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Optimizing Wireless Sensor Network Lifespan Through Advanced Clustering in PDBAC-LEACH

S. Mahmoud Taheri[1*], Weam Saadi Hamzah Alalwany[2,3], Janan Farag Yonan[2,3]

[1] School of Engineering Science, College of Engineering, University of Tehran, Tehran 1417614411, Iran
[2] Department of Information Technology, University of Tehran, Tehran 1417614411, Iran
[3] University of Information Technology and Communications (UOITC), Baghdad 10001, Iraq

Corresponding Author Email: sm_taheri@ut.ac.ir

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ABSTRACT

Wireless sensor networks (WSNs) have tremendous importance in numerous application fields including military, robotics, agriculture and environment. These networks require precise energy control and consistent message delivery which has been the major concern in enhancing WSN and reducing energy use. Many routing algorithms have been developed to fulfill these needs; while some use a hierarchical model, others use clustering. Still, most of the current algorithms are less effective in considering some aspects that may contribute to the increase of network lifetime. Therefore, this paper proposes the advanced framework, PDBAC-LEACH, developed from the LEACH protocol. The primary focus of the PDBAC-LEACH protocol is to maximize the lifespan of the WSN while at the same time offering equal energy utilization by all nodes in the network. The proposed method used in the selection process of which CHs will participate in the next round involves an energy level check as well as or distance of CH to the base station. The nodes capable of CH selection with sufficient energy to provide their neighboring nodes with energy are to be selected first while the selected CH selection scheme not only considers energy in a decreasing order but also distance from the base station in an increasing order. Whenever compressed data is received Elevated CHs employs multi-hop communication to forward the data towards the base station. All these findings are simulated in MATLAB R2020a which confirms that PDBAC-LEACH has a better performance than the traditional LEACH protocols in network lifespan hence its effectiveness in prolonging the lifespan of WSNs.

1. INTRODUCTION

Wireless ad-hoc and sensor networks face constraints due to limited energy, computation, storage, and communication bandwidth. Despite these limitations, they are indispensable for applications such as health monitoring, environmental sensing, and structural monitoring [1]. Research on wireless ad-hoc and sensor networks predominantly focuses on strategies to enhance battery lifespan and energy efficiency [2]. Each sensor device has a finite battery capacity, which is critical in scenarios where recharging is impractical or impossible, such as in remote or hazardous locations.

Recent advancements in wireless ad-hoc and sensor network research have led to the development of low-cost, energy-efficient devices. However, recharging small, battery-powered wireless sensors remains a significant challenge in real-world applications. These sensors are often deployed in areas where human intervention is either difficult or dangerous, necessitating autonomous operation to detect and collect data without manual recharging [3]. The reliability and longevity of a network are paramount, particularly in applications that demand continuous monitoring over extended periods. In wireless ad-hoc and sensor networks, clusters of sensor nodes transmit data to a nearby base station (BS) using multi-hop protocols. The long-term survivability of these networks heavily depends on energy availability. The lifespan of a WSN is a critical metric for evaluating its performance, as it is often determined by the residual energy of the sensor devices [4].

The CH is responsible for collecting data from the other nodes in the cluster, known as "member nodes," and then relaying this information to the BS using either direct hop or multi-hop communication. Clustering facilitates both intra-cluster and inter-cluster data transmission, thereby optimizing energy usage and improving network efficiency [5].

Ad-hoc and sensor networks can comprise thousands of nodes, and densely distributed networks require significant energy for data exchange, especially in the presence of uncertainties and failures. Network longevity is influenced by several factors, including inter-node communication, the efficiency of cluster heads, node algorithms, and the overall network architecture balance. A well-balanced network comprises nodes with similar energy levels, but achieving sustainable energy conservation remains challenging. High-energy nodes designated as cluster heads act as gateways, handling multiple tasks such as pathfinding, data aggregation, error tolerance, and end-to-end communication, thereby enhancing the energy efficiency of the network [6, 7].

