AN ANALYSIS OF ROUTING PROTOCOLSTO MAXIMIZE THE LIFETIME OF WSNFOR UNDERWATER APPLICATIONS

Abstract

A Wireless Sensor Network (WSN) comprises Sensor Nodes (SN) that are battery-powered and deployed across a harsh environment. WSN applications include military, agriculture, monitoring, surveillance, and more. To extend the lifetime of sensor nodes due to limited battery capacity, efficient routing protocols are essential. Repeatedly using a specific energy path can deplete the batteries of SNs in that area, leading to energy holes and network deactivation. Therefore, it is crucial to select a protocol that involves all SNs in data transmission to prolong network lifetime. Clustering is an effective approach for enhancing network lifetime as it ensures efficient and balanced battery consumption while increasing reliability. Numerous clustering methods have been put forth, with room for further improvement. Clustering is particularly valuable for underwater applications, providing valuable insights into marine life. Compared to homogeneous protocols, heterogeneous protocols are more dependable and energy-efficient. We present Heterogeneous Energy Efficient and Reliable Routing (HEERR), a more sophisticated DEEC protocol, in this work. When HEERR is compared to other hierarchical routing methods, it shows that throughput is increased and network lifetime is improved.

Keywords: DEEC, TEEN, SEP, LEACH-C, energy efficient, hierarchical routing.

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I. INTRODUCTION

At the moment, a technology known as Wireless Sensor Networks (WSN) has surfaced that links thousands of nodes to form a large-scale network. WSN is made up of what are known as Sensor Nodes (SN), which are devices with limited computing capability, battery power, tiny size, sensing capabilities, and cost-effectiveness [1]. These SNs play a crucial role in monitoring a range of parameters, including as temperature, motion, humidity, wetness, and unusual activity. They can be used for a variety of purposes, including underwater observation, medical monitoring, intelligence gathering, surveillance, and environmental monitoring, both on land and in the water [2–6]. The parts of a typical SN are a radio transceiver, battery, sensor, and microprocessor [3–10]. Distributed and self-organizing, SNs function in dynamic topologies [11–16]. They also have a lot in common, including self-organization [18], node mobility [19–22], broadcasting [24], multi-hop routing [23], distributed topology management [17], and short-range communication. As seen in Figure 1, these SNs link to form a network architecture known as WSN.

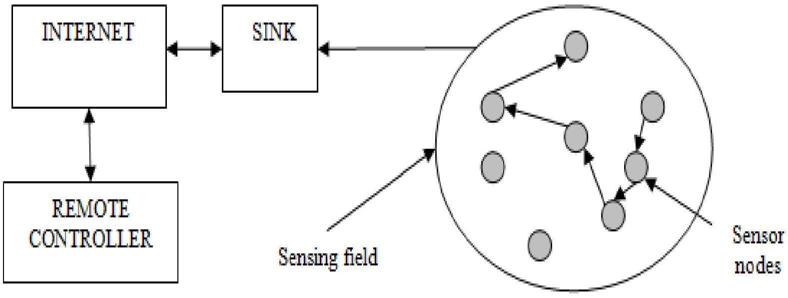

Figure 1: WSN Architecture

The primary challenge lies in achieving a balance between battery consumption and enhancing reliability [21-30]. However, there are additional challenges that demand attention. Sensor Nodes (SNs) are deployed in a random manner within an area, devoid of any existing infrastructure or prior knowledge regarding the network topology [27-30]. In such scenarios, SNs must autonomously establish connectivity and distribution. For instance, in surveillance applications on a battlefield, SNs may be air-dropped into an area. WSN protocols must exhibit fault tolerance to accommodate potential SN failures [31-39]. These protocols should also demonstrate dynamism to adapt to varying SN counts [17,36-39]. Furthermore, they must be designed to transmit data to the Base Station (BS) at specific times, ensuring the attainment of Quality-of-Service (QoS) standards. This research primarily focuses on the application of WSN in underwater environments. In underwater applications, there is a need for the periodic and critical collection of various types of data. This data is essential for monitoring aquatic life, detecting river and sea pollution, compiling oceanographic information, and conducting various monitoring activities. Clustering proves to be an effective approach for transmitting data from Sensor Nodes (SN) to the sink in underwater applications. In the following section, we will explore different routing approaches, including both homogeneous, where all SNs initially have equal energy due to having the same equipment, and heterogeneous, where the initial energy levels of SNs differ due to variations in their equipment.

II. CLUSTERED ROUTING STRATEGIES IN WSN

Taking these challenges into consideration, researchers have developed a range of protocols aimed at improving network lifetime [1-30]. Clustering has proven to be an effective strategy for ensuring the active participation of all Sensor Nodes (SNs), which results in efficient battery usage and increased reliability. The clustering approach plays a crucial role in gathering data from SNs and forwarding it to the Base Station (BS) [25-37]. Here are some of the widely recognized routing protocols in this category:

1. **LEACH Protocol:** The Low Energy Adaptive Cluster Hierarchy (LEACH) protocol, as presented in [7], is a hierarchical cluster-based approach designed to optimize energy consumption. In LEACH, the network is partitioned into autonomous clusters, each of which is overseen by a Cluster Leader (CL). These CLs are responsible for gathering data from their neighboring nodes, aggregating it, and subsequently transmitting the aggregated data to the Base Station (BS). The selection of CLs is carried out using a random procedure [7]. The LEACH algorithm encompasses a periodic process consisting of two phases in each round.

