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Research Article

Advancing S-LEACH Protocol for Real-Time Underwater Observation in Freshwater Ecosystems (Rivers/Lakes)

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ABSTRACT

This research paper aims to develop the Enhanced Sun-Based Low Energy Adaptive Clustering Hierarchy (ESBLEACH) protocol to extend the network lifetime of Underwater Wireless Sensor Networks (UWSNs) by reducing energy consumption. Solar energy (photovoltaic) is harnessed as an external power source for sensor nodes, enhancing the sustainability and longevity of UWSNs. The primary objective of the proposed approach is to optimize route selection to the terminal and the selection of cluster heads (CHs). The methodology integrates two key processes: a multi-hop routing mechanism based on the Coati Optimization Algorithm (COA) and an improved LEACH protocol. The COA approach is used to select CHs and organize clusters based on various factors such as absorption loss, spreading loss, propagation sound, ambient noise, signal-to-noise ratio, transmission loss, and propagation delay. The proposed method is implemented in MATLAB, where its performance is evaluated using metrics such as network lifespan and total energy consumption. Its effectiveness is then compared against established protocols, including the conventional LEACH protocol and the LEACH protocol enhanced with Particle Swarm Optimization (PSO).

Keywords: Network lifetime, Cluster head, Coati optimization algorithm, Absorption loss, UWSN

INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) consist of a large number of underwater wireless sensor nodes that are distributed throughout the marine environment. These networks facilitate data collection, navigation, resource exploration, activity monitoring, and disaster prediction. However, as UWSN technology advances, energy efficiency becomes a critical concern due to the limited battery capacity and the challenges associated with battery replacement or recharging. Previous research suggests that energy efficiency in UWSNs can be improved through routing and clustering techniques. Metaheuristic approaches are commonly employed to address NP-hard optimization problems such as clustering and routing[1]. Due to their wide range of applications, including environmental monitoring, disaster prevention, secondary navigation, and more, UWSNs are gaining increasing popularity in both industry and academia.

The domain of UWSNs has recently attracted significant interest due to its advanced and unique methodologies in underwater surveillance, ocean monitoring, marine security, and underwater detection systems. A typical UWSN comprises a mobile sink, ground stations, and sensor nodes[2]. These sensor nodes are distributed throughout the water column, primarily from the surface to the seabed. Data collected by the sensors is transmitted to the mobile sink, which then relays it to the base station. Sensors continuously monitor shallow water environments, recording parameters such as temperature and transmitting the collected data to a sink node via single or multi-hop communication[3]. Previous studies have introduced various communication protocols for underwater data transmission using acoustic energy, but these protocols face challenges such as high failure rates, propagation delays, and other technical limitations.

The primary objective of routing protocols in UWSNs is to enhance network longevity. Since replacing or recharging sensor node batteries is challenging, energy consumption must be efficiently managed[4]. Two primary methods exist for data transmission: non-cooperative communication, where data is sent directly from the source to the destination, and cooperative communication, where relay nodes assist in data transfer. Cooperative communication is particularly beneficial in reducing data transmission errors and ensuring reliable connectivity between nodes. It transmits data through multiple paths, thereby increasing the probability of successful data reception[5]. Routing protocols in UWSNs are designed to optimize energy consumption and improve network longevity.

OBJECTIVES

The domain of Underwater Wireless Sensor Networks (UWSNs) has recently attracted significant interest due to innovative techniques in undersea surveillance, ocean monitoring[6], marine surveillance, and the development of services for detecting underwater benchmarks. A UWSN typically consists of a mobile sink, ground stations, and sensor nodes[7]. These sensor nodes are distributed throughout the water column, extending from the surface to the seabed. Data collected by the sensor nodes is transmitted to the mobile sink, which then forwards it to the base station. The sensors monitor the shallow water environment[8], such as temperature, and transmit the collected information to a sink node via one or more hops. Previous research has introduced a range of directive protocols for underwater data transmission using acoustic energy[9]. However, these protocols often face challenges, including high failure rates, propagation delays, and other issues[10]. The primary goal of these protocols has been to extend the network's lifespan, as energy-efficient routing is crucial given the difficulty of replacing or recharging sensor node batteries in underwater environments[11].