Moreover, clustering helps in managing the scalability of the network. As the number of sensor nodes increases, efficient clustering ensures that the network can handle large volumes of data without significant degradation in performance [8-10]. This is particularly important in applications where real-time data processing and transmission are critical. By implementing advanced clustering techniques, it is possible to enhance the robustness and reliability of the network, ensuring consistent performance even under varying environmental conditions.

The new technologies introduced in the PDBAC-LEACH protocol are improvements achieve over conventional clustering protocols [11]. As shown in previous approaches, PDBAC-LEACH selects cluster heads by taking into consideration the amount of residual energy in a node in addition to the distance to the base station for equal energy distribution throughout the network and optimal use of energy. Employing this method of choosing two criteria as opposed to one also greatly increases the lifespan of network by eliminating those nodes with low energy levels from becoming cluster heads and also ensures equal distribution of energy usage [12]. Secondly, PDBAC-LEACH achieves multi-hop communication for data transmission whereas the other protocols dealt with direct transmission only; making PDBAC-LEACH even more energy efficient.

In brief, while wireless ad-hoc and sensor networks face significant challenges due to their inherent limitations, innovative approaches such as clustering can significantly improve their energy efficiency and lifespan. This paper explores the Probability Density Based Adaptive-LEACH (PDBAC-LEACH) protocol, which aims to address these challenges by optimizing energy consumption and enhancing the overall performance of wireless sensor networks. Figure 1 illustrates the basic components and structure of a WSN, including sensor nodes, cluster heads, and the base station.

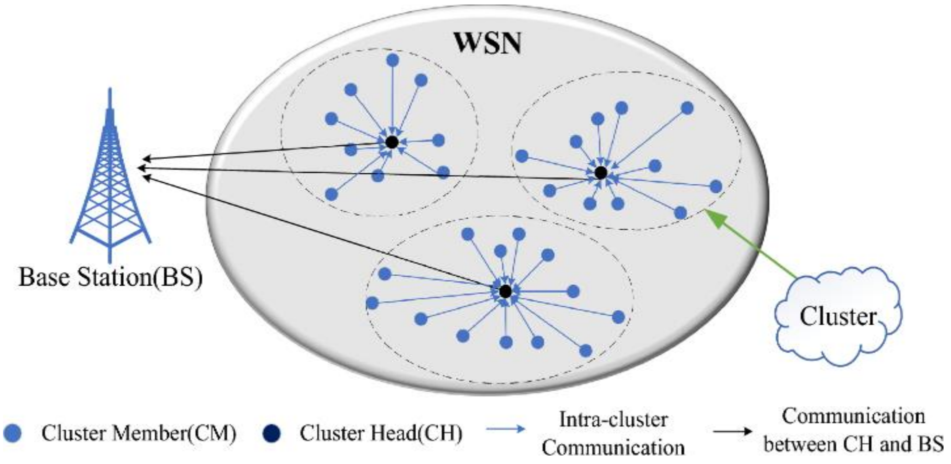

Figure 1. Overview of WSN architecture

Hence, WSN networks are crucial in various sectors due to their unique capabilities, especially in environments where traditional networking fails. Despite challenges like limited energy, computation, and storage capacities, their importance cannot be overstated. Following, are some motivations and applications that drive the development and utilisation of these networks:

1.1 Environmental sensing

WSNs play an increasingly important role in environmental sensing, acting as essential instruments for managing ecosystems and conserving natural resources. These networks allow for precise and ongoing monitoring of many environmental factors without requiring invasive personal intervention, making them well-suited for use in distant and delicate ecological areas [13].

In wildlife and habitat monitoring, WSNs offer a non-invasive means of collecting data that is vital for the preservation and study of biodiversity. These networks are deployed across vast areas where manual data collection would be impractical or disruptive to the habitat. Sensors can monitor a range of ecological factors, including temperature, humidity, soil moisture, and the presence of certain gases, providing researchers with real-time data that is essential for tracking animal movements, studying behavioral patterns, and understanding ecological dynamics [14, 15].