   Setup phase:

   - **Advertisement Phase:** During this stage, the Cluster Leaders (CLs) initiate the transmission of advertisement packets to their respective neighborhoods. These packets serve the purpose of informing nodes about their affiliation with a particular CL. In this process, each node, denoted as 'n' in the network, independently generates a random number 'k' within the range of 0 and 1. If the condition 'k < T(n)' holds true for a given node 'n,' it will assume the role of a cluster head (CL). The selection of CLs follows the equation 1:

$$T(n) = \begin{cases} \dfrac{\text{Prob.}}{1-\text{Prob.}\left[rd*\text{mod}\left(\frac{1}{\text{Prob.}}\right)\right]} & \text{if } n \in Y \\ 0 & \text{Otherwise} \end{cases} \tag{1}$$

   - **Cluster Set-up Phase:** CL received information about its member nodes.

   - **Schedule Creation:** CLs provide a time schedule for each node in which they can send their data to respective CL.

   Steady-State phase:

   - **Data Transmission:** In the initial transmission phase, all nodes within the network send their data to their respective Cluster Leaders (CLs). During the second transmission phase, after the CL has received data from all its member nodes, it performs data reduction techniques to minimize the data while preserving its essential information. This reduction in data size helps conserve energy, as only the minimized data is then forwarded to a designated destination node, typically the sink.

However, since CLs are chosen at random, this can result in non-uniform energy distribution across the network. To address this issue, the LEACH-C protocol [15] was introduced.

2. **LEACH-C Protocol:** The LEACH-C protocol [15] introduces a centralized sink for Cluster Leader (CL) selection, as illustrated in Figure 2. This concept significantly enhances energy efficiency in Wireless Sensor Networks (WSN). The primary distinction between the LEACH protocol and LEACH-C protocol lies in their Setup phase, while the steady-state phase remains consistent in both approaches. In LEACH-C, cluster formation is orchestrated by the base station (sink), whereas in LEACH, nodes autonomously designate themselves as CLs. Initially, in LEACH-C, all nodes within the network transmit their details, such as location and energy levels, to the Base Station (BS) [16]. Subsequently, the BS calculates the optimal number of Sensor Nodes (SNs) that can serve as CLs, considering their energy reserves. An advantage of this protocol over LEACH is that LEACH's number of CLs varies from round to round, while in LEACH-C, the BS determines the number of CLs for each round.

   The limitation of LEACH-C is that the sink necessitates comprehensive knowledge of the entire network during the cluster formation process.

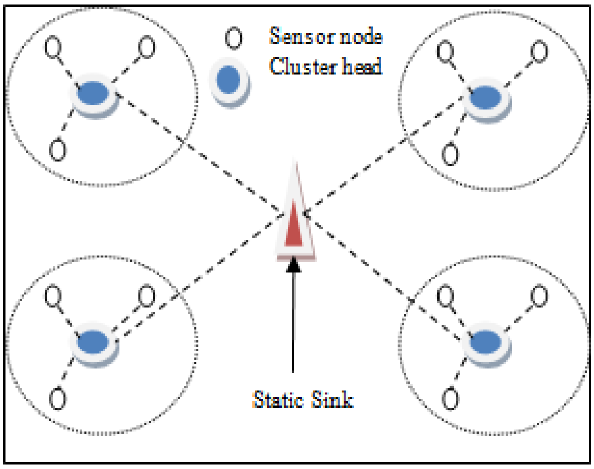

Figure 2: LEACH-C Protocol using Static Sink.

3. **TEEN Protocol:** The Threshold-sensitive Energy-Efficient Sensor Network protocol (TEEN) [17] shares similarities with LEACH as it is also a cluster-based hierarchical routing protocol, involving nodes forming clusters and selecting Cluster Leaders (CL) for data transmission to the Base Station (BS). TEEN combines hierarchical techniques with a data-centric approach and emphasizes less frequent data transmission to conserve energy efficiently. It operates as a reactive protocol, where nodes respond to specific activities such as temperature and weather conditions, making it suitable for time-critical tasks. In contrast, LEACH is a proactive protocol where nodes do not typically respond to

specific events [18,19]. Sensor nodes in TEEN react promptly to immediate and significant changes in sensed attribute values. The protocol utilizes a pair of thresholds to detect changes in sensing data:

- **Hard Threshold:** This threshold value is assigned by the CL to the sensed attribute. When SNs sensed value is larger than the hard threshold value then this is the sign for nodes to switching on their transmitter and inform to its CL.

- **Soft Threshold:** This is the value of the sensed attribute if this value has some small change then it implies the node to switch on its transmitter and transmit.
  Data transmission occurs under two specific conditions: either when the sensed data value exceeds the hard threshold value or when there are significant changes in the sensed attribute's value, equal to or greater than the soft threshold value.

