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# Energy-Efficient Protocols for Wireless Sensor Networks in IoT Applications

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## Abstract

Recent developments in low-power communication and signal processing technologies have led to the extensive implementation of Wireless Sensor Networks (WSNs). In a WSN environment, cluster formation and Cluster Head (CH) selection consume significant energy. Typically, the CH is chosen probabilistically without considering real-time factors such as the remaining energy, number of clusters, distance, location, and number of functional nodes to boost network lifetime. Different strategies must be incorporated based on real-time issues to design a generic protocol suited for applications such as environmental and health monitoring, animal tracking, and home automation. Elementary protocols such as Low Energy Adaptive Clustering Hierarchy (LEACH) and centralized LEACH are well proven, but gradually, limitations evolved due to increasing desire and need for proper modification over time. Since the selection of CHs has always been an essential criterion for clustered networks, this paper overviews the modifications in the threshold value of CH selection in the network. With the evolution of bio-inspired algorithms, the CH selection has also been enhanced considering the behavior of the network. This paper briefly describes LEACH-based and bio-inspired protocols, their pros and cons, assumptions, and the criteria for CH selection. Finally, various protocols' performance factors, such as longevity, scalability, and packet delivery ratio, are compared and discussed.

**Keywords:** Wireless sensor network, Clustering, Hierarchical routing, LEACH protocol, Threshold-based cluster head selection.

## 1 | Introduction

Wireless Sensor Networks (WSNs) have acquired intensive popularity due to the wide range of applications in different fields [1]. A recent emerging application is the Internet of Things (IoT), which allows the interconnection of different objects or devices through the world of the internet [2]. About 5 billion intelligent devices are connected, and the number is quickly increasing worldwide [3]. The number of people interacting can exceed the number of virtual devices that connect to them. As a result, significant traffic will be generated, and humans are the slightest contributor to this traffic [4].

WSNs are of two types: homogenous and heterogeneous [5]. In a homogeneous network, nodes are identical. Resource heterogeneity in WSN can be divided into computational, link, and energy. Computational

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heterogeneity describes those networks where nodes differ in microprocessor's power and storage capacity. Hence, the powerful nodes can perform complex data processing and long-term storage. When nodes differ with bandwidth, the networks come under the link heterogeneity category and are suitable for reliable data transmission. Both link and computational heterogeneity consume a considerable amount of energy, reducing the network lifetime. Hence, the type of WSN must be worked out, where nodes are differentiated in terms of battery power.

The energy source consists of limited battery power, which is one of the major challenges in designing any sensor network [6]. The nodes may be deployed over a hostile location because the application makes the battery recharging almost unmanageable. Moreover, the nodes are expected to perform data acquisition indefinitely to achieve the application requirements. Hence, many researchers are currently exploring various techniques to extend the network lifetime to achieve high quality of service by balancing the energy consumption over the network.

When WSN is applied on larger platforms, topology control becomes an important parameter in balancing the network load to enhance the network lifetime and scalability. Clustering is an energy-efficient method for the hierarchical organization of sensor nodes in a network [7]. However, each node in an ad hoc network communicating directly with the sink node leads to problems such as data collision, network congestion, and unnecessary drainage of power. Low Energy Adaptive Clustering Hierarchy (LEACH) [8] is a classical cluster-based protocol proposed to minimize energy consumption by efficiently selecting CHs. Forming small clusters within the network helps overcome these crucial issues through efficient resource utilization. For each cluster, a CH is elected to act as a hop between the sensing nodes and the sink, thereby reducing the transmission distance. The CHs are elected dynamically after a specific interval to reduce the overhead. Once the CHs are elected, they broadcast an ADV message using the CSMA MAC protocol. Based on the RSSI of the ADV message, the nodes decide which CH wants to join for the current round and send a REQ message back to it using the CSMA MAC protocol.

