Journal of Information Systems Engineering and Management
2025, 10(31s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

An Automatic Repeat Request Strategy for Contention-Free MAC protocol in Underwater Acoustic Communication Networks

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ARTICLE INFO

Received: 26 Dec 2024

Revised: 14 Feb 2025

Accepted: 22 Feb 2025

ABSTRACT

The Contention-Free MAC protocol in underwater acoustic communication channels efficiently utilizes the narrow bandwidth of acoustic waves for data transmission. However, since it does not use any handshake protocol before transmitting data, the packet collision rate at the receiving node is often high due to the low propagation speed of acoustic waves in the underwater environment. When collisions occur, transmitting nodes must enter a sleep state and wait for a certain period before waking up and retransmitting the packet. If sensor nodes transition into sleep mode and then return to transmission mode at inappropriate times, it may lead to further collisions in subsequent transmission steps, causing continuous transmission disruptions. In this study, we propose an Automatic Repeat Request for Contention-Free MAC protocol (ARQ_CF). In the ARQ_CF protocol, a sending node with a packet to transmit or one that has just experienced a packet collision will listen to the channel state. Based on the observed channel state and the type of packets it receives, the node calculates an appropriate sleep and wake-up time to avoid further packet collisions. We will simulate and evaluate the effectiveness of the protocol to demonstrate that the ARQ_CF strategy can reduce the number of retransmissions due to packet collisions at the receiving node. As a result, it significantly improves the packet delivery success rate and enhances the efficiency of channel resource utilization for data transmission.

Keywords: Underwater Communication Networks, MAC protocol, ARQ Strategy, Contention Free MAC Protocol.

1. INTRODUCTION

Underwater communication networks (UWN) utilize acoustic waves to transfer data due to the severe attenuation of radio waves underwater (Alfouzan, 2021; Jiang, 2018; Carriço et al., 2020). The unique characteristics of underwater environments, such as low bandwidth, high propagation delay, and energy constraints, necessitate the design of effective Medium Access Control (MAC) protocols (Chen et al., 2014; Mirzaei et al., 2021; Timmermann., 2023). MAC protocols are essential for coordinating how nodes in a network access the shared communication medium without interference, and they can be broadly classified into contention-free, contention-based, and hybrid approaches (Guqhaiman et al., 2021).

Contention-free MAC protocols, often schedule-based, are designed to allocate transmission slots for nodes, ensuring that only one node transmits at a time. This approach reduces the possibility of collisions and enhances overall network performance, making it particularly suitable for time-sensitive applications (Sivagami et al., 2016; Zradgui et al., 2022). An example of such a protocol is the Cluster-Based MAC (CBMAC), which utilizes Time Division Multiple Access (TDMA) to assign time slots for transmission based on cluster head coordination (Sivagami et al., 2016). Although contention-free protocols like CBMAC promote efficient channel usage and minimize energy consumption, they must contend with challenges such as increased end-to-end delays and potential packet drop issues.

In contrast, contention-based MAC protocols permit multiple nodes to contend for access to the channel, allowing for more flexible network operations. Examples include ALOHA and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), wherein nodes transmit data randomly or wait for acknowledgment before transmission (Nguyen et al., 2015). These protocols are often favored for their energy-efficient characteristics and reduced latency in scenarios where timely data transmission is not critical (Molins et al., 2006). However, contention-based approaches may lead to increased collision rates and lower throughput when the network becomes densely populated.

Hybrid MAC protocols aim to leverage the advantages of both contention-free and contention-based strategies, thus providing a versatile solution for underwater communication networks (Xie et al., 2007). These protocols, such as Reservation-based MAC (RMAC) and Combined Free/Demand Assignment Multiple Access (CFDAMA), incorporate mechanisms from both families to optimize the usage of channel resources while responding to varying traffic loads . For example, RMAC utilizes a handshaking process along with TDMA techniques to reduce energy consumption while maintaining collision avoidance. Nevertheless, hybrid protocols can be complicated to implement due to the required coordination between different transmission modes.

