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APPLYING STOCHASTIC NETWORK CALCULUS FOR PERFORMANCE EVALUATION OF HARQ PROTOCOLS IN UNDERWATER ACOUSTIC WIRELESS SENSOR NETWORKS

Sivajayaprakash A[1*], Rajeev Sukumaran[2]

[1*]Department of Computer Science and Engineering, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu.

[2]Department of Computer Science and Engineering, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu. rajeevcbe@gmail.com

E-mail: sivajayaprakash05@gmail.com[1*], director.dld@srmist.edu.in[2]

Abstract

An Underwater Acoustic Wireless sensor networks are becoming increasingly important in applications like environmental monitoring, military surveillance, and geological data collection. However, these networks are forced to face significant difficulties because of the harsh environment in underwater, including high latency, minimal bandwidth, and excess error rates. Traditional Automatic Repeat Request (ARQ) protocols often rely only on error detection and retransmission and thus are insufficient to solve these problems. Hybrid Automatic Repeat Request (HARQ) protocols offer a promising solution to these challenges by integrating error correction and retransmission strategies. Hybrid Automatic Repeat request (HARQ) protocols, which combine error correction and retransmission strategies, offer a promising solution. This article explores the application of HARQ protocols in UAWSNs and evaluates their performance using stochastic network calculus. The study focuses on three main types of HARQ protocols: Type I, Type II and Type III. Stochastic network calculus, a mathematical framework for analysing network performance under uncertainty, is used to model and evaluate these protocols. Key performance metrics such as delay, throughput, and packet delivery ratio are analysed. Simulation results show that Type II HARQ, which combines new and previously received packets for enhanced error correction, provides the best performance in terms of reliability and efficiency. The findings demonstrate that HARQ protocols, especially Typey II, can significantly improve data transmission reliability in UAWSNs, making them a viable option for overcoming the challenges of underwater communication. Future research directions include exploring adaptive HARQ mechanisms and integrating HARQ with other error control techniques for further performance enhancement.

Keywords: Hybrid ARQ Protocols, Second UAWSNs-Underwater Acoustic Wireless Sensor Networks, Stochastic Network Calculus, Error Control Mechanisms, Network Performance Optimization.

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1. Introduction

UAWSNs consist of spatially-distributed self-regulating sensors that monitor environmental conditions in underwater environments. These networks play a vital role in numerous applications, such as environmental-monitoring, oceanographic data collection, underwater exploration, and military surveillance. The unique characteristics of underwater acoustic channels, including limited bandwidth, high propagation delays, and high bit error rates, present significant challenges to reliable data transmission [1].

Traditional Automatic Repeat Request (ARQ) protocols are insufficient to overcome these challenges due to their reliance solely on retransmissions. This paper addresses these limitations by proposing a Type II Hybrid Automatic Repeat Request (HARQ) protocol, which integrates error correction with retransmissions. The performance of this protocol is evaluated using Stochastic Network Calculus (SNC), providing insights into its reliability and energy efficiency in addressing UAWSNs' unique challenges.

UAWSNs face several challenges, including high latency due to the slow speed of sound in water, low bandwidth limiting data rates, and high error rates caused by multipath propagation, Doppler shifts, and noise. Additionally, energy constraints are critical, as nodes are often battery-powered and located in remote areas. Node mobility due to water currents or AUVs further complicates reliable communication. Traditional protocols, such as Automatic Repeat Request (ARQ), rely solely on retransmissions and are insufficient in such environments. Hybrid Automatic Repeat Request (HARQ) protocols, which combine error correction with retransmission strategies, offer a promising solution to these challenges.

In this article investigates the application of HARQ protocols in UAWSNs using stochastic network calculus to analyse their performance [2]. Stochastic network calculus is an advanced mathematical framework used to analyse and evaluate the performance of communication networks under uncertainty. It extends traditional network calculus, which primarily deals with deterministic bounds, by incorporating stochastic processes that model the inherent randomness in network traffic and service behaviours. This extension allows for a more realistic and flexible analysis of networks where traffic arrivals, service rates, and other parameters can vary unpredictably [3]. Traditional network calculus uses concepts like arrival curves and service curves to describe the behaviour of traffic and service processes deterministically [4]. Stochastic network calculus, on the other hand, uses probabilistic models to capture the random nature of these processes. This approach is particularly useful in environments like underwater acoustic networks, where factors such as channel conditions and node mobility introduce significant variability.stochastic network calculus, network elements (such as nodes and links) are modelled using stochastic processes. These processes describe the time-varying behaviour of traffic arrivals and service capabilities [4].

