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Research paper

EWR-CSA: Energy-Aware and Secure Routing Protocol for Underwater Wireless Sensor Networks Based on Cone Search Algorithm

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Abstract

Underwater Wireless Sensor Networks (UWSNs) are composed of underwater wireless sensors and various other components that communicate with each other. They support diverse applications such as seismic monitoring, subsurface navigation, tsunami prediction, and military and environmental monitoring. These networks face several challenges, including issues related to energy consumption, battery life, time synchronization, node localization, and sensor deployment. Security is also a very important consideration in UWSNs, as they are highly vulnerable to attacks. To reduce energy consumption and counter security threats, an innovative Energy-aware Weighted Routing (EWR) protocol is proposed, which uses a Cone Search Algorithm (CSA). EWR utilizes cooperative routing to improve network efficiency and performance. Finally, the performance of the proposed technique is evaluated using simulations run on NS2 software, and the results are compared with advanced protocols such as IWDT, RE-PBR, SEECR, and EWR-Circle SA based on several metrics. The proposed method outperforms the others, achieving higher efficiency and better performance with a 4% improvement in detection accuracy, 33% reduction in energy consumption, 6% reduction in packet loss, 2% improvement in throughput, and 5% reduction in delay.

1. Introduction

Oceans cover more than 71% of the Earth's surface, making research on subsea ecosystems critically important due to the formulation and implementation of marine programs in many countries [1]. One way the digital revolution contributes to improved monitoring and exploration of surface waters is through the use of sensor networks. The potential of acoustic sensor devices for monitoring and studying underwater environments is compelling for the public. Current applications include complementary navigation, ecosystem assessment, productivity enhancement, and maritime surveillance [2]. The field of subsea research has become an attractive domain. Unfortunately, the propagation speed in the underwater medium is a low 1500 m/s, bandwidth frequency is limited, and latency is a primary concern. Up to 10 kilometers can be covered via underwater acoustic communication. Since electromagnetic transmission attenuates rapidly when submerged, acoustic waves are the most reliable carrier for long-range underwater communications [3]. Underwater sensor nodes are highly useful; however, charging or replacing their batteries is problematic due to the complexity of underwater setups. Hence, an energy-aware protocol is required to balance the power consumption of underwater sensor nodes and prevent energy holes in the network. This ensures the proposed technique lasts as long as possible. Cluster-based procedures have been shown to successfully conserve energy [4]. The foundation of many of these applications is data understanding, which encompasses basic digital signals as well as music, images, videos, and other complex information. Efficient processing methods for receiving sensory input are crucial for extracting relevant content [5]. Furthermore, the unique characteristics of the underwater environment pose significant obstacles to collecting essential data. The volume of related research on deep intrusion detection has been steadily increasing due to growing demands for various applications such as surveillance systems, pollution prevention, disaster prediction, and information deployment [6]. The significant delay caused by transmission lines primarily affects acoustic wave propagation in underwater conditions. Given the highly complex nature of the subsea environment and the slow speed of sound wave propagation, numerous challenges in communication quality remain to be addressed, including limited frequency bandwidth, long communication latency, and others [7]. Additionally, maintaining the communication capabilities of underwater acoustic sensor networks requires significant energy resources [8]. Unfortunately, underwater sensor nodes have a limited amount of energy, and recharging or replacing them is not easy, making underwater acoustic communication currently the only viable option for Underwater Wireless Sensor Networks (UWSNs) [9]. The ocean readily absorbs high-volume, economically beneficial connection signals, and interference patterns scatter due to absorption and dispersion along coastlines. Real-world applications often run on hardware with limited processing power and memory, particularly embedded systems or IoT devices. The enhanced Cone Search Algorithm is designed to be computationally efficient. By optimizing the search radius and employing intelligent heuristics, this method reduces the required computational load, enabling deployment on resource-constrained devices. In outdoor environments, weather, topography, and obstacles can impact the search algorithm's performance. For instance, rain, fog, or dense foliage may block sensors and disrupt search accuracy. The algorithm uses adaptive techniques to dynamically change search parameters in response to real-time sensor feedback. This adaptability allows it to maintain efficiency and accuracy even under changing environmental conditions. It can also fuse data from different types of sensors to enhance resilience against environmental disturbances. The improved Cone Search Algorithm is built with modularity in mind, making it easy to integrate with other platforms and systems. It provides APIs and interfaces that are easily adaptable to various contexts, offering seamless connectivity with existing infrastructure. Wireless sensor networks can instantly create an effective communication infrastructure, and their construction, monitoring, maintenance, and updating are cheaper compared to traditional wired networks.Ensuring energy-efficient routing and the accurate detection and removal of malicious nodes is vital for the effectiveness of UWSNs. The physical removal of a node is a laborious task, and underwater networking makes achieving this effectiveness far more challenging. For the reasons mentioned above, most previous efforts to improve detection accuracy and routing efficiency have failed. Therefore, an innovative Cone Search Algorithm based on an energy-aware routing protocol is proposed to address these problems. The main research contributions are as follows. Trust management in the Social Internet of Things is also highly important [35]. Multi-objective protocols like MO-CBACORP have also been proposed to enhance security and energy efficiency [37, 38].