4. **SEP Protocol:** In a heterogeneous sensor network, not all nodes have the same initial energy level. Various energy-efficient protocols, such as SEP [20] and DEEC [21], are utilized within WSN to conserve energy and enhance network longevity. Heterogeneous protocols encompass three models: two-level, three-level, and multilevel heterogeneity. These models involve equipping two or more nodes with varying initial energy levels. When all sensor nodes within a network possess approximately equal energy levels, it is termed a homogeneous sensor network. Routing schemes like LEACH, LEACH C, and TEEN are typically recommended for homogeneous sensor networks. To address energy-related heterogeneity, the Stable Election Protocol (SEP) [20] was introduced, implementing a two-level heterogeneous sensor network. In this context, two-level heterogeneity denotes that among all sensor nodes, certain nodes possess significantly higher battery power (energy) than the remainder of the nodes in the sensor network.

More energy-dense nodes are referred to as advanced supernovae. Assume there are X total sensor networks (SNs) in the network, and that each node has $E_{initial}$energy. Let Y×X represent the number of advanced supernovae (SNs) for heterogeneity, where Y is a fraction of all SNs. Assume that advanced supernovae have Z times the energy of regular supernovae. For every advanced SN in the network, the starting energy equals $E_{initial}\times(1+Z)$.Thus, equation (2) might be used to express the total starting energy of two-level heterogeneous networks.

$$Etotal = X \times (1-Y) \times \mathrm{E_{initial}} + X \times Y \times \mathrm{E_{initial}}$$

$$Etotal = \mathrm{E_{initial}} \times (1 + Y \times Z) \tag{2}$$

For a node to become a CL it should have optimal probability P_{opt}, defined as in equation (3):

$$Popt = \frac{K_{opt}}{N} \tag{3}$$

Here CK_{opt} is an optimal number of constructed clusters. When the distance of a population of nodes to the sink is less than d_o where $do = \sqrt{\frac{e_{fs}}{e_{mp}}}$, then the value of kopt given by the equation (4):

$$CK_{opt} = \sqrt{\frac{N}{2\pi}\frac{X}{D}} \tag{4}$$

When a population of nodes is farther away from the sink than d0, the value of kopt is determined by equation (5):

$$CK_{opt} = \sqrt{\frac{N}{2\pi}}\sqrt{\frac{e_{fs}}{e_{mp}}}\frac{X}{D^2} \tag{5}$$

Let the network area be X×X, the number of SNs in the network N, and the average distance (D) between a CL and the sink. SANDE_MP e_fsrely on the model of the transmitter amplifier [20]. To reduce node energy consumption, the average number of created CL for each round should be NHPopt and should be fixed (constant).The optimal election probability (Popt) is given a weight by the SEP protocol in order to preserve the fixed number of CL each round. The weighted election probability for advanced and normal nodes, respectively, are therefore displayed by equations (6) and (7):

$$Prob.(nm) = \frac{Popt}{1 + A \cdot M} \tag{6}$$

$$Prob.(av) = \frac{\mathrm{Popt}}{1 + \mathrm{A} \cdot \mathrm{M}} \times (1 + A) \tag{7}$$

Equations (8) and (9) can be used, respectively, to define the threshold value for regular and advanced nodes as election probability change:

$$T(Snm) = \left\{\begin{matrix} \frac{Pnm}{1-Pnm.\left(rmod\frac{1}{Pnm}\right)} if Snm \epsilon Z' \\ 0 \qquad\qquad if Snm \epsilon Z' \end{matrix}\right\} \tag{8}$$

$$T(Sav) = \left\{\begin{matrix} \frac{Pav}{1-Pav.\left(rmod\frac{1}{Pav}\right)} if Sav \epsilon Z'' \\ 0 \qquad\qquad if Sav \epsilon Z'' \end{matrix}\right\} \tag{9}$$

Where Z" is the set of advanced SNs that have not become CLs within the last 1/Pav rounds, and Z' is the set of SNs that have not become CLs within the latest 1/Pnm rounds[20]. The current round is represented by rd in this example.

Lastly, one of the SEP protocol's greatest features is that data routing may be done without requiring a comprehensive understanding of all network nodes. However, SEP is not able to handle heterogeneity in sensor node energy levels greater than two levels.

5. **DEEC Protocol:** The choice of CHs in Distributed Energy Efficient Clustering (DEEC) [21] is not limited to the election probability alone. Furthermore, the DEEC procedure

combines the average energy and the ratio of each SN's remaining energy to determine the election probability. Increased possibilities of becoming CL will correspond with increased levels of residual energy. The average energy at round rd is denoted by (AvgE)̅(r), which is defined as follows in equation(10):

$$\overline{AvgE}(r) = \frac{totalresidualenergyofallnodesatroundr}{noofnodes} \tag{10}$$

The election probability formula for a two-level heterogeneous network can be obtained by incorporating the concepts of residual and average energy, as shown in equation (11).

$$pi = \begin{cases} \frac{P_{opt}E_i(rd)}{(1+AM)\bar{E}(rd)} if s_i isthenormalnode \\ \frac{P_{opt}(1+AM)E_i(rd)}{(1+AM)\bar{E}(rd)} if s_i isadvancednode \end{cases} \tag{11}$$