This section reviews existing research on routing-based approaches aimed at extending the lifespan of UWSNs. To address these challenges, [11] proposed the Directional Selective Power Routing Protocol (DSPR). This protocol determines the optimal route to the surface sink using sender depth data and angle of arrival. Additionally, DSPR employs selective power regulation to ensure connectivity while minimizing energy consumption and improving the delivery ratio. Simulation studies have demonstrated that DSPR outperforms conventional protocols in terms of energy efficiency and delivery success.

introduced the Energy-Efficient protocol for UWSNs (EE-UWSNs) [12], a novel MAC/routing protocol designed to conserve sensor energy and extend network lifespan. EE-UWSNs operate based on five key principles: limited power allocation, multi-hop transmission, transmission range restriction, inactive mode utilization, and balanced energy consumption. [13] developed the Cooperative Energy-Efficient Routing (CEER) protocol, which enhances network longevity and reliability. This protocol employs sink mobility to mitigate the hotspot issue, reducing energy consumption. The deployment area is divided into sections, with sink nodes strategically placed in each section. The cooperative approach further enhances network reliability by ensuring efficient data processing at sink nodes. [14] introduced an energy-efficient packet forwarding strategy using fuzzy logic to optimize UWSN energy consumption.

The proposed protocol considers three key metrics: 3D UWSN length (or Received Signal Strength Indicator, RSSI), the number of clusters within a node's transmission range, and the number of hops required to reach the gateway node. Adaptive transmission times and varying node densities were employed to evaluate the impact on energy consumption and hop count. [15] presented an energy-efficient approach for UWSNs based on the LEACH clustering algorithm. Simulation results indicate that the proposed clustering strategy for UWSNs is comparable to the LEACH method used in terrestrial WSNs. The approach enhances network lifespan and reduces overall energy consumption, ensuring a stable number of active nodes throughout network operation.

METHODS

In this section, we review several works from the literature focused on routing-based approaches to enhance the lifetime of Underwater Wireless Sensor Networks (UWSNs). To address many of these challenges, Manal Al-Bzoor et al. [12] proposed the Directional Selective Power Routing Protocol (DSPR). This protocol calculates the optimal route to the surface sink using the angle of arrival and sender depth information. Additionally, DSPR employs selective power regulation to improve delivery ratios, ensure network connectivity, and reduce energy consumption. Extensive simulations have been conducted to validate the performance of the DSPR protocol. The results demonstrate that DSPR outperforms two variants of the static directional routing (DR) protocol and the variable power depth-based routing (VDBR) protocol in terms of energy consumption and delivery ratio[13]. Another notable contribution is the Energy-Efficient protocol for UWSNs (EE-UWSNs) developed by [14]. This novel MAC/routing protocol aims to conserve sensor energy and extend the lifespan of UWSNs by following five guiding principles: utilizing finite power resources, employing multi-hop transmission, restricting transmission range, incorporating inactivation modes, and balancing energy consumption[15].

[16]introduced the Cooperative Energy-Efficient Routing (CEER) protocol, which seeks to extend network lifetime and enhance network reliability. The protocol addresses the hotspot problem through a sink mobility scheme that reduces energy consumption. The deployment area is divided into multiple sections, with sink nodes placed in each section. The sink nodes collect and process data from sensor nodes, and a cooperative approach is employed to ensure network reliability.[17] proposed an energy-efficient packet forwarding scheme using fuzzy logic to improve the energy efficiency of UWSNs. This protocol utilizes three metrics: distance (or its equivalent, received signal strength indicator, RSSI) in a 3D UWSN architecture, the number of clusters within a node's transmission range, and the hop count to the gateway node. The system's performance is evaluated under different transmission ranges and node densities to assess the impact on energy consumption and hop count.

[18] presented an energy-saving methodology based on the LEACH algorithm for UWSNs. The proposed methodology adapts LEACH, originally designed for terrestrial wireless sensor networks, to UWSNs. Simulation results indicate that the proposed cluster formation strategy for UWSNs is effective in increasing network lifespan and reducing overall energy consumption, similar to the LEACH protocol. The number of active nodes and the network lifetime remains stable in each round.