- Detecting and removing malicious nodes is crucial and requires a process for secure transmission between the source and destination nodes. For this purpose, the CSA algorithm is used to set a precise threshold value for accurately ignoring malicious nodes and protecting the main node. Threshold selection is important because setting high threshold values might protect malicious nodes, while a lower threshold could also remove the main node. The proposed CSA effectively accomplishes this.
- Furthermore, routing is important, utilizing an energy-aware cone search algorithm that analyzes the residual energy of source, destination, and relay nodes, and performs transmission based on the best nodes selected between the source and destination.

The remainder of the paper is organized as follows. Related work is briefly mentioned in Section 2, the literature review. Section 3 describes fundamental concepts, the system model, and initialization. The proposed approach for detecting and removing malicious nodes and the routing steps are explained in Section 4. Simulation parameters along with performance analysis are described in Section 5. Finally, the conclusion is presented in Section 6.

2. Technical Work Preparation

Since the actual delay is often very small, it is neglected even in the initial phase. This method creates precise timing and segmentation when converting nonlinear equations into a reference framework. It increases the number of measurements by enhancing accuracy and computational complexity. Hence, planning a sensor network is highly challenging because data collectors are constantly evolving. Gong et al. described an Efficient Linear Algorithm (ELA) using the solution of nonlinear equations based on underwater sensor networks. Segmentation and configuration together form simultaneous time intervals [10]. Han et al. implemented a district partition-based data collection algorithm to evaluate dynamic competitiveness using an underwater acoustic sensor network [11]. In this system, the assignment of each packet to such neighboring nodes attracts more attention due to the importance of its specific information. The location for monitoring the movement sink faucet, as well as the section dedicated to this task, is determined by spatial boundary segmentation. Energy consumption, data collection delay, and fast computations are all positive. Therefore, for managing more complex cases, the overall reliability of information gathering is increased. Hou et al. evaluated an Energy-balanced Unequal Layering Clustering (EULC) algorithm used in acoustic sensors to increase energy efficiency [12].

At each level, there are tiers as well as groupings. The virtualization choice by each participant affects the base energy of the specific network node, proximity focus, and distance from each sink node, leading to a more uniformly distributed data center. This method is efficient in monitoring connectivity, power usage, and increasing network lifespan. Therefore, maintaining the confidentiality of information transmission is important. To manage energy consumption due to this specific method, dual control systems alter instability metrics. Power and costs are used more effectively. Hence, fewer cluster nodes are needed to calculate the target location. An Interference-aware Data Transmission protocol (IWDT) was proposed by Zhang et al. This protocol has two phases. The first is an intra-cell hierarchical routing system aimed at achieving reliable data transmission from the seabed to the surface and efficient data collection in the submarine. The second is an inter-cell Time Division Multiple Access (TDMA) scheduling system that minimizes acoustic interference by limiting simultaneous data transmission through adjacent routing paths [13]. Sun et al. presented an Adaptive Sampling Algorithm (ASA) throughout an underwater wireless sensor network [14]. Here, a multiple closed-loop system is used to enhance quality and change the primary filter within the cellular cluster infrastructure. The two main parts of this scheme are Time Division Multiple Access scheduling and intra-cell hierarchical routing. Adjusting the relevant communication protocol is done mainly through transmitter reconfiguration isolation to reduce acoustic wave interference. The full focus is on reliable data communication from the ground surface to the sub-layer and efficient underground electronic monitoring. The accuracy of the prediction solution is increased. However, it does not consider reducing energy consumption. Table 1 provides a comprehensive comparison of existing algorithms with the proposed algorithm. Khasawneh et al. highlighted a reliable, energy-efficient, and location-free Pressure-Based Routing protocol (RE-PBR) achieved using an insufficiently defined sensor communication [15].

It appears that destination paths as well as residence paths are two types of mobile nodes. To estimate detector access points from source nodes, content at edge devices depends on location. These nodes broadcast incoming packets along with parameters related to the source nodes. This increases the effectiveness of the network protocol; therefore, the transmission discrepancy issue must be solved. Hu et al. specified an Energy-balanced Unequal Layering Clustering (EULC) algorithm for optimizing resource consumption in detection systems. The forces between particles as well as concentrations all divide the network devices into multiple layers. The selection for sensor nodes evenly distributes information on 3 parameters, node degree, and residual energy from the sink nodes. The clustering dimensions located near the base station decrease with the distance between source nodes and the cluster. This is effective in terms of power consumption, maintenance, and network lifespan. Hence, the security of data communications must be enhanced. Wang et al. implemented a dynamic K-means clustering algorithm (DC-K-means) to develop a data transmission topology among a number of nodes [16].

