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Research Article

Optimizing data transmission system performance in underwater wireless sensor networks using the search and rescue algorithm

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Abstract

Underwater Wireless Sensor Networks (UWSNs) have emerged as essential infrastructures for applications such as disaster management, environmental monitoring, and industrial underwater inspections. These networks consist of low-cost, resource-constrained floating sensor nodes operating in deep-sea environments. UWSNs face unique challenges, including limited bandwidth, high underwater pressure, and high error probability. Furthermore, maintaining node positions and managing energy consumption due to dynamic topologies and 3D deployment complicate their operation. To address these challenges, this study proposes an energy-efficient clustering-based routing method enhanced by a chaotic search and rescue evolutionary algorithm. The approach adjusts node depth, replaces low-energy nodes with higher-energy ones, and balances energy consumption through multi-hop data transmission. The simulation, conducted in a 10 × 10 × 10 km 3D underwater environment with water currents of 1–3 m/s, involved 100–500 sensors. Each sensor had 100 J of energy, 2 km communication range, and 200-byte packets. Performance was assessed using PDR, AEC, delay, dead nodes, and throughput across varying densities and data rates. The proposed method outperformed nine existing protocols, achieving the highest PDR, lowest energy use, and best overall efficiency. Simulation results demonstrate improvements in packet delivery and reception rates, reduced energy consumption, and increased network lifespan, indicating the proposed method's reliability and effectiveness. Managers should prioritize higher sensor densities to enhance performance and energy efficiency in underwater networks. Adaptive data rate strategies can further improve throughput and reduce communication delays. These insights support cost-effective, reliable deployments for long-term underwater monitoring.

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1. Introduction

Underwater Wireless Sensor Networks (UWSNs) have emerged as a promising technology for monitoring marine ecosystems and collecting environmental data from underwater environments (Said et al., 2022). These networks consist of spatially distributed, energy-constrained sensor nodes that operate in harsh aquatic conditions such as high-water pressure, significant signal attenuation, and high transmission error probabilities. These challenges necessitate the development of optimized data transmission strategies to ensure efficient communication, reliability, and extended network lifespan (Akyildiz et al., 2005; Ayaz et al., 2011; Tavakkol et al., 2023).

One of the most critical issues in UWSNs is the selection of optimal data transmission paths, which directly impacts network performance and energy efficiency. Optimization algorithms play a vital role in solving this problem. Among the key considerations in underwater routing are depth control and energy balancing. Depth control improves link stability by dynamically positioning sensors across varying water depths, while energy balancing distributes communication loads to minimize individual node exhaustion, thereby increasing the network's operational lifespan (Xu et al., 2019; Kazemi et al., 2024).

A structure of a three-dimensional underwater wireless sensor network is shown in Fig (1). These networks are distinguished from terrestrial wireless sensor networks due to special environmental characteristics such as the absence of radio signals, signal attenuation, delay in data transmission, water pressure, variable temperatures, different depths and distances, and energy limitations. Among its most important challenges are energy conservation and increasing the lifespan of the network, choosing optimal paths for data transmission due to environmental conditions, noise interference and disturbances are due to the presence of physical barriers and the need for improved methods for managing, collecting and processing data in underwater conditions (Said et al., 2022).

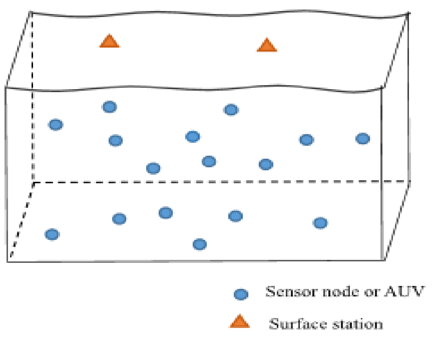

Fig 1. Network Structure of 3D Underwater Wireless Sensor (Ismaeel et al., 2021)

Multiple routing protocols have been proposed for UWSNs, including depth-based (Wahid & Kim, 2012), location-based (Luo et al., 2010), cluster-based (Zaid & Ibrahim, 2020), and energy-aware approaches (Farsi, Deris, & Razak, 2019) which are categorized in Fig (2). However, many existing solutions rely on static metrics or localized decision-making, making them less suitable for dynamic and uncertain underwater conditions. Furthermore, few existing works integrate both depth and energy optimization into a single, global strategy.

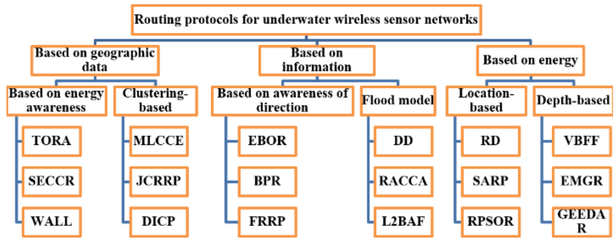

Fig 2. Different Types of Underwater Wireless Sensor Network Protocols

In the classification of energy-based routing protocols, optimal route selection in the classification of information-based routing protocols, the integrity of the data packets is considered to ensure the transmission of information to increase the success rate of data transfer, information related to the geographical location of the sensor nodes have been considered (Ismaeel et al., 2021).