MAC protocols for underwater communication networks play a vital role in facilitating efficient data transmission while addressing the distinct challenges posed by the underwater environment. The choice between contention-free, contention-based, and hybrid approaches hinges on the specific requirements of the applications being supported, including the importance of low latency, energy efficiency, and overall network reliability (Awan et al., 2019; Guqhaiman et al., 2021).

2.RELATED WORKS

In the exploration of Automatic Repeat Request (ARQ) algorithms for Medium Access Control (MAC) protocols in underwater communication networks, various studies highlight the inherent challenges of underwater environments that necessitate specialized solutions. For instance, (Nguyen et al., 2015) introduce an adaptive retransmission scheme, ARS, which emphasizes maximizing successful transmissions while dealing with high end-to-end latency due to the Binary Exponential Backoff (BEB) algorithm. Complementing this, (Shahabudeen et al., 2013) analyze high-performance MAC protocols and underline energy consumption concerns, showing that effective ARQ implementations can significantly reduce packet loss. Other studies, like (Kim et al., 2016), present cooperative ARQ-based MAC protocols that leverage collaboration among underwater nodes to mitigate transmission errors, thereby improving overall network robustness. Additionally, the work by (Coutinho et al., 2016) integrates ARQ mechanisms with routing protocols, demonstrating that strategic routing significantly complements ARQ performance under varying network loads. This body of research indicates a strong trend towards adaptive and cooperative ARQ methodologies, which are essential for optimizing underwater communication reliability and efficiency in the face of the unique challenges posed by underwater environments (Alfouzan, 2021; Carrico et al., 2020; Xie et al., 2007; Liu et al., 2016; Park et al., 2021).

A designated cooperating node transmits data packets stored in its buffer cache, which it successfully received from the previous sending node or other collaborators. The signaling process and node waiting delays are calculated to account for the time required for cooperation among intermediate nodes. In this study, Shih-Yang Lin and colleagues (Lin et al., 2023) proposed an adaptive hybrid automatic repeat request (ARQ) strategy to reduce error rates, retransmissions, and overall retransmission time. This strategy leverages the Q-learning model to dynamically adjust the frequency and timing of retransmissions, enhancing transmission reliability. Additionally, the study introduces several K-loop transmission schemes, incorporating delay T and overlap [T, K], to prevent packet collisions and minimize latency. In the study (Kaythry et al., 2019) by P. Kaythry and colleagues, a recursive Luby transform (RLT) code-based hybrid automatic repeat request (ARQ) model is explored to enhance data transmission efficiency and reliability. RLT is a variant of Luby codes with a small distribution degree. The proposed hybrid ARQ scheme, known as RLTCH, is based on non-proportional coding and integrates RLT with selective retransmission ARQ. RLT codes are employed due to their low complexity in both encoding and decoding processes. To assess the performance of RLTCH, specific underwater channel characteristics are taken into consideration. In study (Wei et al., 2023), Y. Wei and D. Wang proposed a multichannel medium access control (MAC) strategy for underwater acoustic channels, where sensors function as nodes. The proposed protocol is a synchronized MAC scheme that divides time into three phases to enhance system throughput and energy efficiency. In (Zhang et al., 2022), the authors propose a machine learning-based MAC protocol for duplex medium access control (MAC) in single-hop underwater acoustic sensor networks. This protocol aims to enhance network performance by improving delay status, throughput, and fairness in access. In (Ansa et al., 2024), S. S. Ansa and colleagues proposed a MAC protocol for boundary detection applications in underwater environments using underwater mobile sensors. This protocol is specifically designed for

Autonomous Underwater Vehicles (AUVs). (Dong et al., 2022) proposes a MAC protocol with a variable time slot. This protocol requires network-wide synchronization of working time, leading to high energy consumption and ultimately reducing the operating time of sensor nodes.