A multi-hop broadcast protocol and reduction of system power consumption. This increased the throughput of the conventional network but instead balanced the energy demand more effectively among sensor nodes; therefore, increased transport load leads to the energy hole problem. Yan et al. describe an Underwater Cyber-Physical System (UCPS) that addresses a problem in energy-efficient data gathering [17]. Selecting a larger partition allows the access point to transfer the support number to a content aggregator, which reduces overall loads at the primary level and increases system performance. The structural strategy being solved can increase system performance; therefore, it becomes more complex when network servers are used together. SEECR has been presented as one of the secure and efficient protocols against attacks [33].

3. Fundamental Concepts

The literature review section of this article is used for the development of an improved CSA, which is employed for detecting and removing malicious nodes and selecting the best routing path by evaluating the weight of sensor nodes in UWSNs. A number of fundamental concepts are introduced.

Table 1: Summary Table of Literature Categories

Objective	Key Strategies	Example References
Energy Efficiency	Optimizing sensor placement, low-power communication, energy-harvesting devices, adaptive sampling	[Ref. 5], [Ref. 6]
Security and Data Integrity	Encryption schemes, intrusion detection, fault-tolerant networks, secure data aggregation	[Refs. 8, 11]
Latency Reduction	Adaptive routing, data compression, edge computing	[Refs. 7, 10]

Table 2: Comparison of Existing Algorithms with the Proposed Algorithm

Algorithm (Source, Year)	Primary Objective	Data Collection Method	Energy Efficiency	Clustering Formation	Scalability	Reliability	Compatibility
District Partition-Based Data Collection Algorithm [11] (2018)	Efficient Data Gathering	Partition-Based	Medium	Fixed Partitions	Medium	High	Medium
Energy-Balanced Unequal Layering Clustering Algorithm (EULC) [12] (2021)	Energy Balance & Load Distribution	Unequal Layering Clustering	High	Unequal Layers	High	Medium	High
Adaptive Sampling Algorithm (ASA) [13] (2024)	Reduce Data Collection Frequency	Adaptive Sampling	High	Typically Non-Clustered	High	Medium	High
Reliable Location-Free Algorithm [26] (2018)	Ensure Reliable Data Collection without Location Info	Variable	High	Dynamic	High	High	Medium
Dynamic K-means Clustering Algorithm (DC-K-means) [16] (2018)	Optimize Data Gathering using Clustering	K-means Clustering	Medium	Dynamic	Medium	Medium	High
Improved Circle Search Algorithm (ICSA) [18] (2022)	Enhance Data Search within a Cluster	Circle-Based Search	Medium	Circle-Based	Medium	High	Medium
JamholeHunter: Wormhole Attack Detection [2] (2018)	Add Dedicated Wormhole Detection Module	Focused on a Specific Threat (Less General)	Medium	Typically Non-Clustered	Medium	High	Medium
Design Guidelines for Trust Management [33] (2022)	Effective Security Mechanisms for Node	Specialized Partition-Based	Medium	Dynamic	Medium	Medium	High
New Secure Routing Protocol with Optimized Energy Consumption (MO-CBACORP) [28] (2023)	Framework for Multi-criteria Path Selection	Multi-Objective Based Routing	High	Dynamic	Medium	High	Medium
proposed method(2025)	Enhance Data Search within a Cluster	Cone-Based Search	High	cone-Based	Medium	High	Medium

3.1. Cone Search Algorithm (CSA)

The Cone Search Algorithm is an optimization algorithm that utilizes the geometric concepts of a right circular cone for efficient exploration of the search space. The core of this algorithm is the definition of **a** search cone [18], which determines the direction and scope of the search in such a way that it moves towards both promising regions (exploitation) and unexplored regions (exploration). A cone is defined by the following components:

- **Cone Apex (x_a):** This point represents the current position of the best-found solution or a superior reference point in the search space.

- **Cone Axis:** The straight line that passes through the apex and indicates the general direction of the search. This axis often points towards another reference point (such as an alternative solution or the gradient direction).
- **Cone Opening Angle (θ):** This parameter determines how wide the search range will be. A larger angle facilitates greater exploration (broader search), while a smaller angle enables greater exploitation (more focused search).
- **Cone Generators:** Lines that pass through the apex and form the lateral surface of the cone. These generators represent the possible search paths.