This study introduces a novel, energy-aware, and depth-controlled routing protocol based on the Chaotic Search and Rescue Optimization (CSRO) algorithm. The CSRO algorithm is a recent nature-inspired optimization method that simulates the behavioral dynamics of search and rescue teams operating under chaotic conditions (Abdelminam et al., 2021). It leverages chaotic mapping and group-based movement to explore large, complex search spaces while avoiding local optima. In the proposed approach, sensor nodes with low energy are dynamically replaced by more efficient nodes, and their positions are adjusted through CSRO to maintain balanced energy consumption and communication quality in three-dimensional underwater space.

Unlike traditional algorithms such as PSO or GA, the CSRO algorithm incorporates diversity-enhancing mechanisms that enable superior performance in nonlinear environments (Ghasemi Hamedan et al., 2025). By combining chaotic dynamics, depth adjustment, and energy balancing, the proposed method provides an effective routing strategy tailored to the challenging characteristics of underwater networks. This research contributes to the literature by: (1) Integrating depth control and global energy balance into a unified routing framework, (2) Using chaotic search dynamics for improved convergence and exploration, and (3) Demonstrating superior performance in metrics such as packet delivery ratio, energy consumption, and network lifetime compared to existing techniques.

The remainder of the paper is structured as follows: Section 2 presents related work, Section 3 introduces the proposed model and algorithm, Section 4 provides simulation results and performance comparisons, and Section 5 concludes the study and outlines future directions.

2. Literature Review

Energy-based underwater routing protocols take into account the limited energy problem of underwater sensor nodes and design an energy-efficient path to reduce unbalanced node energy consumption and extend network lifespan. Data-based underwater routing protocols design a path that transmits data from the source node to the destination node more efficiently in the underwater networks. Protocols routing based on geographic information based on the spatial information of the nodes chooses the most appropriate route. The review of previous work on underwater wireless sensor network routing protocols and the comparison of latency, energy consumption, packet delivery rate and cost along with their advantages and disadvantages are illustrated in Tables 1, 2, 3 and 4, respectively.

Table (1) compares various energy-aware underwater routing protocols. Among them, HyDRO stands out with the highest packet delivery rate (98%) but suffers from extremely high energy consumption (200 units). Protocols like MARL and CIDP achieve a strong balance, with high delivery rates (~95%) and low to moderate energy usage, making them suitable for energy-sensitive applications. On the other hand, LFEER and EGBLOAD perform poorly in energy consumption despite claiming energy efficiency. Overall, protocols that integrate intelligent algorithms and localization techniques tend to show better performance across multiple metrics but may introduce computational complexity or high overhead.

Table 1.
Comparison of different energy-based underwater routing protocols and their advantages and disadvantages

Protocol	Advantages	Disadvantages	Delay	Energy Cons.	Parcel Delivery Rate	Cost	Reference
RDVHL	Accurate node localization, Fewer void zones, Reduced collisions, Enhanced throughput and efficiency	Computational overhead for reward calculation, Cluster maintenance effort	2.65	35	87	Medium	Kaur and Goyal (2024)
HSTDBR	Energy Efficiency, Improved Delay and Reliability	Initial performance Lag, increased complexity	12.48	8.8	51	Medium	Bhatti et al. (2023)
EnOR	Balance energy consumption, increase network lifespan	Fixed network structure, Empty Hole problem	2.14	21	90	Medium	Abdelimnaam et al. (2022)
WALL	Maximizing network lifespan, Minimizing end-to-end latency	Simple localization, Limited network area	3.47	36	93	Medium	Abdelimnaam et al. (2022)
MLCEE	Balance energy consumption, high communication quality	Data transfer delay, Empty Hole Problem	28	26	96	Medium	Deb et al. (2021a)
CIDP	Reliable data transmission, Mitigating the impact of interference	Cumulative transmission delays, Energy consumption	3.1	10.1	88	Low	Deb et al. (2021b)
LFEER	Energy efficient, Extend network lifespan	Communication uncertainty, Complex calculation	9.8	91	53	a lot	Dhieman (2020)
MARL	Increasing network lifespan, Using smart algorithm	High energy consumption, High package overhead	21	36	95.87	Low	Dhieman (2020)
RECRP	Multi-layer design, Energy efficient	High package overhead, Implementation complexity	1.86		88	Medium	Sivastava and Dus (2020)
EGBLOAD	Extending network lifespan, Reducing data overhead	High energy consumption, Empty cavity problem	5.4	41	55	Low	Dhieman (2020)
cDBR	Energy efficient	Data transfer delays, High cost	20	2.5	64.7	Low	Sharifi and Babamir (2020)
TORA	Increased network lifespan, Hierarchical localization	High energy consumption	4.75	33.34	78	a lot	Sharifi and Babamir (2019)
HyDRO	Low energy consumption, High parcel delivery ratio	Packet distribution, Empty Hole problem	20	200	98	a lot	Sharifi and Babamir (2019)
SEECR	Improving network performance, Using an embedded defense mechanism	High data overhead, Empty Hole problem	23	33	48	Low	Kaboli and Alqalaf (2019)
QERP	Increased network power, Energy efficient	2D network architecture, Empty hole Problem	1.3	84	91	Medium	Kaboli and Alqalaf (2019)
EBLE	Energy efficient, extend network lifespan	Data transfer delay, Packet broadcast	1.96	65	89	Medium	Singh and Dhilon (2019)
QL-EEBDG	Energy balance, Using intelligent algorithm	High power consumption, Data transfer delay	2.76	18	64	Low	Singh and Dhilon (2019)

Table (3) illustrates the Data-Based Protocols. Data-centric approaches like DVOR and FFRP demonstrate very low delay (~0.8–0.9s) and high delivery rates (96–97.3%), indicating their suitability for time-sensitive underwater communication. Protocols such as iDFR and UMDR experience higher delays (16.8–18.7s), largely due to data forwarding and network dynamics. While some protocols, such as SP-CBE2R, exhibit very low delivery performance (23%), others like EBOR provide a solid balance between delivery rate and energy consumption. The key trade-off in data-based methods is between network adaptability and overhead from dynamic routing or retransmission.

