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Posted Date: 15 January 2025

doi: 10.20944/preprints202501.1134.v1

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Pioneering Fuzzy-Based Energy-Efficient Routing for Underwater Sensor Networks

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Abstract: Underwater Wireless Sensor Networks (UWSNs) have garnered significant attention due to their potential in oceanographic research, seismic monitoring, environmental protection, and seabed mapping applications. However, these networks face unique challenges, such as high interference, long propagation times, reduced bandwidth, and dynamic network topologies. Routing protocols play a critical role in overcoming these issues. This paper proposes an enhanced fuzzy-based routing protocol, UWF-RPL, which optimizes decision-making through dynamic path selection and distributed traffic balancing. Our approach builds on the RPL framework, incorporating fuzzy logic to evaluate parameters such as depth, energy consumption, RSSI/ETX ratio, and latency. Simulation results demonstrate that the proposed protocol significantly outperforms existing methods, offering improved energy efficiency, higher packet delivery rates, reduced delay, and minimized queue overflows. The protocol also ensures greater scalability and resilience in dynamic underwater environments, contributing to the efficient operation and extended lifetime of UWSNs.

Keywords: underwater sensor networks; routing; energy; fuzzy logic; multipath; load balancing

I. Introduction

Today, underwater control and monitoring systems are among the most challenging topics in electronics and computer science. The lower the cost-to-efficiency ratio under the same working conditions and quality, the greater the popularity of that method. Equipment known as a sensor can be used to monitor changes in the surrounding environment or the status of each set [1,2]. Every sensor can sense and present changes in the desired environment using specific parameters such as temperature, humidity, and pressure. For example, monitoring and controlling the underwater environment is feasible using information from sensors embedded in the water. The data link layer protocol is responsible for coordinating the access of nodes to the shared wireless media in underwater sensor networks with high throughput and energy efficiency. Network nodes can share a broadcast channel through a media access control protocol [3,4]. For its core functionality, the media access control (MAC) protocol is developed to prevent concurrent data transmissions and manage packet collision resolution [5].

Additionally, it ensures energy efficiency, minimizes channel access delays, and maintains a balanced load across network nodes. Due to the harsh and weak underwater audio channels, the Media Access Control layer protocol is critical in using the underwater sensor network. Developing an interlayer protocol is a significant challenge in developing underwater sensors. It is ideal for an interlayer protocol (between the network and the data link layer) to simultaneously provide optimal underwater media access control with high throughput, low energy consumption, and high-reliability paths for data exchange to select the desired destination [6].

Due to the strain on the medium in underwater UWSNs, the transmission speed of audio frequency is significantly reduced. The delays in the transmission and distribution of information packets in this network will result in the packets not reaching their intended recipients on time, and the meetings between the networks will be lost due to the delays in transmission and distribution. Instead, the simultaneous sending of neighbors, known as hidden terminal, results in congestion in the media environment and noise passing through the surface. As determined by the above decision, crowding and collision are the most significant challenges facing underwater sensor networks. Path congestion, collisions, and queue slippage will also be added to these challenges in the following stage. To address the issues and problems raised in this research, a method is proposed to prevent congestion and, in the event of congestion, a way to reduce and address it. Additionally, we would like to avoid time waste by dynamically varying the work cycle time of meetings between the neighbors of the member nodes of the main paths [7].

A. Motivation and Contributions

By adverse positioning, interference from environmental noise, and Doppler frequency shift, network throughput, data transmission, and reliability of data communication are negatively affected. As a result, data transmission to the sink becomes challenging. Effective route planning ensures efficient data propagation from a node to its sink. Given the slow speed of data propagation in deep-water environments, communication between nodes demands substantial energy consumption. Furthermore, it is a dynamic and complex system. Due to their low energy consumption and low latency, UWSNs differ from other wireless terrestrial network sensors. Establishing extraordinarily secure and efficient network links in harsh underwater conditions should be possible using UWSNs [8]. To maintain network reliability during multiple emergencies, underwater routing protocols must be flexible to handle complex topology modifications. The routing protocol determines how information is transmitted between underwater source nodes and surface destination nodes. Researchers are becoming increasingly interested in UWSNs, and the number of articles and journals researchers publish is impressive.

In most papers, one aspect of the protocol is emphasized, such as the energy consumption of a node or its geographic location. An efficient method of comparing routing protocols in most surveys is needed. Therefore, a comprehensive analysis of multi-path underwater routing protocols is unavailable now [7,9,10]. The second part of this paper presents a comprehensive review of routing protocols for UWSNs. Unlike other recent studies, this review focuses on the multi-hop and multi-path data propagation mechanisms in UWSNs. The protocols can be classified into three main categories:

- Geographical-based protocols: The topology of the underwater wireless network is estimated based on the geographical location of the sensor nodes.
- Energy-based protocols: Using an optimal and low-power protocol to conserve energy and prolong sensor life.
- Data-centric protocols: This routing protocol aims to ensure the integrity of data packets during transmission from the source node to the destination node.

The following categories can be used to categorize energy-based protocols: Protocols based on reactive behavior, proactive behavior, hybrid behavior, depth-based behavior, reinforcement learning behavior, bio-inspired behavior, and cooperative reliability behavior. As part of the second segment of this article, we discuss the basic concepts and architecture of underwater sensor networks. We reviewed previous works on underwater sensor network management techniques and approached them in the third part. The fourth part of this article focuses on routing underwater sensor networks. Our proposed approach is presented in the fifth section. This part consists of the evaluation and simulation results of the proposed method, as well as comparisons with parallel processes. Finally, conclusions and recommendations are presented in the seventh section.

B. The Abbreviations of the Principal Terms

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Table 1. Table of main abbreviations.

Abbreviations	Descriptions
1D-UWSN	One-Dimensional Underwater Wireless Sensor Network
Aggregation	Collecting and combining data from nodes
AHH-VBF	Adaptive Hop-by-Hop Vector-Based Forwarding
AoA	Angle of Arrival
AUV	Autonomous Underwater Vehicle
Cluster Head	Node managing a cluster's communication.
DAO	Destination Advertisement Object
DAO-Ack	Destination Advertisement Object Acknowledgement
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DODAG	Destination Oriented Directed Acyclic Graph
Doppler Effect	Change in frequency or wavelength due to movement
GPS	Global Positioning System
IVAR	Inter-Vehicle Ad Hoc Routing
LLSR	Localized Link State Routing
MAC	Medium Access Control
Multi-hop	Communication across multiple nodes
RF	Radio Frequency
ROV	Remotely Operated Vehicle
RPL	IPv6 Routing Protocol for Low-Power and Lossy Networks
RSSI	Received Signal Strength Indicator
Sink	Central node collecting data
TDoA	Time Difference of Arrival
ToA	Time of Arrival
TWSN	Terrestrial Wireless Sensor Network
UUV	Unmanned Underwater Vehicle
UWSN	Underwater Wireless Sensor Network
VBVA	Void Bypass Vector Assignment

II. Concept and Architecture of UWSN

There are several ways in which UWSN architecture can be classified. First, sensor nodes are ranked based on their mobility. There are three types of sensor networks: static, mobile, and hybrid. As part of the static UWSN architecture, sensor nodes are attached to surface buoys or moored to the ocean floor. In a mobile UWSN architecture, sensor nodes can move autonomously or because of water currents. An example of a mobile node would be an AUV, a UUV, or an ROV [1,11]. Both static and mobile nodes are utilized in the hybrid UWSN architecture. Depending on the application and network requirements, a UWSN may be built to cover a 2D, 3D, or 4D space (with RoV) [12]. This section will briefly debate the fundamental UWSN topology (which provides the foundation for UWSN applications) [13,14]. In the next part, we will consider the basic requirements for UWSNs.

- 1D-UWSN: One-dimensional (1D) Underwater Wireless Sensor Networks (UWSNs) consist of sensors capable of independently sensing, processing, and transmitting data to a base station. A typical example is a buoy designed to measure various water properties. The buoy can submerge

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to gather data over a specific duration and then resurface to communicate the collected information back to the base station.

- 2D-UWSN: A two-dimensional (2D) UWSN design is characterized by a cluster of sensor nodes (cluster) placed underwater. Each set is headed by a cluster head (an anchor node). The clusters are permanent due to their grounding at the water's surface. Each cluster member's responsibility is to collect and transmit data to the anchor node. All buoyant surface nodes receive data from the anchor node, which is passed on to them. There are two dimensions to 2D-UWSN communication: the first is the horizontal communication between cluster members, while the second is the vertical communication between the anchor and surface buoyant nodes.
- 3D-UWSN: Clusters of this type are deployed at different sea depths following such architecture. In this scenario, we are going beyond 2D-UWSN. A cluster consists of multiple nodes communicating with one another, cluster heads communicating with one another, and finally, the cluster heads relaying messages to the rest of the cluster.
- 4D-UWSNA 4D-UWSN differs from a 3D-UWSN by incorporating remotely operated underwater vehicles (ROVs) alongside clusters at varying ocean depths. The ROVs collect data from the cluster heads based on their location and then either relay the information to a buoy or transmit it directly, depending on the situation.

A. Design Challenges for UWSN Routing Protocols

It is important to note that UWSNs and TWSNs differ in many ways. TWSNs communicate using a radio signal (RF), whereas UWSNs communicate using an acoustic signal. UWSNs have sensor nodes that are either stationary or mobile in a specified direction, whereas TWSNs have sensor nodes that are moving because of water currents [7,8,11]. In this regard, directly using the routing protocols in TWSN for UWSN is impossible. As a result of its unique characteristics, the acoustic communication used in UWSNs is unique. UWSN routing algorithms should be designed considering the multiple challenges that UWSNs face, as outlined [1,15–17].

- Acoustic channels have limited bandwidth because radio transmission cannot be used for underwater communication. As acoustic transmission has a limited bandwidth, it requires more energy to transmit a limited amount of information.
- Due to water currents, sensor nodes in UWSNs rush with speeds ranging from 1 to 3 m/s, making it challenging to persist stationary in one place. Therefore, the topology of the network is dynamic.
- Unlike radio frequency, which propagates at 1500 m/sec, acoustic communication propagates at five times the speed, which results in significant propagation delays in the network.
- Avoidance of connectivity voids occurs when a node fails or depletes energy on the route between the source and destination nodes. Furthermore, if holes are generated, the system should be able to work around them to transmit packets to the destination node properly.
- Since sensors in UWSN are equipped with difficult batteries to replace or recharge, it is always important to use energy-efficient communication to give a network a longer lifespan. Moreover, acoustic channels require more energy for communication than terrestrial networks.
- Location estimation is difficult and time-consuming because GPS is not available underwater. Localization adds additional communication overhead when a routing protocol uses locations to create routes.
- UWSNs consume more energy than TWSNs, which use radio frequency as the communication medium. Transmission energy consumption in UWSNs is higher than receiving energy consumption and receiving energy consumption is substantially higher than idle energy consumption.
- Three-Dimensional Deployment Due to the combination of the third dimension, namely depth, three-dimensional deployment poses additional challenges. Sensor nodes must be able to send data through multi-hop routes to sink nodes. Nodes should modify their depths if no relay is available within the current transmission range.