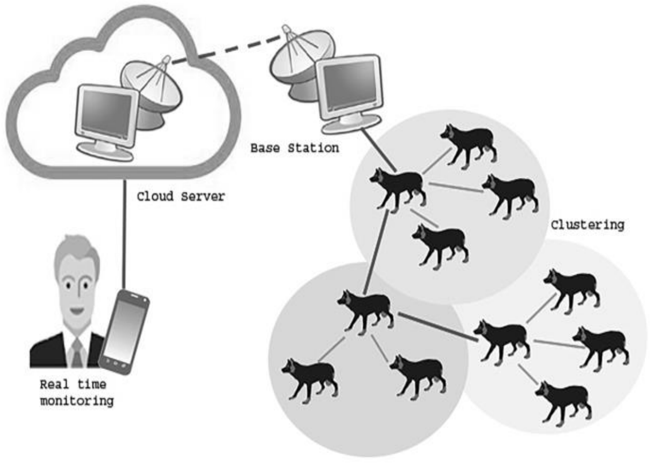

Figure 2. Deployment of WSN in a wildlife habitat [16]

Sensor nodes in wildlife reserves and national parks monitor endangered animals and their ecosystems. This data helps conservationists make informed judgments and detect early symptoms of environmental degradation or invasive species [17]. Figure 2 depicts sensor nodes in a forest sending data to a central base station for analysis.

By delivering accurate and timely environmental pollutant data, WSNs aid pollution tracking. Sensor networks with specialized sensors can detect and analyze particle pollution, hazardous gasses, and volatile organic compounds in real-time. In urban and industrial locations, quick pollution detection is essential to reduce health hazards and comply with environmental rules [18, 19]. In metropolitan areas, WSNs may monitor air quality continuously at strategic points. These sensors identify pollution hotspots and trends, allowing authorities to take targeted measures to limit pollutant emissions. WSNs monitor emissions in industrial areas to ensure compliance with environmental requirements and trigger fast corrective action if pollution levels are exceeded [20]. Figure 3 shows several sensor nodes in high-traffic or industrial sections of a city. Nodes capture air quality data, which a central monitoring system displays.