When multilayer heterogeneity in node energy is taken into account by DEEC, the election probability for CL selection is as follows in equation (12):

$$pi = \frac{P_{opt}N(1+A)Ei(rd)}{(N+\sum_{i=1}^{N}A_i)\bar{E}(rd)} \tag{12}$$

The average energy at round rd of the network given by equation in (13) should be represented by Eavg(rd):

$$Eavg(rd) = \frac{1}{N}Etotal(1-\frac{rd}{R}) \tag{13}$$

Here, R stands for the network's total no round, which is computed using equation (14):

$$R = \frac{Etotal}{Eround} \tag{14}$$

The entire energy lost in the network during a round is called eround, and its value is given by equation (15):

$$Eround = B\left(2N\text{Eelec} + NE_{DA}ke_{mp}D^4{}_{toBS}Ne_{fs}D^2{}_{toCH}\right) \tag{15}$$

Where,
k: number of clusters,
B: no of bits in a data packet,
E_{DA}: Data aggregation cost expended in the CLs,
D_{toBS}: Average distance between the cluster-head and the base station,
D_{toCH} : Average distance between the cluster members and the cluster-head,
Eelec: Energy dissipated per bit to run the transmitter or the receiver circuit [21,22].

6. **EDEEC (Enhanced Distributed Energy Efficient Clustering) Protocol:** A modified variant of DEEC is called EDEEC [23]. EDEEC functions as an SN-based, three-level network composed of normal, advance, and super nodes. The remaining tasks will not

change, with the exception of choosing CL, which will be carried out in accordance with equation (16).

$$p_i=\begin{cases}\dfrac{E_i(rd).P_d}{\left(1+m'.(ad+b.md'_o)\right)\bar{E}(rd)} & normal\ node\\ \dfrac{E_i(rd).P_d(1+ad)}{\left(1+m'.(ad+b.md'_o)\right)\bar{E}(rd)} & advanced\ node\\ \dfrac{E_i(rd).P_d(1+bd)}{\left(1+m'.(ad+b.md'_o)\right)\bar{E}(rd)} & super\ node\end{cases} \tag{16}$$

Where,
md': % of advanced SNs
P_d: desired probability of CLs
md'_o: % of super nodes
ad: portion of advance SNs
bd: portion of SNs
$\bar{E}$(rd): average energy

The threshold for CL selection $T(CL_j)$ is given in (17):

$$T(CL_j)=\begin{cases}\dfrac{P_d}{\left(1-P_d\left(rd*mod\frac{1}{p_d}\right)\right)} & if\ p_d\in M'\\ \dfrac{P_d}{\left(1-P_d\left(rd*mod\frac{1}{p_d}\right)\right)} & if\ p_d\in M''\\ \dfrac{P_d}{\left(1-P_d\left(rd*mod\frac{1}{p_d}\right)\right)} & if\ p_d\in M'''\end{cases} \tag{17}$$

Where M' , M'' &M''' represent group of normal SNs, advanced SNs and super SNs that have not become CLs within the last $1/p_j$ rounds.
The network average energy can be calculated as:

$$\bar{E}(rd)=\frac{1}{N}Etotal\left(1-\frac{rd}{R}\right) \tag{18}$$

R can be calculated as

$$R=\frac{E_{total}}{E_{round}} \tag{19}$$

The total energy of the network E_{total} is calculated by

$$\begin{aligned} E_{total} &= SN.(1-md').E_i + SN.md'.(1-md'_{o}).(1+ad).E_i + SN.md'.md'_{o}.E_i.(1+bd) \\ &= SN.E_i.\left(1+md'.(ad+md'_{o}.bd)\right) \end{aligned} \tag{20}$$

Where,
SN: Total number of nodes
E_o: Initial energy

The probability of CL selection for HEERR is given in (21)

$$p_i=\begin{cases} \left(\dfrac{E_i(rd).P_d}{\left(1+md'.(ad+bd.md'_o)\right)\bar{E}(rd)}\right) * E_T & normal\ node \\ \left(\dfrac{E_i(rd).P_d(1+a)}{\left(1+md'.(ad+bd.md'_o)\right)\bar{E}(rd)}\right) * E_T & advanced\ node \\ \left(\dfrac{E_i(rd).P_d(1+b)}{\left(1+md'.(ad+bd.md'_o)\right)\bar{E}(rd)}\right) * E_T & super\ node \end{cases}$$

Where,
E_T is total energy
Figure 3 depicts the radio dissipation model, where B is message size and d is the distance.

$$E_{Tx}(B,d)=\begin{cases} B\cdot E_{elec}+B\cdot\epsilon_{fs}\cdot d^2 \text{ if } d\le d_{\circ} \\ B\cdot E_{elec}+B\cdot\epsilon_{amp}\cdot d^4 \text{ if } d> d_{\circ} \end{cases} \tag{22}$$

Total energy consumed per round is given as,

$$E_{round}=B(2NE_{elec}+NE_{DA}+k\,\epsilon_{amp}\,d_{to\ BS}^4+N\,\epsilon_{fs}\,d_{to\ CH}^2) \tag{23}$$

$$d_{to\ CH}=\frac{M}{\sqrt{2\pi k}},d_{to\ BS}=0.765\frac{M}{2} \tag{24}$$

$$k=\frac{\sqrt{N}}{\sqrt{2\pi}}\sqrt{\frac{\epsilon_{fs}}{\epsilon_{amp}}}\frac{M}{d_{to\ BS}^2} \tag{25}$$

Where k is the number of clusters.