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- Data transmission is affected by the Doppler effect, which causes a shift in wave frequency as the distance between the transmitter and receiver changes. To generate the Doppler effect, the transmitter, receiver, or both must move due to variations in relative distances.
- In addition to being quite expensive, underwater sensors must also be maintained. In this way, it provides significant coverage for maintenance costs.
- Ambient noise and interference can affect acoustic communication in two distinct ways. Due to the higher noise level in UWSNs than in TWSNs, these kinds of noise need to be considered when developing routing protocols. Due to the reflections from the bottom, surface, and aquatic life in UWSN, interference is also high.
- Due to their small size, a limited amount of memory is available on UWSN sensor nodes.
- Due to the large amount of data collected from the environment by sensor nodes, data compression is necessary to conserve energy and bandwidth. Every sensor node should perform this step before sending data to the sink. Furthermore, the sink node must decompress the data so that no information is lost, and the data readings are preserved.
- A sink receives data collected from many sensor nodes, aggregates it, and then forwards it to the sink. Cluster-based techniques often employ this strategy. Aggregated data is more reliable than individual sensor node readings. In this way, data aggregation enhances the reliability of data [18].
- The undersea medium transforms some of an acoustic wave's energy into heat energy. The loss of acoustic wave energy can be represented by three major components: attenuation, geometric spreading loss, and scattering loss. Path loss can be reduced by reducing the distance traveled and increasing the transmission power. This results in a preference for multi-hop data forwarding over single-hop data forwarding packets to the sink.

III. Related Works

A. UWSN Localization Techniques

Node localization in Underwater Wireless Sensor Networks (UWSNs) is a critical aspect, as accurate location information of the data source is essential for many applications [19–21]. Conventional GPS technology does not function effectively underwater because of the acoustic medium used for communication, which has led to the creation of specialized localization techniques. These techniques generally fall into two categories: range-based and range-free methods. Range-based approaches use sensor nodes' distance or angle measurements to pinpoint their locations. Standard techniques used in this approach include ToA, TDoA, AoA, and RSSI. For example, ToA estimates the distance between nodes by multiplying the speed of acoustic signals by the time it takes for the signal to travel between them. In contrast, range-free schemes do not depend on distance measurements; instead, they estimate positions based on area-based or hop count techniques, instrumental in scenarios with layered ocean deployments [21].

The classification of localization algorithms in UWSNs has been a focal point of research due to the challenges posed by the underwater environment. Based on the deployment of sensor nodes, localization techniques can also be classified into static, mobile, and hybrid categories [21,22]. Static nodes, often attached to buoys or moored to the seabed, contrast with mobile nodes, such as Autonomous Underwater Vehicles (AUVs) or Remotely Operated Vehicles (ROVs), which move either autonomously or due to water currents. Hybrid systems utilize both static and mobile nodes to enhance localization accuracy. Moreover, depending on the application and network scale, UWSN localization techniques can be further divided into small-scale and large-scale approaches, with additional classification based on anchor usage—anchor-based or anchor-free methods [22,23].

Researchers have extensively explored UWSN-based localization methods from various perspectives, addressing the need for accurate and efficient algorithms [24]. The choice of a specific localization method often depends on the network's requirements and the desired accuracy. Hybrid techniques, which combine multiple localization methods, have also gained attention for their ability

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to improve localization performance in complex underwater environments. As UWSNs continue to evolve, the ongoing refinement of these algorithms will be crucial in overcoming the inherent challenges of underwater communication and enhancing the reliability and precision of node localization [21,25].

B. Methods of Collecting UWSN Data

The data collection process involves measuring and collecting data from different parts of the UWSN, where sensing nodes are installed to obtain and observe physical changes in the water, such as temperature, salinity, pressure, and pH levels. Several mobile data collection techniques have recently been presented for TWSNs. Considering the unique characteristics of UWSNs, including 3D deployment, limited bandwidth, high propagation delays, path losses, and limited energy resources, mobile data collection techniques designed for TWSNs are ineffective in UWSNs [26]. It is necessary to consider the many characteristics of the underwater environment when developing efficient mobile data collection techniques for UWSNs. Data collection using AUVs is proper for large-scale UWSNs because they reduce the number of transmissions and balance energy consumption [27]. As a mobile sink equipped with a robust transceiver, an AUV collects data packets continuously from sensors by moving around the underwater area [28]. The data collection tour is launched regularly from the static base station. It collects sensor data packets and delivers them to the fixed base station. Due to the limited number of hops per packet relay, an AUV is useful for extending the life of acoustic sensors. Additionally, it distributes energy evenly so that network coverage can be maintained.

Generally, UWSN's data collection methods can be grouped into six categories [29,30]:

- Void handling algorithms are crucial in efficiently routing network data packets, particularly in challenging environments where void nodes exist. These algorithms are generally divided into two main categories: location-based and pressure-based methods. Location-based techniques, like AHH-VBF and VBVA, adjust routing by considering node positions, using strategies such as unicast and geo-cast to navigate around void regions. These techniques are often employed in geo-routing protocols, which aim to bypass voids by regulating transmission power or utilizing mobility assistance. On the other hand, pressure-based methods, including LLSR and IVAR [27], utilize depth and pressure data to maintain communication in dynamic settings, preventing void areas from causing interruptions. Additionally, other strategies like geographical and opportunistic routing, duty cycling, and mobility-based data collection complement these void-handling techniques to boost network efficiency further. Together, these methods illustrate the importance of void-handling algorithms in maintaining robust network performance [31].
- Using geographic routing is a simple, efficient, and scalable approach that does not require underwater funding and relies on the closest nodes to the source. As a result of a communication gap, geographic routing suffers from the problem of being unable to locate the adjacent node. In addition to greedy algorithms, local directional flooding and hierarchical algorithms are classified as geographic routing algorithms. There are several greedy-based techniques, such as REBAR and HH-VBF. DFR and SBR-DLP are examples of restricted directional flooding techniques. LCAD is another example of a hierarchical approach [32].
- Opportunistic routing involves selecting a nominee node from the void area to give priority to all nodes. The sensor node with the highest priority will collect data from the chosen nominee node. In addition to location-based routing, opportunistic routing can be classified into pressure-based routing. VBF, HH-VBF, and GEDAR are some examples of location-based opportunistic routing. DBR and VAPR can be cited as pressure-based opportunistic routing [33,34].
- To achieve an extended lifetime in UWSN's loaded traffic, the duty cycling technique relies on a periodic sleep-wake cycle for every node in the network. Some duty cycling protocols are SA and LBL [35,36].
- Cluster-based clustering is a valuable technique for extending the life of sensor networks. CH is selected as part of this approach, and packet forwarding is switched regularly among cluster

nodes with the most energy [37,38]. This may result in network partitioning due to the overloading of the CH closest to the base station because of relay traffic [39]. Various protocols can be used to implement cluster-based computing: DUCS, CADC, AEC, and MCCP.
- By incorporating mobility into sensor networks, new opportunities exist for improving network performance in terms of lifetime and latency [20,40]. Data can be transferred more quickly, in real-time, using AUV. DGS and DCRTM are among the mobility-based protocols.

C. The Characteristics of Underwater Acoustic Channels

Since underwater acoustic channels have limited transmission bandwidths and poor communication efficiency, they are commonly regarded as harsh communication channels. The channel's highly frequency-selective and time-varying nature makes developing a robust communication strategy challenging. Different parameters are considered when designing an acoustic communication system [41,42]. The simulation analysis considers several characteristics of the underwater acoustic communication channel, outlined in the following paragraphs.

1). The Sound Speed in the Water

The speed of an acoustic signal is influenced by three factors: the temperature and salinity of the water, as well as the depth of the water [43]. A mathematical formula called the Mackenzie formula is used to calculate the speed of an acoustic signal [44].

$$C = 1448.9 + 4.591T - 5.304 * 10 - 2T2 + 2.374 * 10 - 4T3 + 1.340(S - 35) + 1.63 * 10 - 2D + 1.675 * 10 - 7D2 - 1.025 * 10 - 2T(S - 35) - 7.139 * 10 - 3TD3C = 1448.9 + 4.591T - 5.304 * 10 - 2T2 + 2.374 * 10 - 4T3 + 1.340(S - 35) + 1.63 * 10 - 2D + 1.675 * 10 - 7D2 - 1.025 * 10 - 2T(S - 35) - 7.139 * 10 - 3TD3 \quad (1)$$

C represents the speed of the acoustic signal calculated in Celsius degrees (0∘C≤T≤30∘C), T represents the temperature of the underwater environment, S represents the salinity of the water (30 ≤ S ≤ 40 PPT), and ***D*** represents the depth of the water (0≤D≤8000m). As we can see from Eq. (1), as water temperature, salinity, and depth increase, the acoustic channel's speed increases.

2). Attenuation and Propagation Loss

We will first define a few related concepts to understand the propagation of energy loss. When sound waves propagate from an underwater environment, some of their strength is converted into heat. There are two categories of energy loss associated with sound wave propagation [14,30,45]:
- The acoustic signal generated by the source nodes propagates outward in wavefronts due to the geometric spreading loss [46]. In this case, the signal does not depend on the wave's frequency but rather on its distance from the source. There are generally two parts to the ocean. The shallow ocean ranges from the water's surface up to 100 meters, and the deep sea has a depth ranging from 100 meters up to 10,000 meters. Geometric spreading can be classified into two categories. Firstly, the cylindrical spreading describes communication in shallow water; secondly, the spherical spreading represents communication in deep water.
- Acoustic communication is characterized by converting acoustic energy into heat, which reduces attenuation. After the heat has been transformed, it is absorbed by the underwater environment. A direct relationship exists between attenuation and distance d and frequency ***f***, as shown in Equation (2). The underwater acoustic channel has a path loss of the acoustic signals, which can be calculated using the following Equation. As a result of this path loss, two factors must be considered: the distance ***d*** in kilometers and the frequency ***f*** in kHz.

$$10logA(d,f) = k * 10logd + d * 10log\alpha(f)10log\ A(d,f) = k * 10log\ d + d * 10log\ \alpha(f) \quad (2)$$

- ***A(d,f)*** represents the path loss of the acoustic signal. On the right side, the first part represents propagation loss, and the second represents absorption loss. ***k*** represents the propagation's geometry, represented by the propagation coefficient. A spherical wave propagates in shallow

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water with ***k* = 1**, a practical wave with ***k* = 1.5**, and a spherical wave in deep water with ***k* = 2**. Where α(f) denotes the absorption coefficient in dB/km, and f represents the frequency in kHz. The frequency ***f* = 25** kHz was used in this paper.

