Paper

Sensor Hop-based Energy Efficient Networking Approach for Routing in Underwater Acoustic Communication

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Abstract—Underwater Wireless Sensor Networks are deployed to explore the world under the water, measure different parameters and communicate the data to the surface, in the widespread applications. The main operating technology of these networks is the acoustic communication. The communication among the sensors and finally to the surface station requires a routing protocol. The sensors being battery limited and unfeasible to be replaced under the water requires an energy efficient routing protocol. Clustering imparted in routing is an energy saving technique in sensor networks. The routing may involve single or multi hop communication in the sensor networks. The paper gives a comparative study of the benchmark protocol multi-hop LEACH with the proposed Sensor Hop-based Energy Efficient Networking Approach (SHEENA) for the shallow as well as deep water in three dimensional Underwater Wireless Sensor Networks. The network energy model for the Underwater Wireless Sensor Networks is based among the different acoustic channel characteristics. The proposed approach is found to give better response.

Keywords—attenuation, clustering, multi-hop routing, signal to noise ratio, transmission loss.

1. Introduction

A category of Wireless Sensor Networks (WSN), known as Underwater Wireless Sensor Network (UWSN), comprises of the sensors or the nodes which are wirelessly connected to each other, deployed under the sea or ocean or any water body. Underwater wireless sensor nodes are tiny devices, equipped with sensing units, capable of detecting data from the external environment and communicating this data to the surface sink or the Base Station (BS). Each sensor node transmits and receives data packets. Underwater acoustic communication is the technique of sending and receiving message below water [1].

Figure 1 shows the basic view of UWSN environment. The deployment of nodes may be two-dimensional (2D) or three-dimensional (3D) in UWSN. The 2D UWSN involves the nodes to be anchored to the bottom of the ocean. The arrangement of nodes is in the form of clusters or groups. Each cluster has a cluster head, which acts as a gateway or relay for transmitting the collected data to the surface station after processing it. In 3D UWSN, the nodes are placed at the different depth levels of the water. The nodes either may be hanged from the surface buoy floating on the top of the water surface or may be deployed with the help of anchor drawn sensor devices placed at the bottom [2].

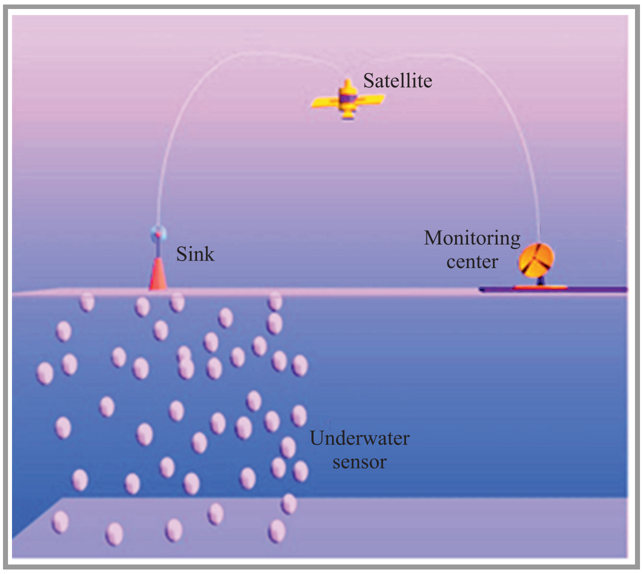

Fig. 1. Underwater Wireless Sensor Network concept.

UWSNs are being widely utilized in different areas of marine research including environmental monitoring, disaster prevention, micro-habitat monitoring, oil and gas exploration, sensing of chemical contamination and biological phenomena, distributed tactical surveillance, seismic studies, etc. [1], [3]. The topic is still in the beginning stage compared to its terrestrial counterpart due to the involvement of high cost and physical challenges.

To understand the basics of UWSNs, we can utilize many design principles and tools used in terrestrial sensor networks. But they are characteristically different in some fundamental points. Most importantly, radio is unsuitable for underwater sensors due to their limited propagation ability [4]. This is when acoustic signals are being utilized for underwater communication, which again poses many challenges like path loss, noise, multi-path, Doppler spread, and high and variable propagation delay [5]. Hence, the requirement for specially designed routing protocols for UWSNs becomes inevitable. Thus, intense research is being undertaken for designing efficient protocols considering the unique characteristics of underwater communication networks.