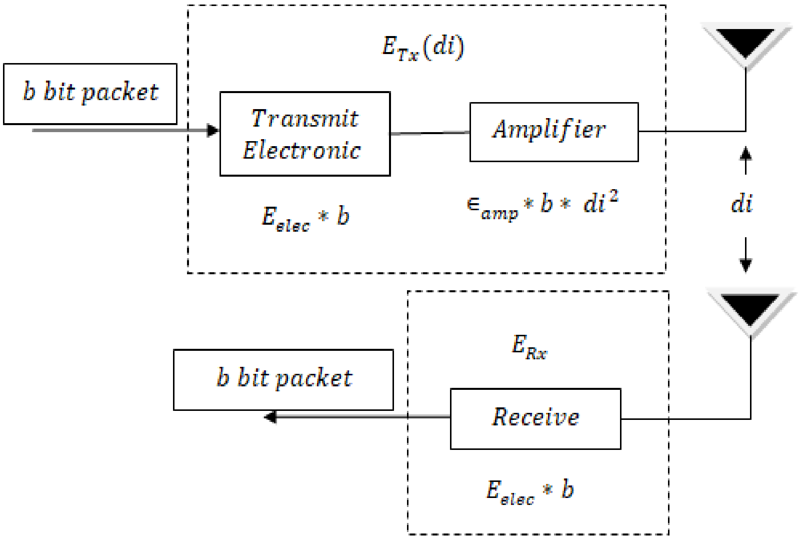

Figure 3: Radio Dissipation Model

III. ALGORITHM FOR THE SIMULATED PROTOCOLS

In this study, we have employed several clustered routing protocols, and the following assumptions need to be taken into account.

1. The sink will have an inexhaustible power supply.
2. The sink remains stationary at the center.
3. The SNs possess power control capabilities to adjust their transmission power.
4. At regular intervals, each SN monitors the environment and transmits data to the CL or BS.
5. All SNs remain stationary.

The simulated protocol algorithm is illustrated in Figure 4, while the criteria for selecting CL are depicted in Figure 5.