This research aims to introduce an Enhanced Solar-Based Low Energy Adaptive Clustering Hierarchy (ESBLEACH) protocol designed to reduce energy consumption and extend the network lifetime in UWSNs. The proposed technique also focuses on enhancing energy efficiency. It integrates a Coati Optimization Algorithm (COA)-based LEACH protocol for efficient cluster formation. The LEACH protocol is employed as the routing approach, while COA is used for selecting cluster heads (CHs). The approach considers multiple objective functions, including absorption loss, spreading loss, propagation sound, ambient noise, signal-to-noise ratio, transmission loss, and propagation delay. The architecture of UWSNs is illustrated in Figure. 1.

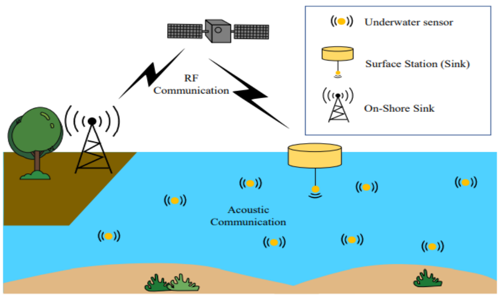

Figure. 1. System Architecture

Solar energy is employed for energy harvesting to provide an external power source for sensor nodes in this system. The lifespan of Underwater Wireless Sensor Networks (UWSNs) is extended through this solar-powered external energy system. The primary objective of the proposed strategy is to select cluster heads (CHs) and determine the optimal routing paths to a terminal. This approach integrates two main procedures: the COA-based LEACH protocol for multi-hop routing. The COA technique is used to select CHs and organize clusters based on multiple factors, including absorption loss, spreading loss, propagation sound, ambient noise, signal-to-noise ratio, transmission loss, and propagation delay[19]. Below is a detailed explanation of the proposed strategy.

Multi-Objective Function

Efficient transmission is a crucial factor in UWSNs for enabling reliable communication. Several parameters influence transmission in UWSNs, including absorption loss, spreading loss, propagation sound, ambient noise, signal-to-noise ratio, transmission loss, and propagation delay[20]. To ensure efficient transmission, a multi-objective function is formulated as follows:

where: $MOF = Min(AL + SL + AN + SNR + TL + PD)$ (1)

- PD: Propagation delay
- TL: Transmission loss
- SNR: Signal-to-noise ratio
- AN: Ambient noise
- SL: Spreading loss
- AL: Absorption loss

Absorption Loss

Absorption loss refers to energy dissipation as heat due to ionic relaxation and viscous friction occurring when a sound wave propagates underwater[21]. It is given by:

where: $AL = \alpha \times R \times 10^{-3}$ (2)

- R is the transmission range (m)
- α is the attenuation coefficient (dB/km)

Spreading Loss

Spreading loss is a type of transmission loss that occurs as sound travels from the source to the destination[22]. It is calculated as:

where: $SL(R) = K \times 10\log(R)$ (3)

- K is the spreading factor

Ambient Noise

Ambient noise in UWSNs is the cumulative effect of thermal, wave, shipping, and turbulence noise:

- **Thermal noise:** $10\ logn_{th}(F) = -15 + 20\log(F)$ (4)
- **Wave noise:** $10logn_w(F) = 50 + 7.5\sqrt{w} + 20\log(F) - 40\log(F + 0.4)$ (5)
- **Shipping noise:** $10logn_s(F) = 40 + 20(s - 0.5) + 26\log(F)$ (6)
- **Turbulence noise:** $10\ logn_t(F) = -17 + 30\log(F)$ (7)

Signal-to-Noise Ratio (SNR)

SNR is the ratio of signal intensity to background noise and is computed as:

where: $SNR(L, F) = \frac{P(L)}{(n(F)a(L,F)b(L))}$ (8)

- $a(L, F)$ is the attenuation level
- $n(F)$ is the noise level

Transmission Loss

Transmission loss is the reduction in sound strength as it travels from the transmitting node to the receiving node[23]. It is given by:

where: $TL = SS + \alpha \times 10^{-3}$ (9)

$SS = 20 \log R$ (10)