- The coefficient of absorption is represented by Equation (3). Equation (1) applies to high frequencies, while Equation (2) applies to low frequencies. For lower frequencies, the fourth option is appropriate [47].

$$10log\alpha(f) = 0.11f21 + f2 + 44f24100 + f2 + 2.75f2104 + 0.003\ \ \boldsymbol{for}\ f \geq 0.4\left(\frac{dB}{km}\right) 10\log\alpha(f) = 0.11f21 + f2 + 44f24100 + f2 + 2.75f2104 + 0.003\ \ \boldsymbol{for}\ f > = 0.4(dB\ /\ km) \tag{3}$$

$$10log\alpha(f) = 0.11f21 + f2 + 0.001f2 + 0.002\quad \boldsymbol{for}\quad f < 0.4\left(\frac{dB}{km}\right) 10lo\ g\ \alpha(f) = 0.11f21 + f2 + 0.001f2 + 0.002\quad \boldsymbol{for}\ f < 0.4(dB/km) \tag{4}$$

3). Noise

All communication systems are subject to noise, which is an unavoidable characteristic. Noise is a quality of communication system that reduces the intensity of the signal. It is important to note that underwater acoustic communication involves two types of noise. The two types of noise are those produced by humans and those generated by the environment. There are two types of noise that we will discuss [48,49]:

- Human noises can be interpreted differently, such as those produced by ships, military units, fishing vessels, sonar, heavy machinery, and aircraft. The sending and receiving of many data operations cause disturbances and interference during acoustic communication.
- Ambient noise is a collection of sources that cannot be identified individually. According to the equation, ambient noise can be divided into four categories (eq 5). According to Eqs. (6) – (9), these noises– (consist of turbulence, shipping, wind, and thermal noises. Underwater acoustic communications are adversely affected by turbulent noise because of low-frequency disturbances in the water surface caused by tides or waves. Among the primary sources of ambient noise are shipped. In underwater acoustic communication, many ships are far from communication systems, causing considerable traffic noise. As a result of air bubbles or waves breaking, wind noise is generated. Depending on the wind speed, wind noise can be predicted and forecasted using weather forecasts. In losing all other noises caused by different sources, thermal noise is considered the underlying noise. There is a direct correlation between thermal noise and frequency in acoustic communication. A mathematical formula can calculate the total ambient noise in underwater acoustic communication. Accordingly, (5):

$$N(f) = Nt(f) + Ns(f) + N\omega(f) + Nth(f) \tag{5}$$

Where ***Nt(f)***, ***Ns(f)***, ***Nω(f)***, and ***Nth(f)*** refer to the noise caused by turbulence, shipping, wind, and thermal conditions, respectively, and are measured in dB re ***μ Pa*** and frequency in kHz. The following are some examples of these noises:

$$10logNt(f) = 17 - 30logf10logNt(f) = 17 - 30logf \tag{6}$$

$$10logNs(f) = 40 + 20(s - 0.5) + 26logf - 60log(f + 0.03)10logNs(f) = 40 + 20(s - 0.5) + 26logf - 60log(f + 0.03) \tag{7}$$

$$10\ \log\ N\omega(f) = 50 + 7.5\ w^{1/2} + 20\ \log f - 40\ \log\ (f + 0.4) \tag{8}$$

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$$10logNth(f) = -15 + 20logf10logNth(f) = -15 + 20logf \quad (9)$$

IV. Routing Methods in UWSN

A. Classification of Routing Protocols

This section describes two types of routing protocols based on their localization requirements [7,8,16]. There are two protocols within each class: (1) protocols that consider node mobility and (2) protocols that do not. There are two types of routing protocols: location-based and location-free. This figure illustrates how routing protocols are classified for UWSNs. (Figure 1).

B. Location-Based Routing Protocols for UWSN

The location information of the sensor nodes is required to determine the routes between a source and sink node in this routing protocol category [50,51]. Location-based routing protocols can also be classified according to whether they consider the mobility of the nodes. Vector-based routing and cluster-based routing are location-based routing protocols that consider node mobility.

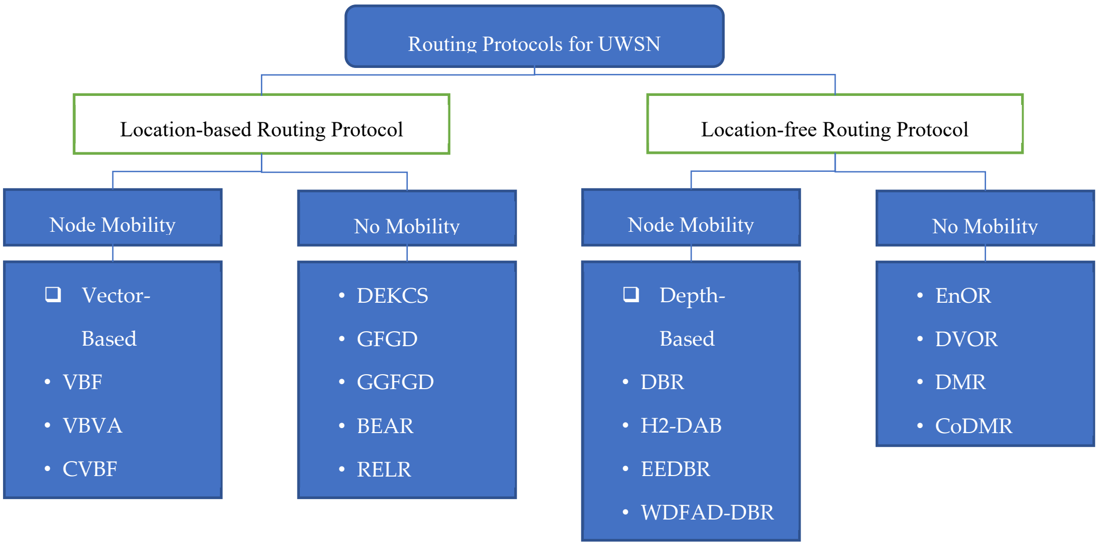

Figure 1. Classification Routing Protocols in UWSN.

C. Routing Protocols Based on Energy Awareness

In each node, the amount of energy consumed is determined by the communication mode and the amount of processing load applied to the signal [12,39]. Three trivial factors determine a node's energy consumption. Considering the distance between nodes is vital since sending a signal to a node further away from the source requires a more significant amount of energy. In addition, it is essential to consider the node's surroundings since harsher environmental conditions would require a considerable amount of energy to transmit a signal. Finally, battery capacity should also be considered. For the sender, all these factors are taken into consideration, and the following Equation is derived:

$$E_{tx} = \begin{cases} l \in_{elec} + l \in_{fs} d^2, d < d_0 \\ l \in_{elec} + l \in_{fs} d^4, d \geq d_0 \end{cases} \quad (10)$$

In Equation (10), $\boldsymbol{l}$ denotes the number of bits in each packet, and $\boldsymbol{d}$ refers to the distance separating the transmitter from the receiver. In this context, $\boldsymbol{d_0}$ represents the minimum distance for data transmission, $\in_{elec}$ represents the energy required for radio transmission. The parameter $\boldsymbol{mp}$ is the multi-path transmitter amplifier coefficient, and $\boldsymbol{f_s}$ is the coefficient for free-space transmission. Unlike terrestrial WSNs, which do not account for the acoustic signal's distinct energy consumption

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characteristics, UWSNs have unique energy models. An amplifier coefficient $\boldsymbol{a}(\boldsymbol{f^d})$ is used to compute the energy required for acoustic signal transmission. In this scenario, the transmitter and receiver are separated by distance ***d***, and the signal frequency is represented by ***f***. Since acoustic signals consume less energy compared to radio signals, the energy model designed for terrestrial WSNs is inadequate for UWSNs. UWSNs rely on both multi-path and free-space models. The amplifier coefficient is expressed as $\boldsymbol{a}(\boldsymbol{f^d})$, where the absorption coefficient is ***a(f)***, the distance between the sender and receiver is ***d***, and the acoustic signal frequency is ***f***. The value of ***a(f)*** can be estimated using Thorp's empirical formula. For example, at a frequency of 1000 Hz:

$$loga(f) = 0.011\frac{f^2}{1+f^2} + 4.4\frac{f^2}{4100+f^2} + 2.75 * 10^{-5}f^2 + 0.003 \quad (11)$$

This leads to the following calculation for energy consumption in UWSNs. The transmission of data packets in an underwater environment can be expressed using the formula below, where ***d*** represents the distance between two nodes and ***f*** denotes the signal frequency:

$$E_{tx} = \begin{cases} l \in_{elec} + la(f)^d d^2, & d < d_0 \\ l \in_{elec} + la(f)^d d^4, & d \geq d_0 \end{cases} \quad (12)$$

As a result of receiving data packets, energy is required as follows:

$$E_{tx} = l \in_{elec} \quad (13)$$

In the network layer, sensors are linked to observers, facilitating data routing and enabling cooperative sensing. To meet the desired levels of energy efficiency, scalability, stability, and convergence in UWSNs, routing protocols must be carefully established. These protocols aim to ensure reliable, energy-efficient paths for nodes while extending the overall network lifespan. Various factors impact the energy consumption of a routing system, such as neighbor discovery, communication processes, and computational demands. Table 2 shows the protocol comparisons based on energy consumption [11,39,52,53].

Table 2. Protocol comparisons based on energy consumption [11,39,52,53].