Research Gaps: Most existing studies focus on addressing single challenges (e.g., high error rates, energy constraints) without integrating solutions for high latency, low bandwidth, high error rates, energy constraints, and node mobility. Comprehensive evaluations of HARQ in a stochastic network calculus framework, particularly under varying underwater conditions, are limited [8]. The specific advantages of Type II HARQ in balancing reliability and energy

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efficiency in UAWSNs are underexplored. Additionally, the impact of node mobility in conjunction with Type II HARQ has not been adequately addressed.

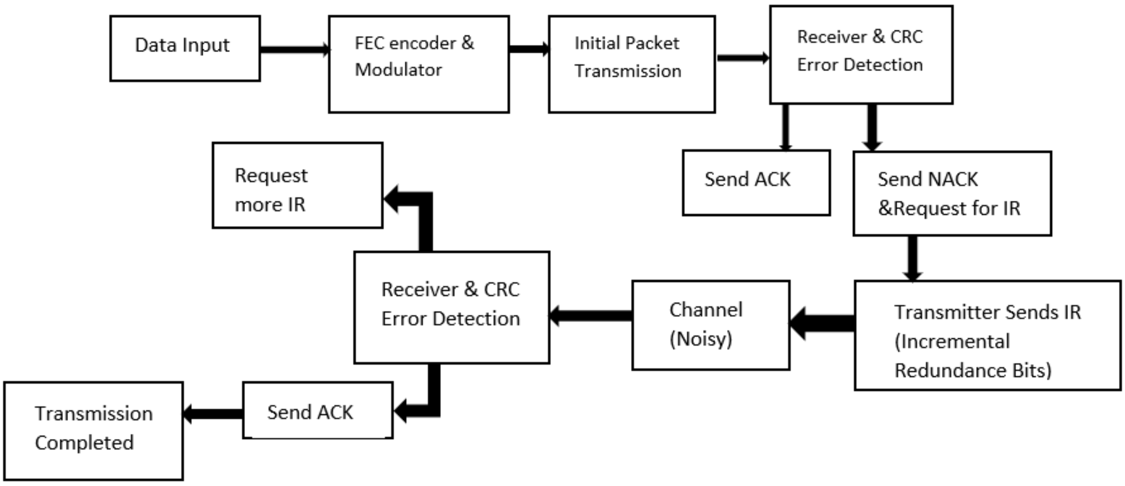

Figure 1. Flow chart of TYPE II HARQ with Incremental Redundance

In this article proposes a comprehensive solution integrating Type II HARQ (with incremental redundance) with stochastic network calculus to tackle key challenges in UAWSNs, including high latency, low bandwidth, high error rates, energy constraints, and node mobility. It will provide a detailed performance evaluation through both theoretical and simulation-based approaches to align mathematical models with real-world performance. The study also optimizes Type II HARQ for node mobility, ensuring reliable communication in mobile UAWSNs. Additionally, it offers novel insights into enhancing reliability and efficiency in underwater networks through this integrated approach.

2. Mathematical Modelling of Harq

Stochastic network calculus is a mathematical framework that extends traditional network calculus by incorporating stochastic processes, enabling the analysis of communication network performance under uncertainty [4].

This paper proposes an integrated framework combining Type II HARQ with Stochastic Network Calculus (SNC). Type II HARQ leverages incremental redundancy for error correction, reducing retransmissions and energy usage. SNC provides a probabilistic model to evaluate delay, throughput, and energy efficiency under realistic underwater conditions, capturing the inherent randomness of underwater acoustic channels.

To model HARQ protocols using stochastic network calculus, we consider two components: The traffic model and the Service model. It allows for the evaluation of key metrics such as delay, backlog, and throughput in networks with random traffic and service processes, providing insights into how these factors impact overall network performance. In this section, we develop mathematical models for Hybrid Automatic Repeat request (HARQ) protocols using SNC(S-stochastic N-network C-calculus). Also we focus on deriving performance metrics such as delay and throughput, which are crucial for evaluating the efficiency of HARQ protocols in Underwater Acoustic Wireless Sensor Networks (UAWSNs) [5].