Another recent study on MAC protocols is introduced in (Guo et al., 2024), where a performance analysis of a MAC protocol for underwater acoustic channels is presented. This protocol considers both the unique characteristics of underwater acoustic networks (UANs) and the diversity of MAC protocols. However, to accurately estimate energy consumption, throughput, and delay, it requires the design of a successful transmission probability model and a packet service time model. As a result, the performance of this approach depends heavily on the accuracy of the probability model. The study (Lin et al., 2023) proposes an Adaptive Hybrid Automatic Repeat Request (A-HARQ) scheme designed to reduce the average block error rate, the average number of retransmissions, and the round-trip time (RTT). It leverages a Q-learning model to dynamically adjust the timing and frequency of retransmissions, enhancing transmission reliability.

Due to the complexity of the communication channel, suggested MAC protocols can only reduce packet collisions, but collisions may still occur. When a packet collision happens, nodes must enter a sleep state and wait for a certain period before retransmitting the packet. If the colliding packets attempt to retransmit at the same intervals, collisions will occur repeatedly without resolution, potentially leading to network paralysis. Therefore, a sleep-wake algorithm that detects a busy channel or an unsuccessful transmission and then schedules retransmission is essential to mitigate network congestion caused by repeated packet collisions.

3.ARQ_CF ALGORITHM DESCRIPTION

3.1 Underwater Acoustic Sensor Communication Network Model

We constructed a model in which UW-Sensor nodes and UW-Master nodes are deployed beneath the seabed in a 2D layout, typically anchored to the ocean floor (Figure 1). Therefore, the network nodes are positioned at the same depth or on horizontal planes in shallow waters. The sensor nodes (UW-Sensors, which are fixed around a UW-Master receiving node as shown in Figure 1) operate within a specific area and are capable of collecting data.

The UW-Sensor nodes will transmit the collected data to the central processing node, UW-Master, which is also positioned on the seabed. The UW-Master node then sends the data to the surface Gateway station via a wired or wireless optical fiber link, which subsequently transmits the information either directly to the onshore station or through a satellite. The number of UW-Sensors can be adjusted depending on the configuration requirements for seabed data collection within a specific network cluster.

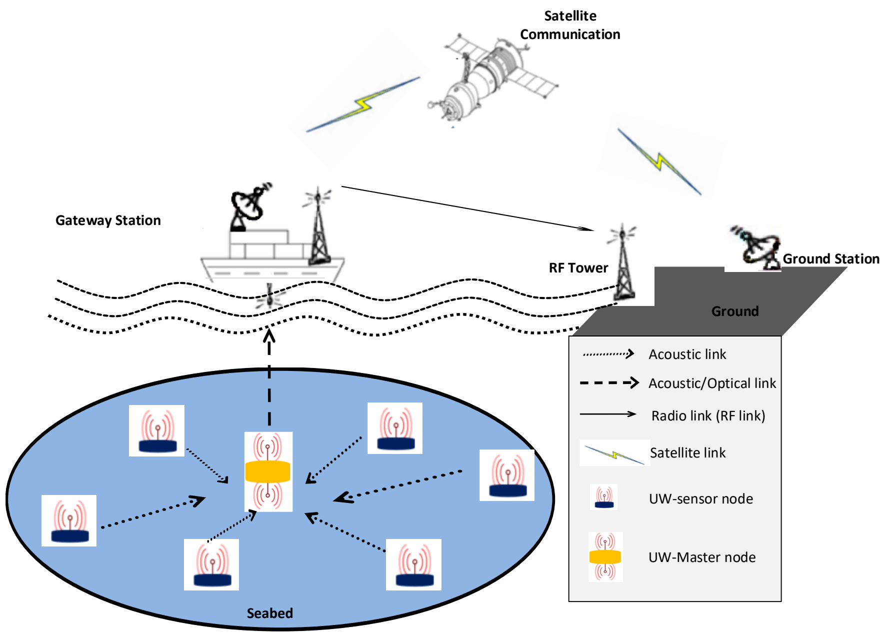

Figure 1. Underwater acoustic sensors network architecture

We assume that during network deployment, the UW-Master node and sensor nodes will be submerged and anchored at predetermined positions (neglecting coordinate deviations when submerging any node from the surface to the seabed) to collect data within a specific area. The network nodes are powered by batteries, where the UW-Master's battery can be recharged, while the UW-Sensors' batteries cannot. UW-Sensors can be replaced or supplemented to expand the seabed data collection coverage.