- SS is the spherical spreading factor
- α is the attenuation coefficient

Propagation Delay

Propagation delay is the time taken for a signal to travel from the transmitter to the receiver and is calculated as:

where: $T_P = \frac{D}{C}$ (11)

- C is the distance between nodes
- D is the speed of sound in water (m/s)

Enhanced LEACH Protocol

This paper proposes a novel approach that integrates the COA with the LEACH routing protocol. LEACH protocol involves selecting cluster heads based on various factors, and COA enhances this selection process[24]. The COA technique determines the most efficient CHs based on a multi-objective function. CHs are selected considering Euclidean distance and node weighting, which is determined by the energy level of sensor nodes. A CH is only retained if it meets the weightage parameter threshold[25].

The energy required for transmission in UWSNs is computed as:

where: $e_{ch} = N\left(K * \left(e_{elec} + e_{fs} * D^2\right)\right) \quad for\ D < 0$ (12)

$e_{ch} = N\left(K * \left(e_{elec} + e_{amp} * D^2\right)\right) \quad for\ D \geq 0$ (13)

- D is the transmission distance to the sink node
- e_{amp} is the amplification factor for free-space propagation
- e_{fs} is the free-space propagation variable
- e_{elec} is the energy needed for data transmission and reception
- K is the number of message bits
- N is the number of managed nodes in the cluster

CH selection considers Euclidean distance, calculated as:

where: $D\{Y_I, H_C\} = (Y_I - H_C)^2$ (14)

- D is the Euclidean distance function

Coati Optimization Algorithm (COA)

The COA is employed for optimal CH selection. Inspired by the behaviour of coatis (coatimundis), this algorithm mimics their hunting and survival strategies. Each coati's position in the search space is determined using:

where: $$x_I = x_{I,J} = LB_J + R.(UB_J - LB_J), I = 1,2,..,n:\ J = 1,2,..,M \quad (15)$$

- UB_J and LB_J are the upper and lower bounds of the decision variables
- R is a random number in the range [0,1]
- M is the number of decision parameters
- n is the number of coatis
- $x_{I,J}$ represents decision parameter values

The algorithm updates positions based on the coatis' aggressive hunting of iguanas and their evasion tactics: This optimization strategy enhances CH selection, improving UWSN performance by balancing energy consumption and transmission efficiency[26].

Outcome Validation

This section details the validation of the proposed method through comparative analysis and performance evaluation. The proposed approach is designed to enhance energy efficiency in UWSNs by considering various parameters. It has been implemented in MATLAB (version 2018a) on a system equipped with an Intel Core i5 processor (5th generation), 8GB RAM. The implementation variables for this approach are presented in Table 1.

Table. 1. Simulation variables

Sr. No	Description	Parameters
1	Number of nodes	50
2	Number of rounds	1000
3	Net size	300
4	Eo	0.5
5	Number of iterations	500

The effectiveness of the proposed technique is validated by considering the number of active nodes. It is compared with traditional approaches such as LEACH-PSO and LEACH. The count of live nodes is assessed based on the number of rounds. After 200 rounds, the proposed method retains 70 live nodes. Similarly, at 200 and 300 rounds, it maintains 65 and 60 live nodes, respectively. In contrast, the conventional LEACH protocol techniques have 50 and 48 live nodes after 100 rounds. Compared to these conventional methods, the proposed approach achieves a higher count of live nodes. Additionally, validation is performed by evaluating the number of dead nodes as shown in figure 2. The proposed method is compared with LEACH-PSO and LEACH, using the number of rounds to assess the count of dead nodes. After 1000 rounds, the proposed method records 25 dead nodes, while at 800 and 900 rounds, it has 22 and 24 dead nodes, respectively. In comparison, the conventional LEACH protocol techniques report 35 and 37 dead nodes after 1000 rounds. Thus, the proposed approach demonstrates a lower count of dead nodes compared to conventional techniques.