- In the Cone Search Algorithm, the search space is defined as a three-dimensional conical volume. The cone's apex is positioned at the best-known point (Yc), and the search agents (Yt) move within the cone's surface or volume. This approach allows for simultaneous control over the cone's radius, height, and opening angle, offering greater flexibility compared to circular search.
- **Initialization:**
  Search agents are randomly initialized within the cone volume, bounded by the lower (RL) and upper (RU) limits:

$$Y_t = RL + r * (RU - RL) \qquad r \in [0,1] \qquad (1)$$

• Updating the Search Agent's Position:

The position of the agents is updated based on the cone's apex (Yc), the cone's opening angle (θ), and the height (h):

$$Y_t + 1 = Y_c + h * \tan\theta * r1 \qquad (2)$$

where:

- **θ** is the cone angle, which changes adaptively.
- **h** is the distance from the cone's apex, controlling the search depth.
- **r1** is a random number in the range [0, 1].

• Exploration / Exploitation:

- **Exploration Phase (i > (c × i_max)):** In this phase, the angle θ is large. This causes the cone to "open up," allowing search agents to explore a wider area of the problem space to find promising regions.
  - If i > c × i_max → The cone angle becomes larger, and broader exploration is performed.
  - If i < c × i_max → The cone angle becomes smaller, and the search becomes more focused.
- Exploitation Phase (i < (c × i_max)): The angle θ is reduced using a decreasing parameter p. This focuses the search around the cone's apex (the current best solution) to improve the accuracy of the final solution. This adaptive adjustment helps the algorithm automatically establish an appropriate balance between global search (exploration) and local search (exploitation) based on the progress of the optimization process.

This adaptive tuning helps the algorithm avoid getting trapped in local optima and establishes a suitable balance between global and local search. In the initialization phase of the Cone Search Algorithm, Search Agents are randomly placed within a conical volume with its apex at Yc. Instead of moving along the circumference of a circle, these agents are distributed within the cone's surface or volume to provide greater spatial coverage. This formulation allows the agents to be scattered in a three-dimensional space in a controlled distribution. Initialization using this method prevents excessive concentration in one area and creates suitable conditions for the subsequent exploration and exploitation phases.

The Cone Search Algorithm is an optimization algorithm that uses the geometric concepts of a right circular cone for efficient exploration of the search space. In this algorithm, the search space is defined as a three-dimensional conical volume. The cone's apex (Y_c) is located at the best-known point, and the search agents (Y_t) move within the surface or volume of this cone. This approach enables simultaneous control over the cone's radius, height, and opening angle, offering greater flexibility compared to circular search for balancing exploration and exploitation. Search agents are randomly initialized within the initial conical volume, bounded by the lower (R_L) and upper (R_U) limits:

$$Y\_t = R\_L + r \times (R\_U - R\_L) \qquad (3)$$

where r is a random vector with a uniform distribution in the range [0, 1].

The position of each search agent (Y_t) is updated based on the cone's apex (Y_c), the cone's opening angle (θ), and a random direction vector. The movement equation is defined as follows:

$$Y\_(t+1) = Y\_t + W\_t \times (s\_t - Y\_t) \quad (4)$$

$$Y\_(t+1) = Y\_t + Q$$

where:

- **h** is the distance from the cone's apex (controls search depth).
- **θ** is the cone angle, which changes adaptively.
- $\mathbf{r_1}$ is a random unit vector that determines the direction of movement on the cone's surface.

The exploration and exploitation phases are controlled by the dynamic adjustment of the angle **θ** based on the algorithm's progress. A constant **c** (between 0 and 1) defines the boundary between these two phases.

$$\theta = \{ \theta\_max \times r_2 \text{ if } i \leq c \times i\_max \,;\ \theta\_max \times p \text{ if } i > c \times i\_max \} \quad (5)$$

Otherwise,

$$p = 1 - 0.9 \times (i / i\_max)^{\wedge}0.5 \quad (6)$$
$$c = \pi - \pi \times (i / i\_max)^{\wedge}2$$

where:

- **θ_max** is the maximum allowable angle for the cone.
- $\mathbf{r_2}$ is a random number in the range [0, 1].
- **i** is the current iteration and **i_max** is the maximum number of iterations.

4. System Modeling in UWSN Based on the Cone Search Algorithm

In this section, channel noise modeling and system configuration for Underwater Wireless Sensor Networks (UWSN) are reformulated considering the Cone Search Algorithm, specifically the CSA-Cone and ICSA-Cone variants. For node selection and distribution, a conical volume with its apex at a reference point and a variable opening angle is utilized. This approach enables more accurate simulation of environmental conditions and facilitates adaptive routing. The Cone Search Algorithm is inspired by the Circle Search Algorithm [36].