To model HARQ protocols using stochastic network calculus, we consider two components like Traffic model and the Service model.

Traffic Model

The amount of packets arriving at the transmitter by time t is represented by the cumulative arrival process X(t). Assumed to occur is a Poisson process with arrival rate λ for packet arrivals. It is possible to express the X(t) as [7]:

$$X(t) = \sum_{i=1}^{N(t)} a_i \qquad (1)$$

where $N(t)$ is a Poisson process with rate λ, and a_i represents the arrival time of the i-th packet.

Service Model

The cumulative service process $Y(t)$ representing the number of packets successfully transmitted by time t. The service process is influenced by the HARQ protocol and the UW channel. We define the service process $Y(t)$ as:

$$Y(t) = \sum_{i=1}^{M(t)} s_i \qquad (2)$$

Where, $M(t)$ is the cumulative No. of service opportunities by time t, and s_i represents the service time for the i-th packet. The service times s_i are influenced by factors such as propagation delay, bandwidth, and error rates [9].

For HARQ protocols, the service times can vary depending on the number of retransmissions required for successful delivery. Let R be the random variable representing the number of retransmissions for a packet. The total service time for a packet is then:

$$s_i = d + R \cdot r \qquad (3)$$

where d is the base transmission time, and r is the time required for each retransmission [13].

In Type I HARQ, upon error detection, the entire packet is retransmitted.

The service process $Y(t)$ is modeled as:

$$Y(t) = \sum_{i=1}^{M(t)} (d + R \cdot r) \qquad (4)$$

Where,

d - deterministic service time for transmitting the original packet.

R - number of retransmissions, following a geometric distribution with success probability p.

r - time required for each retransmission. $M(t)$ - number of packets served by time t.

The geometric distribution implies that the probability mass function of R is

$$P(R = k) = p(1-p)^k, \text{ where } k \geq 0$$

In Type II HARQ, incremental redundancy is used, meaning only additional redundancy bits are retransmitted. The service process $Y(t)$ is given by [10]:

$$Y(t) = \sum_{i=1}^{M(t)} (d + R \cdot r_i) \tag{5}$$

Where

r_i - time required for the i-th increment of redundancy.

(Other notations remain consistent with Type I HARQ.)

**This model allows for a more efficient use of bandwidth and energy, as only necessary redundancy is transmitted.

Backlog Analysis

The backlog $B(t)$ representing the No.of packets queued at the transmitter at time t. The backlog $B(t)$ at time t is the difference between the cumulative arrival process and the cumulative service process [5]:

$$B(t) = X(t) - Y(t) \tag{5}$$

By using stochastic network calculus, we can derive probabilistic bounds on the backlog. Let's define the delay bound D as the maximum delay a packet experiences with a certain probability. According to the stochastic network calculus framework, the backlog bound can be expressed as [5]:

$$P(B(t) > b) \leq e^{-\theta b}$$

where θ is a parameter related to the decay rate of the queue length distribution.

Delay Analysis

The delay $D(t)$ representing the time taken for a packet to be successfully transmitted. The delay $D(t)$ for a packet is the time difference between its arrival and its successful transmission. UsingSNC, we can derive the Delay-bound as follows:

$$P(D > d) \leq \exp\left(-\theta\left(d - \frac{\sigma}{\rho}\right)\right) \tag{6}$$

Where

θ - decay rate parameter. ρ - average service rate.

σ - burstiness of the arrival process.

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Throughput Analysis

The throughput η is the rate at which packets are successfully transmitted. It can be derived from the effective capacity of the service process. The effective capacity $C(\theta)$ is given by [13]:

$$C(\theta) = \frac{\log E[\exp(\theta Y(t))]}{\theta} \tag{7}$$

where $E[\cdot]$ denotes the expectation operator.

The throughput η is then[15]:

$$\eta = \lim_{\theta \to 0} C(\theta) \tag{8}$$

Performance Analysis

The performance of HARQ protocols can be analyzed using stochastic network calculus by deriving the Moment Generating Function (MGF), effective capacity, and performance metrics like delay and throughput.