Table 2.
Comparison of different data-based underwater routing protocols and exploring their advantages and disadvantages

Protocol	Advantages	Disadvantages	Delay	Energy Cons.	Parcel Delivery Rate	Cost	Reference
DVOR	Shortest path, Effective data submission	Packeting forwarding, Waiting for data transfer	0.9	-	97.3	Medium	Zein et al. (2022)
FFRP	Data traffic balance, High packet delivery rate	Network dynamics problem	0.81	13	96	Low	Zein et al. (2022)
L2-ABF	Dynamic network structure, Reducing end-to-end latency	High data overhead, High power consumption	5	1.4	73	Medium	Dai et al. (2022)
iDFR	High parcel delivery rate, High reliability	High data overhead, Delay in data transfer	16.8	15	87	Medium	Kamboj et al. (2022)
UMDR	Increasing throughput, Reducing end-to-end latency	High data overhead, Theoretical research	18.7	-	82	Low	Al-Betar et al. (2022)
RACAA	High parcel delivery rate, Reliable route	High power consumption, Data collision	55	6.25	-	Medium	Srivastava and Das (2022)
PBR	Extending network lifespan, Extensibility	High cost, High energy consumption	0.42	9.04	78.2	Low	Said et al. (2021)
EBOR	Extending network lifespan, Efficient communication	Data transfer delay, High data overhead	8.7	18.3	93.3	a lot	Said et al. (2021)
SP-CBE2R	Shortest path, Extend network lifespan	Power consumption imbalance, Data retransmission	2.7	-	23	Medium	Said et al. (2021)
Omani	Multimodal networks, Increasing data transmission	Data transfer delays, High cost	9.5	19.3	91	a lot	Al-Betar et al. (2020)
DQELR	Increasing lifespan, Using smart algorithm	Data transfer latency, High data overhead	3.54	41.9	-	Medium	Alkoffash et al. (2021)

Geographic routing protocols show moderate to high delivery rates (e.g., SORP at 93.3%) but often struggle with latency and packet loss due to issues like the empty hole problem and scattered network topology. Protocols like EMGGR and FVBF offer low energy consumption (7.5–10 units) but with compromises in delay. RD and LTER highlight the recurring challenge of high-power consumption and packet loss, common in location-based systems. This category excels in network lifespan and energy balance but requires improved handling of sparse deployments and dynamic condition (See Table 3).

Table 3.
Comparison of different underwater routing protocols based on geographic information and investigating their advantages and disadvantages

Protocol	Advantages	Disadvantages	Delay	Energy Cons.	Parcel Delivery Rate	Cost	Reference
LTER	Increasing network lifespan, Dynamic network structure	Packet loss, High power consumption	2.9	42	-	a lot	Rehman et al. (2022)
DRADS	Maximizing grid efficiency, Lower energy consumption	Packet loss, Empty cavity problem	6	67	71	Medium	Kapileswar et al. (2022)
EMGGR	Energy efficiency, increased lifespan	High data overhead, Data transfer delay	22	10	71	Low	Basavaraju et al. (2022)
FVBF	Increased lifespan, Using an intelligent algorithm	Data transfer delay, Empty hole problem	6.4	7.5	72	Medium	Kumar et al. (2022)
SORP	High package delivery rate, Node energy reliability	Data transfer delay, Resend packet	3.16	68	93.3	Medium	Hossain et al. (2021)
RD	Increased lifespan, High package delivery rate	Data transfer delay, High power consumption	20	67	64	Low	Nguyen et al. (2021)
RSAR	Energy balance allocation, Stability of grid operations	Single link, Empty Hole problem	4.5	32	50	Medium	Eldesouky et al. (2021)
RPSOR	Reduced empty Hole information, Packaging delivery rate	High end-to-end latency in scattered networks	4.1	20	79	Medium	Luo et al. (2021)
IVBF	Energy efficient, High parcel delivery rate	Empty cavity problem	10.5	14	66	Low	Qin et al. (2021)

This table presents a range of hybrid protocols combining clustering, depth, direction, and position awareness. Protocols like GDPT and EAVARP incorporate multiple awareness factors and smart routing (e.g., greedy algorithms, dynamic grids) to enhance energy efficiency and packet delivery. However, challenges like high routing overhead, energy imbalance, and data flooding are persistent. Clustering with energy and depth-awareness, such as in CBE2R and SPRVA, offers structured and layered approaches but may suffer from fast energy drain or redundant transmissions. Overall, hybrid models demonstrate potential for balanced performance but need to address the overhead and complexity trade-offs.