Classification	Protocol	Method	Disadvantage	Advantage
Reactive Protocols	CTP-SEEC	To extend the network's lifetime, improve throughput, and maximise packet distribution, transmit power control, mobile sink, and clustering are integrated.	Clustering in a sparse network creates unnecessary complexity and adds cost	It can be deployed in sparse and dense network
	((U−ACH))2	Evaluate terrestrial-based routing protocol performance in the UWSN environment	High deployment cost	Enhance the network performance
Proactive Protocol	SPRINT	Achieve trade-off between energy consumption and throughput	Computational complexity	High reliability
	PA-EPS-CASE	It utilised proactive routing to determine the shortest path between the source and sink	Overheating and greater overhead	Void hole avoidance
Hybrid Protocol	multi-hop ARQ	Use of hybrid acknowledgement packet for transmitting data	Increased Delay	Avoids void region using stop and wait for protocol

	Extend the lifetime of the system	Varying and high aggregate energy consumption by relay nodes, lack of local relay selection process	Reduced packet forwarding load on the source, improved packet delivery ratio	Extend the lifetime of the system
Clustering Protocol	EERU-CA	Monitoring application	High End-to-End Delay	CH have high energy
	CUWSN	Better throughput	The early death of the sensor	It provides a Better Throughput
Depth-Based Protocol	EEDBR	Application based on packet suppression scheme	Low lifetime	Reduced data transfer rate
	EECMR	Uses Multi-hop to perform routing	High latency	Less complexity
	EEEDBR	Ideal nodes at medium depth	Low Throughput	Lifetime increases
RL-Based Protocol	QL-EEBDG-ADN	Void avoidance using adjacent nodes	Adds extra delay	Ensures packet delivery
	QL-EEBDG	Balance energy consumption of aggregation nodes	Not suitable for sparse network	Use of RL to learn about energy consumption
	EDORQ	Combines Q-learning and opportunistic routing to improve energy conversion	High Computational Cost	Reduced delay
	QDTR	Reduce energy consumption	Not suitable for a dense network	Reduces overhead
	QLEAR	Increase the lifetime of nodes	Energy consumption	Lifetime increases
Cooperative-Reliability-based protocol	SEECR	Reduce the computation cost	Node movement not accounted	Less end-to-end delay
	LEER	Efficient delivery rate using a layered network	Unbalanced energy consumption	No localization needed
	EECOR	Find the best path using less energy	High delay	Find the shortest path
	RER	Increase reliability and efficiency	Control Overhead	Minimum transmission delay
Bio-inspired Protocol	FFRP	Reliable routing route	High computational cost	High packet delivery ratio
	MFPR	Energy-efficient and reliable data transmission	Network Dynamic issue	Improves link quality

D. Routing Protocols Based on Geographic Information

Position-based routing, also known as geographic routing, is an effective and scalable routing method. The entire pathway to the destination does not need to be established or maintained. Additionally, updating routing path states does not require routing messages. In contrast, the route is chosen at the local level. During each hop, the nearest neighbor to the destination is selected as the next-hop node to continue forwarding the packet. During this process, packets are iterated until they reach their final destination [7]. A combination of geographic routing and opportunistic routing (OR) improves data delivery and reduces energy consumption compared to packet retransmissions [11]. As part of the opportunistic routing paradigm, each packet is broadcast to a set of forwarding neighbors. How the nodes are arranged depends on their priority. This means that if a next-hop node receives a packet successfully, it will no more than forward it if its greatest-priority nodes cannot. Next-hop forwarder nodes will cancel scheduled packet transmissions if a higher-priority node

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transmits a packet. Whenever all nodes in a set fail to acquire a packet, opportunistic routing becomes the desired transmission mode. One of the significant disadvantages of geo-opportunistic routing is the communication void region problem. This issue occurs when the forwarder node has no neighbours closer to the destination, i.e., if it is a void node. Routing protocols should either take a recovery approach or reject packets caught in void nodes. Table 3 shows the comparison of routing protocols based on geographic information [8,54–57].

Table 3. Comparison of Routing protocols based on geographic information [8,54–57].

Classification	Protocol	Idea	Disadvantage	Advantage
Depth-based	DBR	Data is forwarded to the sink based on depth information	No void detection mechanism	High delivery ratio
	LDBR	Optimizes energy consumption by utilizing node residual energy	Low packet delivery rate	Balanced energy load
	SORP	Identify and avoid communication voids	Redundant retransmission of data and high delay	Void detection
	RSAR	Reliable and stability-aware routing using energy-assigned nodes	There is no void detection, and it uses a single sink to transmit data	A stable network and balanced energy distribution
	RD	Balances the energy consumption using energy as a metric for data forwarding	High delay and energy consumption	High packet delivery ratio
	LETR	Utilises location error and load balancing to avoid void communication zones	Low packet delivery rate and high energy consumption	Longer node lifespan
Location-based	QLACO	Combines ML and ACO to improve the delivery ratio, delay time	The role of AUV was not discussed in the paper	High delivery ratio and energy-efficient
	ESRVR	It avoids routing holes using two-hop neighbor information	Few nodes take part in packet exchange so that exhausts faster	Scalable and void hole detection
	VBF	It uses a virtual pipeline to deliver the packet	Unbalanced energy utilization	Robust transmission and scalable
	GEDAR	Depth-adjustment control by recovering void nodes	High end-to-end delay	Void avoidance
Pressure-based	HYDROCAST	It avoids hidden terminal problems and minimizes co-channel interference	Nodes closer to the sink get exhausted faster	Less redundant transmission and void detection
	VAPR	Specifies the next hop through greedy forwarding and constant beacons	High energy cost	Detects and avoids void regions

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	ACAR	A method for selecting paths and improving delivery rates that employ ant colonies	Added acceptance factor complicates the computation	Less delay and better lifetime
Adaptive-based	MA-RF ARP	Utilises modulation to enhance transmission capability	Incompatible with harsh underwater conditions	Transmits both acoustic and RF signals
Sender-based	RDBF	It fits the forwarding node to improve delivery rates	Complex computation	High delivery date
	RMTG	Optimizes overhead by using greedy forwarding and knowledge of previous hops	Not suitable for sparse network	Void avoidance, Less overhead
Cluster-based	EERA-CA	Energy efficiency pairing clustering and particular nodes	Node adds computation complexity	Energy efficient
	CMSE2R	Use of clustering paired with the shortest path to maximize energy efficiency.	High end-to-end delay	Increases the link quality among nodes
	MRP	Eliminating localization by layering	Unbalanced Power consumption,	Elimination of delay and localization through the use of super nodes
	DEKCS	Use of K-Means for Optimum Clustering	Lack of QoS metrics in algorithm	Using energy and Distance

V. Proposed Algorithm

The proposed network architecture is built on several foundational assumptions that aim to enhance both efficiency and scalability in underwater sensor networks. One fundamental assumption is that reducing the waiting time for data exchanges between nodes can significantly increase network throughput. The system ensures faster data transmission and optimizes resource usage by minimizing delays, especially in underwater environments where communication can be slow and challenging. This reduction in wait times directly contributes to a more responsive network, enabling quicker decision-making and higher overall performance.

Another central assumption is the importance of historical data in local decision-making. Each node in the network is equipped to track and analyze its past data exchanges, allowing it to make informed, autonomous decisions. This localized decision-making process reduces the reliance on central controllers or nodes, fostering a more distributed and adaptive network. Nodes can adjust their behavior based on previous interactions, optimizing routing paths, energy consumption, and overall network efficiency. By enabling nodes to operate independently using their data, the network becomes more energy-efficient and resilient to disruptions.

Furthermore, this decentralized approach significantly improves the network's scalability. As nodes can make decisions independently, the need for constant communication with a central controller or coordinator is reduced, thereby minimizing the overhead associated with control and coordination messages. This reduction in control traffic alleviates the burden on the central nodes, freeing up bandwidth and resources for actual data transmission. Consequently, the network can expand and accommodate more nodes without suffering from the typical bottlenecks associated with centralized systems. Due to this distributed control mechanism, the network's size and complexity remain stable and energy efficient.

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In summary, the proposed network architecture offers improved throughput, energy efficiency, and scalability by reducing node wait times, enabling localized decision-making based on historical data, and minimizing the need for centralized coordination. This design makes it well-suited for underwater environments, where communication constraints and the need for energy conservation are paramount.

A. Network Model

The network model in this study is based on several critical assumptions and configurations that govern its operation in a 3D environment. First, the network nodes are randomly distributed throughout the 3D space, allowing for a flexible and realistic representation of node placement in underwater sensor networks. Each node's radio range and initial energy levels are predefined at the beginning of the network's operational time, ensuring that all nodes have a uniform communication and power consumption starting point. This uniformity provides a controlled environment to evaluate energy usage over time.

Additionally, the network follows specific data transmission standards, including the effects of noise attenuation and audio frequency attenuation. These standards, along with the use of a standard energy consumption model, ensure that the network behavior aligns with real-world underwater communication dynamics. These models allow for accurate simulation of the energy costs of transmitting data underwater, where signals experience significant degradation.

To evaluate the network's performance, a standard dataset is referenced to determine the rate of data generation across the network. This ensures that the data flow within the network is consistent and comparable to other studies, allowing for meaningful benchmarking. Throughout the simulation, the mobility of the nodes is kept minimal, meaning that their transmission ranges remain largely unaffected. This assumption simplifies the model and focuses the study on the effects of energy consumption and data transmission under near-static conditions.

Lastly, the network includes a default depth gauge module that provides each node with information about its depth relative to the Z-axis. This depth information allows the nodes to adjust their operations based on their vertical position within the 3D environment, further enhancing the accuracy of the simulation in representing underwater conditions. These assumptions and configurations create a well-defined framework for analyzing energy efficiency and communication effectiveness in a 3D underwater sensor network.

B. The system Model

This IPv6 distance vector routing protocol functions at the physical layer and utilizes the IEEE 802.15.4 data link, making it ideal for sensor networks with limited power and bandwidth. Technological advances have created more efficient facilities and communication platforms for these networks than in the previous decade.

This research aims to introduce a new variation of the RPL protocol, called UWF-RPL, which is explicitly designed for underwater environments. UWF-RPL includes a motionless version for stationary nodes and one that accommodates limited mobility in submarine sensor networks. Implementing these new methods required substantial structural modifications to ensure that the RPL protocol could effectively function in underwater settings.