3.2 ARQ_CF Algorithm Description

Each UW-Sensor node joining the network must register by sending a Register (RGT) packet to the UW-Master node and will receive a Registered Successful (RSF) packet from the UW-Master, confirming successful registration (see Figure 2). The registration order of sensor nodes within a cluster is also determined to assign priority in packet transmission timing in case of conflicts at the receiving node. This priority order is arranged from 1 to n (where n is the number of nodes in a cluster). The UW-Master assigns this order to UW-Sensors through the RSF packet when initializing the network or registering a new member. The registration process also determines the transmission delay time of a packet from a UW-Sensor node to the UW-Master node, as described in Figure 2 and Equation (1).

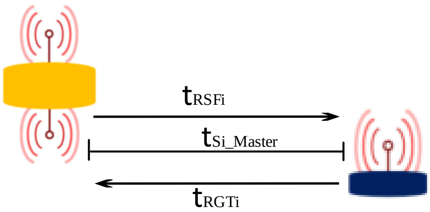

Figure 2. The membership registration process of the UW-Sensor node.

$$t_{Si\_Master} = \frac{t_{RSFi} - t_{RGTi}}{2} \quad (1)$$

Where, t_{RGTi} is the timestamp when the RGTi packet from the ith UW-Sensor node is sent to the UW-Master node; t_{RSFi} is the timestamp when the ith UW-Sensor node starts receiving the RSFi packet; t_{Si_Master} is the time required for the acoustic wave to propagate from the ith UW-Sensor node to the UW-Master node.

3.2.1 Operation of the UW-Master Node (Figure 3)

After initializing the network (Init state in Figure 3), the UW-Master node will be in an Idle state. When a data packet arrives, the node transitions to the data reception state, where one of the following three scenarios may occur:

Case 1: If the UW-Master node successfully receives an RGT packet, it will send back an RSF packet containing the corresponding decoded node ID. After that, the node will transition back to the Idle state.

Case 2: If a packet collision occurs, preventing the successful decoding of the received packet, the UW-Master node will send a NACK packet on the channel, including the corresponding decoded node ID. After that, the node will transition back to the Idle state.

Case 3: If the UW-Master successfully receives a Data Packet, it will send an ACK packet, including the corresponding decoded node ID. After that, the node will transition back to the Idle state.

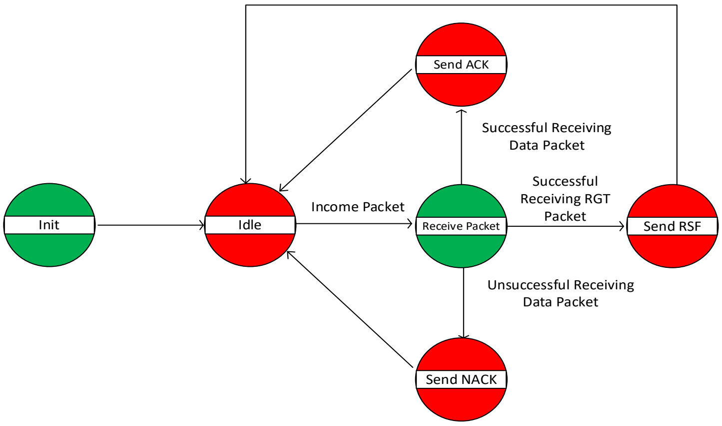

Figure 3. Operations of UW-Master node

3.2.2 Operation of UW-Sensor Node (Figure 4)

In the ARQ_CF algorithm, when a UW-sensor node has data to send to the UW-Master node, it will first check the status of the communication channel. The channel status may fall into the following cases:

Case 1: If the transmission channel is in an idle state (no existing carrier signal), the node with a packet to send will immediately transmit the packet to the UW-Master Node and enter the acknowledgment waiting state. If the sender receives an ACK packet (ACK for itself) from the Master Node, it confirms that the data packet was successfully transmitted. If the sender receives a NACK or xNACK packet (NACK for itself, xNACK for another node), it confirms that the data transmission has failed. At this point, the sender will enter sleep mode and set a timer to wait for the wake-up time to retransmit the packet. The wake-up time for retransmission is calculated based on the ARQ_CF algorithm using Equation (2) and is referred to as tARQ_CF.

