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IoT-based framework for optimizing energy efficiency and reliability in acoustic sensor networks using mobile sinks

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In today's world, there is an increasing demand for environmental monitoring, surveillance, and oceanographic research, which poses challenges in improving energy efficiency and data transfer reliability in Acoustic Sensor Networks. Existing methods face hurdles due to limited energy resources and unreliable data transmission. We propose a Reliable and Energy-Efficient Framework with Sink Mobility (REEFSM) to address these issues. This framework optimizes energy consumption and enhances data reliability by incorporating advanced energy management strategies such as adaptive duty cycling and efficient data transmission mechanisms by minimizing forwarding nodes. Simulation results demonstrate that REEFSM reduces energy consumption by up to 43% and increases data reliability by 35% compared to protocols like EERBCR and DEADS. REEFSM ensures zero dead nodes, minimizes packet drops, and maintains high data accuracy throughout the simulation. This research outcome provides a sustainable and reliable solution for energy-efficient data collection in underwater environments. The future research directions, including integrating autonomous path planning, energy harvesting, and machine learning techniques, hold great potential for further advancements in the field.

Keywords Underwater Acoustic Network, Reliable Communication, Energy efficient Scheme, Neighbor Discovery Algorithm, Sensor Network.

In recent years, there has been a growing interest in underwater acoustic sensor networks (UWSNs) due to their remarkable potential for various applications within aquatic environments. These applications include underwater exploration, environmental monitoring, oceanographic research, and offshore enterprises. UWSNs utilize acoustic waves for communication, as radio signals are ineffective underwater due to significant attenuation and dispersion. Although optical waves have been suggested as an alternative, their efficacy is limited by attenuation and dispersion, rendering them less viable for long-distance communication in murky water environments[1]. The critical challenge in UWSNs lies in optimizing energy efficiency and network longevity due to the constrained battery capacity of sensor nodes. Underwater communication, sensing, data forwarding, and processing consume substantial energy, necessitating the development of energy-efficient protocols and techniques. The need for energy-efficient solutions is further emphasized by the considerable energy consumption involved in these activities[2]. Nevertheless, the distinctive characteristics of submerged habitats give rise to several obstacles. The need to optimize network lifetime arises due to the constrained battery capacity of sensor nodes, hence requiring the creation of energy-efficient protocols and techniques. The significance of maximizing energy utilization, including hardware design and networking protocols, is highlighted by the considerable energy consumption in underwater communication, sensing, data forwarding, and processing[3]. Additionally, absorption and scattering reduce the amplitude of acoustic waves as they travel through a medium. High-frequency attenuation is faster, restricting acoustic wave distance and significantly impacting routing and communication protocol development. Therefore, technologies that reduce latency and provide quick and reliable data transport are essential. Noise and interference mitigation are crucial to underwater communication reliability[4]. Research and development are motivated by the challenges of enhancing UWSNs to satisfy the requirements of aquatic applications. Network longevity is constrained by reliance on forwarder nodes, network topology, node density and deployment techniques, node failure, overloaded nodes, infrastructure, and protocols. A limited number of forwarder nodes

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can restrict network operation and result in several complications. This study hypothesizes that implementing mobile sinks in a well-structured network architecture can significantly reduce energy consumption and enhance data reliability in UWSNs. By minimizing the need for intermediary nodes and optimizing sensor node wake-up and sleep cycles, REEFSM is expected to extend the network's lifespan and improve overall performance[5]. This study hypothesizes that implementing mobile sinks in a well-structured network architecture can significantly reduce energy consumption and enhance data reliability in UWSNs. By minimizing the need for intermediary nodes and optimizing sensor node wake-up and sleep cycles[6]., REEFSM is expected to extend the network's lifespan and improve overall performance. Author[7] proposes a centralized control-based clustering scheme to enhance energy efficiency in underwater networks by optimizing node deployment and duty cycling.

Current protocols like EERBCR and DEADS have improved energy efficiency and data reliability in UWSNs. However, these protocols often rely on stationary sink nodes, leading to unbalanced energy consumption and inefficiencies. For instance, stationary surface sinks may hinder protocols like EEDBR from covering all data, and predetermined mobile sink patterns in EERBCR still leave room for improvement in energy management during sensor node operations. Moreover, these protocols do not adequately address the unique characteristics of UWSNs, such as node mobility and the Doppler effect, which impact the calculation of performance metrics and overall network scalability[8]. A data-model fusion-driven method approach combines the advantages of data-based and model-based methods to improve prediction accuracy and reduce computational expense[9]. Existing approaches assume accurate AUV models and do not consider parameter uncertainties; new control strategies need to be developed for uncertain heterogeneous AUV systems[7].

This research addresses these gaps by proposing a novel framework that leverages mobile sinks for direct communication with sensor nodes. This reduces the reliance on forwarder nodes and improves energy efficiency and reliability. The proposed REEFSM framework aims to overcome the limitations of existing methods by ensuring balanced energy consumption, reducing packet loss, and maintaining high data accuracy throughout the network's operation.

Motivation and contribution

The primary motivation behind this research is to develop an energy-efficient routing framework that can balance energy consumption among sensor nodes, thereby enhancing the reliability and longevity of UWSNs. Existing methods often result in unbalanced energy consumption, where some nodes deplete their energy faster than others, leading to network partitions and reduced performance. This study addresses these issues by proposing a Reliable and Energy-Efficient Framework with Sink Mobility (REEFSM). REEFSM optimizes energy consumption and enhances data reliability by incorporating advanced energy management strategies such as adaptive duty cycling and efficient data transmission mechanisms. By optimizing energy usage and balancing the energy load, the framework facilitates:

Direct Communication with Mobile Sinks. The framework facilitates direct communication between sensor nodes and mobile sinks by employing four mobile sinks, each located centrally within their designated zones. This strategic placement minimizes the need for intermediary nodes, thereby improving reliability and reducing packet loss ratios.

Energy Conservation and Extended Network Lifespan. Reducing the reliance on forwarder nodes helps conserve energy and extend the network's lifespan. The framework optimizes the wake-up and sleep cycles of sensor nodes, activated only by sink nodes' broadcast messages (Hello and Bye). This strategy minimizes energy consumption by avoiding unnecessary relay node usage and employing relay nodes only when necessary.

Enhanced Network Architecture: The framework divides the network into four distinct regions, each further subdivided into three horizontal segments. This structured division and the strategic placement of mobile sinks ensure balanced coverage and minimize latency. The network architecture is further enhanced by optimizing sensor node listening, wake-up, and sleep cycles, reducing energy consumption.