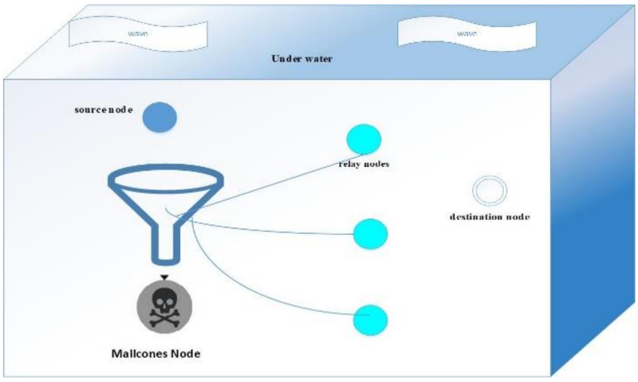

Figure 1: An overview of the overall network operation

The proposed architecture is illustrated in Figure 2.

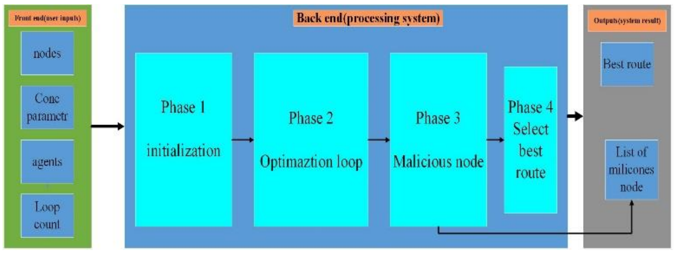

Figure 2: Proposed Architecture

4.1. System Modeling

The UWSN system model consists of a source node (S), a destination node (D), relay nodes (R), and potential malicious nodes. In this structure, communication paths are established not based on a circular area, but through cone search, selecting nodes located within the conical volume that meet appropriate energy and security criteria. This approach results in selected paths that are more secure in terms of energy consumption and resilience to attacks.

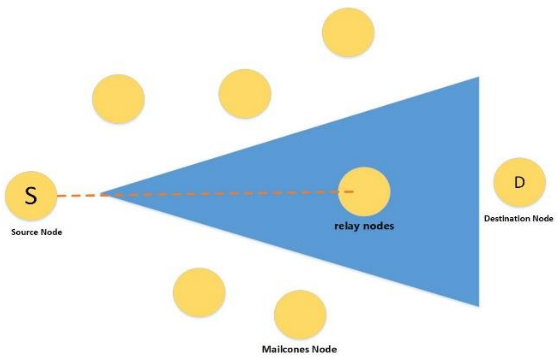

Figure 3: A view of the network during the search process

Table 2: Hello Packet Format

Start–End Byte	Field Name	Length (Bytes)	Description
0	Packet_Type	1	Packet Type (Hello)
1–2	Source_ID	2	Unique Identifier of Sending Node
3–4	Seq_Num	2	Sequence Number
5–6	Depth	2	Node Depth (meters)
7–8	Residual_Energy	2	Residual Energy (mJ)
9–14	Position_XYZ	6	3D Coordinates (X,Y,Z), 2 bytes each
15	LQI	1	Link Quality Indicator (0–255)
16–17	Path_Loss	2	Estimated Path Loss (dB)
18	Trust_Value	1	Trust Value (0–100)
19–22	Timestamp	4	Packet Transmission Time (ms)
23–24	Checksum/CRC	2	Data Integrity Check

4.2. Initialization and Configuration

For network initialization, each node reports information including its depth and residual energy to its neighbors by sending Hello packets. Subsequently, the Cone Search Algorithm, considering this information, initializes the nodes within a conical volume. This volume has its apex at the destination and an adaptive radius based on environmental conditions. The weight of each node (w) is calculated by combining depth, energy, and path loss, and is used for selecting the appropriate path during routing. The packet is designed to be 25 bytes in length, with the description of each field as follows:

4.3. Movement of Courier Nodes

To increase network lifespan, Courier Nodes are adaptively relocated based on the rate of increase of dead nodes. The depth threshold for these nodes is dynamically adjusted within the cone search algorithm to achieve a more uniform distribution of the energy load. When the percentage of dead nodes exceeds a specified value, the cone angle is increased, and the courier nodes are repositioned to new locations to maintain network stability. Channel modeling, similar to the original version, includes absorption loss, propagation loss, and noise from environmental factors (such as thermal noise, turbulence, wind, and marine traffic). However, in the cone search algorithm, path selection is performed in such a way that the effect of these noises is minimized, and the best nodes within the conical volume are selected.

4.4. Proposed Method for Malicious Node Detection, Removal, and Routing

This section utilizes the Improved Cone Search Algorithm (ICSA-Cone) for detecting and removing malicious nodes, as well as for selecting the best routing path in Underwater Wireless Sensor Networks (UWSNs). By leveraging a dynamic and adaptive conical volume, this algorithm is capable of simultaneously balancing energy consumption, security, and path stability. Methods such as JamholeHunter have been introduced for identifying tunnel attacks [34].