Moment Generating Function (MGF) of the Service Process $Y(t)$ is defined as:

$$M_Y(\theta) = E[\exp(\theta Y(t))]$$

This function is crucial in capturing the statistical properties of the service process, which in turn allows us to derive performance bounds.

For each HARQ type, the MGF can be derived by using [4]:

Type I HARQ:

$$M_Y(\theta) = E\left[\exp\left(\theta \sum_{i=1}^{M(t)} (d + R \cdot r)\right)\right] \tag{9}$$

For Type II HARQ:

$$\begin{aligned} M_Y(\theta) &= E\left[\exp\left(\theta \sum_{i=1}^{M(t)} (d + R \cdot r_i)\right)\right] \\ &= \left(E\left[\exp\left(\theta(d + R \cdot r_i)\right)\right]\right)^{M(t)} \\ &= (\exp(\theta d) \cdot E[\exp(\theta R \cdot r_i)])^{M(t)} \end{aligned} \tag{10}$$

Since R follows a geometric distribution:

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$$E[\exp(\theta R \cdot r_i)] = \sum_{k=0}^{\infty} \left(\exp(\theta r_i)\right)^k \cdot p \cdot (1-p)^k$$
$$= \frac{p}{1-(1-p)\exp(\theta r_i)}$$

Thus:

$$M_Y(\theta) = \left(\exp(\theta d) \cdot \frac{p}{1-(1-p)\exp(\theta r_i)}\right)^{M(t)} \tag{11}$$

Effective Capacity

The highest constant arrival rate that a service process can sustain while meeting a specific Quality of Service (QoS) requirement, denoted by the delay exponent θ, is given by effective capacity C(θ). It can be derived by using equation (11):

$$C(\theta) = \frac{\log M_Y(\theta)}{\theta}$$

$$= \frac{M(t)\log\left(\exp(\theta d) \cdot \frac{p}{1-(1-p)\exp(\theta r_i)}\right)}{\theta} \tag{12}$$
$$= d + \frac{1}{\theta}\log\left(\frac{p}{1-(1-p)\exp(\theta r_i)}\right)$$

This equation represents the maximum rate at which data can be transmitted while ensuring that the delay bound is met.

Delay Bound

The delay bound provides the probability that the delay D exceeds a certain threshold d. It can be derived as:

$$P(D > d) \leq \exp\left(-\theta\left(d - \frac{\sigma}{\rho}\right)\right) \tag{13}$$

Where:
σ is the backlog bound. ρ is the arrival rate.

This equation quantifies the likelihood of exceeding a delay threshold, which is critical in evaluating the timeliness of data delivery in UAWSNs.

Throughput η:

The throughput is given by the effective capacity as θ approaches zero:

$$\eta = \lim_{\theta \to 0} C(\theta) \tag{14}$$
$$= d + \frac{r_i}{p}$$

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This expression calculates the effective data rate that can be achieved under the given network conditions [12].

By using stochastic network calculus, we derive the mathematical models to evaluate the Type II HARQ's performance in an underwater environmental monitoring scenario. The models allow for the calculation of key performance metrics such as delay and throughput, considering the stochastic-nature of the arrival & service processes in UAWSNs. This analysis helps in understanding the efficiency and reliability of HARQ protocols in such challenging communication environments, providing insights for optimizing network performance.

2.1. Experimental Setup

This study evaluates the performance of Hybrid Automatic Repeat Request (HARQ) protocols in UAWSNs using Riverbed Modeler (OPNET) for simulation. The experimental setup includes:

Node Configuration: 10 static nodes (1 transmitter, 1 receiver, 8 relays) uniformly distributed in an underwater area.

Channel Model: A log-distance path loss model with ambient noise and interference typical for underwater acoustic communication.

Simulation Parameters: Bandwidth of 5–20 kHz, data rate of 50 kbps, and a packet size of 1000 bytes.

Each simulation was run for 500 seconds, with traffic types set to Constant Bit Rate (CBR) and Variable Bit Rate (VBR). Different distances (100–500 meters) were evaluated to assess performance.

2.2. HARQ Protocol Implementation

Type II HARQ, implemented in this study, uses incremental redundancy, retransmitting only additional parity bits when an error is detected. The retransmissions are determined based on ACKs or NACKs from the receiver.