Neighbor Discovery and Packet Forwarding Algorithms: The proposed algorithms facilitate direct communication between sensor nodes and geographically proximate mobile sinks, bypassing the need for relay nodes. These algorithms reduce the number of cycles that sensor nodes complete, further conserving energy and enhancing network reliability.

Section 2 presents a literature review. Section 3 elaborates on the proposed system model and framework. Section 4 contains results, analysis, and discussions. Section 5 discusses conclusions and future work.

Related work

Most underwater wireless sensor networks (UWSNs) send data packets to surface-level sink nodes using depth-based routing (DBR). Nodes near sinks waste DBR energy by relaying data packets. In response, EEDBR was founded. This protocol evaluates node energy to divide network energy when building routing paths. Stationary surface sinks may hinder EEDBR from covering all data. Moveable sink nodes with predetermined patterns cover three locations on each route in EERBCR, boosting energy efficiency. Coverage gaps are eliminated by linking all sensor nodes in a region to a sink node. Energy management during sensor node operations reduces EERBCR's efficiency. Sensor nodes must efficiently flip between dormant and active states for low-energy sink signals. Energy consumption during state transitions, especially waking and sleeping, dramatically impacts network energy efficiency. Energy management research by EERBCR is needed to improve UWSN performance[10]. The unequal energy utilization in underwater wireless sensor networks results from the uneven distribution of nodes across different depths. The energy-efficient data collecting system (EEDG) has been developed to tackle the difficulties effectively by employing a three-step procedure. The nodes are arranged into smaller clusters and supervised by temporary forwarder nodes. The primary duty of forwarder nodes is to gather data from a designated subset of nodes over a one-hop connection in each iteration. Network nodes transmit their data solely to designated forwarder nodes within specific intervals. The utilization of graph structure has been found to significantly mitigate the latency in collecting data over the entire network. The accomplishment is attained by utilizing a mobile sink that encounters forwarder nodes by their designated degree inside the graph. The effectiveness of the Energy Efficient Data Gathering (EEDG) mechanism is assessed in terms of its energy usage, end-to-end delay, and throughput[4]. The EH-ARCUN Protocol delineates a streamlined method for transmitting data, outlining a coordination mechanism between the source and relay nodes. Additionally, it elucidates the integration of piezoelectric energy harvesting and relay nodes. The user examines the influence of harvesting parameters (duration, stability, delivery ratio) on network performance. They conducted a comparative analysis of EH-ARCUN, ARCUN, and RACE regarding energy consumption and performance. It fails to tackle the issue of empty spaces or changing network structures. The energy harvesting model may necessitate more refinement[11].

The CR-NBEER Protocol outlines the functioning of cooperative relaying and the selection procedure based on surrounding information. The remaining energy and the density of nodes determine the selection parameters for relays. The authors Examine the effects of CR-NBEER on network longevity, power usage, and delivery success rate. Analyzes the performance metrics of CR-NBEER, EEUC, and M-CBR. There is a deficiency in the investigation of incorporating energy harvesting systems. There may be a need for systems that facilitate the interchange of data and the discovery of neighboring entities[12]. A technique employing mobile autonomous underwater vehicles (AUVs) as intermediaries to alleviate gaps in coverage. The technique being discussed is a relay selection system focusing on distance and energy efficiency. Evaluates the proposed method and technique for network coverage, energy efficiency, and the duration required to fix gaps in coverage. The proposed method is being compared against static anchor-based methods. Specifics may be required for coordination tactics and AUV movement patterns. Additional research is needed to determine how much the approach can be scaled up to accommodate larger networks[8]. The cooperative routing process is significantly challenged by the dynamic movement of sensor nodes in response to water currents. The proposed methodology incorporates sensor nodes' spatial coordinates and vertical placement to ascertain the most advantageous destination nodes. Integrating these two attributes does not necessitate familiarity with the positional coordinates of the nodes but rather prioritizes the selection of destination nodes near the water surface. In addition, it should be noted that a source node is responsible for choosing both a relay node and a destination node. Moreover, the source node expects to receive acknowledgment regarding the successful reception or retransmission of the data packets[13]. The purpose of single-hop clustering methods is to provide direct communication between the cluster head and the base station. The proposed study aims to improve data transmission efficiency through multi-hop clustering. The process entails the choice of Relay Autonomous Underwater Vehicles (Relay-AUV) according to parameters such as minimizing latency and maximizing channel capacity in acoustic wireless communication. The data transmission rate demonstrates a notable increase in successive transmission rate, throughput, cost of execution time, and packet delivery ratio. The proposed CB-BG mechanism exhibits improved efficiency and dependability in communication[14]. The research methodology employed in this study successfully addresses the issue of transmission loss by decreasing the distance over which the signal is carried. The initial method employs a unique selection strategy based on the principles of Boltzmann distribution. The primary aim of the second method is to improve the solutions obtained by the preceding algorithm by minimizing transmission loss. The observation has been made that an efficient allocation of sensor nodes to a chosen group of relays can be achieved in polynomial time by rephrasing a certain aspect of the problem as a bipartite matching problem with minimal cost[5]. This study introduces a novel Cooperative Ray Optimization (CoROA) technique to mitigate the adverse impacts of geometric spreading and Doppler effects in underwater acoustic networks, thereby minimizing packet loss and delay. The existing approaches effectively handle the tasks of routing and energy management inside an underwater network, considering the variables of temperature and salinity. The CoROA approach enhances many performance metrics, including packet delivery optimization, throughput improvement, latency reduction, and packet drop mitigation. This is achieved by leveraging multiple pathways across relay nodes to reach the intended destination node[11] efficiently[15]. A topology optimization strategy based on a minimum-weighted rigid graph is developed for sensor deployment. A mechanism is developed at the local level for each sensor node to transmit the acquired data to the data collectors (sinks) by utilizing the most efficient network topology. The Autonomous Underwater Vehicle (AUV) is designed using a dynamic value-based path planning methodology, which enables it to navigate and visit data collectors efficiently. This technique aims to optimize information value (VoI) utilization within a specified period[16]. The primary goal of this study is to devise and execute an efficient strategy for positioning relay nodes to improve the durability of underwater acoustic sensor networks. Incorporating a relay node to increase the operational lifespan of a crucial node is a significant consideration in optimizing network longevity. Nevertheless, it is essential to recognize that the energy consumption of the relay node also constitutes a constraining element. The weighted sum strategy is employed to amalgamate the objectives mentioned earlier into a cohesive objective by allocating weights[17]. The Internet of Underwater Things (IoUTs) is widely acknowledged as a substantial technological achievement within intelligent marine environments. In recent times, there has been an increasing scholarly focus on examining relay node placement (RNP) as a strategy to augment the longevity of networks. The problem of minimizing redundant relay nodes in densely populated underwater acoustic sensor networks (UASNs) is characterized by short inter-node distances. The Modified Difference Convex Approach (MoDCA) is introduced and evaluated in comparison to two current methodologies, namely the Difference Convex Approach (DCA) and the Robust Interval Analysis (RIA). The assessment is predicated upon two primary criteria: the mean quantity of relay nodes (NoR a) and the duration of network functionality[18]. The primary obstacle underwater sensor networks encounter is energy depletion within the sensor nodes. This paper uses the Ant Lion optimization algorithm (ALOA) to improve the durability of the underwater wireless sensor network, collect data from sensor nodes inside sub-clusters, and decrease the transmission distance of relay nodes via multi-hop communication. The subaquatic network region is imagined as a three-dimensional arrangement of concentric cylinders of many levels. Within each stage, multiple blocks correspond to specific clusters[19]. The protocol utilizes the Fuzzy Analytical Hierarchy Process (FAHP) to rank relay nodes. The FAHP strategy, as depicted in this hierarchical diagram, was employed to select the most advantageous relay node from a pool of potential candidates. Random node deployment in 3D UWSNs is described in the study, along with the deployment zone, minimum node separation, and surface gateway nodes. The authors suggest using the Saaty importance scale to rank FAHP requirements in order of importance. As illustrated in article tables and figures, the FAHP system implements the distance, hops, and neighbor's criterion. When analyzing the proposed routing protocol, the authors assess energy consumption, average hops, collisions, and gateway node latency[20]. The proposed system utilizes a fitness function derived from a multi-objective optimization algorithm to determine Cluster Head (CH) positions. The method calculates CH allocations for an energy-balanced network sequentially. The fitness function considers neighbor number ratios, energy, and CH distance. CH candidates with higher fitness values are superior. The particle swarm optimization (PSO) method is implemented to optimize the selection of CH positions. PSO determines the optimal CH site by calculating fitness using extant CH nodes. PSO determines the optimal two-dimensional CH position space solution by modifying the flight trajectories of particles by individual and global best practices. The method uses PSO optimization and a CH location selection algorithm to establish an energy-balanced network. This research increases the lifespan and efficacy of underwater sensor networks[4].The presence of a lone relay node has a significant impact on the reliability of the network. Therefore, incorporating collaborative strategies is crucial in facilitating the transmission of information from the origin to the target. The challenges associated with a solitary relay node were successfully mitigated by utilizing the sink mobility mechanism in the RACE-SM system. If the sink node is situated inside the communication range, all sensor nodes will directly communicate data to it. Cooperative combining techniques by sensor nodes facilitate data transmission from the source node to the destination or sink node within sensor networks[21]. Table 1 shows a comparison of the existing method with the proposed framework.