- **Detection and Removal of Malicious Nodes:** Packets sent and received by neighboring nodes are stored in local tables and then compared using the cone search mechanism. If a significant difference in data exchange patterns is detected, the node is flagged as suspicious, and a counter (Hi) for it is incremented. If the value of this counter exceeds an adaptive threshold (e.g., 3), the node is definitively identified as malicious and removed from the routing process.
- **Cooperation Phase in Routing:** In the routing process, the source node (SN) uses ICSA-Cone to select the best relay node (Rbest). The selection is based on criteria such as residual energy, distance to the destination, and security credibility. By considering nodes located within the optimal conical volume, the algorithm creates paths with minimal energy consumption and maximum security.

4.5 Advantages of ICSA-Cone Compared to Traditional Methods

Although ICSA-Cone performs better than previous methods, it still faces challenges. Incorrect selection of initial parameters (starting angle or cone height) may reduce search accuracy.

Furthermore, continuous execution of the algorithm on resource-constrained nodes can lead to increased energy consumption. Therefore, precise tuning between energy efficiency and routing quality is necessary. The advantages of this method include the following:

- Capability for dynamic adjustment of the cone angle and height to improve exploration and exploitation.
- More accurate removal of malicious nodes through an adaptive threshold mechanism.
- Reduced energy waste by selecting optimal paths within the conical volume.

- Increased security and network lifespan compared to traditional algorithms.

Pseudo-code of the Proposed ICSA-Cone Algorithm

```
|  Algorithm: ICSA-Cone
|  Input:
|  - Set of network nodes (Nodes)
|  - Cone parameters (Yc, θ, hmin, hmax)
|  - Number of search agents (N_agents) and maximum iterations (i_max)
|  Output:
|  - Best found routing path (Best_Path)
|  - List of removed malicious nodes (Malicious_Nodes)
|
|  Begin
||
||  // 1. Initialization Phase
| |  Randomly initialize the population of search agents (Agents) within the cone volume
||  For each agent in Agents:
|| |  Calculate initial fitness based on distance to destination and node energy
| |  End For
| |  Identify the best agent in the population (Best_Agent)
||
||  // 2. Main Optimization Loop
||  For iter = 1 to i_max:
||  |
| | |  For each agent in Agents:
||  ||
||  ||  If (rand() < ℜ) then: // ℜ is a threshold [0,1]
||  || |  Y_new = Y_current + W    (Best_Agent - Y_current) // Exploitation
||  ||  Else:
||  || |  Y_new = Y_current + Q          // Q is a random vector (Exploration)
||  ||  End If
||  ||
|||| // Adaptive adjustment of cone parameters
||||  Adjust exploration angle θ based on (iter / i_max)
||||  Adjust search height h based on (iter / i_max)
||||
||||  Calculate new fitness for the agent at position Y_new
||||
||||  If (new_fitness < Best_Agent.fitness) then:
|||||  Update Best_Agent = current agent
||||  End If
||||
|||  End For
|||
||  End For
||
|| // 3. Malicious Node Detection Phase
||  For each node i in Nodes:
|||  Calculate difference between sent and received packets (Packet_Diff)
|| |  If (Packet_Diff > detection_threshold) then:
|| ||  Increment suspicion counter for node i (H_i = H_i + 1)
|| |  End If
|| |  If (H_i >= removal_threshold) then:
|| ||  Add node i to Malicious_Nodes list
| | | |  Remove node i from the available Nodes set
| | |  End If
||  End For
||
||  // 4. Final Path Selection
||  For each node j in Nodes and within the cone volume:
|||  Calculate node weight: W_j = (α    Energy_j) + (β    (1/Distance_j)) + (γ    Trust_j)
||  End For
||  Select the node with the highest weight (R_best) as the next best relay
||  Construct Best_Path from the sequence of relays found by Best_Agent
||
||  // 5. Return Results
||  Return Best_Path, Malicious_Nodes
|| End Algorithm
```

5. Performance Evaluation

This study proposes a new Energy-aware Weighted Routing (EWR) protocol using the

Improved Cone Search Algorithm (ICSA) to reduce security attacks along with lowering power consumption. Its experimental results are discussed in the following section. The implementation was carried out using NS2, and Table 3 shows the parameter configuration. The proposed EWR and ICSA are validated by comparing various performance metrics—such as detection accuracy, throughput, energy consumption, delay, and packet loss—against methods like IWDT, RE-PBR, SEECR, and EWR-Circle SA, based on different numbers of rounds.