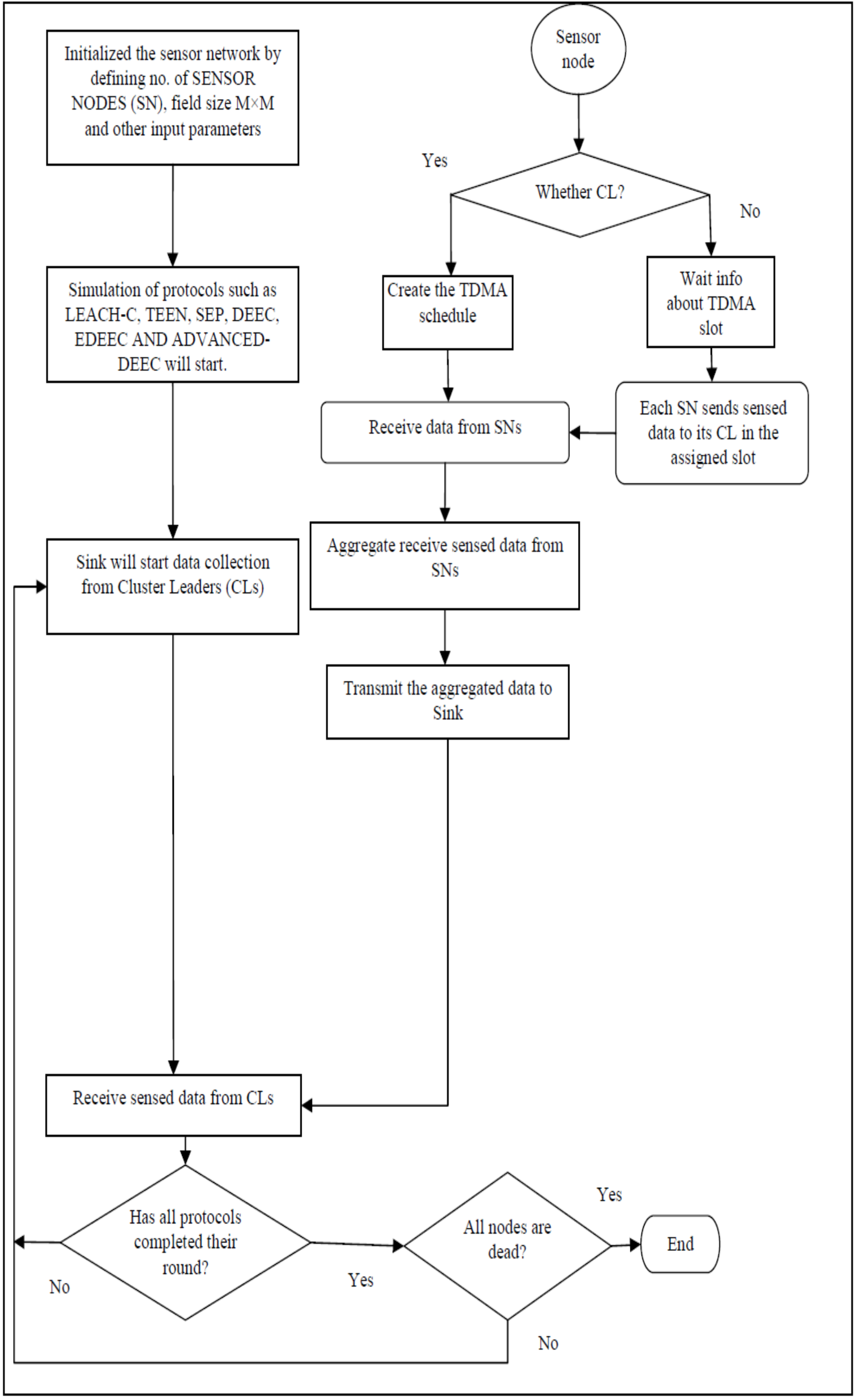

Figure 4: Framework for simulated protocols

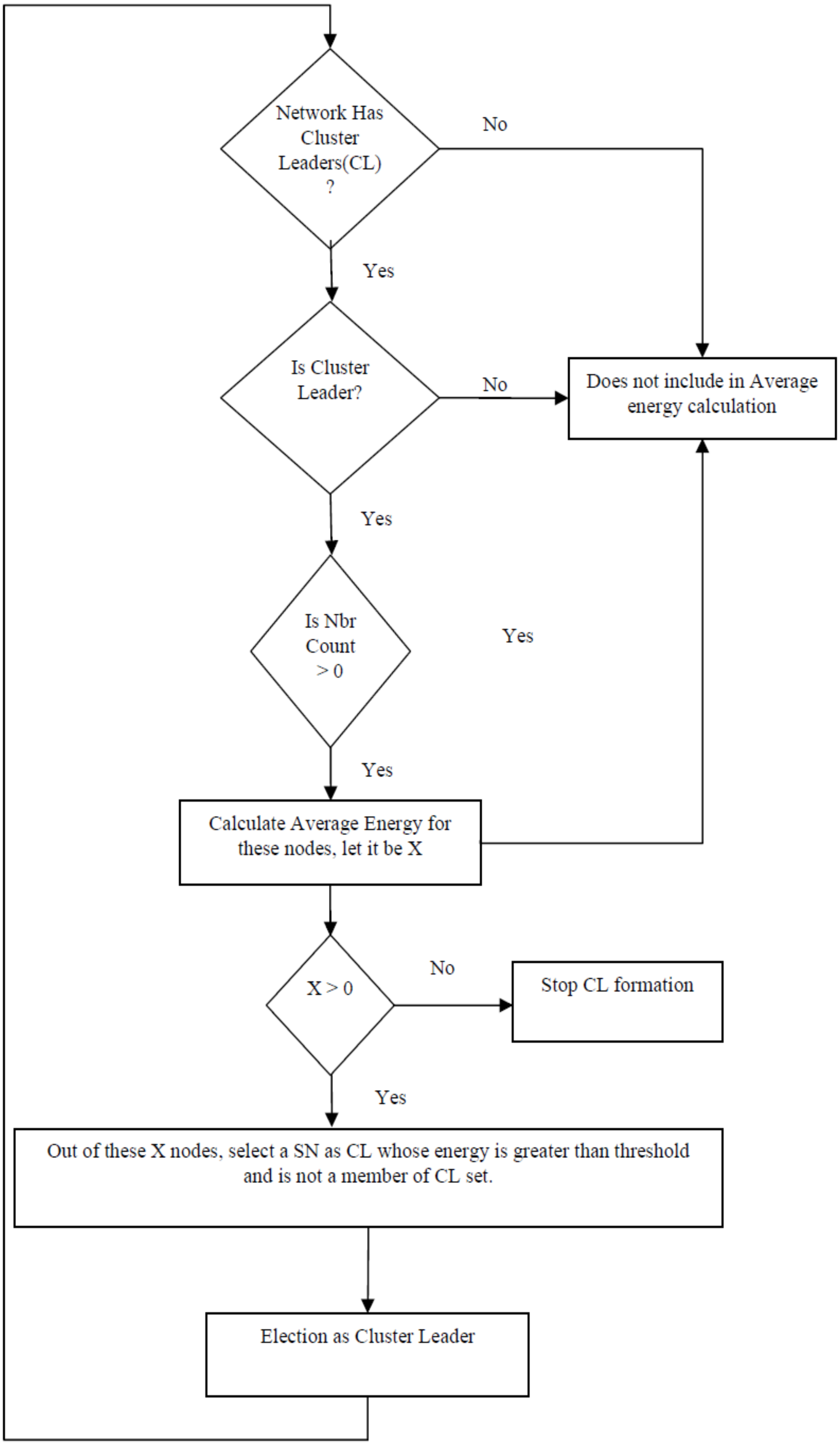

Figure 5: Cluster Leader Formation by Base Station

IV. IMPLEMENTATION AND RESULTS

Several protocols, such as LEACH, TEEN, SEP, DEEC, and recently enhanced protocols like E-DEEC and HEERR within the same category, were compared and simulated in this section. MATLAB 8.1 was utilized to conduct these simulations, which concentrated on many characteristics like energy efficiency, heterogeneity level, cluster stability, and CL selection criteria. To do this, we utilized a randomly distributed WSN comprising 100 SNs within a 100m² field, with the assumed base station located at the center of the sensing region. In this analysis, we considered various scenarios and evaluated multiple performance metrics. The radio parameters used for these simulations are detailed in Table 1.