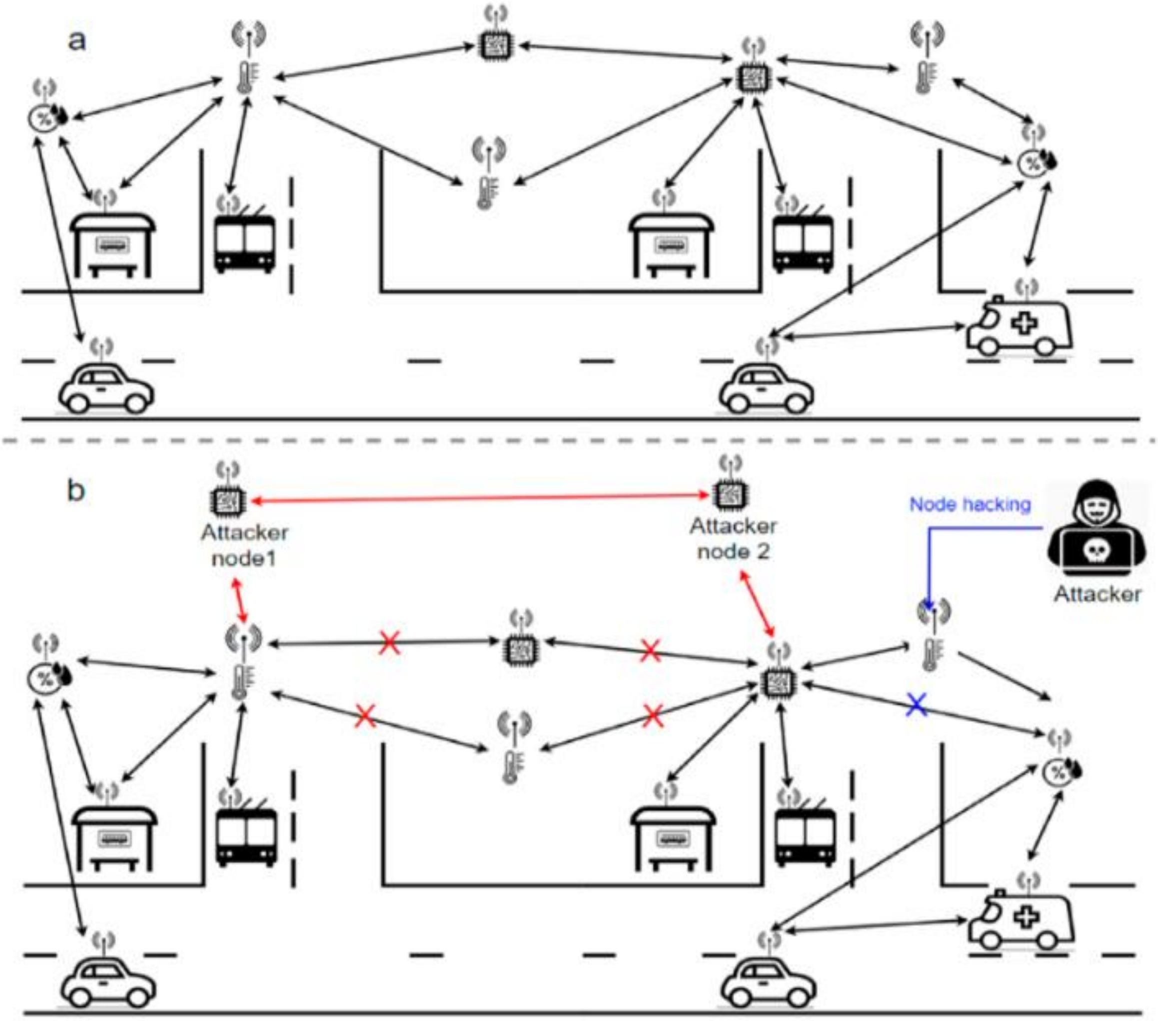

Figure 3. WSN monitor air quality in urban area [21]