Figure 2 highlights the critical distinctions between the proposed method and the standard RPL protocol in grey. Below are definitions and further details regarding the proposed protocol:

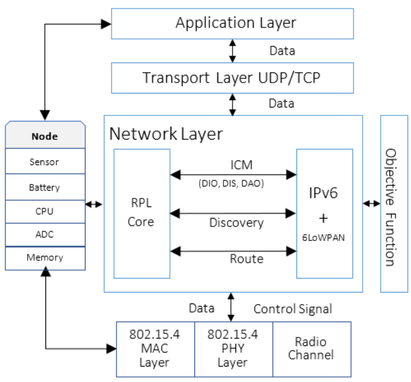
- Rank $R(u, j)$: This metric defines the logical distance of node u, a member of the network set $N(u \in N)$, from the root of the network graph J, as calculated by the RPL protocol's objective function (OF). The rank value R typically increases as the node moves further from the graph's root. Depending on the specific application, this rank can be determined by the node's depth relative to the water surface or by combining both step depth and node depth.
- Preferred Parent DODAG (DPP): Let u be a node within the graph G, $N(u)$ its set of one-hop neighbors, and $DPP(u,j)$ a finite subset of $N(u)$. For any neighbor node v in $N(u)$, v will be part

of ***DPP(u,j)*** if it has the lowest rank relative to the root ***R(u, j)*** in the specified DODAG ***j∈B***. In the enhanced version of RPL, each node will have multiple preferred parents rather than just one. Node ***u*** will select the best parent dynamically based on conditions when sending a packet, ensuring more efficient and reliable data transmission.

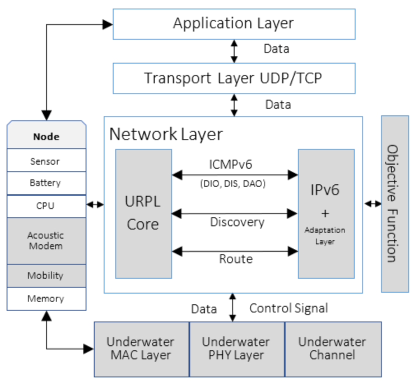
- DODAG Root List (DRL): Every node ***v∈N(u)*** is required to broadcast Destination Information Object (DIO) packets, which must include information about the location of the DODAG root. Thus, each node ***u*** in the network maintains a root location list, ***DRL(j)***, which stores the locations of DODAG roots. This allows nodes to efficiently route data by referencing the root locations stored in their DRL.

The parameters we aim to make fuzzy for the proposed system are outlined below:

- Depth or Vertical Distance: The vertical distance of each sensor node from the water surface plays a critical role in determining communication efficiency and signal strength.
- Energy Consumption per Communication: The total energy consumed by each node during data transmission influences the network's overall energy efficiency and the node's operational lifespan.
- RSSI/ETX Ratio per Link: The Received Signal Strength Indicator (RSSI) to Expected Transmission Count (ETX) ratio for each link helps assess the link quality and reliability between nodes.
- Packet Latency: The delay encountered during the transmission of each packet or the cumulative latency from the source to the destination, which impacts the speed and efficiency of the data delivery process.



A. RPL in Wireless Sensor Networks



B. RPL in Underwater Wireless Sensor Networks

Figure 2. RPL protocol structure in two typical sensor network environments and underwater sensors [58].

These parameters are essential for optimizing the performance of the underwater sensor network, and incorporating fuzzy logic will help adapt to the dynamic nature of the environment.

The model employed in this research follows a triangular structure and method to implement a cross-layer design in the enhanced RPL protocol for underwater applications. This subsection details

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the procedure for integrating this cross-layer approach. Specifically, the cross-layer design in underwater networks is based on exchanging information and variables between different network layers. The primary objective of this technique is to optimize network parameters and enhance overall network performance.

As previously discussed, the challenges of using RPL in underwater environments necessitate using a cross-layer design. This design must account for the fact that RPL is compatible with underwater IEEE 802.15.4 MAC and Physical Layers. Since network layer parameters influence service quality, they also affect the link's reliability, and the energy consumed. Therefore, it is highly advantageous to select and combine parameters from the lower layers and combine them into a composite metric when developing a new objective function (OF). This approach improves the parent node selection process, ultimately enhancing network performance.

In the proposed method, the physical layer parameter is the depth of the node, while the RSSI and energy consumption (EC) are parameters from the underwater IEEE 802.15.4 PHY layer. The latency metric is also derived from the underwater IEEE 802.15.4 MAC layer. These parameters combine to form a more comprehensive and practical approach to node selection, improving the performance of underwater sensor networks.

C. Metrics of Interest

Here, we review the metrics used in developing our OF and indicate their influential degree. In particular, our proposed method is designed to improve essential dimensions. As a first step, we will investigate the energy efficiency of the network, where the best route will be chosen based on the nodes that consume the least energy, thus extending the network's life. We incorporate the IEEE 802.15.4 PYH EC parameter into our composite metric. Second, a route is reliable, with the highest packet delivery ratio considered trustworthy. It is believed that this need to go with links with the best quality is in high demand due to various environmental conditions that may affect underwater sensor networks, such as cross-link interferences, large moving objects, and weather/ocean conditions. The reliability of the proposed objective function is assessed by incorporating the critical link estimators, namely RSSI and ETX, into the analysis. As a final consideration, real-time delivery is an essential aspect of underwater sensor networks, particularly for applications that require near real-time measurements, such as urgent accidents or underwater applications for drilling. This dimension is considered by including the latency metric in our proposed objective function. The following is provided to demonstrate the mathematical aspects of the metrics used.

- The pressure gauges that are part of the underwater sensor network are used to measure the depth parameter of each node in the network. It is based on the amount of pressure per unit of surface. In underwater per distance from the surface, these networks calculate the depth.
- An important node-based metric is energy consumption, a physical layer parameter. Nodes consume energy not only because of their communications over the network but also because of their local computations (CPU processing). The NS2 underwater motes datasheet indicates that the node's energy range is between 0 and 1000 J. We used the standard formula mentioned before to calculate the energy consumed during communication. Our proposed method defines a node's energy consumption along the path to the DODAG root as the EC metric. Accordingly, the EC metric incorporates not only an individual node's energy consumption, as outlined in the equations above but also the energy consumption by all nodes on the path to the destination (DODAG root).
- The latency metric is based on the MAC (layer 2) link. In other words, it indicates the time required for a packet to be transmitted from the source and received from the destination. An indicator of latency, measured in milliseconds, is the summation of the latencies of all nodes on the path to the DODAG root (i.e., it is a cumulative indicator)—several parameters of the simulation environment, including the network's size, influence this metric's value. Currently, there is no way to measure latency in RPL using the NS2 simulator. Coders and measurers typically use reasoning and thinking derived from the code's implementer or RPL designer. To

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accommodate the most common rationale of RPL designers, we code the latency to include the time from when the DIO is launched from the sender (DODAG root) until it reaches the destination. After conducting massive simulations to determine the simulation environment, which will be discussed shortly, we decided that there is an upper bound on the latency, which is n seconds. This formula is used to calculate the latency factor:

$$Latency(n) = \begin{cases} Latency(P) + Latency_{n\to P} \\ 0 \quad , \quad If\ n\ is\ the\ root \end{cases} \tag{14}$$

In this case, ***n*** and ***P*** correspond to the node and its parent, respectively. Latency n→P indicates the time delay between nodes n and their parents.

E. Fuzzification

This section outlines the overall architecture of fuzzy logic, including the processes of fuzzification, fuzzy inference, and defuzzification for selecting the preferred parent node. In this study, we propose an objective function (OF) that outperforms existing OFs by effectively combining multiple metrics to enhance the performance of underwater RPL. Fuzzy logic is recognized as one of the most efficient techniques for integrating several metrics into a single decision-making process. It converts multiple input variables into one output variable. The four-input metrics are depth, energy consumption, latency, and the RSSI/ETX ratio. These inputs are combined through a detailed fuzzy logic process to produce one output: the neighbor's quality. Figure 3 illustrates the critical steps in the fuzzy logic design for our UWF-RPL objective function.

1). Procedure for Fuzzification

In fuzzification, numerical input variables are allocated to fuzzy sets with some membership level. A description of the fuzzification technique is provided in the following subsections, including the identification of linguistic variables and membership functions for each metric.

2). Homogenization or Normalization of Variables

In Fuzzy systems, rather than numbers, the values of the linguistic variable are words. There are three fuzzy sets for each input metric in the UWF-RPL objective function, while eight are for each output variable. In addition, the following details are provided. Fuzzifying the X input variable. The fuzzy sets of metrics input metrics have five linguistic names, "Very Low", "Low", "Medium", "High", and "Very High". Table 4 presents the fuzzy sets along with their ranges, besides the membership function of this metric. Enhancing the quality of neighbor output variables by fuzzing. There are eight fuzzy sets of linguistic names for the quality of neighbor output.

Table 4. a linguistic variable and fuzzy set of RSSI input metrics.

Fuzzy set	Fuzzy set range(ms)	Membership function
Very Low	0~20	0.2
Low	10~30	0.4
Medium	40~60	0.6
High	50~70	0.8
Very High	80~100	1

This metric is represented in Table 5 as fuzzy sets, their ranges, and their membership functions.

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Table 5. Quality output metrics based on linguistic variables and fuzzy sets.

Fuzzy set	Fuzzy set range	Membership function
Very Low	0~20	Triangle fuzzy function
Low	10~30	Triangle fuzzy function
Medium	40~60	Triangle fuzzy function
High	50~70	Triangle fuzzy function
Very High	80~100	Triangle fuzzy function

Table 6. The number of fuzzy states of each parameter relative to high and low levels.