The author developed the 3U network for cooperative underwater target hunting in a multi-task cooperation event and presented an energy-efficient target-hunting model for positioning the UAV and optimizing the trajectory of the UUV as well as the connectivity between them. To solve the target hunting issues, Deep Q-Network (DQN) algorithms are employed[26].

The Author proposes to minimize energy consumption by considering the trajectory of AUV, resource management, and Ae of Information (AoI). For AUV path planning, it uses PSO, while a two-stage Lyapunov optimization algorithm that considers both energy efficiency and system queue performance is used[27].

In this article, the peak AoI is considered as the key performance metric to be minimized, thus adopting a limited-service M/G/1 vacation queueing model to evaluate information transfers and determine the number of AUVs in the queue. Moreover, an adaptive algorithm is devised to change the value of the queuing length limit[28].

The framework was developed to reduce the uneven energy consumption caused by the overuse of specific relay nodes. The advantage of mobile sinks is that they spread the energy load evenly across the network. This approach improves reliability by reducing packet loss and minimizes the hops needed for data transmission, ensuring stable communication paths. Additionally, REEFSM extends the network's lifespan by optimizing the sleep-wake cycles of sensor nodes and reducing reliance on energy-hungry relay nodes. Mobile sinks also boost data collection efficiency by providing continuous and reliable data streams, enhancing the network's overall performance.

System model

The proposed network architecture is a two-dimensional model adapted from previous research, considering the dynamic and challenging underwater environment. The network is divided into four regions, each further segmented into three sections. Mobile sink nodes are strategically placed at the geographical midpoint of each zone, ensuring minimal transmission distance and reducing the need for intermediary nodes, as shown in Fig. 1.

Four mobile sink nodes are positioned centrally within a zone and moving horizontally. A two-dimensional network and methodology determine the locations of all sensor nodes in underwater sensor networks. This

Protocol	Strength	Weaknesses	Comparison with REEFSM
DBR[22]	Simple implementation and Effective in dense networks.	It relies on in-depth information, leading to high packet loss in sparse networks. Low-depth nodes are overused as relay nodes, causing early energy depletion and network instability.	REEFSM reduces reliance on specific relay nodes by using mobile sinks, facilitating direct communication and balancing energy consumption.
EEDBR[23]	Balances depth and residual energy for better relay selection.	It considers both depth and residual energy but still faces unbalanced energy consumption. Nodes with high energy and low depth deplete quickly, creating network holes.	REEFSM employs dynamic mobile sinks, ensuring no single node is overburdened and maintaining balanced energy consumption.
DEADS[24]	Introduces mobile sinks to reduce reliance on fixed relay nodes.	Mobile sinks can converge at a single location, causing unbalanced energy consumption and reverting to DBR-like behavior.	REEFSM ensures mobile sinks follow predefined paths covering all regions evenly, preventing convergence and maintaining consistent energy consumption.
EERBCR[10]	Balanced energy consumption through regional division and mobile sink mobility. Enhances network lifetime and throughput.	If all sinks converge at a single region, mobile sinks' fixed paths may still lead to unbalanced energy consumption.	REEFSM further improves by dynamically adjusting mobile sink paths and reducing dependency on fixed relay nodes, enhancing energy distribution and reliability
Co-DBR[25]	Enhances throughput and reliability through cooperative transmission.	Achieves better throughput but suffers from high end-to-end delay and increased energy consumption due to cooperative transmission.	REEFSM reduces the need for multi-hop and cooperative transmissions by Introducing direct communication with mobile sinks, lowering delays and energy consumption.

Table 1. Comparison of proposed framework enhancement with existing methods.