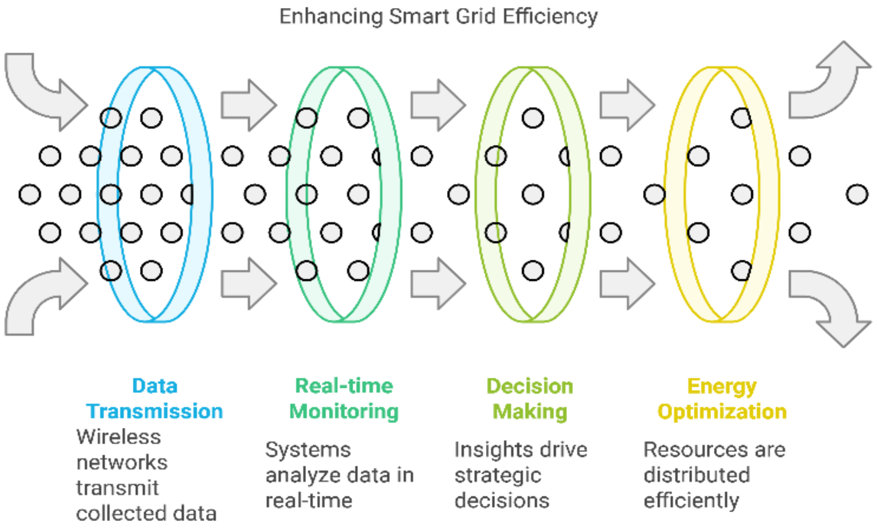

Figure 4. WSN in a smart grid

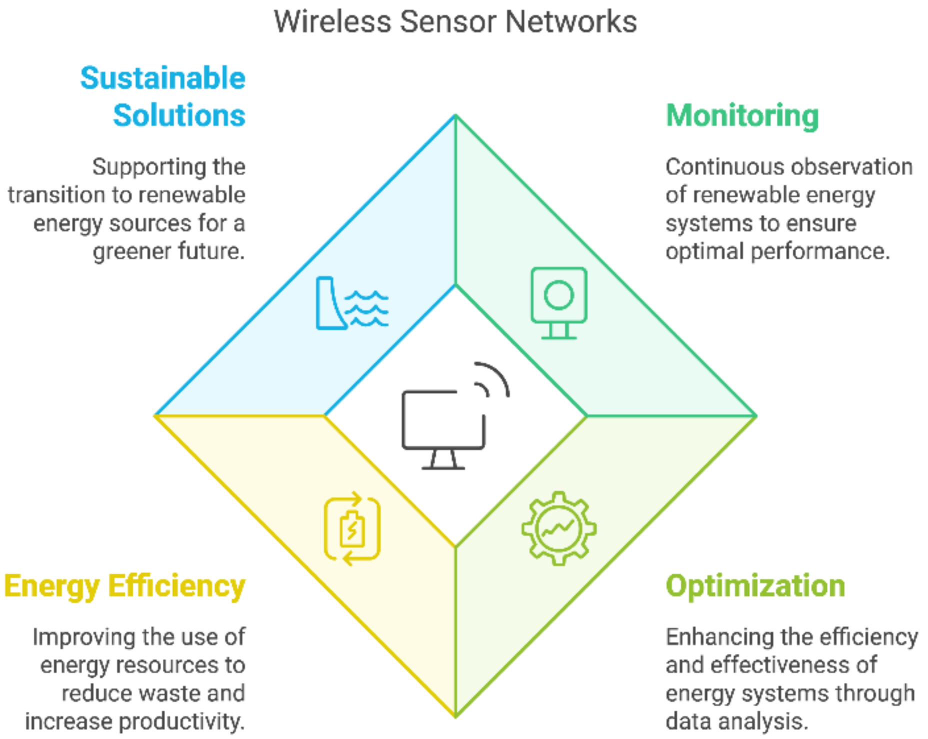

Figure 5. WSN renewable energy sources

1.2 Energy efficiency

WSNs provide the ability to collect and transmit data in real-time, allowing for intelligent management of resources and enhancing energy efficiency in various sectors. WSNs are having a significant effect on the operation and management of smart grids as well as the monitoring of renewable energy sources. Smart grids incorporate sophisticated communication and information technology to modernize conventional electrical networks. This transition utilizes WSNs to enhance energy efficiency and enhance the reliability of the grid. Sensor nodes deployed across the entire grid monitor energy use, grid status, and environmental factors. Real-time data enables the timely adjustment of energy distribution to efficiently satisfy demand and minimize energy losses [22, 23].

Sensors have the capability to notify the control center about power grid failures and faults, hence reducing the amount of time that the system is not operational. They oversee grid components such as transformers and substations in order to forecast maintenance needs and mitigate issues. Smart meters used in residential and commercial buildings transmit data about energy consumption to utility companies. This allows for better management of energy demand and provides consumers with complete information about their energy usage [24]. Figure 4 depicts the placement of sensor nodes in substations, transformers, and residential areas within a smart grid. These sensor nodes transmit data to a central control system, where it is analyzed and managed in real-time.

Transitioning to wind and solar electricity is essential for achieving sustainable development. WSNs offer uninterrupted performance and output data for monitoring and controlling renewable energy facilities. The energy production, operational state, and environmental aspects of wind turbines and solar panels are measured by sensor nodes [25, 26]. Sensors are used to monitor the speed and direction of the wind, as well as the health of the turbine, to maximize performance and detect any potential issues at an early stage. Sensors gauge the temperature of solar panels, the amount of sunlight they are exposed to, and the efficiency with which they convert energy. This data is essential for assessing the performance and longevity of renewable energy installations. Data analysis enables operators to make informed decisions regarding maintenance schedules, system upgrades, and energy storage choices, thereby enhancing the efficiency and reliability of renewable energy sources [27]. Figure 5 shows sensor nodes on wind turbines and solar panels sending performance information to a central monitoring system for analysis and optimization.