Table 4.
Different types of clustering with multi-step routing protocol for underwater wireless sensor networks

Protocol	Features	Disadvantages	Classification	Categories	Reference
CBE2R	Energy efficiency, Seven layers based on depth, Node motion control	Empty zone, Fast energy consumption	Energy-based	Cluster, Depth	Shovon et al. (2022)
SPRVA	Energy efficiency, The shortest path, Multi-level priority	Lack of communication between sink nodes, Repeat packet transfer	Energy-based	Energy-Aware, Depth	Pandith et al. (2022)
UHRP	Combined flood and reactive characteristics	Waste of energy, High routing message overhead, Worst link quality	Data-driven	Silasa, Location	Subramani et al. (2022)
EAVARP	Dynamic grid, Avoiding emptiness, Energy efficiency	Single knot mobile sink	Data-driven	Energy Aware, Directional Aware	Ismail et al. (2022)
EDBF	Timely Engagement, Weight delivery strategy, Avoiding discredit	Top message overhead, Data flood crisis	Data-driven	Direction-Aware, Depth	Banothu et al. (2022)
GDPT	Greedy algorithm, Network split, Shortest path	Iterative packet transfer, QoS down	Data-driven	Energy Aware, Directional Aware, Position Aware	Vignesh et al. (2022)
RDBF	Transfer efficiency, Optimal routing	High power consumption of sink nodes, Broadcasting data packets	Based on geographic information	Position – Direction-aware	Chenthiland Jesu Jayarin (2022)
GEDAR	Depth adjustment, Empty node recovery, Underwater wireless sensor network	High message overhead, High energy consumption of nodes movement	Based on geographic information	Position – Direction-aware	Pradeep and Tapas Bapu (2022)
PER	Energy efficiency, Fuzzy logic, Decision tree	Repeat packet transfer	Energy-based	Energy Aware, Directional Aware	Mahalle et al. (2021)
CADC	Adaptation to multiple environments, Optimal global solution	High closed overhead, Undesirable channel conditions, Empty zones	Energy-based	Cluster – Directional Aware	Mahalle et al. (2021)

Across all tables, no single protocol excels in all aspects. Trade-offs between energy consumption, delay, overhead, and delivery rate are evident. Hybrid and adaptive protocols, especially those leveraging directional, depth, and position-awareness with intelligent algorithms, show the most promise for enhancing underwater sensor network performance in dynamic and energy-constrained environments.

3. Proposed Approach

In this section, the proposed multi-step data transfer method based on the algorithm of optimization of chaotic search and rescue with controlled energy balance and depth routing in ocean networks according to Fig (3) in 9 phases is presented. In which the depth, pressure, water temperature, and energy level of the sensors are collected and patterns and trends are identified and the strengths and weaknesses of the sensor network are determined accordingly. Then, using machine learning algorithms, the best routes are predicted, and based on the chaotic search and rescue optimization algorithm, the optimal path is selected based on the controlled energy balance and depth, and the data transfer is done based on several steps. In order to verify the success of the data transfer, the process of confirming the data receipt and checking for possible errors and problems during the transmission is done in the destination sensor.

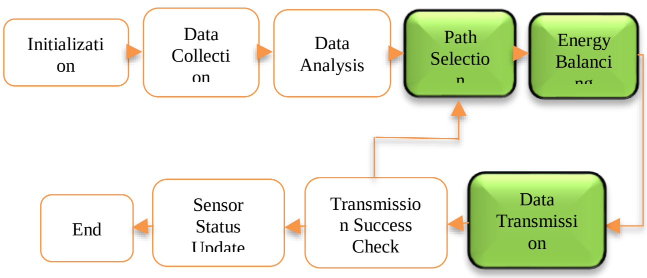

Fig 3. The general process of the proposed method

The process of implementing the multi-step data transfer steps based on the chaotic search and rescue optimization algorithm with routing based on controlled energy balance and depth in ocean networks is as follows:

- Initialization

In this phase, the basic network parameters such as the number of sensors and their position, and the initial energy level of each node are determined and data transmission goals, such as energy consumption, latency, packet delivery rate, packet loss rate, number of live nodes, and network lifespan are defined.

- Data Collection

In this phase, different types of environmental data such as temperature, pressure, and water depth are collected periodically by the sensors, as well as information about the energy level of the sensors is recorded.

- Data Analysis

In this phase, the information collected by the sensors is analyzed in order to identify the patterns and environmental conditions, and the status of each sensor is predicted and the weaknesses of the network are identified.

- Path Selection

In this phase, the best routes are predicted using machine learning algorithms and based on the chaotic search and rescue optimization algorithm, the optimal path is selected based on the controlled energy balance and depth. In this way, the sensors send a message, the information of all the adjacent nodes that are located in their radio range, such as the ID, the residual energy, and the size of the depth, and search for and select the optimal path based on the following fitness function.

$$PS = \alpha_1\left(\frac{E_r}{E_i}\right) + \alpha_2\left(1 - \frac{Dep_{ch}}{Dep}\right) + \alpha_3\left(\frac{Num_{ch}}{Tot_{ch}}\right) + \alpha_4 Li_q \quad (1)$$

where $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$, E_r is the residual energy, E_i is the initial energy, Dep_{ch} is the size of the depth, Num_{ch} is the number of sensors, Tot_{ch} is the total number of adjacent sensors and Li_q is the communication quality.