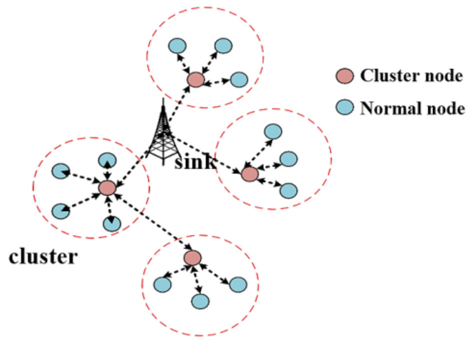


**Fig. 1. Clustered-based WSN.**

The clustered network helps the system maintain a longer life term by scheduling a duty cycle between nodes in a cluster without affecting the normal functionalities of the network. The CH sets a Time Division Multiple Access (TDMA) schedule for data transmission to prevent any collision of messages. The non-CH node sends its data to the respective CHs through Direct Sequence Spread Spectrum (DSSS) communication, in which each cluster has its unique propagation code to reduce interference. The CHs add received data and send it to BS through a fixed propagation code with CSMA.

Energy-saving is the utmost priority of a sensor network. Different methods have been adopted according to the requirements of the application and user. The characteristics of WSN-based IoT diverge from traditional network paradigms such as the internet and ad hoc networks. Unlike ad hoc networks, WSNs designed for IoT applications confront a slew of additional hurdles, including node density, hardware, communication mode, battery capacity, and computational cost, to mention a few. In an IoT paradigm, nodes are given additional functions and must overcome new hurdles in terms of security, QoS, and energy management. Ring routing, as proposed by Maurya et al. [9], targets to reduce overhead by introducing mobile sink nodes.

These concerns can be alleviated by implementing technology upgrades in traditional WSN methods and schemes. The potential applications of WSN-based IoT required data to be sent to the user with a minimum delay to provide an immediate response to an event, as in the case of tracking. The query response time in a WSN is another key factor in applications such as forest fire detection. Mobile forest fire patrol units can inject queries into the WSN to monitor environmental variables such as temperature and humidity. The WSN must respond to the inquiries as soon as feasible to speed up response to a fire and enhance fire prevention efforts. The monitoring applications require successful data reception by the server irrespective of the transmission time.

WSNs were first used for military and defense applications, further motivating researchers to explore new technologies that could enhance their performance. The main domains of applications of the WSNs are as follows:

Environment monitoring: Since the attention to sustainable energy solutions has increased substantially, smart technologies for energy conservation have gained importance. Monitoring environmental conditions has been one of the popular applications of WSN, which controls and manages services such as air, water, and soil monitoring. This network allows the end-user to gather data at a resolution in areas where accessing data is otherwise difficult.

Home application: With the expansion of WSN-integrated IoT, tiny sensor nodes can be implanted into household equipment such as electric appliances and furniture to access from a remote place [10]. For instance, the nodes can be incorporated into microwave ovens, vacuum cleaners, washing machines, and air conditioners connected to a room server.

Healthcare application: Driven by the convergence of data collection regarding people's health and maintaining accuracy in collected information with minimal cost, WSN for healthcare has evolved in recent years. Researchers have invented a new branch of WSN exclusive for healthcare, Body Area Network (BAN), that provides better treatment at a lesser cost. BAN is administered to monitor patients' physiological, cognitive, and psychological information.

Tracking and military application: Battlefield surveillance was the most critical application of wireless mediums' sensor networks. Characteristics such as self-association, fast organization, and good adaptation to node failures make WSN an extremely desired sensing technique for military applications. Sensor nodes could be located in remote areas to sense and receive data as long as possible that can alert the user about possible blast locations, enemy positions, and chemical attacks.

Transportation: WSN helps drivers alert any congestion or traffic problems by regularly monitoring traffic statistics. Vehicular motions can be tracked instantaneously to avoid blockage or accidents. WSN also reduces the length of the wiring harness and saves time when it comes to the installation cost.