Rule	**The number of possible states**	**Definition and fuzzy states**
1	$Dn_{S1} \times CE_{S1} \times ETX/RSSI_{S1} \times Ln_{S1}$	The depth of each node from the water surface for two fuzzy values: Dn_{S1} and Dn_{S2}
2	$Dn_{S1} \times CE_{S1} \times ETX/RSSI_{S1} \times Ln_{S2}$	
3	$Dn_{S1} \times CE_{S1} \times ETX/RSSI_{S2} \times Ln_{S1}$	
4	$Dn_{S1} \times CE_{S1} \times ETX/RSSI_{S2} \times Ln_{S2}$	
5	$Dn_{S1} \times CE_{S2} \times ETX/RSSI_{S1} \times Ln_{S1}$	Energy consumption rate per node connection in two fuzzy values: CE_{S1} and CE_{S2}
6	$Dn_{S1} \times CE_{S2} \times ETX/RSSI_{S1} \times Ln_{S2}$	
7	$Dn_{S1} \times CE_{S2} \times ETX/RSSI_{S2} \times Ln_{S1}$	
8	$Dn_{S1} \times CE_{S2} \times ETX/RSSI_{S2} \times Ln_{S2}$	
9	$Dn_{S2} \times CE_{S1} \times ETX/RSSI_{S1} \times Ln_{S1}$	ETX and RSSI rates indicate the quality of the link and the number of effective attempts to access the media in two fuzzy values: $ETX/RSSI_{S1}$ and $ETX/RSSI_{S2}$
10	$Dn_{S2} \times CE_{S1} \times ETX/RSSI_{S1} \times Ln_{S2}$	
11	$Dn_{S2} \times CE_{S1} \times ETX/RSSI_{S2} \times Ln_{S1}$	
12	$Dn_{S2} \times CE_{S1} \times ETX/RSSI_{S2} \times Ln_{S2}$	
13	$Dn_{S2} \times CE_{S2} \times ETX/RSSI_{S1} \times Ln_{S1}$	
14	$Dn_{S2} \times CE_{S2} \times ETX/RSSI_{S1} \times Ln_{S2}$	
15	$Dn_{S2} \times CE_{S2} \times ETX/RSSI_{S2} \times Ln_{S1}$	The amount of communication delay between the node and the target for two fuzzy values: Ln_{S1} and Ln_{S2}
16	$Dn_{S2} \times CE_{S2} \times ETX/RSSI_{S2} \times Ln_{S2}$	
		The number of possible states: $2^n = 2^4 = 16$

3). The Membership Functions

A fuzzy set can be graphically represented using the membership function. There is a range of degrees of Membership between 0 and 1. Several factors influence the selection of a membership function, including extensive simulations based on trial-and-error techniques, prior literature, application requirements, and datasheets for the device. Since Trapezoidal functions are commonly used in fuzzy logic, we chose them as input metrics for our design (Brule, 1985). Aside from the Trapezoidal process, two special functions, R- and L-functions, are derived from it [59–61].

4). System of Fuzzy Inferences

These subsections explain the procedures for evaluating rules based on fuzzy sets and aggregating rules using the Mamdani inference system and how rules are evaluated in 5.4.5. In the following, we introduce the rule evaluation. (A fuzzy logic rule is constructed at this stage using IF-

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THEN conditions. According to the UWF-RPL objective function, the number of generated rules depends on the number of input metrics and fuzzy sets associated with each metric).

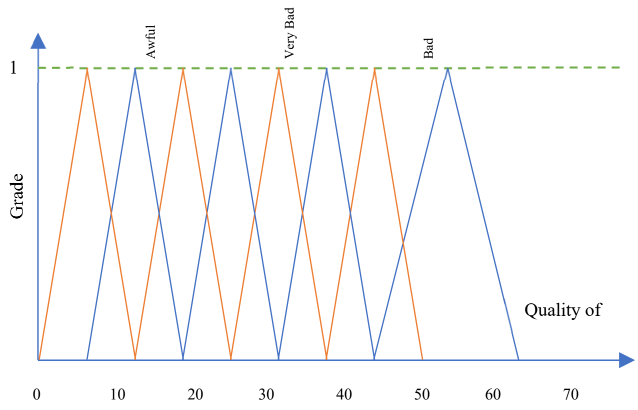

Figure 3. The quality of the neighbor output metric comprises membership functions.

5). Fuzzy Base Rules

In the fuzzy system, we have applied the Mamdani leveling method, ensuring that each specific situation is assigned a corresponding fuzzy value for that level. While some results may appear similar due to the closeness of levels, combining all factors in the fuzzy output effectively resolves these similarity percentages, ensuring distinct and accurate outcomes.

Table 7. Summary of rules table and fuzzy leveling in the UWF-RPL method.

Rule No.	Input metric				Quality Output
	Param 1	Param 2	Param 3	Param 4	
1	VL	VH	VL	VL	Excellent
…	…	…	…	…	…
…	L	L	L	L	Very Good
…	…	…	…	…	…
…	M	M	M	M	Medium
…	…	…	…	…	…
…	H	H	H	H	Bad
…	…	…	…	…	…
125	VH	VL	VH	VH	Awful

6). Membership Fuzzy

Our research employs the Mamdani inference system to handle the fuzzy logic decision-making process. This system combines individual rules' outputs through a fuzzy aggregation operator. Specifically, we use "AND" and "OR" operations, which are represented by the "Minimum" and "Maximum" operators, respectively, in the fuzzy aggregation process. These operators help determine how the different rules are integrated to form a final decision. For example, the "Average" fuzzy output set combines the outputs of several regulations. In our design, five specific rules are triggered, or "fired," based on the input variables. The "Maximum" operator is used to aggregate the outputs of these rules, which ensures that the most influential rule is given priority in determining the outcome. This aggregation approach is critical in scenarios where multiple rules contribute to a decision and help select the most suitable outcome from various options.

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Given that five out of the eleven possible rules are activated to determine the "Average" output quality, we apply the following formula to measure the output quality of the "Average" fuzzy set. This formula considers the number of fired rules and their respective contributions to the final output. Fuzzy logic allows us to combine these rules flexibly and dynamically, ensuring that the system adapts to different input scenarios and produces an appropriate decision based on the aggregated information. This method improves the robustness of our approach by allowing the system to make decisions even when only a subset of rules is activated, ultimately enhancing the overall performance of the fuzzy logic system.

$$Average = Max\begin{pmatrix} Min(Far\ Dn, CE, ETX\&RSSI, and\ long\ Ln), \\ Min(Near\ Dn, CE, ETX\&RSSI, and\ Short\ Ln) \\ Min(Close\ Dn, CE, ETX\&RSSI, and\ long\ Ln), \\ Min(Near\ Dn, CE, ETX\&RSSI, and\ Average\ Ln), \end{pmatrix} \tag{15}$$

7). Defuzzification Process

Optimizing the fitness function is necessary to improve the efficiency of the network and reduce congestion.

$$NC_n = (\sum_{i=1}^{16} U_i \times w_j) \Big/ (\sum_{i=1}^{16} U_i) \tag{16}$$

$$Fitness\ Function\ (f_i) = Max\left(\frac{1}{\min \frac{\left(\sum_{i=1}^{16} \begin{matrix} ((w_1 \times D_i)+(w_2 \times CE_i) + \\ (w_3 \times ETX\&RSS_i) + (w_4 \times Ln_i) \end{matrix}\right)}{\sum_{i=1}^{16} U_i}} \right) \tag{17}$$

Where $\boldsymbol{i}$, is the number of fuzzy rules ranging from 1 to 16 (based on Table 8). And w_1, w_2, w_3, w_4 are the weights of each state on the algorithm and fuzzy calculations.

Table 8. Simulation conditions and parameters.

Parameters	**Value (s)**
Network topology	Random position
Deployment area	1000 × 1000 × 500 m3
Initial node energy	One kJ
Initial sink energy	50 kJ
Number of nodes	180
Nodes mobility	Limited under one m/s
Mobility model	Random mobility
Cost of long transmission	1.3 W
Cost of short transmission	0.8 W
Cost of reception	0.7 W
Idle power	0.008 W
Data aggregation power	0.22 W
The communication range of ASN	150 m
Acoustic transmission range(sink)	400 m
Frequency	30.5 kHz
Channel	Underwater channel
Maximum Bandwidth	30 kbps
Packet size	50 bytes
DIO packet size	4 bytes
DAO packet size	4 bytes

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DAO-Ack packet size	4 bytes
DIS packet size	4 bytes
Packet generation rate	$\lambda = 0.5{\sim}0.83$ pkt/s
Memory size	12 MB
Sink position	Surface (500×500×0)
Antenna	Omni-directional
Simulation time	500
Iterations	10
Number of Channels	11 (30.511, 30.518, 30.525, 30.532, 30.539, 30.546, 30.560, 30.553, 30.567, 30.574, 30.581) kHz

*Bellhop calculates the path loss between each node in each location.

8). Selecting Parent

This section details how the UWF-RPL method constructs a DODAG (Directed Acyclic Graph), enabling nodes to select their preferred parent. Data transmission is facilitated through the DODAG, which establishes the connections between each node and the DODAG root. The structure begins at the root node, or sink, which typically collects network data. The root distributes information about the DODAG structure using DIO (Destination Information Object) messages. Once nodes within the communication range of the root receive these messages, they process the information and determine whether to join the DODAG based on its attributes.

Each RPL instance can contain one or more DODAGs, with each DODAG being uniquely identified by an ID corresponding to the RPL instance. The root node assigns this identifier, which is represented as an 8-bit value. A node can only belong to one DODAG within a given RPL instance. While RPL instances operate independently, they share the same objective function (OF) specific to each instance. Each DODAG is assigned a unique identifier by the root, distinguishing it from other DODAG instances. The DODAG root also allocates IPv6 addresses to identify the DODAGs. The DODAG identification entry includes an 8-bit unsigned integer, the RPL instance identifier, and the DODAG identifier. When a new version of a DODAG is created, the version number is incremented at the root (Figure 4).

An increase in the DODAG version number indicates that a global repair process has been initiated at the root, leading to the release of a new version. Path repairs are executed to fix inconsistencies, such as loop detection or link failures. Local repairs aim to resolve these issues without rebuilding the entire DODAG, but if they fail to yield optimal results, a global repair may be required. A DODAG version represents a specific iteration, identified by a unique DODAG ID and defined by three attributes: the RPL instance identifier, the DODAG identifier, and the version number. In this method, the root node can send a DIO message to neighboring nodes, which can verify its authenticity by checking the DODAG version and parent ID fields. It is up to the receiving node to confirm if the first transmission was received successfully and then proceed with the necessary steps. The node from which the DIO message was received is added to the parent list of the receiving node.

Alternatively, the network's stability improves as the frequency and rate of DIO messages decrease. In cases of extreme instability, the interval between DIO messages is minimized, meaning the frequency of DIO messages is set to its maximum. The following illustration outlines the critical steps for selecting parents in this study.

Within the DIO message's DODAG configuration option is a field called OCP (Objective Code Point). The OCP, an unsigned 16-bit integer, is used to identify Objective Functions (OFs). This allows for selecting the appropriate OF based on the OCP value. Several OFs have been developed using single and multiple criteria, with common OCP values representing these OFs. Our research introduces a new OF by implementing a novel fuzzy logic system. In this system, the fuzzification step is applied to determine the membership function of each input, forming the foundation for our fuzzy logic design.