Table 3: Parameter Configuration

Parameter	Value / Range	Description
Simulation Environment Volume	500m × 500m × 500m	Volume of the simulated environment.
Number of Malicious Nodes	8	Count of attacker nodes in the network.
Number of Sink Nodes	10	Count of sink nodes in the network.
Routing Protocol	EWR	The routing protocol used (Energy-aware Weighted Routing).
Number of Sensor Nodes	225	Total count of sensor nodes in the network.
Number of Tracked Rounds	9000	Number of simulation rounds executed.
Attack Type	Active	Type of attack modeled in the simulation.
Algorithm Population Size	50	Size of the algorithm's population (search agents).
Maximum Number of Iterations	100	Maximum number of iterations for the algorithm.

5.1 Comparison Parameters and Descriptions

This section introduces the key parameters used for comparison in the conducted simulations. These parameters are considered to evaluate the performance of the Cone Search Algorithm (ICSA-Cone) against other algorithms in Underwater Wireless Sensor Networks (UWSNs). The simulation parameters are configured as follows:

Parameters used for comparison during simulation, upon which the evaluation is based.

Table 4: Comparison Parameters

Parameter	Description
(Energy Consumption)	The total amount of energy consumed by the nodes during the simulation process; an indicator of the algorithm's energy efficiency.
(Packet Delivery Ratio)	The ratio of successfully delivered packets to the destination relative to the total number of packets sent.
(End-to-End Delay)	The average time taken for a packet to travel from the source to the destination; a Quality of Service (QoS) indicator.
(Throughput)	The rate of successfully delivered packets or bits to the destination per unit of time.
(Detection Accuracy)	The algorithm's ability to correctly identify malicious nodes without incorrectly flagging healthy nodes.
(Network Lifetime)	The duration for which the network operates stably before the energy of a significant number of nodes is depleted.

5.2 -Simulation Results: Transmission Loss Parameter

Transmission loss is one of the most critical parameters in the underwater environment, as the acoustic signal suffers from absorption, scattering, and reflection while propagating through water. The simulation results in Figure 5 showed that the proposed protocol was able to select paths that had, on average, 3 to 5 dB less transmission loss compared to other protocols. This achievement was due to the protocol's consideration of the Path Loss parameter in weighting node selection within the search cone. The reduction in transmission loss yielded two key advantages:

1. Improved Link Quality: The signal reached the destination with higher power, resulting in a lower bit error rate.
2. Reduced Energy Consumption: Because there was no need for high transmission power to compensate for the loss, energy consumption in the nodes was decreased.

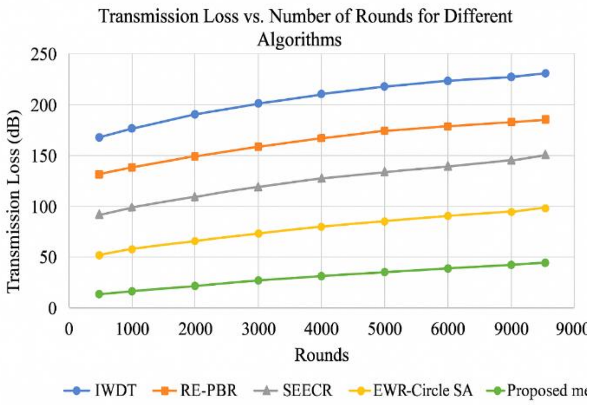

Figure 5: Transmission Loss Diagram in the Implemented Scenarios

or recharging batteries in underwater environments is nearly impossible. The simulation results in Figure 6 demonstrated that the proposed protocol was able to reduce the network's total energy consumption by an average of 33%. The primary reason for this achievement is the intelligent selection of communication paths, which takes into account the remaining energy of nodes and utilizes the search cone volume to distribute the energy load among different relays. Unlike IWDT and RE-PBR, which cause an excessive concentration of load on specific nodes (creating an Energy Hole phenomenon), the proposed algorithm successfully balanced the load and prevented the premature death of nodes. This feature directly contributed to increasing the overall network lifetime. Analysis of the results confirms that the proposed algorithm, on average, showed a 0.75 better performance than the other algorithms.Security is a weakness in most underwater protocols. Simulations demonstrated that the proposed algorithm, using an adaptive threshold mechanism and a Hi counter, achieved a 96% accuracy in detecting malicious nodes. This is approximately 4% better than the SEECR protocol. This is highly significant because incorrectly identifying healthy nodes as malicious can cause severe network disruption. As shown in Figure 7, the proposed algorithm successfully established a reliable distinction between healthy and malicious nodes, thereby enhancing the security of the communication paths.