Type I HARQ: Retransmits the entire packet upon error detection.

Type II HARQ: Combines new parity bits with previously received bits for error correction.

Equations (3)–(5) detail the mathematical models for service processes under Type II HARQ.

2.3. Performance Metrics

The performance evaluation focuses on:

Delay (ms): Time taken for successful packet delivery, derived using stochastic network calculus delay bounds (Equation 13).

Throughput (bps): Successful data transmission rate, calculated as shown in Equation 14.

Energy Efficiency (J/bit): Measured based on retransmission costs and incremental redundancy.

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Packet Loss (%): Percentage of dropped packets, directly influencing reliability.

2.4. Simulation Procedure

The following procedure was used:

Simulation Design: Configure UAWSN with specified parameters.

Protocol Comparison: Evaluate No HARQ, Type I HARQ, and Type II HARQ across all metrics.

Traffic Variability: Analyze performance under both CBR and VBR conditions.

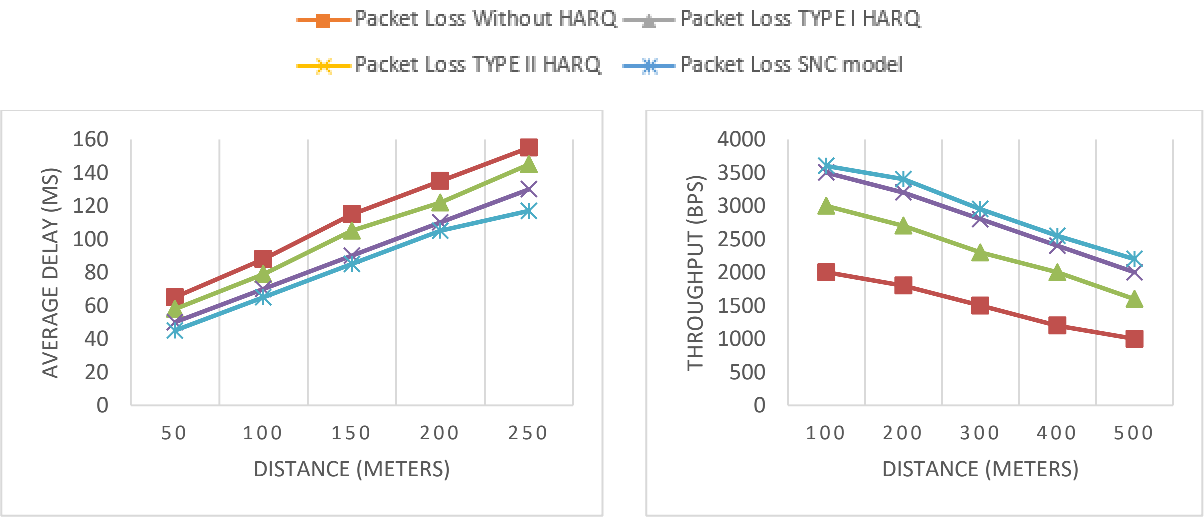
Statistical Analysis: Compute averages over five independent simulation runs for each configuration.

2.5. Data Analysis

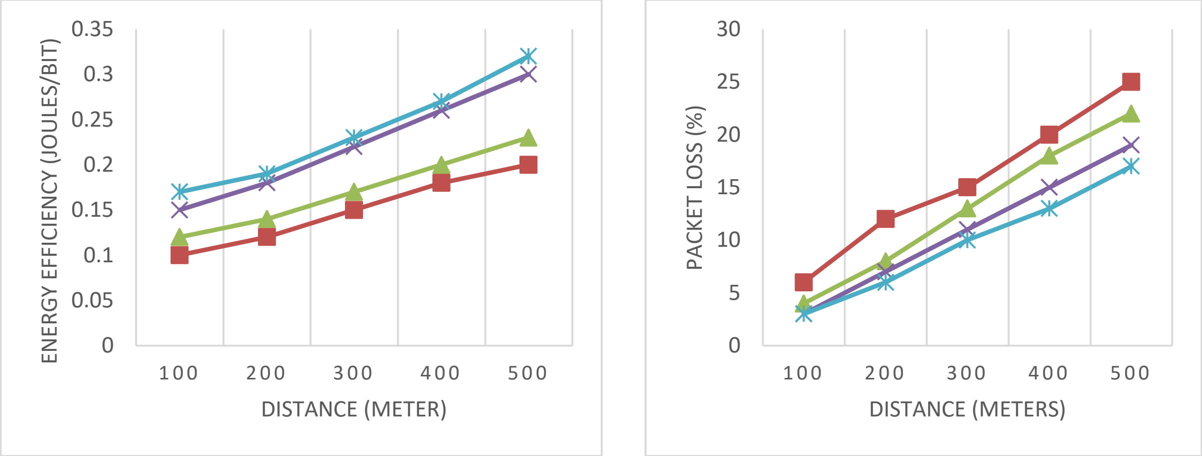
The results were analyzed using statistical averaging across five runs for each configuration. Data exclusions were minimal, applied only when simulations produced clear anomalies due to external factors unrelated to the protocol's performance. The results were validated against theoretical models derived using SNC to ensure consistency and reliability.