$$t_{ARQ\_CF} = t_{dis\_max} - t_{Si\_Master} + i * t_{dis\_max} + t_{data} \quad (2)$$

Where, t_{ARQ_CF} is the duration a node stays in sleep mode before waking up to transmit data; t_{dis_max} is the propagation delay from the UW-Master Node to the farthest location in the network where the receiving node can decode the information; i is the priority order of a UW-Sensor when a collision occurs at the receiving node (this priority order is arranged from 1 to n); t_{dis_max} is the time length of a data packet encoded into an acoustic wave.

Case 2: If the Sender node listens to determine the channel status and receives a packet identified as an xACK packet (xACK is an ACK packet for another node), it will proceed to transmit its packet immediately after the channel is free of any existing carrier signals.

Case 3: If the channel has a carrier signal and the sender node determines that it is a NACK packet (NACK for itself) or an xNACK packet (NACK for another node), the sender will switch to sleep mode and schedule its wake-up time to retransmit the packet. The wake-up time for retransmission is calculated based on the ARQ_CF algorithm and formula (2).

Case 4: If the sender node receives an xData Packet (xData Packet is a data packet for another node), it will continue to listen to the channel for a duration of tlistent, which is calculated using formula (3). During this period, if it receives an xACK packet, it will follow Case 2. If it receives a NACK or xNACK packet, confirming that the reception at the receiving node has failed, it will follow Case 3.

$$t_{listen\_i} = 2 * t_{Si\_Master} + t_{data} + t_{ACK/NACK} \quad (3)$$

Where, $t_{ACK/NACK}$ is the time duration of an ACK/NACK packet encoded as an acoustic wave.

Case 5: If the Sender detects a carrier signal but cannot determine the type of information being transmitted on the channel, it will continue listening to the channel for a duration of $2 * t_{Si\_Master}$. During this period, only Case 1, Case 2, Case 3, and Case 4 may occur. The Sender will operate according to the corresponding Case as previously described.

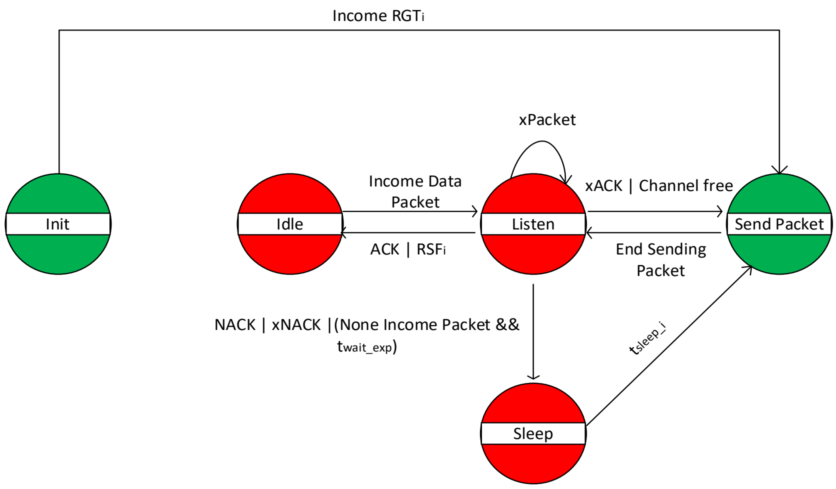

Figure 4. Operations of UW-Sensor Node

In our network setup, the distance from the UW-Master, which is located at the center, to the UW-Sensor node that is the farthest away is denoted as dmax, and the propagation delay time is tdelay_max.

In the ARQ_CF protocol, when a node detects that a collision has just occurred at the receiving node, it transitions into sleep mode. The wake-up time for retransmitting data is determined by Equation (2). At this point, the entire communication channel is allocated to the node, ensuring a completely successful data transmission to the UW-Master node. Therefore, to optimize channel resource utilization, the UW-Master node does not send an ACK packet to confirm success.