- Energy Balancing

In this phase, the energy consumption of the sensors for sending and receiving data is calculated according to the equation 2 and the optimal energy is distributed between the sensors fairly. The purpose of this is to consume the energy of the sensors in order to increase the life of the network.

$$En_{transfer} = Time_{transfer} Power_0 A(l)$$
$$En_{receive} = Time_{receive} Power_0 \qquad (2)$$

where $En_{transfer}$ is the amount of energy consumed to transmit data, $En_{receive}$ is the amount of energy consumed to receive the data, $Time_{transfer}$ is the amount of time required to send, $Time_{receive}$ is the time required to receive the data, $Power_0$is the minimum power of the sensors to receive the data, the $Power_0 A(l)$ is minimum power of the sensors to transmit the data, and the $A(l)$ is the attenuation function are calculated from the relationship $A(l) = l^k a^l$.
where the l is the distance between the sensors, k is the energy diffusion coefficient and a is the absorption coefficient, which is calculated from the equation 3:

$$a = 10^{a(f)}/_{10}$$
$$a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 * 10^{-4} f^2 + 0.003 \qquad (3)$$

- Data Transmission

In this phase, the transfer of information between the sensors or from the sensors to the base station or control center is done in a multi-step manner using the Time Division Multiple Access Plan (TDMA). In order to reduce the energy consumption, each of the sensors goes to sleep mode after the data transfer and wakes up at the time of receiving the data and continues the transmission process.

- Transmission Success Check

In this phase, in order to check the accuracy and correctness of the data transfer, the process of confirming the data receipt and checking for possible errors and problems during the transfer is done in the destination sensor, and if the transfer process is successful, the next phase will be executed, otherwise it will return to the path selection phase.

- Won Sensor Status Update

In this phase, after each data transfer, the energy and performance information of the sensors is recalculated according to the 2 and 3 equations and updated for further analysis and optimization.

- End

This is the termination phase of the data transfer process. where the system is in a state of readiness to run the new process.

4. Simulation Results and Discussion

The simulations were carried out in a three-dimensional underwater area with dimensions of 10 × 10 × 10 km, water flow velocity from 1 to 3 meters, with a number of sensors between 100 and 500, with an initial energy of 100 joules, a radio range of 2 km, and a package size of 200 bytes. The performance criteria of the proposed approach are defined as follows.

- Packet Delivery Rate (PDR)

This parameter is used to measure network performance in terms of reliability and increases as the data rate and sensor density increases. And according to the equation 4, it is calculated from the ratio of the total number of incoming packets to the total number of packets.

$$PDR = (\frac{NP_r}{N}) * 100 \qquad (4)$$

In Fig (4), the packet delivery ratio is shown with different data rates and densities. According to the figure, as the data rate increases, the transmission speed increases and there are more routes to choose the optimal route.

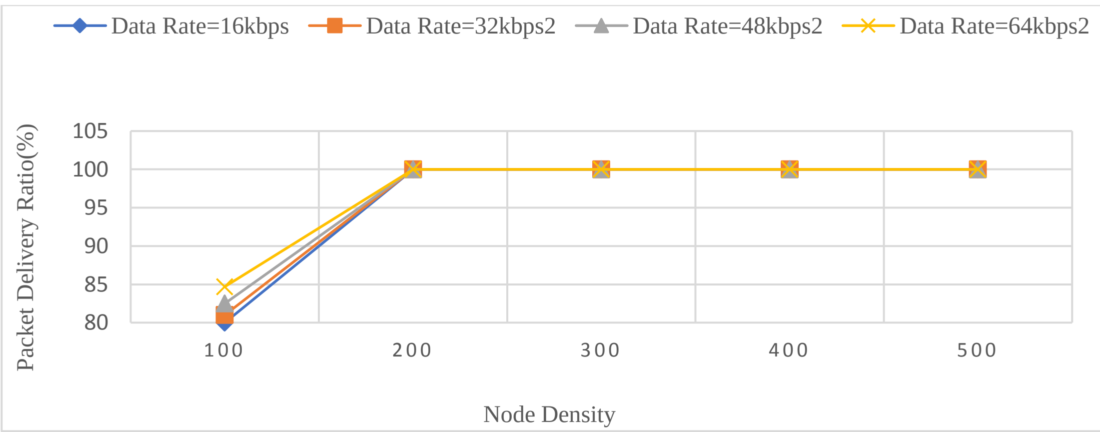

Fig 4. Packet delivery ratio vs node density for various data rates

- Average Energy Consumption

This parameter is used to measure the amount of energy consumed by sensors during the data transmission process. And it is calculated according to the equation 5.

$$AEC = \frac{\sum_{i-1}^{N}(E_{int} - E_{res})}{N} \qquad (5)$$

where E_{int} is the primary energy, E_{res} is the residual energy of the sensors and N is the total number of sensors. In Fig (5), the average energy consumption of the sensors is shown at different data rates and densities.

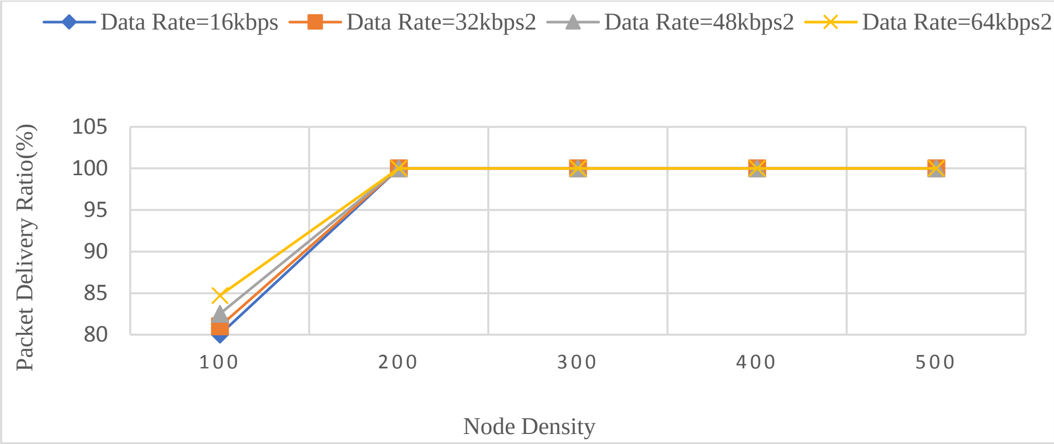

Fig 5. Average energy consumption vs node density for various data rates

- Average End to End delay

This parameter is used to measure how long it takes for data packets to be successfully transferred from origin to destination. And it is calculated from equation 6:

$$ADelay = \frac{\sum_{i-1}^{P}(T_{arr} - T_{send})}{N} \quad (6)$$

where T_{arr} is the time to receive and T_{send} is the time to send the packets. Fig (6) shows the average delay at different data rates and sensor densities. As expected, the higher the data rate, the greater the number of paths available for routing and the higher the transmission speed. And the data transfer time and network congestion decrease. As can be seen in the figure, the average delay decreases with increasing data rates and sensor densities.

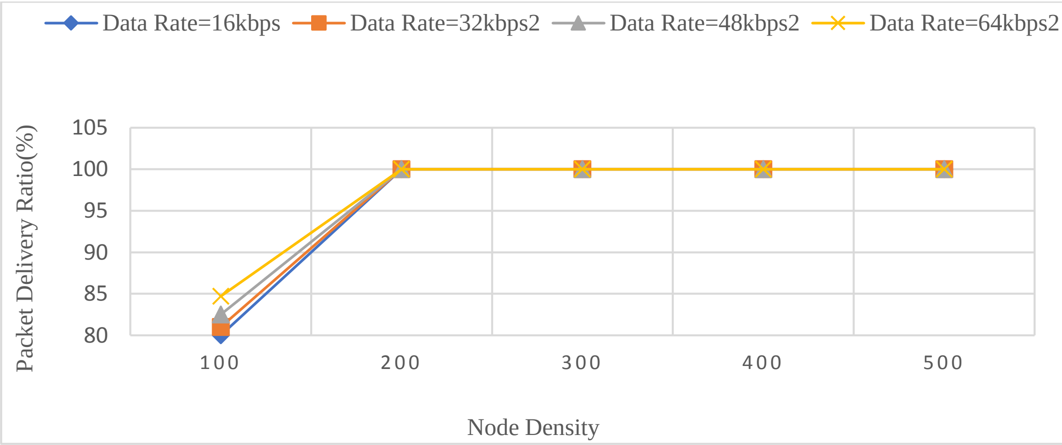

Fig. 6. End-to-end delay vs node density for various data rates

- Number of dead sensors

This parameter is used to measure the number of sensors that have run out of energy and do not play a role in data transmission. An increase in the number of dead sensors leads to the destruction of the network. To increase the efficiency of the network, this parameter must be kept to a minimum. Fig (7) shows the sum of dead sensors in different data rates and densities. The lower the density of the sensors, the greater the distance between them and the energy used to transmit data, causing the sensors to die sooner. And vice versa, the higher the density of the sensors, the distance between the sensors and their energy consumption is reduced, and the number of dead sensors is reduced

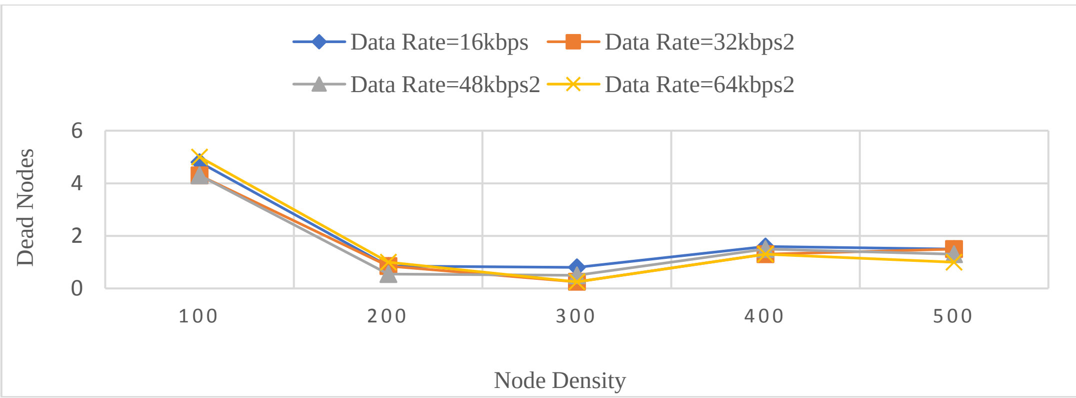

Fig 7. Dead nodes vs node density for various data rates

- Throughput

This parameter is used to measure the total number of data that have successfully reached the destination per unit of time. And it is calculated from the equation 7:

$$Throughput = \left(\frac{NP_{receive}}{T_{total}}\right) * 1000 \qquad (7)$$

In Fig (8), the network throughput is shown with different data rates and sensor density. Increasing the data rate and density increases the number of connections, speed and data transfer volume in less time and improves network throughput

Fig 8. Network throughput vs node density for various data rates

In this section, the proposed approach is compared with LEACH, EGRC, FPSSO, FCMMFO, DUCS, LEACH-ANT, EECRP, CUWSN, and EOCA algorithms based on the parameters stated above. In Fig (9), the package delivery rate of the proposed approach is shown with other methods in a different number of iterations. The analyses show that the LEACH algorithm had the lowest and the proposed approach had the highest package delivery rate.