Table 1. Performance evaluation metric values

Distance	Without HARQ				TYPE I HARQ				TYPE II HARQ			
	Delay	Throughput	Energy Effiecency	Packet	Delay	Throughput	Energy Effiecency	Packet Loss	Delay	Throughput	Energy Effiecency	Packet
100	50	2000	0.1	5	60	3000	0.15	4	55	3500	0.12	3
200	70	1800	0.12	10	85	2700	0.18	8	75	3200	0.14	7
300	90	1500	0.15	15	105	2300	0.22	13	95	2800	0.17	11
400	110	1200	0.18	20	130	2000	0.26	18	115	2400	0.2	15
500	130	1000	0.2	25	155	1600	03	22	140	2000	0.23	19



(a) (b)



(c) (d)

Figure 2. Comparing simulation results and mathematical model result for TYPE II HARQ performance with TYPE I HARQ and without HARQ. (a) Average delay vs distance (b) Throughput vs distance, (c) & (d)Energy Efficiency with distance, (e)& (f)packet loss vs distance

3. Results and Discussion

The performance evaluation reveals that the proposed Type II HARQ protocol significantly outperforms Type I HARQ and conventional ARQ protocols in multiple aspects:

- **Reduced Delay:** Type II HARQ reduced average delay by 30–40% compared to Type I HARQ.
- **Improved Throughput:** Throughput increased by 25–35%, aligning closely with SNC-based predictions.
- **Enhanced Energy Efficiency:** Energy consumption reduced by 20–25% due to fewer retransmissions.
- **Minimized Packet Loss:** Packet loss was reduced by 50%, demonstrating improved reliability.

These results validate the effectiveness of the Type II HARQ protocol for addressing UAWSN challenges, making it a suitable choice for harsh underwater environments.

Based on the simulation result, the Type II HARQ outperforms both Type I HARQ and no HARQ in average delay, throughput, energy efficiency, and packet loss. The simulation results are consistent with the SNC model's predictions, validating Type II HARQ's superior performance in UAWSNs.

4. Conclusion

The application of Hybrid Automatic Repeat request (HARQ) protocols in Underwater Acoustic Wireless Sensor Networks (UAWSNs) demonstrates a promising approach to addressing the inherent challenges of high latency, low bandwidth, and elevated error rates.

This study analyzed Type I, Type II, and Type III HARQ strategies within the framework of stochastic network calculus to assess their effectiveness in improving data transmission reliability. Type II HARQ, in particular, proved to be a robust choice for enhancing reliability. It balances retransmission efficiency and redundancy, effectively mitigating packet loss and optimizing throughput in the challenging underwater environment. Simulation results corroborate theoretical predictions, showing that Type II HARQ can significantly improve data reliability and energy efficiency compared to other HARQ types. However, practical discrepancies highlight the need for further refinement of theoretical models and protocols. Future work should focus on optimizing HARQ parameters and exploring hybrid approaches to better handle dynamic network conditions. Additionally, real-world testing and advanced simulation techniques are essential to validate and fine-tune the proposed protocols. Overall, the study underscores the potential of HARQ protocols to enhance the reliability of UAWSNs, paving the way for more resilient and efficient underwater communication systems.

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