Industrial applications: WSNs offer momentous cost reductions and investments that allow innovative functionalities for industry-based technologies. Continuous environmental sensing, condition monitoring, and process automation are some of the requirements of Industrial WSNs. The solutions need to be simple to use and install yet versatile, with low-cost devices and a long lifetime.

## 2 | Overview

WSN is a bridge element that combines the digital virtual world with the real world. A WSN is formed by collecting many sensors called nodes, which have limited computing, sensing, and communication functions. The sensor nodes are implemented in a geographical area to monitor physical phenomena such as humidity, temperature, and vibrations. The nodes are small devices with essential components, such as subsystems' detection, processing, and communication and a power supply unit, as shown in *Fig. 2*.

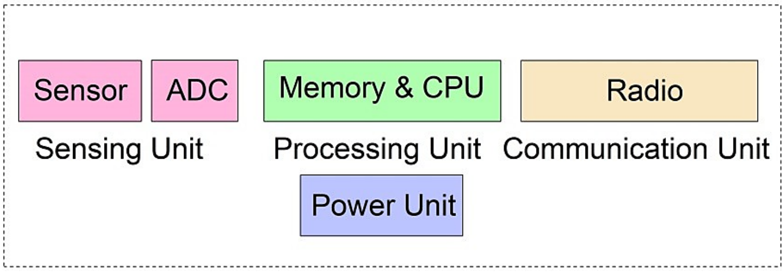


**Fig. 2. Sensor node structure.**

The node architecture shown in Figure 4 has four important units. Sensors and an ADC (analog to digital converter) constitute the sensing unit. The analog signals generated by sensors are converted to their digital form by the ADC. They are then forwarded to the processing unit, which consists of a memory-equipped microprocessor or microcontroller. The processing unit is also responsible for controlling the sensor nodes intelligently. The communication unit handles data transmission and reception via a Radio Frequency (RF) channel. It also connects the nodes to the rest of the network. The most vital component is the power unit, containing a battery that supplies energy to all the system components. Considering the low cost of production and energy consumption, these units are integrated into a small module. There can be other sub-units of the node that are application dependents, such as a power generator, location-finding system, and a mobilizer.

## 2.1 | Energy Consumption in WSN

Researchers consider various approaches to prolong network lifetime in WSNs because sensors become inaccessible after deployment. Hence, energy reduction is an essential criterion in the design process of a sensor network [11]. The protocol stack for WSN is given in *Fig. 3*, with five distinct layers. Energy minimization approaches in WSN can be analyzed in each layer.

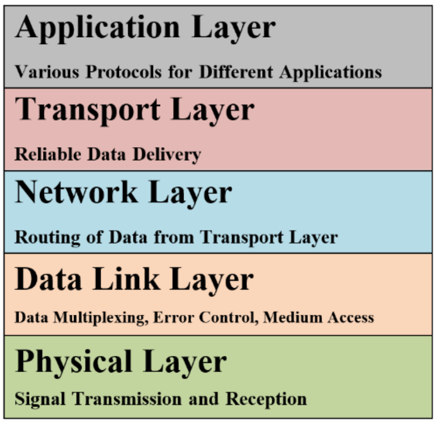


**Fig. 5. Protocol stack for WSN.**

Physical layer: To receive and transfer data collected from the hardware, the physical layer must meet the needs of the receiving and transmitting device. The layer generates and selects the carrier frequency, signal detection, modulation, encryption, and reception. Due to the radio channel's usage for transmission and reception of data, the amount of energy consumed is significant. The channel can be operated in Idle, Active, and Sleep modes. Consequently, the energy consumed can be minimized by shutting off the radio when the channel is idle.

Datalink layer: This layer prevents neighboring signals from interfering with each other in a noisy environment. It should have the appropriate access, error control, multiplexing, and error detection and correction. TDMA-based protocols have been extensively used to avoid packet collisions. Another method for efficient energy management is to reduce the time between transmission of a frame and idle listening.