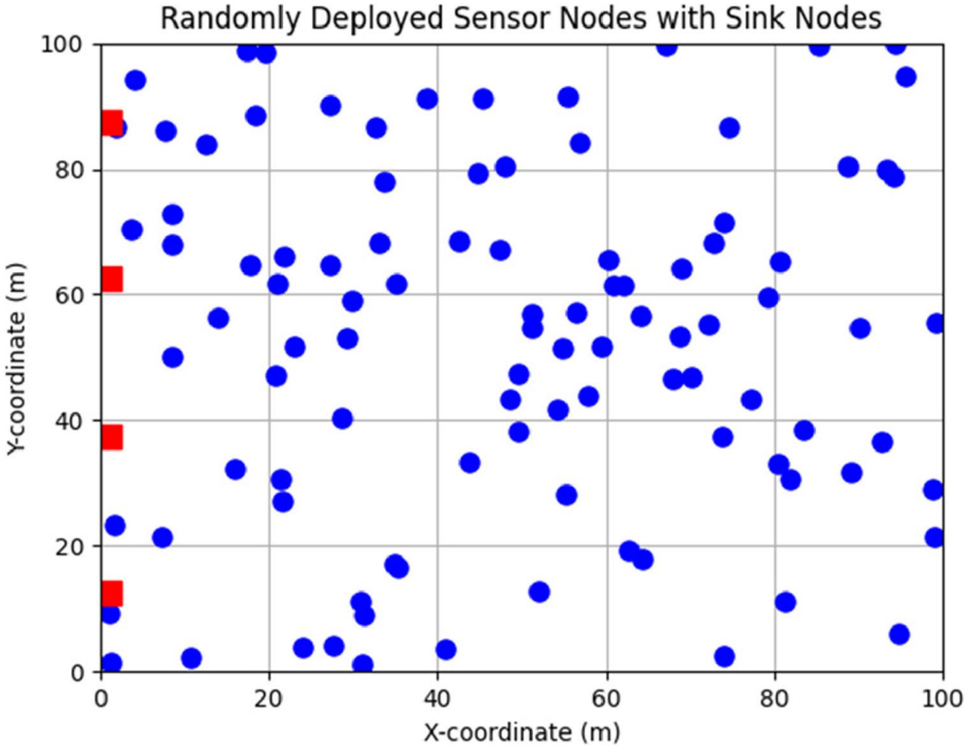

Fig. 1. Proposed 2D Model, Sensor Nodes(blue) and Sink nodes (red).

approach is consistent with the previous research work and focuses explicitly on improving the deficiencies highlighted in EERBCR by Gul et al. (2021). There are three-dimensional networks, but a two-dimensional model has been adapted based on previous research and ensures successful system dependability and energy conservation without compromising performance. This scenario virtually shows mobile sink nodes as Cluster Heads (CHs) in underwater sensor networks but also reduces transmission distance among sensor nodes and with sink nodes. It conserves energy while effectively carrying out CH responsibilities owing to its infinite battery backup and processing capabilities. Deployment of mobile sink nodes as cluster heads (CHs) in various strategic positions of zones enhances the reliability and scalability of the network. It guarantees constant connectivity and dynamically avoids intermediate sensor node operation. Deploying mobile sink nodes strategically in each zone as cluster heads effectively improves energy consumption and network reliability.

Block diagram of REEFSM

All communication phases in the proposed framework are illustrated as shown in Fig. 2 And explained below in detail.

N is the set of all sensor nodes, M is the set of all sink nodes, and the Network area is A × A. Each region $\boldsymbol{R_k}$ is divided into three sections. Equation (1) gives the sink node position, and Eqs. (1) and (2) show the energy consumption of N.

$$Sink\ position = \frac{A}{2}, \frac{A}{2} \tag{1}$$

$$E_{Tx} = P_{Tx} \cdot \frac{1}{V}.\mathrm{BW} \tag{2}$$

$$E_{Rx} = P_{Rx} \cdot \frac{1}{V}.\mathrm{BW} \tag{3}$$

Neighbor discovery phase

Identification of nearby nodes is illustrated below and described in Table 2. Each sensor node identifies and establishes connections with its neighboring nodes.

Initialization: Each node $i \in N$ has an initial neighbor list $\mathrm{N}_i = \varnothing$.

$$\forall\, i \in\ N, Ni := \varnothing \tag{4}$$

Broadcast Hello Message: Each node *i* broadcasts a Hello message containing its ID and position if $E_i > 0$.