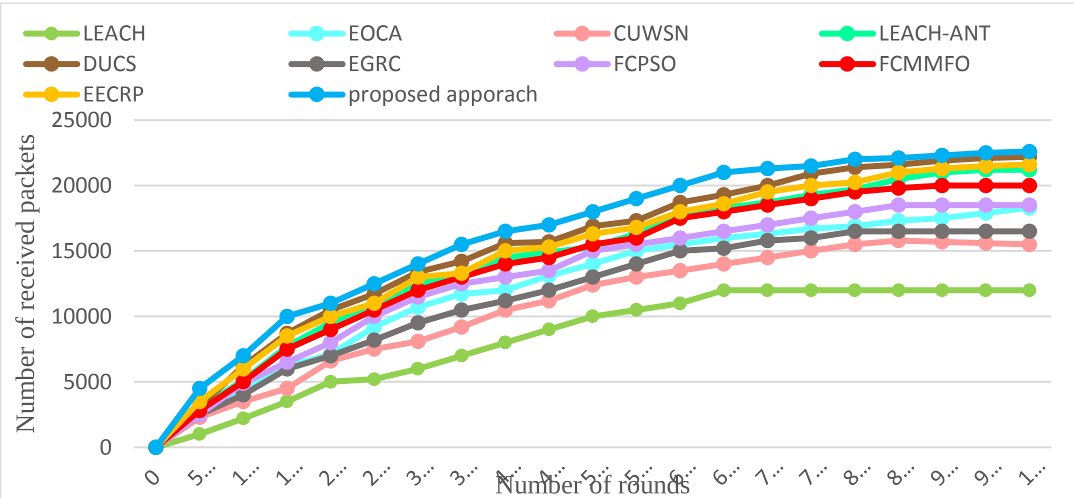

Fig 9. Comparison of the package delivery rate of the proposed approach with other methods in different replications

In Fig (10), the average energy consumption of the proposed approach is compared with the other methods. The average energy consumption increases with the increase of grid cycles for all algorithms. According to the form of the LEACH protocol, the highest value and the proposed approach shows the lowest value for energy consumption.

In Fig (11), the proposed approach with other algorithms is shown in terms of the criterion of the number of dead nodes. According to this figure, the LEACH algorithm shows the highest value and the proposed approach shows the lowest value.

Fig (12) shows the number of live nodes of the proposed approach with other methods in the number of different iterations. According to the figure of the LEACH algorithm, the worst result with the least number of remaining live nodes and the proposed approach with the highest number of remaining live nodes had a better performance.

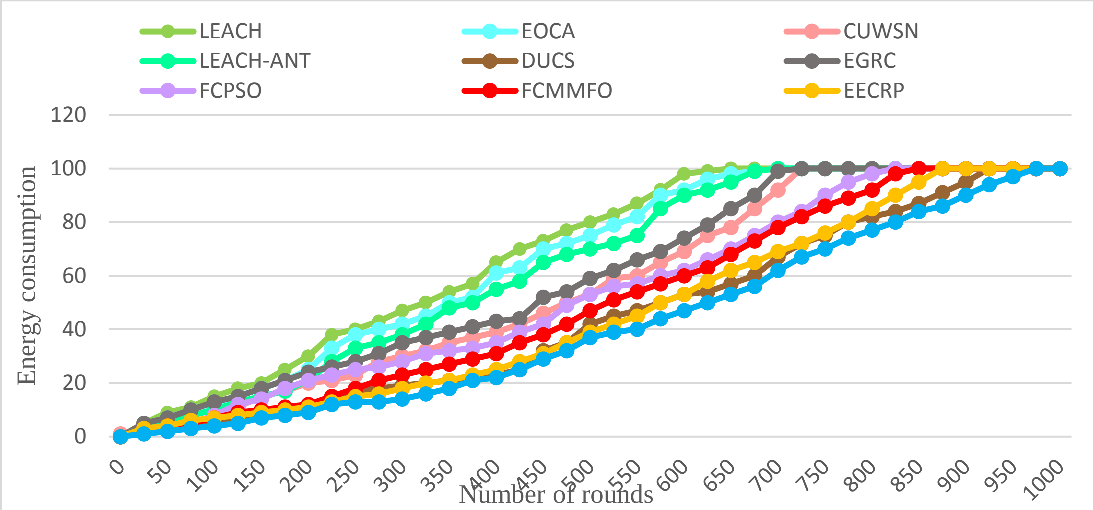

Fig 10. Comparison of the energy consumption of the proposed approach with other methods