Network layer: Several approaches, including topology control and routing schemes, have been adopted in this layer, increasing network lifetime. Selecting a suitable topology that provides a well-connected network is often complex. Routing plays a major role in lifetime enhancement by choosing the most energy-efficient path from sensing nodes to the Base Station (BS). Routing techniques can be categorized as location-based, datacentric, hierarchical, mobility-based, and QoS-based. However, hierarchical clustering routing algorithms have proved effective in enhancing lifetime and reducing power consumption by determining the optimal route.

Transport layer: The transport layer regulates traffic flow and distributes network traffic to the distant end. Additionally, traffic is provided with reliability measures. It is divided into sequential segments to forward upper-layer application data, which are then reassembled into data packages. The transport layer can perform flow control, congestion control, and error checking at a higher level.

Application layer: The application layer serves as a connection point between users and the network services dedicated to electronic mail, file transfers, virtual terminals, and file servers. Energy extraction from the environment through solar, thermal, and vibration technologies has evolved as the latest technologies to deal with the energy problem. Energy harvesting is emerging as an efficient technique that recharges sensors after depletion.

## 2.2 | Clustering Strategies in WSN

Because battery power is limited, proper clustering is essential for significantly increasing the network's life span. There are many methods to perform clustering [12]. The clustering strategies in WSN can be classified as shown in *Fig. 4*.

I. Deterministic: Here, the CHs are set at fixed positions in the network. The sensors broadcast a HELLO message to their neighbors, and the node that first receives the maximum number of these messages is elected as CHs and initiates the cluster formation phase. The important attributes of these clustering schemes are node identity numbers (IDs) and node degree (number of neighboring nodes).

II. Adaptive: Instead of random CH selection, adaptive clustering schemes are based on choosing CH considering particular parameters, such as remnant energy, the distance between nodes, energy dissipated in the last round, and distance to BS. Specific combinations of these parameters form the objective function for CH selection that can adapt to the rapid variations in the network. Adaptive schemes can be further categorized as BS-assisted or probabilistic (self-organized) based on who has the power to initiate the CH selection process. Again, considering the parameters for the role of a sensor node, the probabilistic scheme can be classified as resource adaptive and fixed parameters.

III. Hybrid: This clustering strategy considers combined clustering metrics with other architectures to increase energy efficiency.

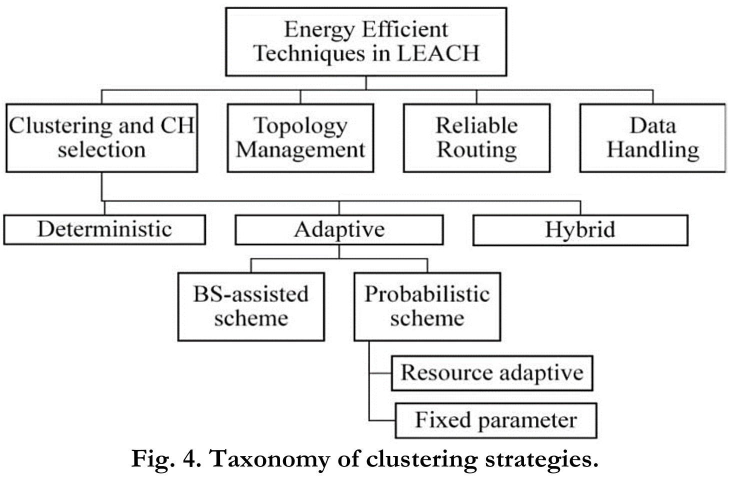


**Fig. 4. Taxonomy of clustering strategies.**

# 3|Classical Routing Protocols

Due to the network being homogenous, nodes will be identical regarding hardware complexity and battery energy. In these networks, static clustering has been used only. This implementation utilizes a single network topology, and it is not complicated. However, the most significant drawback of a homogeneous sensor network is that all network nodes may be able to act as CHs, which means they must have the hardware capabilities to meet the hardware requirements. Since energy is an extremely critical resource, various routing protocols have been proposed to minimize energy consumption at different levels of the network.