2. Routing in Underwater Wireless Sensor Networks

WSNs are formed by miniature devices interacting over radio wireless links without using a determined networked infrastructure. Because of restricted transmission range, communication between any two devices requires associating intermediate forwarding network nodes [6].

Routing is a process of determining a path between source and destination upon request of data transmission. Designing an optimum routing protocol is the basic issue involved with any network. The sensor networks generally depend on gateway nodes to handle huge amounts of data over extended ranges. The field of underwater sensor networking and routing protocols are in the incipient stage of research. Earth comprising of majority of water, gives a lot of opportunity to explore this field. Sensor networks being limited in battery power, allows finding method to support the development of energy efficient protocols in wireless sensor network [7].

Grouping sensor nodes into clusters has been widely adopted by researchers to assure the scalability and achieve high-energy efficiency to prolong network lifetime in WSN environments. The hierarchical cluster-based organization of the sensor nodes allow data fusion and aggregation, thus leading to significant energy savings. Clustering involves hierarchically organizing the network topology. Sensor nodes in cluster architecture are grouped into clusters in which a cluster head is elected and group of source sensor nodes are directly attached to the cluster head. The cluster head usually performs the special tasks like (fusion and aggregation) and several common sensor nodes as members [8]. Figure 2 shows the cluster arrangement in WSNs.

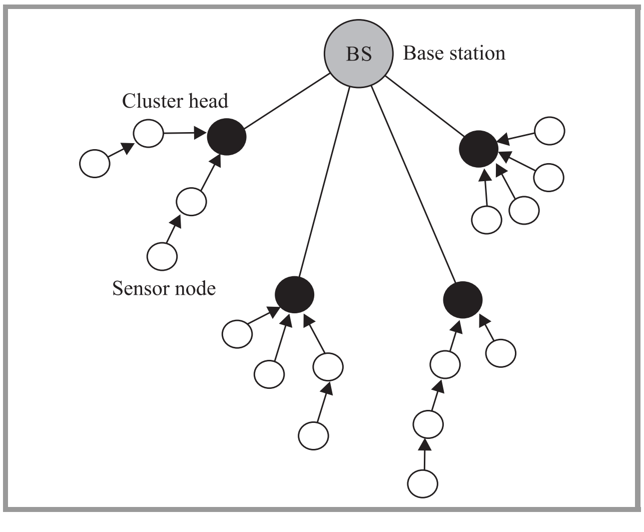

Fig. 2. Clustering in WSNs.

Generally, a clustered network employs single hop routing in each cluster. The one-hop clustering can reduce the energy consumption of communication by forwarding source nodes data to the cluster head via one hop. However, when communication distance increases, single-hop communication consumes more energy and becomes less energy efficient method. For a large network, where internodes' distance is important, multi-hop communication is a more energy efficient approach [9]. Therefore, a new approach called Sensor Hop-based Energy Efficient Networking Approach (SHEENA) for 3D UWSNs is proposed and compared with the widely used protocol called multi-hop Low-Energy Adaptive Clustering Hierarchy (LEACH).

2.1. LEACH Protocol

LEACH [10] is the first self-adaptive and self-organized protocol of hierarchical routings, which proposed data fusion. It is of milestone significance in clustering routing protocols. LEACH protocol uses round as unit. Each round is made up of setup stage and steady-state stage. For reducing unnecessary energy costs, the later must be much longer than the former one.

At the stage of cluster forming, a node randomly picks a number between 0 to 1, compares this number to the threshold values $t(n)$, if the number is less than $t(n)$, then it becomes cluster head in this round, else it becomes the common node. Threshold $t(n)$ is determined by the following equation:

$$t(n) = \frac{P}{1 - P\left(r \bmod \frac{1}{P}\right)} \quad \text{if} \quad n \in G \quad \text{else} \quad 0\,, \tag{1}$$

where P is the percentage of the cluster head nodes in all nodes, r is the number of rounds and G is the collection of the nodes that have not yet been head nodes in the first $\frac{1}{P}$ rounds.

When clusters have been formed, the nodes start to transmit the captured data. Cluster heads receive data sent from the other nodes and forward it to the sink after being fused. This is a frame data transmission. In order to reduce unnecessary energy cost, steady stage is composed of multiple frames and the steady stage is much longer than the setup stage. Here we perform multi-hop LEACH [11] for acoustic channel. Multi-hop LEACH protocol is almost the same as LEACH protocol, only makes communication mode from single-hop to multi-hop between cluster heads and sink.