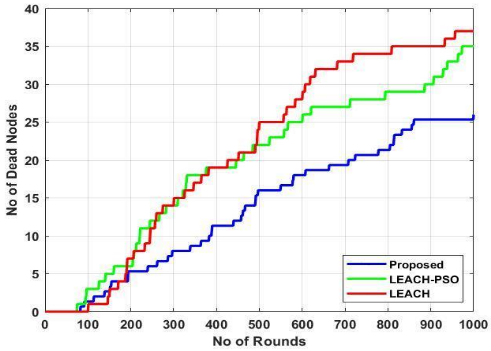

Figure. 2. Number of dead nodes

The effectiveness of the proposed approach is validated by analyzing the average residual energy. It is compared with established methods such as LEACH-PSO and LEACH. The validation of average residual energy is conducted based on the number of rounds. After 100 rounds, the proposed method achieves an average residual energy of 38. Similarly, for 200 and 300 rounds, the proposed method records values of 15 and 14, respectively. In contrast, conventional LEACH protocol techniques demonstrate average residual energy values of 24 and 25 after 100 rounds. Compared to these conventional techniques, the proposed approach exhibits a higher average residual energy as shown in figure 3. Furthermore, the number of packets sent is used to assess the effectiveness of the proposed methodology. It is compared with established methods such as LEACH-PSO and LEACH, with validation based on the number of rounds. After 200 rounds, the proposed method records 0.5×10^4 packets sent in UWSNs. Similarly, for 300 and 400 rounds, the number of packets sent increases to 0.7×10^4 and 0.6×10^4, respectively. In comparison, conventional LEACH protocol techniques record 0.3×10^4 and 0.2×10^4 packets sent after 200 rounds. The results indicate that the proposed approach achieves a higher number of transmitted packets than conventional techniques.

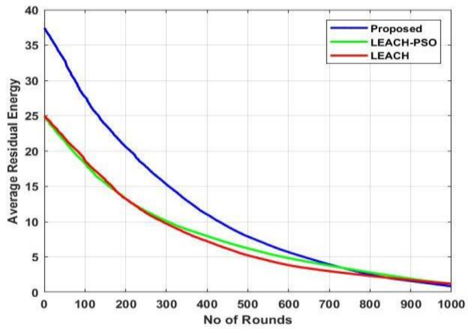

Figure. 3. Average residual energy

Additionally, throughput is considered as a validation metric for the proposed approach, using the number of rounds as a reference. After 200 rounds, the proposed method achieves a throughput of 1.5×10^4 in UWSNs. Similarly, for 300 and 400 rounds, the throughput increases to 2×10^4 and 2.6×10^4, respectively. In contrast, conventional LEACH protocol techniques achieve throughput values of 0.4×10^4 and 0.3×10^4 after 100 rounds. When compared with these conventional techniques, the proposed approach demonstrates superior throughput performance shown in figure 4.

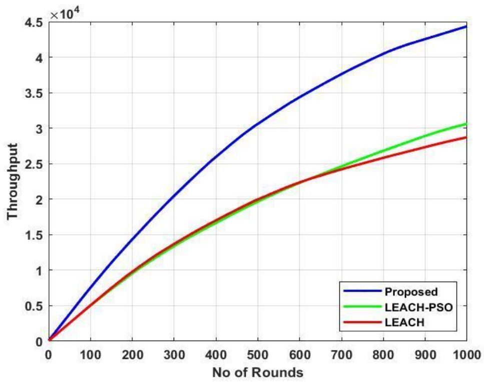

Figure. 4. Throughput

CONCLUSION

To enhance the network lifetime of UWSNs, this research introduces ESBLEACH, designed to reduce energy consumption. Solar energy is employed for energy harvesting, supplementing sensor nodes with external power sources. This solar-based power scheme is implemented to extend the network lifespan of UWSNs. The primary goal of the proposed approach is to efficiently select cluster heads (CHs) and establish optimal routes to a destination. It integrates two key procedures: a COA-based LEACH protocol for multi-hop routing. The COA method selects CHs and organizes clusters based on various factors, including absorption loss, spreading loss, propagation sound, ambient noise, signal-to-noise ratio, transmission loss, and propagation delay. Performance metrics such as network lifespan and total energy consumption are used to assess the effectiveness of the proposed technique, which has been implemented in MATLAB. The method is compared against traditional approaches, including the LEACH protocol and LEACH with PSO, to evaluate its efficiency. Additionally, the proposed method is compared against conventional techniques, including the LEACH protocol and the LEACH protocol enhanced with Particle Swarm Optimization (PSO).

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