## 3.1|Low Energy Adaptive Clustering Hierarchy

LEACH [13] is a TDMA-based Medium Access Control (MAC) protocol that uses a clustering strategy to ensure uniform energy distribution among sensors on the network. The sensor nodes are organized in groups, transmitting important data to the BS through the CH. As indicated in *Fig. 5*, the end-users can receive data through the core network via the Internet. Additionally, the data transmission modes in cluster-based networks can be categorized into three types: intra-cluster, inter-cluster, and long-haul communication. When cluster members transmit data to their respective CHs according to TDMA scheduling, it is called intra-cluster transmission. The data exchange between CHs is managed through inter-cluster transmission. Finally, the CH sends their combined data to the BS using the long-haul transmission method [14].

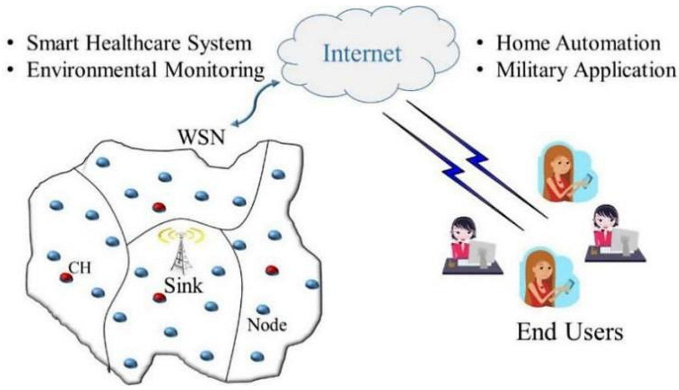


**Fig. 5. System model of a clustered sensor network.**

The LEACH protocol operation consists of several rounds, each consisting of two broad phases: The setup phase and the steady-state phase, as shown in *Fig. 6*.

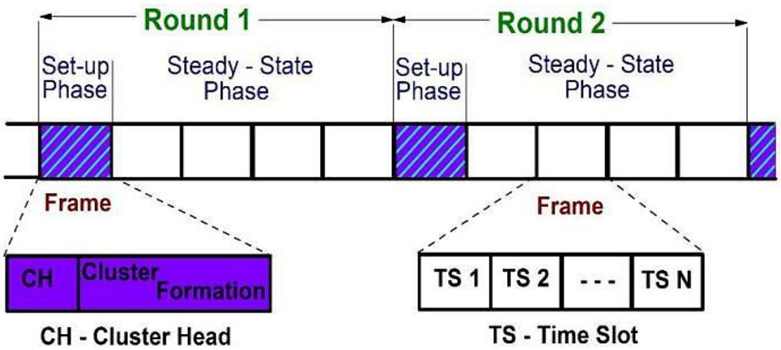


**Fig. 6. Phases of LEACH protocol.**

The initial setup phase consists of clustering and CH selection. Each cluster node is involved by a random value generated in the window [0, 1] during the CH selection process. The node will be declared CH if the number generated is lower than the member node's predefined T(n) value. *Eq. (1)* indicates the value of the T(n) threshold. The CH is also responsible for assigning TDMA schedules to the corresponding cluster members.

$$T(n) = \frac{\int_1 \text{, for all neG}}{0, \text{Othorwise}} \quad (1)$$

where P is the desired percentage of sensor nodes, which may be CH, r refers to the current round, and G is a set of nodes that in the previous 1/P rounds have not been involved in the CH selection. Since only these nodes participate in the CH selection process, which in the last 1/P rounds was not CH, every sensor node of a cluster is, therefore, equally likely to become CH. The energy dissipation between the sensor nodes is thus spread uniformly over the network.