Table 1: Network Parameters

PARAMETERS	Values
Simulation Area (in meters)	100 ×100
Initial Energy Allotted to SN (in Joules)	0.5
Total no. of SNs	100
E_{TX}	50nJ/bit
E_{RX}	50nJ/bit
E_{DA}	5 nJ/b/message
CL Probability	0.05
Data Packet Size(in bits)	4000
Threshold distance(d_0) (in meters)	87.7
Transmit Amplifier Energy	
E_{FS}	0.0013 pJ/b/m^4
E_{MP}	10pJb/m^2

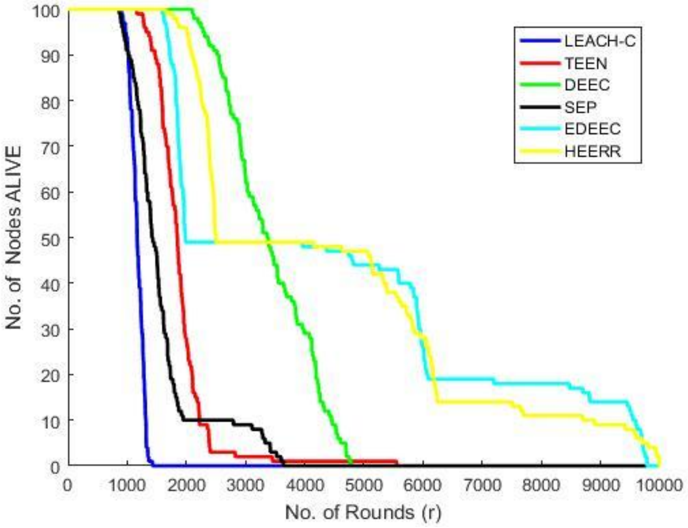

Figure 6: Comparison of LEACH C, TEEN, DEEC, SEP and Proposed Protocols in terms of nodes alive.

Figure 6 depicts a plot illustrating the relationship between the number of alive SNs and the number of rounds for various protocols, including LEACH-C, TEEN, DEEC, SEP, E-DEEC, and HEERR Protocols. This plot provides valuable insights, particularly in scenarios involving extensive network coverage, such as agriculture fields where a higher number of SNs is required. The analysis reveals that E-DEEC and HEERR protocols exhibit superior performance, with a larger proportion of SNs remaining operational across multiple rounds. Notably, while other simulated protocols experience the depletion of all SNs, E-DEEC and HEERR maintain 50% of SNs in an active state even under challenging conditions.

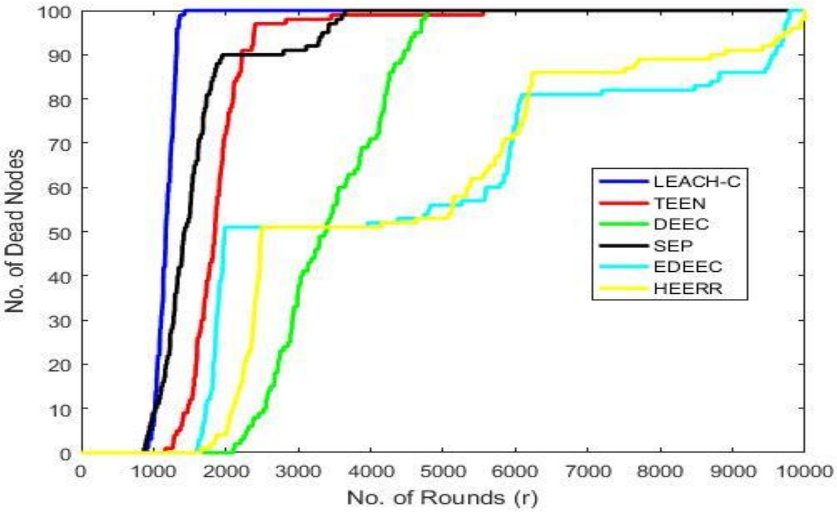

Figure 7: Comparison of LEACH C, TEEN, DEEC and SEP in terms of nodes dead.

Refer Figure 7, An analysis of the results reveals that E-DEEC and HEERR protocols exhibit superior performance and greater stability in comparison to the other protocols, with LEACH-C performing the least effectively.