2.2. SHEENA

UWSNs are composed of a large number of pre-powered battery operated sensors deployed in the target environment. To achieve energy-efficient, scalable and fault-tolerant system structure, SHEENA is proposed as strategy to reduce the power consumption. In this model, network is presented with a predefined number of nodes. These nodes are divided into their respective roles. The node roles possible in presented model are as sensor nodes, cluster heads and super heads. Nodes are randomly deployed under the water. The sensor nodes sense and send the data to their respective cluster heads. The cluster heads forward the collected data to the super heads, which are assumed as energy rich devices, capable of doing data aggregation and processing in an efficient manner. The super head is a powerful node in the underwater wireless sensor network and it can reach a wide range of communication area. The super head serves as the gateway for external communication. If the super head has been invaded then the whole network will be taken over, so it is assumed that the super head is well protected and can always be trusted. Cluster head is selected based on energy. Node having maximum energy among all other sensors is elected as a cluster head. The same applies for the super heads too.

Both the approaches have been explained in Figs. 3 and 4.

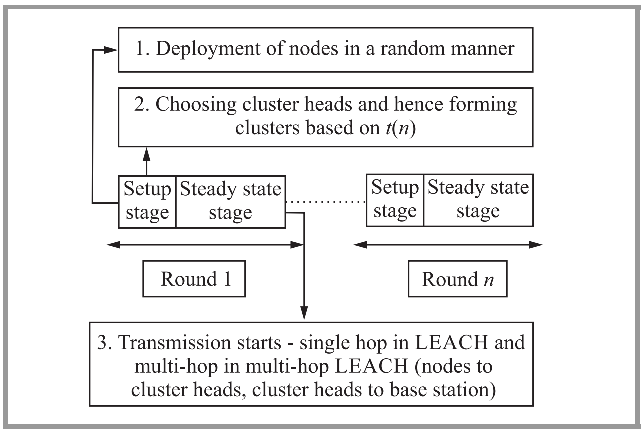

Fig. 3. Routing in LEACH protocol.

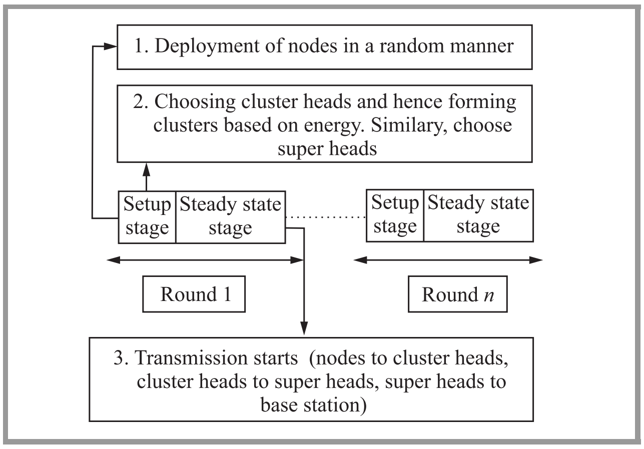

Fig. 4. Routing in SHEENA.

These approaches have been applied here to 3D UWSN. It is considered that sensor nodes are deployed at different depths in a 3D UWSN. A generic model for the same has each sensor node assigned with a triple of coordinates (x, y, z). The function (u, v) defines the distance between two nodes in a 3D Euclidean space as:

$$\delta(u, v) = \sqrt{(u_x - v_x)^2 + (u_y - v_y)^2 + (u_z - v_z)^2}\,. \qquad (2)$$

3. Energy Model for UWSNs

To transmit data from one node to another node over a distance d, the energy dissipation in underwater channel is given by [12]:

$$E(d) = E_t(d) + E_r(d)\,, \qquad (3)$$

$$E_t(d) = l\,(E_{elec} + E_{amp}) + P_t \cdot \frac{l}{h \cdot B(d)}\,, \qquad (4)$$

$$E_r(d) = l\,(E_{elec} + E_{DA}) + P_r \cdot \frac{l}{h \cdot B(d)}\,. \qquad (5)$$

