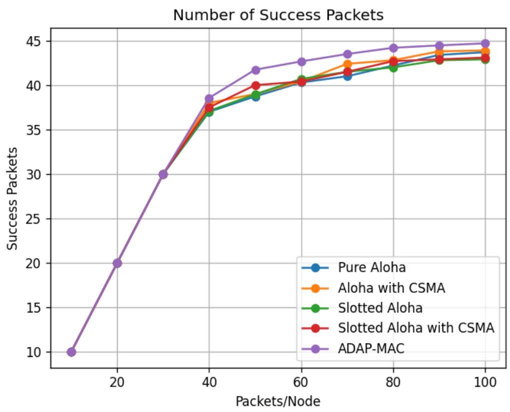

Figure 5. Number of Success Packets

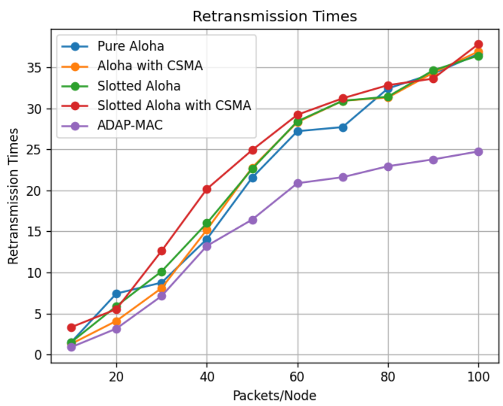

Figure 6. Retransmission Times

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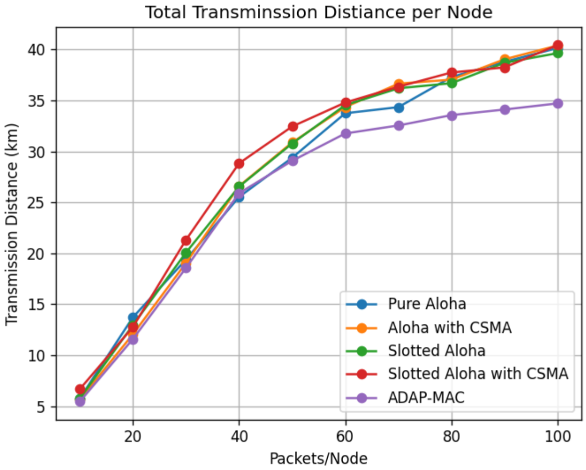

Figure 7. Total Transmission Distance per Node

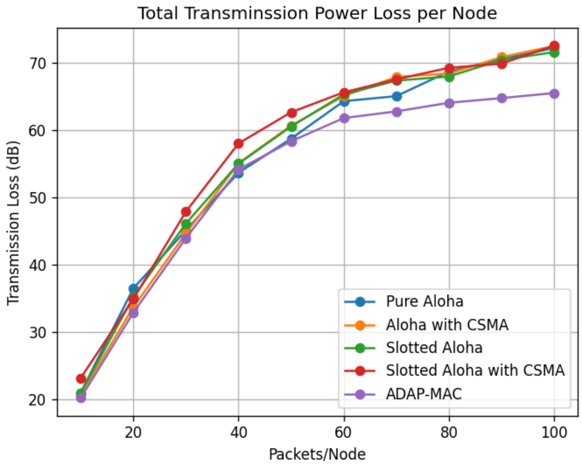

Figure 8. Transmission Power Loss

In the next stages, from λ equal to 30 to 60, the number of packets to be transmitted by each sensor node increases, and consequently, the number of successfully transmitted packets also increases, as shown in Figure 5. Due to the increased network traffic in these stages, the packet collision rate at the receiving node rises quickly, leading to a rapid increase in the number of retransmission times, as illustrated in Figure 6. During these stages, the effectiveness of the ADAP-MAC protocol becomes evident, particularly in its ability to recover from collisions. The time-slot allocation significantly reduces the number of collisions, as reflected by the fewer retransmissions with larger gaps compared to the Pure Aloha, Aloha with CSMA, Slotted Aloha, and Slotted Aloha with CSMA protocols (Figure 6). This is also demonstrated in the packet success rate in Figure 9, the total transmission distance in Figure 7, and the total power consumption in Figure 8. The ADAP-MAC protocol shows higher efficiency than the other protocols.

When the number of packets generated per node exceeds 60, the network gradually approaches saturation regarding its capacity to transmit packets successfully. During this phase, the ADAP-MAC protocol consistently outperforms other protocols in the number of packets successfully transmitted. Additionally, the number of retransmissions is lower with the ADAP-MAC protocol. As the transmission demand increases for each sensor node, the ADAP-MAC protocol demonstrates stability in its retransmission count. This stability is due to the inefficiency of collision

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avoidance in protocols such as Pure Aloha, Aloha with CSMA, Slotted Aloha, and Slotted Aloha with CSMA when network traffic rises. By transitioning to a synchronized state after a collision, the ADAP-MAC protocol significantly reduces the likelihood of subsequent collisions following the initial one.

In Pure Aloha, Aloha with CSMA, Slotted Aloha, and Slotted Aloha with CSMA protocols, the transmission range is established to ensure it can reach all sensor nodes. Consequently, the transmission distance is typically set to the maximum possible distance between any two nodes in the network.

In our proposed protocol, we optimize the transmission distance and time slot allocation for each node when transitioning to a synchronized state by determining the distance between network nodes. This approach reduces packet collisions, leading to fewer retransmissions (Figure 6) and an improved successful packet transmission rate (Figure 9). Additionally, it optimizes the transmission distance (Figure 7) and transmission power (Figure 8).

These enhancements help conserve the battery energy of each sensor node, which is crucial for extending their lifespan.

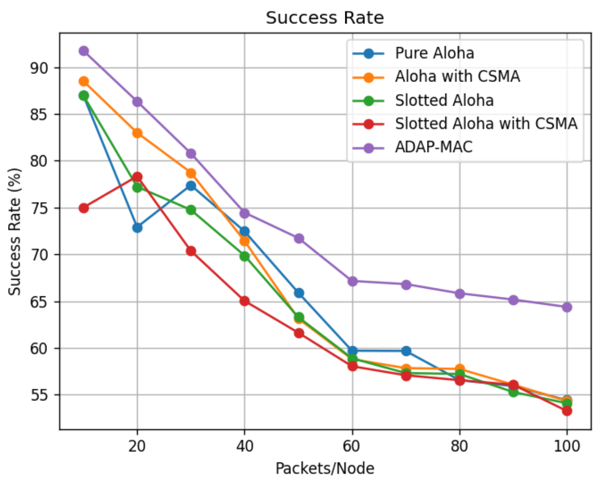

Figure 9. Success Rate

7. CONCLUSIONS

In this study, we proposed a MAC protocol that combines the advantages of previous protocols, such as CSMA, contention-free, and contention-based MAC protocols, to maximize the utilization of channel resources in underwater communication networks. Additionally, an Automatic Repeat Request Algorithm combined with a transmission power optimization method has also been proposed. The simulation results evaluate the effectiveness of the proposed protocol by assessing various parameters: the number of successfully transmitted packets, the transmission success rate of network nodes, the number of retransmissions due to packet collisions at the receiver, the transmission distance, and the power consumption for packet transmission. The simulation evaluation results demonstrate that the ADAP-MAC protocol outperforms the corresponding protocols, including Pure Aloha, Aloha with CSMA, Slotted Aloha, and Slotted Aloha with CSMA.

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