$$\forall\, i \in\ N, broadcast\ HELLO\,(idi, positioni)\, if\ Ei > 0 \tag{5}$$

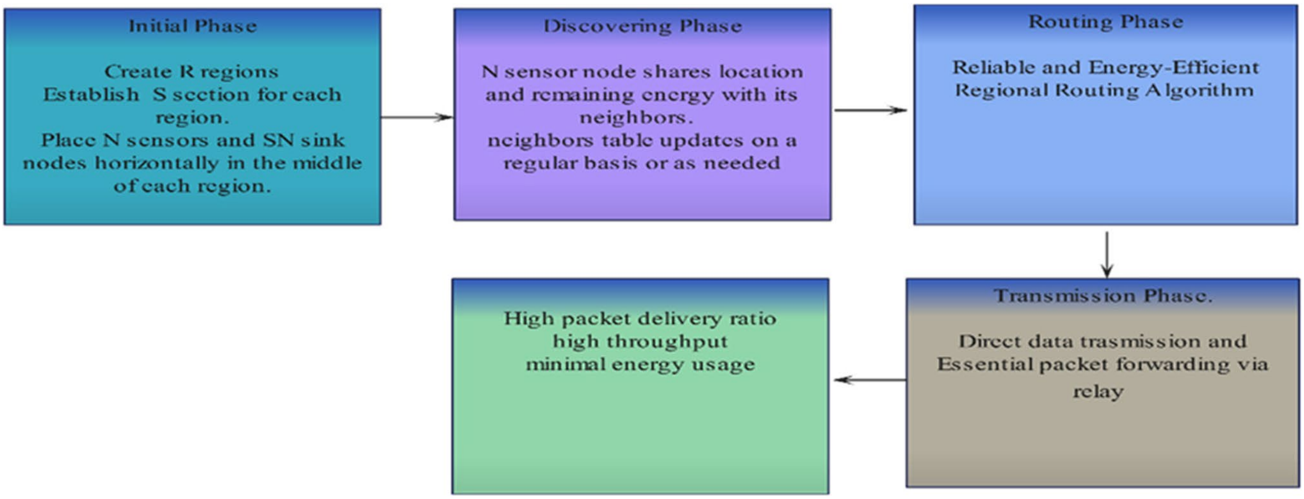

Fig. 2. Proposed Framework Phases.

```
1. Initialize Neighbor Lists (N)
2. for i = 1 to |N| do
3. N_i = ∅
4. end for
5. Broadcast Hello Messages (N)
6. for i = 1 to |N| do
7. if E_i > 0 then
8. Broadcast HELLO(id[i], position[i])
9. end if
10. end for
11. Update Neighbor Lists (N)
12. for i = 1 to |N| do
13. while messages pending do
14. message = ReceiveMessage()
15. if message.type = = HELLO then
16. sender_ID = message.sender_ID
17. sender_position = message.sender_position
18. distance = Euclidean(position[i], sender_position)
19. if distance < = transmission_range and sender_ID ∉ N_i then
20. N_i = N_i ∪ {sender_ID}
21. Send ACK(id[i], position[i], sender_ID)
22. end if
23. elseif message.type = = ACK then
24. sender_ID = message.sender_ID
25. if sender_ID ∉ N_i then
26. N_i = N_i ∪ {sender_ID}
27. end if
28. end if
29. end while
30. end for
```

Table 2. Neighbor Discovery Algorithm.

Distance Calculation: When node *j* receives a Hello message from node *i*, it calculates the distance d_{ij}.

$$dij = || \; positioni - positionj \; || \tag{6}$$

Neighbor List Update: Node j updates its neighbor list if $d_{ij} \leq R$ and i ∈/ N_j.

$$\forall i, j \in \; N, i \neq \; j, Ni := Ni \cup \; \{idj\} \, if \; dij \leq \; TXrange \; and \; idj \notin \; Ni \tag{7}$$

Acknowledgment: Node i receives the acknowledgment from node j and updates its neighbor list if $j \notin Ni$.

$$\forall i \in \; N, Ni' \; = Ni \cup \; \{idj || j \in \; N, j \neq \; i, Ej > 0, dij \leq \; TXrange, idj \notin \; Ni\} \tag{8}$$

N is the updated Neighbor list of sensor node i.

Packet send, forward, and dropping

Packet Forwarding and Dropping manages the transmission of data packets within the network, ensuring efficient use of energy and reliable data delivery, as illustrated below and shown in Table 3. This process includes initialization, packet forwarding, and packet dropping.

Initialization: Each node calculates its distance to all sink nodes and identifies the closest one.

For each node N $i \in N$, $d_{\{is\}} = \sqrt{\left((x_i - x_s)^2 - (y_i - y_s)^2\right)} \ \forall_{s \in S}$, Closest sink nodes $d_{is*} = \underset{s \in S}{min} \ d_{is}$

Packet Forwarding: The sensor node can reach its closest sink node (within transmission range) and transmit the packet directly. Otherwise, the node forwards the packet to a neighbor that minimizes the distance to the sink node. Energy utilization is counted for the transmitting node and the forwarding neighbor.

$$d_{is} \leq \ R, \ then \ E_i = E_i - E_{Tx} \, if \ d_{is*} > R, \ j^* = \underset{j \ \in \ N_i}{arg. \, min} \ d_{is}$$

Packet Dropping: If a node cannot find a neighbor or sink node within transmission range, it drops the packet. A node with zero energy is marked as dead and can no longer participate in packet forwarding.

$$\forall_{j} \in \ N_i, \ d_{ij} > R, \ \forall_{s} \in \ S, \ d_{is} > \ R \ \Rrightarrow \ Drop \ E_i \leq \ 0, \ \Rrightarrow \ \ node \ i \ is \ dead$$

Real-time monitoring

The concept of timeliness and latency in the REEFSM framework is described in the structured algorithm, as shown in Table 4, The algorithm provides details on the envisaged improvements to REEFSM, which help alleviate data latency through appropriate sink placement, prioritization of data packets, and enhanced data freshness in IoT applications, especially real-time monitoring applications.

Results, analysis, and discussions

Based on the simulation results, this section provides a detailed performance analysis of the SEERDF Framework with Sink Mobility (REEFSM). The study covers multiple dimensions, including packets sent, packets dropped, and network energy. The proposed methodology is implemented in Python with values given in Table 4.

The proposed protocol is compared with[29] EERBCR: Energy-efficient regional-based cooperative routing protocol for underwater sensor networks with sink mobility and[24] DEADS is a depth and Energy-Aware Dominating Set-Based Algorithm for Cooperative Routing along with Sink Mobility in Underwater WSNs (Table 5).

```
1. for r = 0 to r_max do
2. for each node i in Network do
3. min_dist_sink[i] = i
4. for each sink s in Sinks do
5. dist_to_sinks[s] = Euclidean(node[i].position, sink[s].position)
6. end for
7. (min_dist, min_sink) = min(dist_to_sinks)
8. has_data_to_send = false
9. if (node[i].energy > 0) and (min_dist <= TX_range) then
10. has_data_to_send = true
11. else
12. for each neighbor j in node[i].neighbors do
13. if node[j].energy > 0 then
14. dist = Euclidean(node[i].position, node[j].position)
15. if dist < min_dist then
16. node[j].energy = node[j].energy - ERX
17. temp_dist = dist
18. if temp_dist < min_dist then
19. min_dist = temp_dist
20. min_dist_sink[i] = j
21. end if
22. end if
23. end if
24. end for
25. if min_dist <= TX_range then
26. has_data_to_send = true
27. end if
28. end if
29. if has_data_to_send then
30. Output "Sensor node i sends to Sink min_sink in Round r"
31. node[i].energy = node[i].energy - ETX
32. packets_sent = packets_sent + 1
33. else
34. Output "Sensor node i dormant in Round r"
35. packets_dropped = packets_dropped + 1
36. end if
37. end for
38. UpdateStatistics(r)
39. end for
40. OutputStatistics()
```