Here, P_t and P_r are the transmission and reception power levels for transmission energy E_t and reception energy E_r of the network respectively, l is packet size, $B(d)$ is the bandwidth available, E_{elec} is the energy consumed by the electronics to process one bit of message, E_{amp} is the energy consumed by amplifier, E_{DA} is the energy for data aggregation. The variable h is the bandwidth efficiency of modulation (in b/s/Hz), given by:

$$h = \log_2(l + SNR)\,. \qquad (6)$$

In UWSNs, signal to noise ratio (SNR) of a transmitted signal by a node is expressed in the terms of source level (SL), transmission loss (TL), ambient noise or noise level (NL) and directivity index (DI). SNR (in dB) is expressed as [13]:

$$SNR = SL - TL - NL + DI\,. \qquad (7)$$

The SL (in dB re μPa) depends upon transmission power intensity I_t and transmission power (P_t), expressed as:

$$SL = 10\,\log\left(\frac{I_t}{0.067 \cdot 10^{-18}}\right). \qquad (8)$$

Given the Transmission Power (P_t), Transmission Power Intensity (I_t) of an underwater signal at 1 m from the source can be obtained for the shallow water (in W/m^2) through the following expression:

$$I_t = \left(\frac{P_t}{2\pi \cdot 1m \cdot d}\right). \qquad (9)$$

where d is depth in meters.

Equation (9) will be varied by replacing 2π to 4π for deep-water scenarios as referred in [14].

Transmission loss (TL) is the abatement in sound intensity through the path from transmitting node to receiving node in the network [15]. It is dependent on the transmission range and attenuation. The transmission loss (in dB) is expressed as:

$$TL = SS + \alpha \cdot 10^{-3}\,, \qquad (10)$$

where SS is spherical spreading factor $SS = 20\log r$, α is attenuation factor (in dB), calculated from Thorp formula as given in Eq. (11), and r is transmission range (in meters).

Attenuation occurs due to the transformation of acoustic energy into heat. Energy absorbed by the water is proportional to the frequency of the signal. The Thorp model proposed in [16] involves the simplest equation for attenuation, taking into account the effect of the frequency utilized. The Thorp equation is formulated as:

$$\alpha = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75\cdot 10^{-4} f^2 + 0.003\,, \quad (11)$$

where f is frequency in kHz.

The Directivity Index (DL) is set to zero (because we assume omnidirectional hydrophones). The Noise Level (NL), i.e. the ambient noise of underwater wireless sensor networks is expressed in terms of summation of turbulence noise, shipping noise, wave noise and thermal noise, summing up into [17]:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)\,. \quad (12)$$

In the Eq. (12) the turbulence noise may be expressed as

$$10\log N_t(f) = 17 - 30\log(f)\,. \quad (13)$$

The shipping noise is calculated by:

$$10\log N_s(f) = 40 + 20(s-0.5) + 26\log(f)\,, \quad (14)$$

where s is the shipping factor, which ranges from 0 to 1 for low to high activities, respectively.

The wave noise is given by

$$10\log N_s(f) = 50 + 7.5\sqrt{w} + 20\log(f) - 40\log(f+0.4)\,, \quad (15)$$

where w is the wind speed.

The thermal noise is represented by

$$10\log N_{th}(f) = -15 + 20\log(f)\,. \quad (16)$$

In all equations for noise components f is the frequency in kHz.

4. Simulation and Analysis

During simulation in Matlab [18] the network of 100 nodes using random topology in $200\times 200\times 200$ m environment have been deployed. The base station is placed at (200, 200, 200).

We applied multi-hop LEACH and Sensor Hop-based Energy Efficient Networking Approach to the 3D Underwater Wireless Sensor Network. The scenario for the proposed approach is shown in Fig. 5, in which all the deployed nodes are connected to their respective cluster heads represented by the blue lines. Cluster heads are connected with each other as depicted by the green lines. Further, the cluster heads can be connected with super head as shown by red lines in the picture.

As the energy parameter depletes after some duration of time, i.e. after some number of rounds, some of the sensor nodes will have energy level much below threshold and they can be regarded as dead nodes. The aim of the proposed approach is to delay the dying of nodes by saving the energy of the network.

The simulation parameters included in the implementation are given in Table 1. Some of the values have been referred from [12].