After successfully transmitting the data packet, the channel is reassigned to other network nodes. As a result, a node that has executed the ARQ_CF protocol must wait for a period of twait_i before returning to the normal Contention-Free operational state. The waiting time twait_i is calculated according to Equation (4).

$$t_{wait\_i} = n * t_{dis\_max} - t_{ARQ\_CF} + t_{data} \quad (4)$$

4. SIMULATION AND RESULTS

4.1 Setup Simulation Conditions

We will conduct network performance simulations to compare the proposed ARQ-CF protocol with UW-Aloha-QM, A-HARQ, NR-MAC, and CSMA/CA by programming the activities for each node, as shown in Figure 1. The network consists of one UW-Master node and ten UW-Sensor nodes, which are randomly deployed and fixed at positions on the seabed within a 1 km² area. The data packet size is set to 1000 bits, while control packets (ACK/NACK/RGT/RSF) are set to 100 bits. The maximum transmission range of each node is 707 meters. Each simulation runs for 1800 seconds, and the transmission time for the maximum distance is 0.5 seconds. The UW-Master node collects data packets randomly sent from UW-Sensor nodes. The data packets are generated at each node following a random process within an allocated time frame, calculated as the simulation time divided by the number of UW-Sensor nodes. In our experiments, we vary the offered load per node from 40 packets per node until the network protocols reach saturation in terms of channel utilization. For each offered load scenario, we run five simulations and compute the average results across these five runs. The results are then averaged for each network node. We collect simulation data and evaluate the performance of each network protocol based on the following parameters: Number of retransmissions due to packet collisions at the receiving node; Packet delivery success rate, measuring the percentage of successfully transmitted packets. Channel utilization efficiency, assessing how effectively each protocol utilizes the available transmission resources.

4.2 Simulation Results Analysis

The simulation results in Figure 5 regarding the Number of Retransmissions show that when the number of packets generated per node is still low, ranging from 40 to 60 packets per node, the overall network traffic is low. As a result, all protocols experience a low packet collision rate. As shown in Figure 5, the number of retransmissions falls within the range of 15 to 30 times, with the proposed ARQ-CF protocol performing better at around 10 to 15 retransmissions.

Within this range of generated packets per node, the low number of retransmissions leads to a relatively high packet success rate, as illustrated in Figure 6. The success rate reaches 60% to 80%, with the ARQ-CF protocol achieving a significantly higher success rate of approximately 70% to 80%. In contrast, the A-HARQ, NR-MAC, CSMA/CA, and UW-Aloha-QM protocols show lower success rates, achieving 60 to 70 successfully transmitted packets. Additionally, in the 40 to 60 packets per node range, due to the relatively low packet generation rate, the transmission channel has more idle periods, leading to lower channel utilization efficiency, which remains between 30% and 37.7%. The ARQ-CF protocol still outperforms others, achieving 34% to 37.5% channel utilization, whereas the A-HARQ, NR-MAC, CSMA/CA, and UW-Aloha-QM protocols exhibit lower efficiency, ranging from 30% to 36%.