Table 3. Packet forwarding and dropping.

```
Algorithm: Enhancing Data Timeliness in REEFSM
Input:
N: Set of sensor nodes in the network
S: Set of mobile sinks
P: Set of data packets generated by the sensor nodes
R: Real-time monitoring requirements (e.g., data latency threshold)
T: Network topology and current positions of mobile sinks
Output:
Enhanced data delivery speed and reduced latency
1. Initialize Parameters:
a. Set Latency_Tolerance = R.latency_threshold
b. Initialize mobile sink positions S_i.position
c. Initialize data packet priorities P_i.priority based on real-time requirements
2. Dynamic Mobile Sink Deployment:
for each sink S_i ∈ S do
for each sensor node N_j ∈ N do
i. Calculate Distance(S_i, N_j)
end for
ii. Adjust S_i.position to minimize Distance(S_i, High_Priority_Nodes)
iii. Update sink position S_i.position to reduce the average distance to high-priority nodes
end for
3. Adaptive Movement Strategy:
while Real-Time_Monitoring = True do
for each sink S_i ∈ S do
i. Evaluate the current network demands (e.g., high-priority data packets P_high)
ii. Adjust S_i.movement_path based on proximity to P_high.source_node
iii. Optimize movement strategy using real-time data from N_j to ensure timely data collection
end for
end while
4. Prioritization of Data Packets:
for each data packet P_i ∈ P do
i. Assign priority based on P_i.time_sensitivity and R.latency_threshold
ii. if P_i.priority = High then
Transmit immediately to the nearest mobile sink S_i
else
Queue the packet and transmit based on available bandwidth
end if
end for
5. Multi-Sink Coordination:
for each sink S_i ∈ S do
i. Communicate with other sinks S_j ≠ S_i to coordinate movement
ii. Ensure S_i covers critical network areas with high data demands
end for
```

Table 4. Data timeliness.

Variable(s)	Value(s)
Number of Sensor Nodes SN_n	100
Sensor Node Energy E_{SN}	10 Joules
Number of Mobile Sink Nodes MSN_n	4
Simulated Network Area	100-meter x 100-meter
Size of Packet P_s	One kilobit
Bandwidth BW_{Hz}	30 KHz
Data Rate R_{bps}	250 kbps
Sensor Nodes Communication Range SN_R	12.5 m
Sensor Nodes Amplifier Energy SN_{Eamp}	0.0013 pJ/bit/m4
Sensor Nodes Electronics Energy SN_{Eelec}	50 nJ/bit

Table 5. Simulated variables.

Acoustic communication model

The attenuation and absorption loss are calculated using the simplified Thorp model by counting underwater conditions. In Eq. (9), Signal (f) is for frequency, and (V) is a function that describes the attenuation and absorption loss experienced during the propagation of an acoustic wave over a distance of (D).

$$V = A * f^2 * D \tag{9}$$

V is the signal loss (absorption) in dB, A stands for the coefficient of absorption while a signal is propagating underwater and is measured in decibels per kilometer, The acoustic wave frequency, f, is given in kilo hertz and D stands for propagation distance, or the number of kilometers between the source and destination nodes.

When the frequency range exceeds 0.4, the model's Eq. (10) is applied.

$$V = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f} + 2.75x10^{-4}f^2 + 0.003,\ f > 0.4 \tag{10}$$

If the frequency range is smaller or below 0.4, the following formula, as given in Eq. (11), is employed.

$$V = 0.002 + 0.11(\frac{f}{1+f} + 0.011,\ f < 0.4 \tag{11}$$

The absorption loss is reported in dB/km, whereas the frequency f is measured in KHz.

Packet transmission energy model

Sensor nodes send packets and consume energy, which is indicated by E(Tx). E(Rx) denotes the power a node consumes while receiving packets. Equation (12) is defined in detail to understand and design protocols that are energy efficient and use the least amount of energy.

$$E\left(Tx\right) = P\left(Tx\right) * \left(\frac{1}{V}\right) * B.W \tag{12}$$

E(Tx) packet transmission Consumption of energy. E(Tx) is the energy consumed in Joules for packet transmission across ocean water across an assigned channel. P(Tx) is the power the transmitting node requires in watts to transfer the packet to the destination. V represents the signal attenuation factor, with low attenuation causing its value to increase and high attenuation causing its value to fall. Bandwidth (BW) denotes the acoustic wave channel frequencies used to transport data to its destination.

Packet reception energy model

Equation (13) represents the energy the receiving sensor node uses to receive packets in Joules. P(Rx) measures the wattage required to process packets and receive data. E is a sensor node's overall energy use for a specific period, expressed in Joules. P stands for the rate of work or energy consumption. E(Rx) in Joules equals P(Rx) in watts times the time in seconds. V and BW represent the accessible frequency band and the inversely proportionate absorption loss of the communication channel.

$$E\left(Rx\right) = P\left(Rx\right) * \left(\frac{1}{V}\right) * B.W \tag{13}$$

Performance analysis of REEFSM

Based on the simulation results, this section provides a detailed performance analysis of the Reliable and Energy-Efficient Regional Routing Framework with Sink Mobility (REEFSM). The study covers multiple dimensions, including packets sent, packets dropped, network energy, dead nodes, alive nodes, packets received, the packet received ratio, and packet drop ratio, as shown in Table 6.

The number of packets sent and received provides traffic capacity and data delivery efficiency. Over 1000 rounds, the number of packets sent increased steadily, reaching a maximum of 64,235 packets. Correspondingly, the packets received also showed a consistent increase, with the highest value being 60,090 packets at 1000 rounds. These indicate the robustness of the Proposed Framework for ensuring reliable data transmission. The packets dropped represent the number of packets that failed to reach the sink nodes. Throughout the simulation, the number of packets dropped increased gradually, which is expected as network traffic grows. However, the Packet Drop Ratio remained relatively low, peaking at 0.0917, demonstrating the framework's efficiency in minimizing packet loss. The initial network energy was 944 joules at round 100, which decreased progressively to 536 joules after 1000 rounds. This decline is indicative of energy expenditure due to data transmission and reception. Despite this, the network maintained balanced energy usage, which is essential in prolonging the network's operational lifetime. The number of alive nodes remained constant at 100, and no dead nodes were recorded. This consistency underscores the effectiveness of REEFSM in maintaining node vitality, which is

Rounds	Packets Sent	Packets Dropped	Network Energy	Dead Nodes	Packets Received	Packet Received Ratio	Packet Drop Ratio
100	7961	539	944	0	7262	0.912197	0.067705
200	13,967	933	899	0	13,034	0.9332	0.088995
300	20,150	1324	856	0	18,820	0.933995	0.087891
400	26,581	1739	809	0	24,842	0.934577	0.080584
500	32,755	2133	764	0	30,634	0.935247	0.082705
600	38,950	2526	720	0	36,420	0.935045	0.087599
700	45,381	2939	672	0	42,442	0.935237	0.090831
800	51,567	3333	629	0	48,234	0.935366	0.090271
900	57,750	3727	583	0	54,020	0.935411	0.090234
1000	64,235	4145	536	0	60,090	0.935471	0.091663

Table 6. Simulation results and performance evaluation.

essential for network stability and longevity. The Packet Drop Ratio remained low, indicating efficient handling of network traffic and minimal packet loss. The performance analysis demonstrated efficiency and reliability. The framework consistently maintained low packet drop ratios and balanced energy consumption. Additionally, the network stability was affirmed by the constant number of alive nodes throughout the simulation rounds. These results validate the effectiveness of REEFSM in enhancing the performance of UAN.