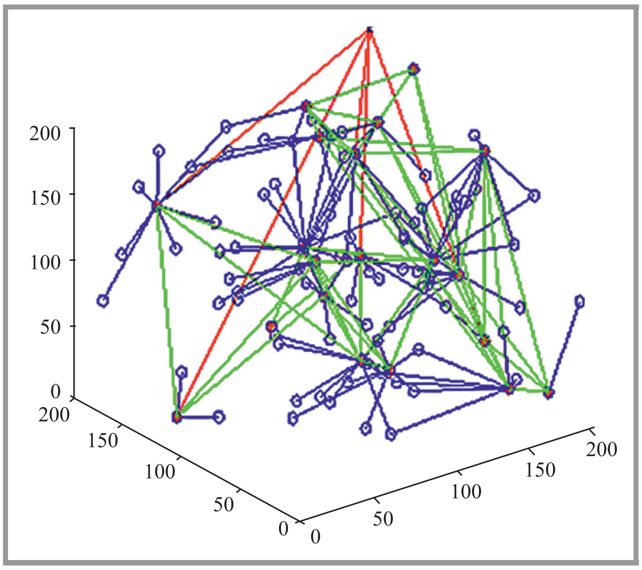

Fig. 5. Interconnection of nodes. (See color pictures online at www.nit.eu/ publications/journal-jtit)

Table 1
The simulation parameters

Parameter	Variable	Value
Network sink		$200\times 200\times 200$ m
Size		200, 200, 200
Number of nodes		100
Data packet size		240 bytes
Initial energy of every node	E_0	5 J
Amplifier energy	E_{amp}	0.0013 pJ/bit/m^4
Electronics energy	E_{elec}	50 nJ/bit
Energy for data aggregation	E_{DA}	5 nJ/bit
Number of simulation rounds	$r_{\max}$	6000
Bandwidth	$B(d)$	4 kHz
Frequency	f	10 kHz
Distance	d	20 m
Range	r	50 m
Transmission power	P_t	70 mW
Reception power	P_r	16 mW
Shipping factor	s	0.5
Wind speed	w	6 m/s

4.1. Energy Consumption for Shallow and Deep Water

The main parameter of analysis to be considered is the energy consumption in the network. The energy model described in Section 3 is followed to calculate consumption of energy for the network in case of both traditional multi-hop LEACH and the proposed scheme. Table 2 and Fig. 6 show the results obtained on implementation depicting the variation in energy consumption in the network for LEACH and SHEENA at shallow water.

Table 2
Energy consumed by the UWSN in shallow water

No.	Depth [m]	Energy consumption for LEACH [J]	Energy consumption for SHEENA [J]
1	20	32.57	18.89
2	40	37.3	17.83
3	60	32.6	16.51
4	80	31.44	16.22
5	100	29.22	18.77

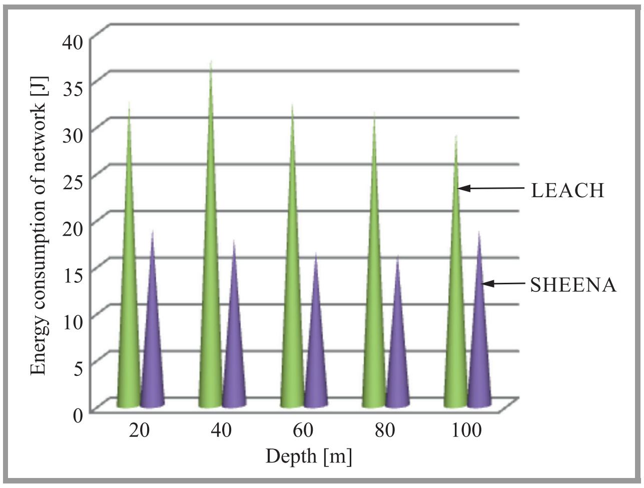

Fig. 6. Energy consumption vs. depth (shallow water).

The energy consumed by LEACH network is larger in contrast to hop-based clustering scheme, proving the proposed approach to be an energy saving one.

Table 3
Energy consumed by the UWSN in deep water

No.	Depth [m]	Energy consumption for LEACH [J]	Energy consumption for SHEENA [J]
1	500	29.4	25.02
2	2000	27.466	15.28
3	4000	26.62	13.922
4	6000	26.52	17.14
5	8000	25.05	18.851

Next, deep water is considered. Table 3 and Fig. 7 show the variation in energy consumption for LEACH and SHEENA at deep water. The proposed approach is energy efficient as compared to multi-hop LEACH even in deep water.