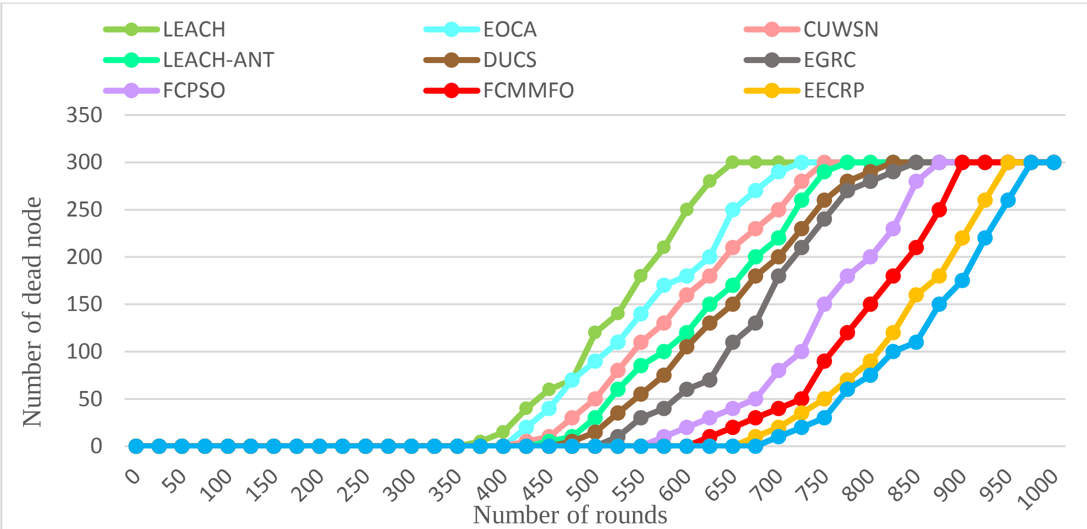

Fig 11. Comparison of the number of dead nodes of the proposed approach with other methods

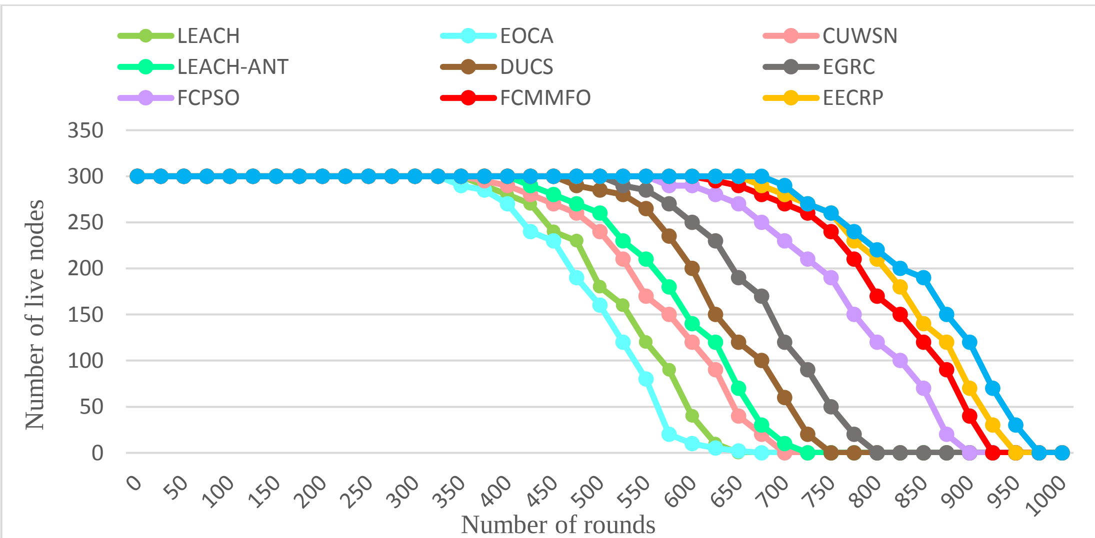

Fig 12. Comparison of the number of live nodes of the proposed approach with previous methods

The simulation was conducted in a three-dimensional underwater environment measuring 10 × 10 × 10 km, with water flow velocities ranging from 1 to 3 m/s. Sensors numbering between 100 and 500 were deployed, each with an initial energy of 100 joules, a communication range of 2 km, and a packet size of 200 bytes. Performance was evaluated based on five metrics: packet delivery rate (PDR), average energy consumption (AEC), end-to-end delay, number of dead nodes, and throughput. Results show that PDR increases with higher data rates and sensor densities due to more routing options and improved transmission efficiency. Similarly, higher densities reduced AEC, end-to-end delay, and the number of dead nodes by shortening communication distances and lowering energy usage. Throughput also improved with increased node density and data rate, reflecting better connectivity and faster data delivery. Comparative analysis against protocols such as LEACH, EGRC, FPSSO, FCMMFO, DUCS, LEACH-ANT, EECRP, CUWSN, and EOCA demonstrated that the proposed approach achieved the highest PDR, lowest energy consumption, fewest dead nodes, and the greatest number of live nodes over time, confirming its superior performance and energy efficiency in underwater sensor networks.

5. Conclusion

Underwater wireless sensor networks are faced with a number of limitations such as bandwidth, pressure, and high error probability. Also, it is difficult to update the position of the sensors due to the deployment of 3D nodes in the underwater environment and the change in the network topology due to the water flow. Therefore, in this paper, by examining different routing protocols in underwater wireless sensor networks and addressing the major challenges in them, including Reliability, energy conservation, closed and delayed delivery rates, energy-based routing protocol and multi-step depth control are proposed for underwater acoustic sensor networks with chaotic search and rescue algorithm in 9 phases. Machine learning algorithms predict the best routes and based on the optimization algorithm of chaotic search and rescue, the optimal energy-oriented path and controlled depth are selected and the data transfer is done based on several steps. In this paper, in order to verify the success of data transfer, the process of confirming data receipt and investigating possible errors and problems during transmission in the destination sensor is performed. The results of the simulations show that the proposed approach has been improved in the parameters of packet delivery rate, packet reception rate, energy consumption, and network lifespan compared to other methods, which indicates the high reliability and efficiency of the underwater wireless sensor network in the proposed approach.

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