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A. Queue management phase

In the second phase of the proposed protocol, after forming the network graph and transferring data to the root, the network's state will evolve due to changes in bottlenecks, traffic rates, and the queue status of network nodes. The primary RPL method lacks mechanisms to manage node direction, control bottlenecks, or prevent queue overflow. To address this, our proposed method introduces a strategy to estimate and prevent bottlenecks and queue overflows at the parent nodes, particularly those near the sink.

Our solution operates as follows: to handle parent nodes prone to congestion and bottlenecks, especially when selected by multiple children simultaneously. The rate of packets entering and leaving the parent node's queue (incoming and outgoing packets) is monitored, and this process is modeled using Equation 18. When a parent node's queue reaches a critical threshold, it informs its child nodes of the situation—reaching this crucial point risks queue overflow, increasing the likelihood of packet loss. This notification is sent via a beacon, the network's most minor control message. Based on the message received from the parent, child nodes have three options: continue sending data at a regular rate, pausing data transmission briefly, or resume sending data once the congestion subsides.

A third option is to change the parent node, though this incurs network costs and overhead. If a node is experiencing congestion itself and faces a queue overflow, it cannot change its parent. In this case, the node's children must adjust the sending rate. The queue indicator is calculated using Equation 18 to manage this process.

$$Queue\ State = \begin{cases} \left(\dfrac{\lambda\Delta t}{\mu\Delta t}\right) \leq 1 \\ \left(\dfrac{\lambda\Delta t}{\mu\Delta t}\right) > 1 \end{cases} \qquad (18)$$

In this context, $\boldsymbol{\lambda\Delta t}$ represents the rate at which packets enter the node's queue, while $\boldsymbol{\mu\Delta t}$ signifies the rate at which packets leave the queue. In the first scenario, when the entry rate is lower than the exit rate, the probability of congestion is low. In the second scenario, the likelihood of congestion increases when the entry rate exceeds the exit rate. The difference between these rates, $\boldsymbol{\lambda\Delta t - \mu\Delta t}$, plays a critical role in determining the node's behavior.

If the difference between the entry and exit rates is smaller than the remaining slots in the queue, the node will refrain from sending a beacon message. However, if the difference exceeds the number of available slots in the queue, the node will send a beacon to reduce incoming traffic by half. Should the queue overflow again, the node will broadcast another beacon to its neighboring nodes, requesting an additional 50% reduction in traffic. This stepwise reduction typically results in a total traffic decrease of around 75%, as illustrated in Figure 5.

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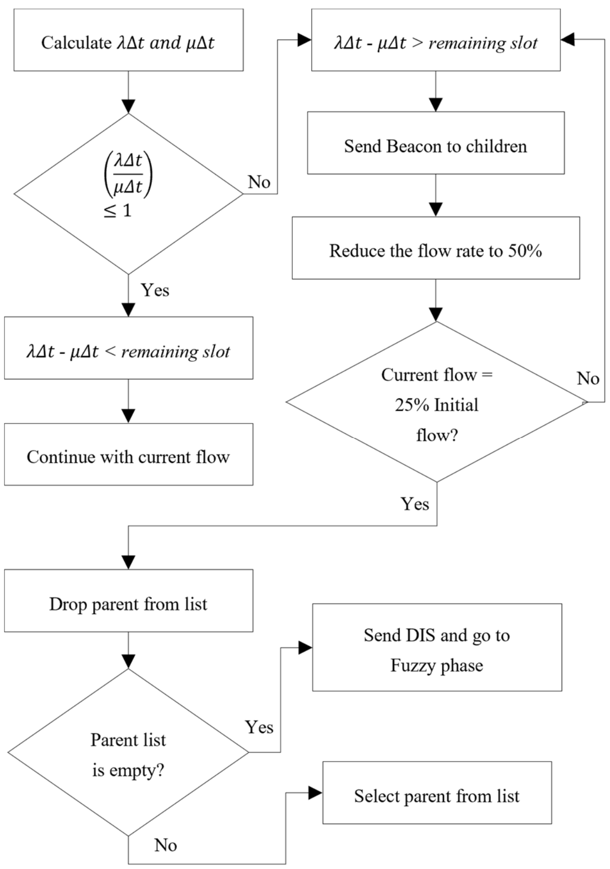

Figure 5. The process of Queue management.

VI. Evaluation and Comparison

In this section, we evaluate and compare the UWF-RPL method with other similar approaches. Implementing the basic RPL model for the underwater environment is based on IETF-standardized articles. Several significant modifications have been made to adapt this standard model to the underwater environment, including switching from a magnetic channel to an acoustic one, altering all network layers, and customizing the network for underwater use. The RPL method bases its decisions on ranking up to the network graph's root node. In contrast, UWF-RPL modifies the RPL's objective function, incorporating more effective criteria and parameters for parent selection.

To assess the UWF-RPL method against current techniques such as DEKCS and RPL, we used NS simulation version 2.31 and the Aquasim package version 2. The beamwidth of each underwater sensor node varied between 0 and 360 degrees, as did the UWF-RPL version. To evaluate the effectiveness of the proposed method, we included the DEKCS method from 2022 in our comparison. A summary of the simulation conditions in the NS2 environment is provided in Table 7. The tests used to compare UWF-RPL with the basic RPL and DEKCS methods include network convergence time, number of alive nodes, packet delivery ratio, delay per hop, energy consumption, and network overhead rate.

A. Network Convergence Time Test

This test lasts when the network is formed; in other words, the network graph is created, and the nodes are ready to send packets to the well. To perform this test, we considered the network traffic and data production rate at two values of 30 and 50 packets per minute to measure efficiency in the quiet and busy traffic environment. The convergence time criteria will change during the simulation time because network nodes may be lost, and local repairs are required. In the UWF-RPL network, fuzzy calculations are performed in each node and periodically sent to the neighbors by the DIO message in the RPL structure.

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As a result, no additional overhead is imposed on the network. To calculate this time, cumulatively sampled in time units every 25 seconds, the duration of local and global convergence is aggregated in the network. As expected, the UWF-RPL method in this test has performed better than the other two methods point-wise and, finally, on average. Figure 6 shows the timing diagram of local and global convergences. In this test, due to the instability of RPL and DEKCS methods, a difference of about 10-25% is observed. The higher the number of instabilities in the network, the worse the results will be. Figure 7 shows the average graph of this convergence time for three protocols in two modes with transmission densities of 30 and 50 packets per minute.

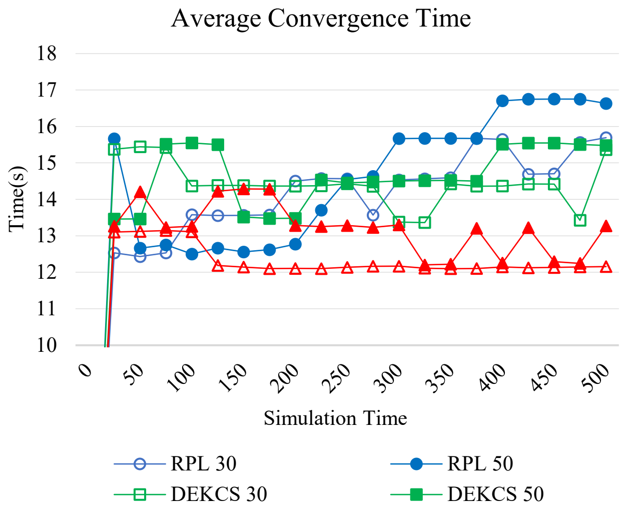
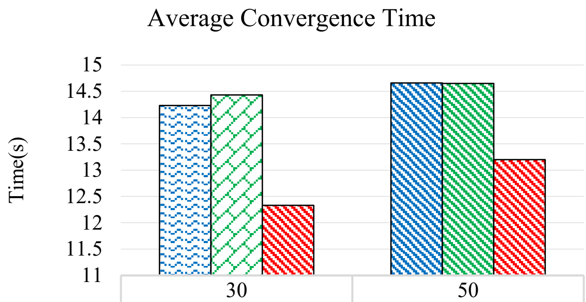


Figure 6. Convergence time of network nodes in 500 seconds and with two traffics of 30 and 50 pkt/m.



	30	50
RPL	14.23	14.66
DEKCS	14.43	14.65
UWF-RPL	12.331	13.2

Figure 7. The average convergence time of network nodes with two traffic rates of 30 and 50 pkt/m.

B. Testing the Number of Live Network Nodes

In the underwater sensor network, it is evident that the aggregation and exchange of packets consume energy with the passage of time and the activity of network nodes. If a node has exhausted its battery energy, it is removed from the network. Nodes consume energy for each of their internal and network activities (Figure 8). Even though the network nodes may not be necessary at the edges of the graph when they appear as routers or aggregators, their death can harm the system's performance.

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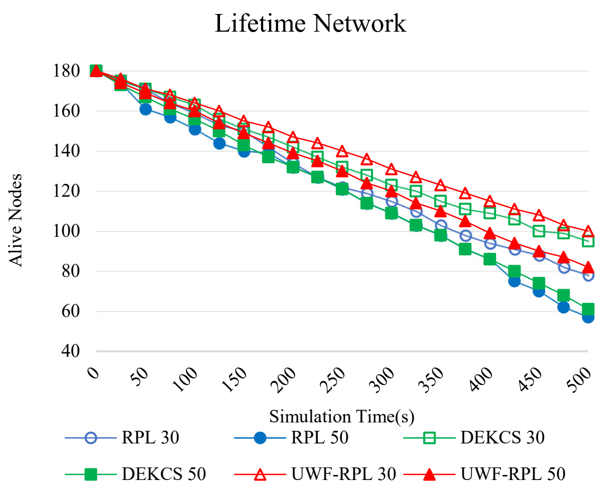

Figure 8. Number of live network nodes during 500s simulations.

Therefore, we can expect to see a postponement of the death time of the nodes as the energy consumption rate is distributed throughout the network. Based on a fuzzy objective function, the UWF-RPL method selects the next step in the network based on the fuzzy value of the neighboring node. If the node does not have the desired value, it is separated from the parent list of children by agreement and acts as a leaf node until its neighbors have reached the same level. As part of the objective function of this case, it is clear that the network nodes need to interact more in this process, and the control overhead is considerably less than the control overhead incurred by the early death of network nodes or messages from parentless children.