During the steady-state stage, cluster nodes transmit sensed data based on the assigned TDMA schedule to their CH nodes. The nodes can transmit data only during a particular time slot; all other nodes go to sleep state by switching off their radios. In this way, the intra-cluster collision can be avoided. The main objective of the LEACH protocol is to increase energy efficiency by adopting a rotation-based CH selection procedure using a random number.

**Advantages of LEAC**

I. The concept of clustering in LEACH effectively increases the network lifetime.

II. Traffic reduction due to aggregation of data at the CH level.

III. One-hop data routing from node to CH reduces energy consumption.

IV. Global knowledge of the network is not required as LEACH is a distributed protocol, and BS does not control nodes in cluster formation.

V. Intra-cluster collisions are avoided due to the allocation of TDMA slots for data transfer.

**Disadvantages of LEACH**

I. Due to the random selection of CH, the probability of CH election remains the same for each node, indicating that the probability of a node with high residual and low residual energy remains the same. However, if a low residual energy node gets elected as CH, it will eventually limit the network lifetime to a short span.

II. The number of CHs in each round varies randomly in LEACH. Moreover, the position of CH is not fixed and may be centrally or boundary placed. This will eventually contribute to extra energy consumption in cluster-level communication and degrade network performance.

III. CHs are responsible for data collection, aggregation, and transfer to BS. Hence, it is very likely that the CHs will deplete energy faster than other nodes. Moreover, if a CH fails, all the member nodes connected to it will run out of power, resulting in a broken network.

IV. The CHs communicate with the BS in a single-hop mode, making LEACH unsuitable for large-scale WSNs.

## 3.2 | Review of Existing Protocols

### 3.2.1 | Low-energy adaptive clustering hierarchy

I. Mechanism: Describe how LEACH organizes nodes into clusters, with CH selected based on energy levels to minimize energy consumption during data transmission.

II. Advantages: Highlight the reduction in energy usage and extended network lifetime.

III. Limitations: Discuss potential issues like uneven energy distribution among nodes leading to premature death of non-CH.

### 3.2.2 | Stable election protocol

I. Mechanism: Explain how SEP improves upon LEACH by considering node energy levels and establishing a more balanced selection process for CH.

II. Advantages: Emphasize enhanced stability and prolonged operational time for the network.

III. Limitations: Mention challenges like increased overhead and potential delays in data transmission.

#### 3.2.3 | Threshold-sensitive energy efficient network protocol

I. Mechanism: Describe TEEN's approach to data transmission, where nodes transmit data only when certain thresholds are met, effectively reducing unnecessary transmissions.

II. Advantages: Discuss significant energy savings and reduced data traffic.

III. Limitations: Point out the potential for data loss due to the strict thresholds that may prevent transmission when conditions are not met.

### 3.3 | Comparative Analysis of Protocols

I. Performance metrics: Compare protocols based on energy consumption, data delivery ratio, latency, and network lifetime.

II. Graphs and tables: Include visual representations of data from studies and simulations that illustrate each protocol's strengths and weaknesses.

III. Key insights: Summarize findings on which protocols perform better under specific conditions and why.

### 3.4 | Emerging Trends and Future Directions

I. Hybrid approaches: Discuss the potential for hybrid protocols that combine features from multiple protocols for improved performance.

II. Integration with AI and machine learning: Explore how advanced algorithms could optimize energy use and enhance decision-making processes in WSNs.

III. Security considerations: Highlight the need for energy-efficient security protocols to protect data without significantly increasing energy consumption.

## 4 | Methodology

### 4.1 | Simulation Setup

Environment: Describe the simulation environment for testing the protocols, such as MATLAB, NS-2, or OMNeT++. Specify why this environment is chosen (e.g., ease of use, flexibility).

Network topology: Define the network layout, including the number of sensor nodes, their placement (random vs. grid), and the position of the sink node. Discuss the impact of topology on energy consumption and data transmission.