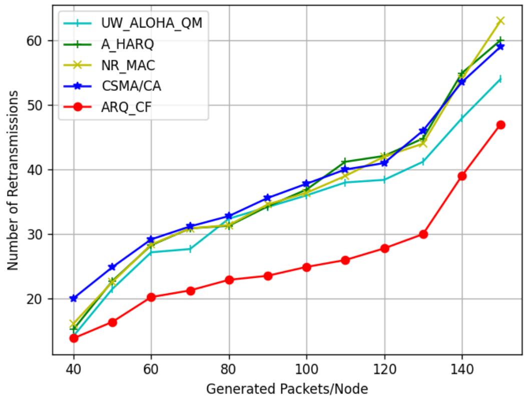

Figure 5. Retransmission Times

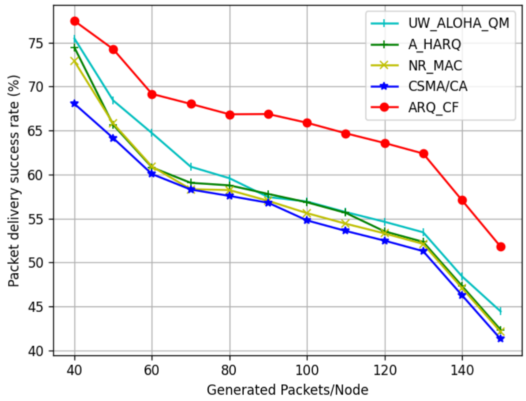

Figure 6. Packet delivery success rate

In the phase where the number of packets generated per node ranges from 60 to 130 packets, the increased packet generation leads to a higher number of packet collisions at the receiving node. As a result, the number of packet retransmissions also increases, as shown in Figure 5. During this phase, the ARQ-CF protocol continues to perform better than A-HARQ, NR-MAC, CSMA/CA, and UW-Aloha-QM in terms of retransmissions. Specifically, ARQ-CF maintains a retransmission count between 20 and 30 times, whereas the other protocols experience higher retransmission rates, ranging from 27 to 45 times. The higher retransmission count negatively impacts the packet success rate and channel resource utilization of these protocols. The success rate declines from 65% down to 52%, while the channel utilization efficiency decreases from 36% to 43%. In contrast, ARQ-CF achieves better performance due to its efficient channel resource utilization. This leads to a higher packet success rate, which only drops slightly from 68% to 63%. Similarly, ARQ-CF also maintains better channel utilization, ranging from 37.5% to 42% during this phase.

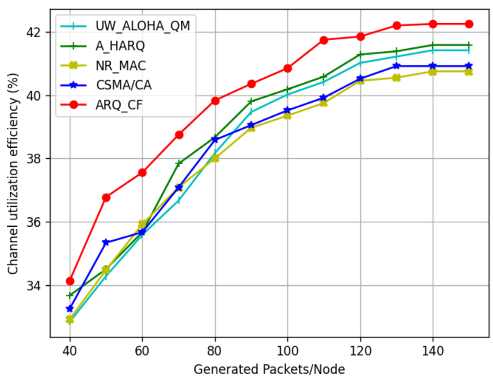

Figure 7. Channel utilization efficiency

In the phase where the number of packets generated per node ranges from 60 to 130 packets, the retransmission count increases rapidly from 39 to 63 times for the A-HARQ, NR-MAC, CSMA/CA, and UW-Aloha-QM protocols. Consequently, the success rate declines significantly, dropping from 53% to 42% for these protocols. In contrast, the ARQ-CF protocol experiences a lower retransmission count, ranging from 30 to 48 times, with a higher success rate, ranging from 63% to 52%. This indicates that packet collisions at the receiving node are severe, and the network throughput has reached a saturation state, as shown in Figure 7. During this phase, channel resource utilization does not increase further for any of the protocols, remaining at approximately 41% for A-HARQ, NR-MAC, CSMA/CA, and UW-Aloha-QM, while ARQ-CF achieves a slightly higher utilization rate of 43%.

5. CONCLUSION

In this study, we proposed an ARQ-CF strategy for a protocol applied to underwater communication channels. This protocol employs a Contention-Free channel access method to maximize network resource utilization, meaning that no handshake mechanism is used before data transmission. We implemented an appropriate sleep-and-wake-up algorithm based on calculating the transmission time interval from each UW-Sensor node to the UW-Master node. Additionally, we considered the longest transmission time of a packet to determine the optimal retransmission timing for each network node, ensuring that packets do not overlap at the receiving node. Our simulation results, compared with both the original and modified versions of the Contention-Free Based MAC Protocol, demonstrate the high effectiveness of the proposed method. Overall, the approach increased the global packet delivery success rate by approximately 8% (Figure 6, when the number of generated packets ranged from 100 to 120 per node). The resource utilization efficiency of our protocol also showed significant improvement compared to previous proposals, as illustrated in Figure 7.

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