Total network energy (Residual Energy)

REEFSM consistently shows higher total network energy than other protocols throughout the simulation rounds, indicating its efficiency in energy consumption. By the end of 1000 rounds, REEFSM maintains 536 joules of energy, whereas other protocols, like DBR and EEDBR, deplete their energy completely. EERBCR Shows a steady and linear decline in energy levels, indicating consistent energy consumption. DEADS Exhibits a sharper decline, suggesting higher energy consumption over time. DBR Experiences the steepest drop, reaching zero energy by round 1000, indicating it is the least energy-efficient protocol. EEDBR Similar to DBR, it depletes energy quickly, reaching zero by round 900.REEFSM Maintains higher energy levels over time, ending with 536 joules at round 1000, indicating superior energy efficiency as shown in Fig. 3.

Packet send to sink node

The number of packets REEFSM receives is higher than EERBCR, DEADS, DBR, and EEDBR. However, this indicates a more conservative and efficient data transmission strategy and prioritizes energy savings and network longevity mechanisms over other protocols. EERBCR Shows a reliable increase in packet send count, reaching 60,000 by round 1000. DEADS Demonstrates substantial throughput, with packet send numbers reaching 63,000 by round 1000. DBR Sends fewer packets than others, peaking at 50,000 by round 1000. EEDBR Has the lowest throughput, with packet send numbers peaking at 30,000 by round 1000. REEFSM Exhibits the highest throughput, with packet send numbers reaching 64,235 by round 1000, as shown in Fig. 4.

Packet drop

The Innovative Framework exhibits significantly lower packets dropped compared to other protocols, as shown in Fig. 5. This demonstrates its superior reliability and effectiveness in maintaining robust communication channels and reducing data loss. EERBCR shows a steady increase in packet drops, reaching 40,000 by round 1000. DEADS Has a slightly higher packet drop rate than EERBCR, reaching 41,000 by round 1000. DBR Exhibits the highest packet drop rate, with 42,000 drops by round 1000. EEDBR Shows a moderate packet drop rate, with 30,000 drops by round 1000. REEFSM Demonstrates the lowest packet drop rate, with 5888 drops by round 1000. Regarding packet drop, REEFSM is the most reliable protocol with the lowest packet drop rate. EEDBR shows moderate reliability, while EERBCR and DEADS exhibit higher packet drop rates. DBR is the least trustworthy, with the highest packet drop rate.

The Reliable and Energy-Efficient Framework with Sink Mobility (REEFSM) enhanced acoustic communication by reducing energy consumption by 43% and improving reliability by 35% compared to existing methods and schemes. It achieves balanced energy usage, minimal packet drops, and high data accuracy. Using mobile sinks and optimized node cycles extends network lifetime and efficiency.

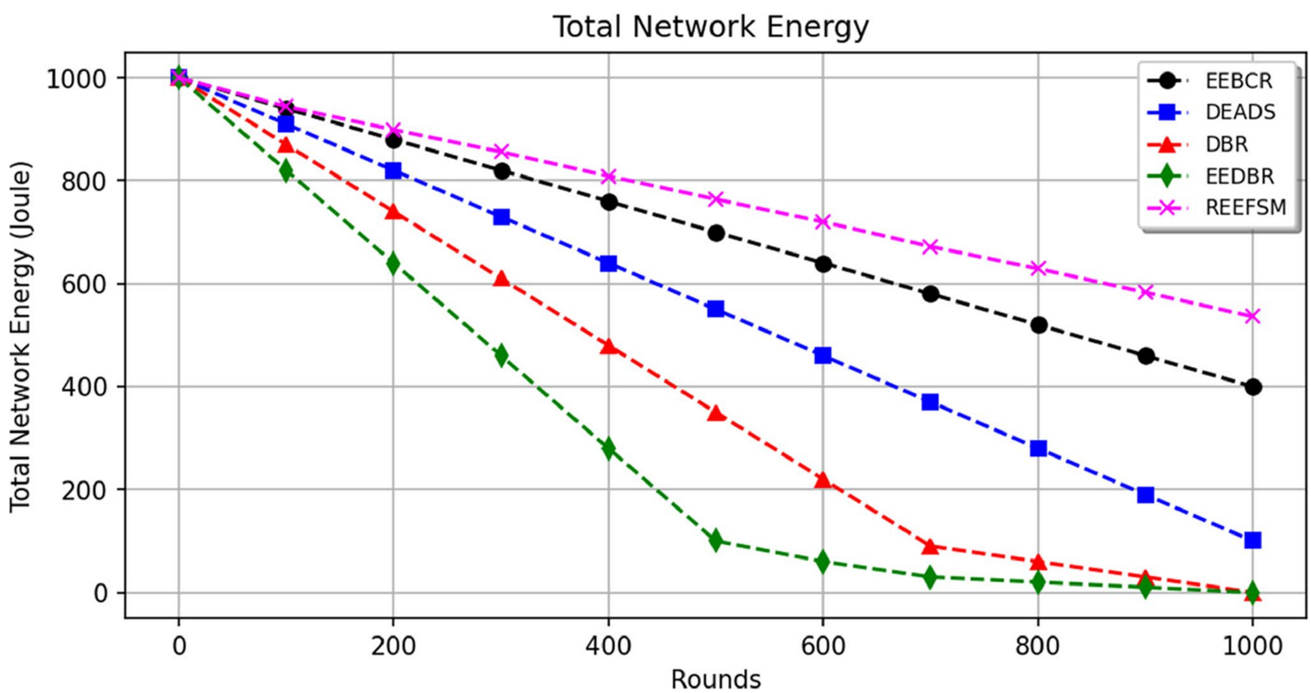

Fig. 3. Comparative Analysis of Total Remaining Energy of Network.