Node specifications: Detail the specifications of the sensor nodes, including:

I. Battery capacity (e.g., mAh).

II. Energy consumption rates for various states (idle, transmitting, receiving).

III. Data payload sizes and the range of communication.

### 4.2 | Protocol Implementation

Protocol selection: List the protocols being tested (e.g., LEACH, SEP, TEEN, and the proposed framework). Briefly explain the implementation details for each protocol in the simulation.

Parameters for custom protocol: If proposing a new protocol, outline the design principles, including:

I. Cluster formation criteria.

II. Data aggregation techniques.

III. Energy harvesting integration (if applicable).

IV. Adaptive transmission strategies based on node energy levels.

## 4.3 | Performance Metrics

Energy consumption: Measure the total energy used by the network over a defined period and analyze how different protocols affect energy efficiency.

Data delivery ratio: Calculate the ratio of successfully delivered packets to the total packets sent to assess network reliability.

Latency: Measure the time taken for data to travel from the sensor node to the sink node, highlighting the impact of different protocols on transmission speed.

Network lifetime: Define network lifetime as the time until the first node dies and the overall operational time until a significant portion of nodes is non-functional.

## 4.4 | Data Collection and Analysis

Simulation runs: Perform multiple simulation runs for each protocol to account for variability and ensure statistical significance.

Data analysis tools: Describe the tools or software used for data analysis, such as statistical software (e.g., R, Python) for processing simulation results and generating visualizations.

Visualization: Include graphs and charts illustrating the performance metrics across different protocols, helping visualize comparisons and trends.

## 4.5 | Limitations of the Methodology

Assumptions: Acknowledge any assumptions made during simulations (e.g., constant environmental conditions, uniform node distribution) and their potential impact on results.

Scalability: Discuss the limitations of the simulation in terms of scalability to real-world scenarios and how these might be addressed in future research.

# 5 | Conclusions

Routing techniques differ depending on the applications and dependability of the node's hazardous condition. The robustness of the routing strategy is dependent on the network architecture and design of the WSN. The design challenges for routing protocols in WSNs are outlined. Numerous clustering strategies are highlighted and projected with comprehensive routing techniques, improving performance. Fully demonstrated and tested LEACH extends network longevity while eliminating intra-cluster collisions. Researchers have mostly focused on enhancing the CH selection criteria, which have been shown to save energy more efficiently. Owing to challenges such as power, network scalability, security, and packet-delivery ratio, researchers have modified the LEACH protocol over time. This paper intends to present a more comprehensive survey of LEACH-based classical and bio-inspired protocols to help researchers understand routing protocols with diverse architectures, novel strategies, and enhanced performance. The LEACH-MAC protocol can be used in networks where life is a significant issue. I-LEACH protocol can be beneficial on large-scale as well as small networks. Similarly, the LEACH-KH protocol yields a high PDR and can be adopted in networks where reliability is the prime factor.

Research possibilities in real-time applications still exist that solve difficulties with video and image sensors. The network must include node mobility because stationary sensor nodes cannot match demand. The primary issue is that the frequent updating locations of the sensor nodes and BS's position deplete the network energy. As a result, the overhead of mobility and topological fluctuations necessitates the invention of unique protocols. Additionally, the wireless connection technology used in a WSN commonly facilitates various cyber-attacks when transferring data packets. The randomly moving sensors provide hackers with several opportunities to launch denial-of-service attacks, thus decreasing the WSN's security. Despite significant research efforts and advances in recent years, many unanswered research concerns with routing in WSNs need to be addressed. The development of cryptographic methods for authenticated encryption in WSNs that enable privacy and network security can be explored.


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# Author Contribution

Anish Bhargav was solely responsible for the conception, design, execution, and analysis of the research presented in this paper.

The author conducted all aspects of writing, data collection, and interpretation.


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This research received no external funding.


# Data Availability

The data used and analyzed during the current study are available from the corresponding author upon reasonable request.

# Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

If necessary, these sections should be tailored to reflect the specific details and contributions.

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