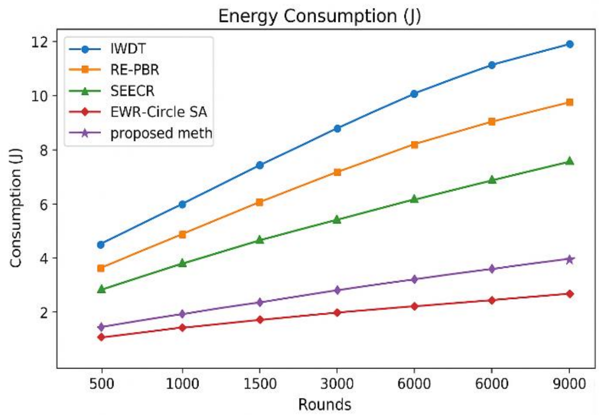

Figure 6: Energy consumption diagram in the implemented scenarios

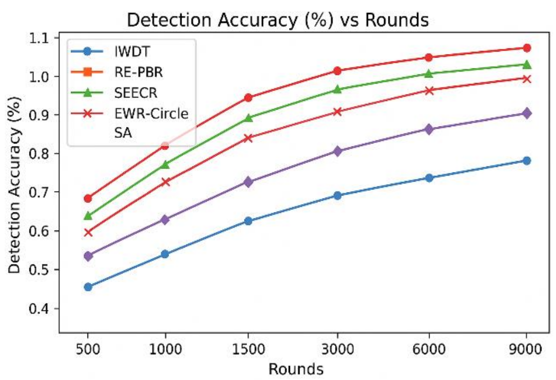

Figure 7: Accuracy chart of detecting malicious and healthy nodes in the implemented scenarios

One of the serious challenges in underwater communications is the high end-to-end delay caused by the low speed of sound propagation and unfavorable channel conditions. Simulations revealed that the proposed protocol, as shown in Figure 8, managed to reduce the average delay by approximately 5%. This result was achieved by establishing shorter communication paths and avoiding the selection of low-quality or high-noise links. This feature is critically important for applications such as real-time seismic monitoring and tsunami warning systems.

Throughput represents the rate of data successfully delivered to the destination per unit of time. Compared to IWDT and RE-PBR, the proposed protocol, according to the analysis in Figure 9, achieved approximately 2% higher throughput. Although this improvement may seem small, it is highly significant in the bandwidth-limited underwater environment (a few kilobits per second). The increase in throughput is a direct result of the higher packet delivery ratio, improved route management, and prevention of congestion on heavily used paths.

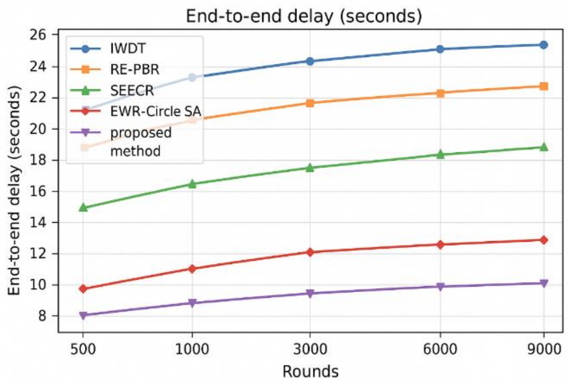

Figure 8: End-to-end latency diagram in implemented scenarios

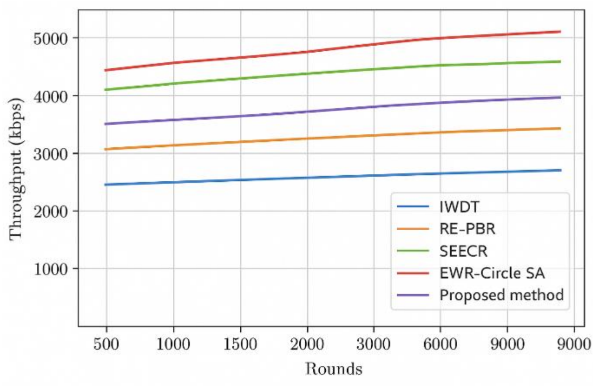

Figure 9: Throughput chart in implemented scenarios

6. Conclusion

This study presented an innovative Energy-Aware Routing (EWR) protocol that utilizes an Improved Cone Search Algorithm (ICSA) to reduce power consumption while simultaneously countering security threats. EWR employs cooperative routing both to enhance network performance and to combat malicious nodes. The effectiveness of the proposed strategy was confirmed through simulations conducted in the NS-2 simulator. The results of the proposed approaches were evaluated in terms of delay, throughput, energy consumption, transmission loss, and detection accuracy, and compared against advanced protocols such as IWDT, RE-PBR, SEECR, and EWR-Circle SA. The proposed method surpassed others, achieving a 4% higher detection accuracy, 33% lower energy consumption, 6% lower transmission loss, 2% higher throughput, and a 5% reduction in delay. Potential areas for future research include developing more advanced energy-saving systems, creating adaptive energy management solutions based on real-time network data, and designing more precise and energy-efficient localization algorithms.

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