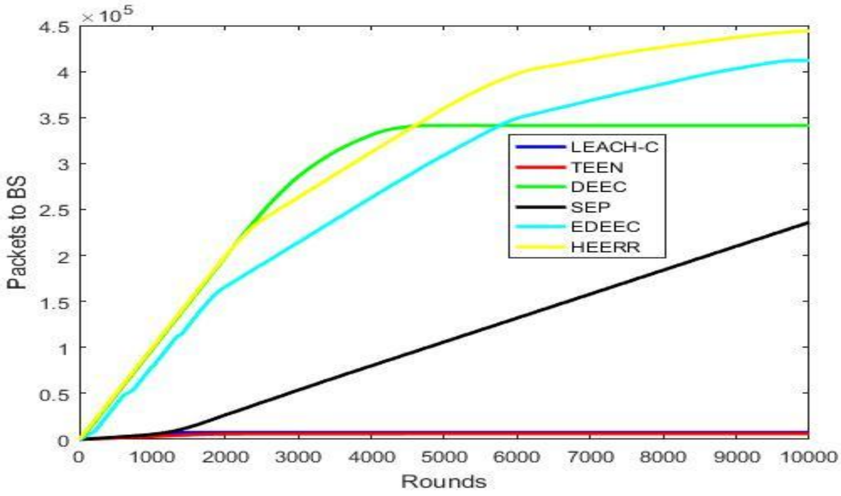

Figure 8: Comparison of LEACH C, TEEN, DEEC, SEP, E-DEEC and HEERR PROTOCOLS in terms of packets sent to BS

Figure 8 The provided information illustrates the quantity of data packets transmitted to the sink across multiple rounds. Notably, the HEERR protocol exhibits a higher data transfer rate from Cluster Leaders (CL) to the sink. As a result, the proposed protocols demonstrate enhanced reliability in comparison to LEACH-C, SEP, and TEEN. Hierarchical routing protocols follow specific procedures for Cluster Head (CH) selection and possess distinctive architectures along with various parameters for routing operations. Table 2 compares different protocols according to a number of criteria, such as architecture, hop count, heterogeneity degree, cluster stability, etc.

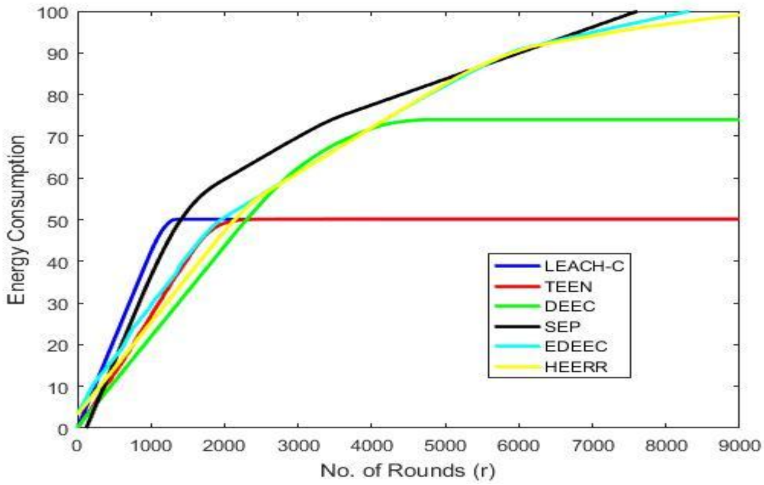

Figure 9: Comparison of LEACH C, TEEN, DEEC, SEP, E-DEEC and HEERR PROTOCOLS in terms of Energy Consumption

Picture 9 The energy consumption per round for protocols such as TEEN, DEEC, SEP, HEERR, EDEEC, and LEACH-C is depicted in the graph. The graph makes it clear that heterogeneous protocols outperform homogeneous protocols in terms of stability and battery efficiency.

Table 2: Comparison of various routing protocol

Performance Criteria	LEACH	LEACH-C	TEEN	SEP	DEEC	E-DEEC	HEERR
Architecture	Distributed	Centralized	Distributed	Distributed	Distributed	Distributed	Distributed
Hop	Single Hop	Single Hop	Multi Hop	Multi Hop	Multi Hop	Multi Hop	Multi Hop
Heterogeneity level	Not present	Not present	Not present	Two level	Multilevel	Multilevel	Multilevel
CL Selection Criterion	Elected rotation-wise by probabilistic approach	Selected by BS w.r.t. nodes energy and distance	Randomly	Based on Initial and Residual Energy	Based on Initial, Residual and Average Energy	Based on Initial, Residual and Average Energy of the	Based on Initial, Residual and Average Energy of the network

					of the network	network	
Cluster Stability	Lower	Higher than leach	Very High	Moderate	High	High	High
Global knowledge of network	Not Required	Required	Not Required	Not Required	Not Required	Not Required	Not Required
Energy Efficiency	Very low	Low	Moderate	High	High	High	High

V. CONCLUSION

In huge areas such as underwater fields, the best way to achieve energy efficiency targets is through cluster-based routing for hierarchical protocols. We compared and ran simulations using protocols such as TEEN, DEEC, SEP, E-DEEC, HEERR, and LEACH-C in this investigation. Several performance indicators were used to assess these methods' performance. The outcomes show that compared to other tactics, the E-DEEC and HEERR protocols are more dependable and energy-efficient. It is also clear that in terms of dependability and energy efficiency, the heterogeneous strategy performs better than the homogeneous method. We may infer from the simulation findings that HEERR is especially dependable because, in comparison to other routing protocols, it sends the greatest number of data packets to the sink.

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