C. Package Delivery Rate Test

Another important factor in wireless networks' qualitative and quantitative assessment is their ability to deliver network packets to their destinations. The number of attempts to transfer and the percentage of successful transfers are considered in this test. This criterion directly relates to route control, flow rate, and the number of active routes in front of network trace nodes. It is possible to achieve a higher delivery rate when network flows are more distributed. It is important to note that the shortest path is sometimes the best. In our UWF-RPL fuzzy method, delay measures, ETX rate, and RSSI are critical players in reducing collisions and packet failures.

In the UWF-RPL method, a combination of these metrics and queue management has been included in the decisions of the nodes to select the parent. So, simulation results indicate that the UWF-RPL method achieves between 91 and 73 percent of packet delivery in networks with low density and between 86 and 64 percent in networks with high density. According to the average results, the UWF-RPL method has a delivery rate of 84% for low traffic and 76% for high traffic. However, the base RPL method values are 68 and 60%, respectively; in the DEKCS method, they are 78 and 73% (Figure 9).

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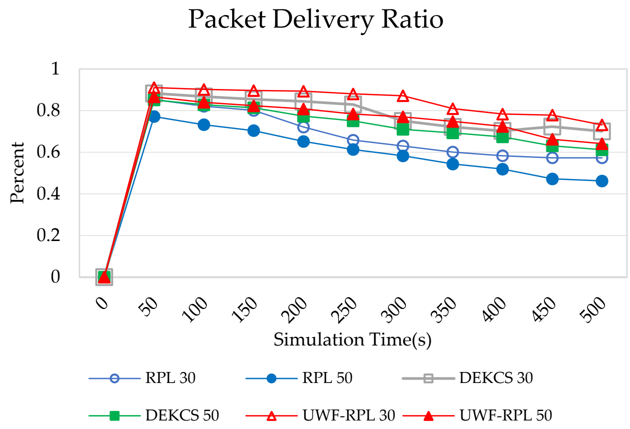

Figure 9. Delivery rate in low and high-traffic environments during 500s simulation.

D. Delay Per Hop Test

Network latency is defined by the average end-to-end packet transmission delay time. Therefore, the network's delay parameter depends on the number of steps a packet takes to reach its destination. According to the definition of overall delay caused by processing, it is queuing, transmission, and propagation.

The more steps between the source and destination of a packet, the more cumulative the end-to-end delay rate increases. On the other hand, due to the funnel effect in the network, the packet delay rate in the lower layers close to the leaves is lower due to the lack of density and crowding, and the closer we get to the root, the more likely the collision and funnel effect will be. This test measured the average end-to-end delay rate of network packets in steps between 1 and 4.

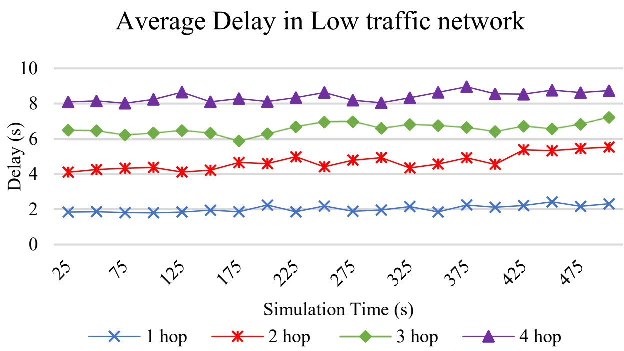

Figure 10. Evaluation of UWF-RPL network for the traffic of 30 packets per minute.

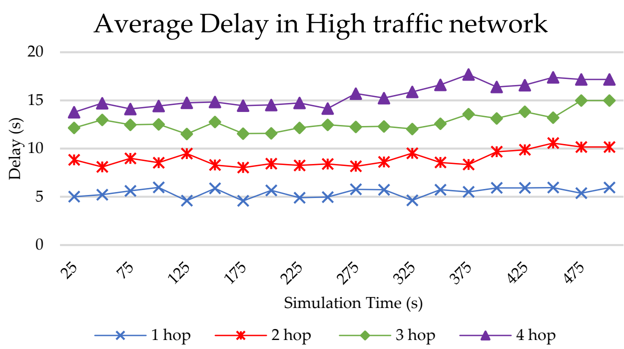

Figure 11. Evaluation of UWF-RPL network for the traffic of 50 packets per minute.

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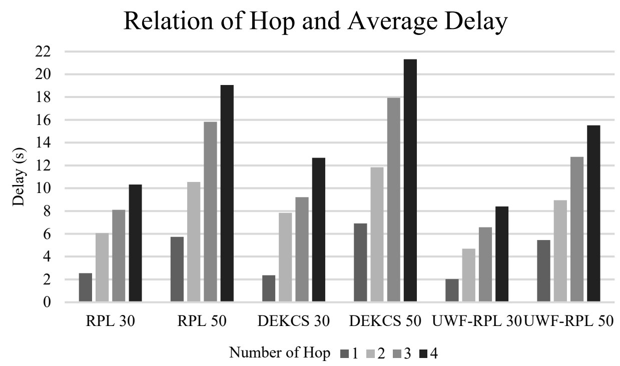

Figure 12. Graph of the average delay rate concerning the number of steps per traffic of 30 and 50 packets per minute.

E. Network Energy Consumption Test

Due to the limitation and non-chargeability of node batteries in the underwater sensor network, the energy consumption of the network nodes during the activity time is significant. Accordingly, the lower slope of the energy consumption in the network nodes shows the protocol's ability to manage energy consumption more significantly. This test shows the relationship between the number of remaining nodes and the time of rounds. The network's lifetime is a high threshold for sensor network use and highly depends on the lifetime of the individual nodes that make up the network. Also, the network's lifetime is considered the time when the first node dies. When a conventional static sink is used, the neighbors of one step of the sink decrease their energy faster than other nodes due to the increase of relay overheads. When the nodes around the sink reduce their energy, the well is separated from the network. This process is known as the encirclement of the sink. It is essential to check the network's lifetime because charging or replacing the sensor nodes after deployment is almost impossible. In this test, the number of live nodes of the tested protocols decreases during successive rounds. Candidate nodes' location information and residual energy are considered to detect their stability during rounds. Also, the energy consumption process is taken from it (Figures 13 and 14).

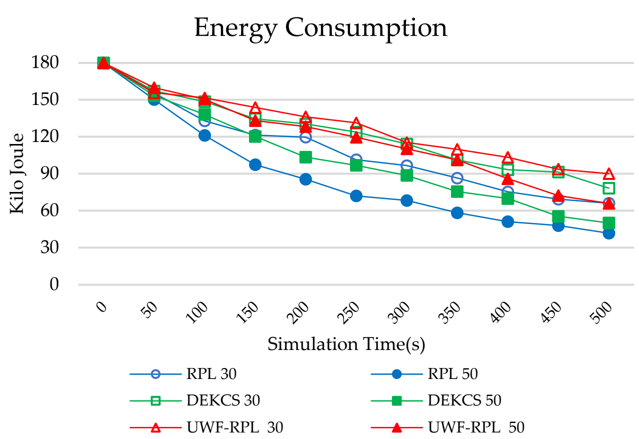

Figure 13. Network energy consumption rate in 500 seconds of simulation.

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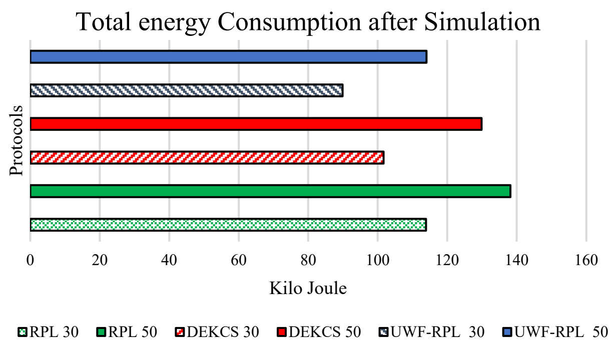

Figure 14. The total of energy consumed after 500 seconds of simulation.

F. Overhead Control Packets

Based on this parameter, we determine the extent to which the UWF-RPL protocol has been implemented to create a path and transmit the packet from the source to the destination. In the simulation performed, the UWF-RPL method with the primary method of the mentioned test shows the number of sent and received packets so that it can be concluded from this evaluation to what extent the protocol has safely delivered the packets generated in the network to the destination.

However, to transfer these data packets in the network, it is necessary to exchange some control packets, which are DIO, DAO, and DAO-Ack, in the base method. These packets are also used in the UWF-RPL method, but changes have been made to their content. The UWF-RPL method has reduced the rate of production and transmission of control packets. Since the distribution of the network nodes in the simulations is considered random, different results are output every time the simulation is repeated. Nevertheless, the significant difference between the UWF-RPL and basic methods is considered in all the iterations (Figure 15).

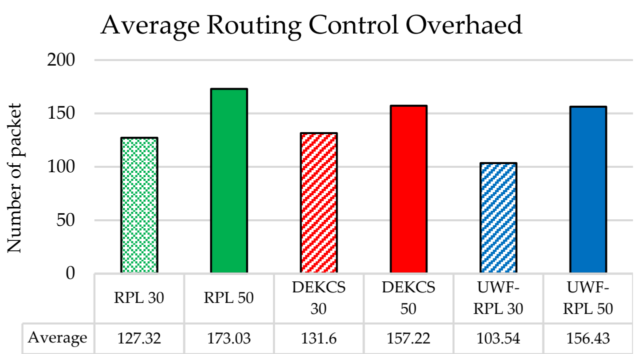

Figure 15. Chart of control message rate in 500 seconds of simulation.

VII. Conclusion

This article investigates the concept and structure of underwater wireless sensor networks. Underwater wireless sensor networks' specific challenges and requirements influence the forming, communicating, and transferring of data between their implementations. Therefore, the limitations of each method have been reviewed, and data transfer methods in this network model and their approaches, challenges, positive points, and weak points have been compared. Based on the results obtained from the comparisons, the cluster methods or hierarchical routing are known as efficient data transmission methods. The RPL protocol with components, infrastructures, and layer changes was considered for the first time. The changes in RPL network layers and the use of fuzzy logic to select the next step in the network are the highlights of this article. In the other part, a network load

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control method with a queue management method is suggested to prevent queue overflow. The following UWF-RPL method was evaluated using both fundamental and new methods. The results indicate that the proposed method has obtained better results than others in terms of quality of service in the network. Nevertheless, for future work, we consider the mobility criterion in the network and develop a dynamic model to reduce the communication delay in these underwater wireless sensor networks.

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