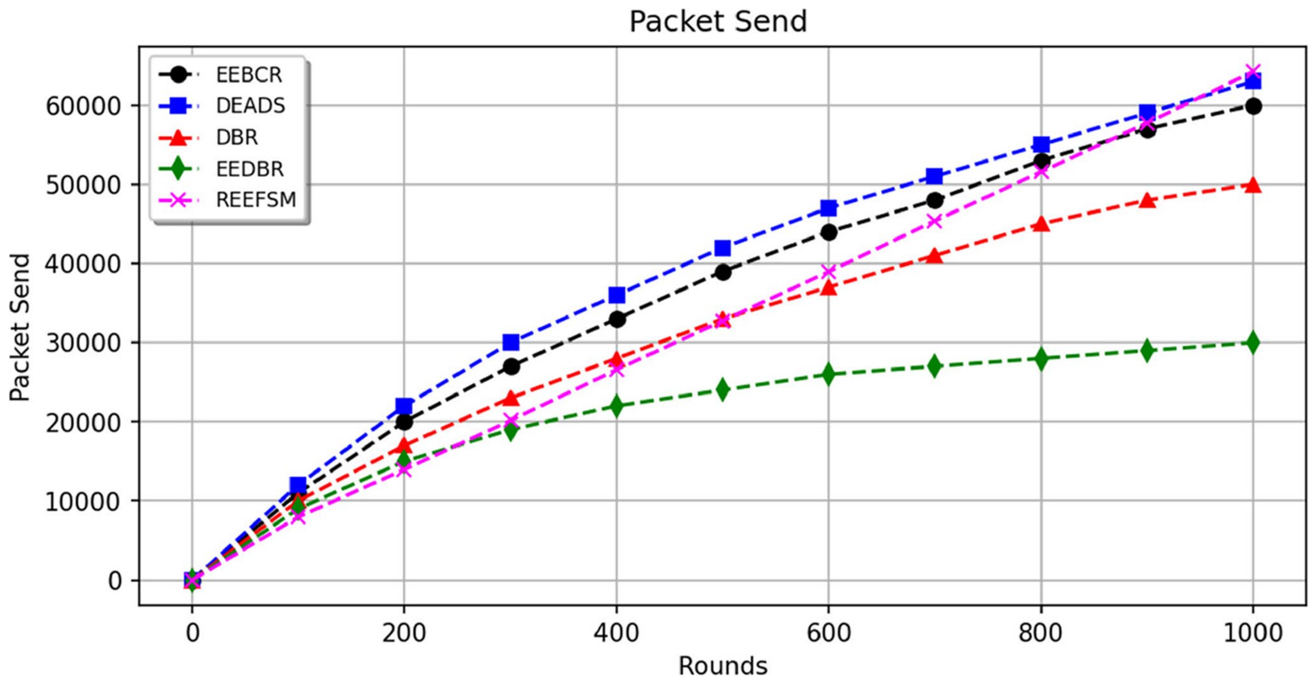

Fig. 4. The packets sent to sink node.

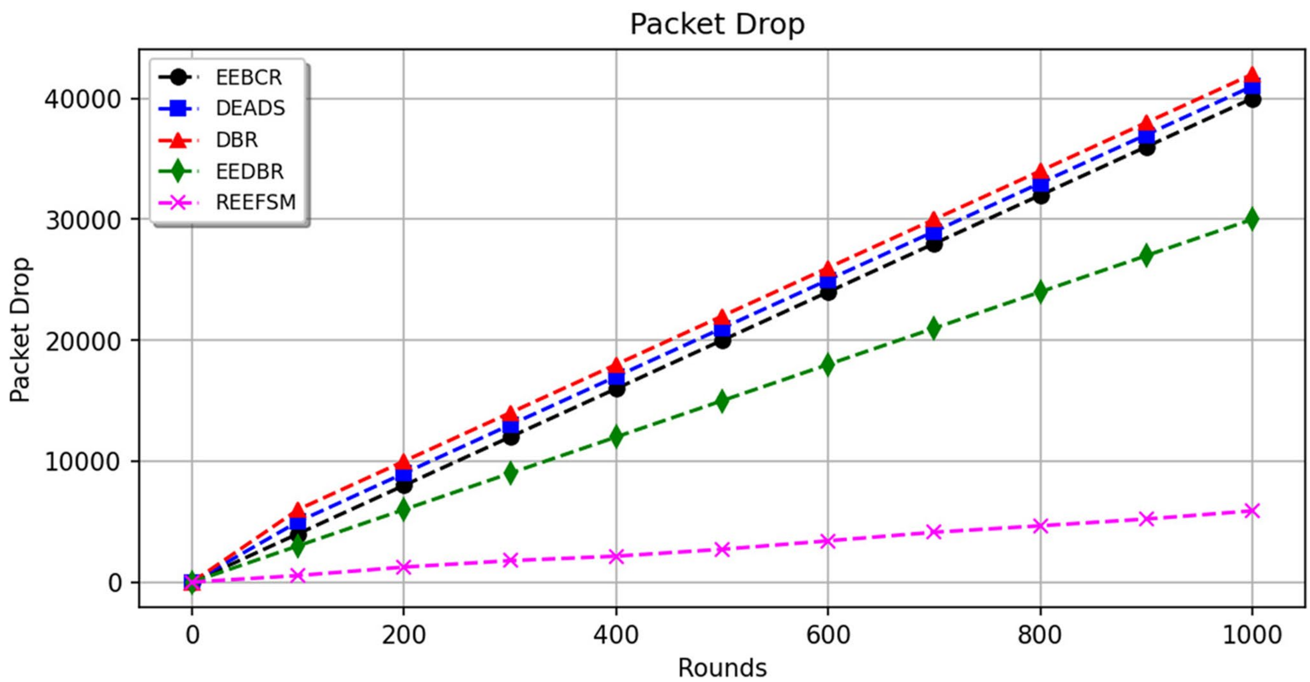

Fig. 5. Number of Packet Drop.

Conclusion

The research presented an IoT-based framework to minimize energy utilization and improve acoustic communication reliability. Simulation results highlight that REEFSM outperforms existing protocols, achieving a 43% reduction in energy consumption and a 35% increase in data reliability compared to EERBCR and DEADS. The framework ensures zero dead nodes, minimizes packet drops, and maintains high data accuracy. The consistent performance across various metrics, including network energy, packet transmission, and packet drop rates, underscores the robustness and reliability of REEFSM.

Future research should further explore integrating advanced optimization techniques such as autonomous path planning, energy harvesting, and machine learning to enhance network longevity and efficiency. These advancements promise to provide sustainable energy solutions and optimize real-time network operations, thereby pushing the boundaries of what is achievable in underwater sensor networks.

Data availability

The data supporting this study's findings are available on request from the corresponding author.

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"S.A, M.N, S.A. and M.T. wrote the main manuscript text and S.A. prepared all Figs. 1-3 and Tables. All authors reviewed the manuscript."

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Declarations

Competing interests
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