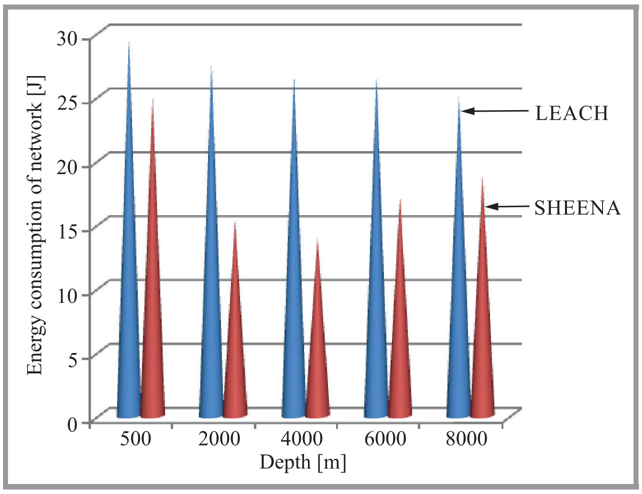

Fig. 7. Energy consumption vs. depth (deep water).

4.2. Dying of Nodes

The lifetime of a network depends upon the time when the first node of the network dies and when whole network becomes dead due to lack of energy in all the nodes.

Table 4
Dying of nodes

Depth	First node dead		Last node dead	
	Hop-based clustering scheme	LEACH multi-hop	Hop-based clustering scheme	LEACH multi-hop
Shallow water	13	9	150	100
Deep water	10	6	100	86

Table 4 shows the round number when the first and the last node becomes dead in both LEACH and SHEENA for the shallow and deep water. Figures 8 and 9 illustrate the same respectively.

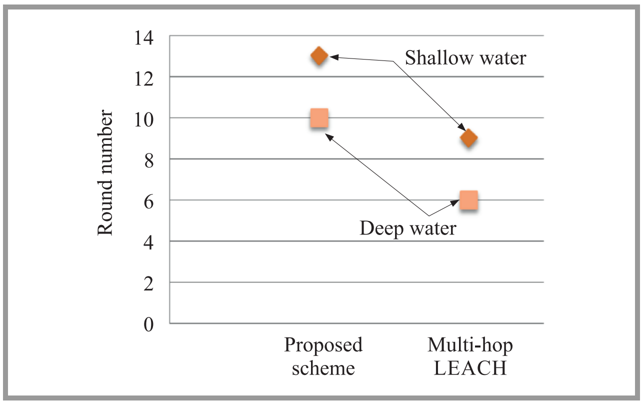

Fig. 8. Round number vs. first node dead in two approaches.

The results show that the nodes start dying later in the proposed SHEENA for both shallow and deep water,

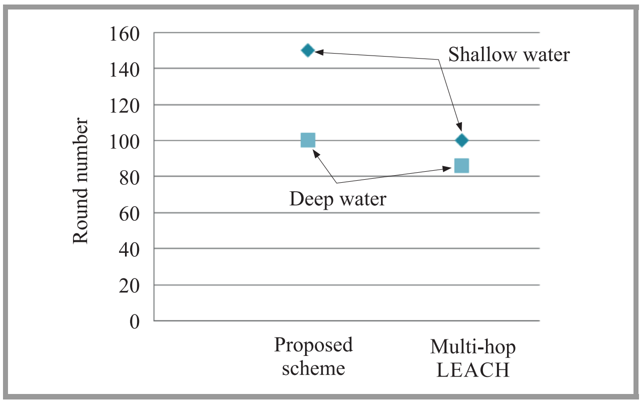

Fig. 9. Round number vs. last node dead in two approaches.

letting to increase the network lifetime in contrast to multi-hop LEACH.

5. Conclusion

The analysis of the research conducted shows that the proposed Sensor Hop-based Energy Efficient Networking Approach (SHEENA) gives better lifetime and consumes lesser energy in both shallow and deep water environments when compared with the traditional multi-hop LEACH protocol. The energy consumed in the network having Hop based clustering scheme is less than that of LEACH network. The dying of nodes is slower leading to increase the lifetime of the network in the proposed technique.

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