1.3 Agricultural applications

WSNs have transformed agriculture by giving accurate, real-time data to help farmers make decisions and maximize resource use. WSNs are used in precision farming and livestock monitoring. Agricultural uses WSNs to accurately monitor and regulate environmental and crop conditions. Sensor nodes on farms measure soil moisture, temperature, humidity, and crop health. The data is sent to a central system for analysis to yield actionable insights [28, 29]. Soil moisture sensors can detect dry or wet sections of the field, allowing precision watering that conserves water and boosts crop output. Temperature and humidity sensors forecast pest and disease outbreaks, allowing prompt crop protection. Crop health sensors can also detect nutrient deficits and water stress early, allowing targeted fertilization and watering [30]. Precision farming with WSNs boosts production, sustainability, and resource efficiency. Data-driven decisions by farmers can decrease waste, save money, and boost yields, improving food security and the environment. Figure 6 shows farm-wide sensor nodes monitoring soil moisture, temperature, humidity, and crop health. These nodes' data transmission channels to a central analysis system are shown.

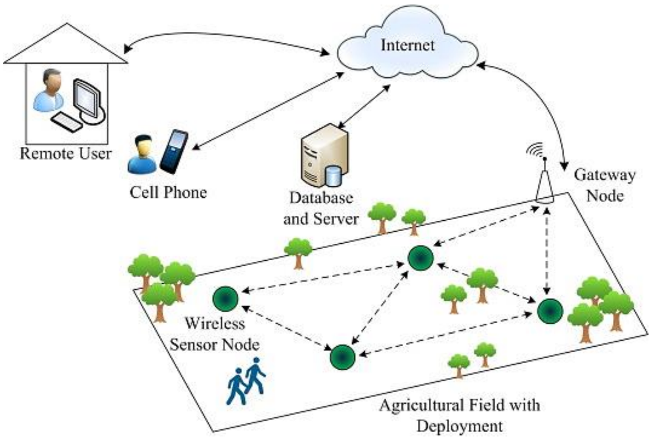

Figure 6. WSN in high-performance farming [30]

WSNs assist in monitoring the health and movement of cattle. Livestock sensors can quantify body temperature, heart rate, and activity levels. Such as data are essential for monitoring the overall health of the herd, detecting illnesses, and ensuring the well-being of the animals [31, 32]. Temperature sensors in animals can identify elevated body temperature, indicating the presence of a fever, which can be an indication of infection. This enables prompt veterinary intervention. Activity sensors can identify alterations in movement patterns that may indicate changes in health or behaviour. GPS-enabled devices can be used to monitor livestock, minimizing losses and ensuring they graze only in allowed areas [33]. Monitoring cattle with WSNs enhances herd management by providing up-to-date data that may be used for making informed decisions. It provides disease prevention, reduces death rates, and enhances animal efficiency. Figure 7 depicts the process of livestock sensors gathering health and movement data, which is then transmitted to a central monitoring system for analysis.

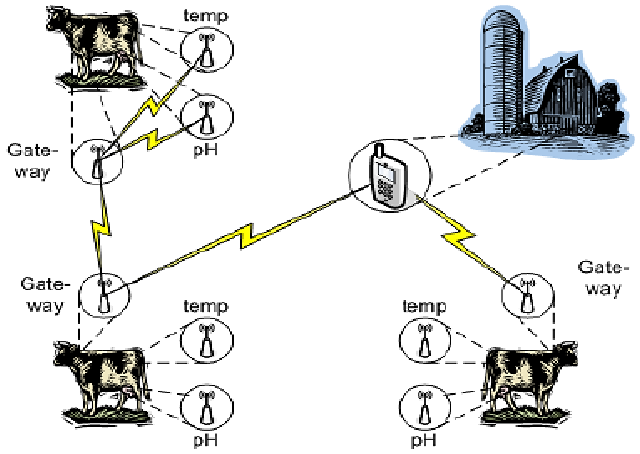

Figure 7. WSN for livestock monitoring [33]

Therefore, WSNs are bringing about a significant transformation in multiple industries, such as smart grids, renewable energy monitoring, precision farming, and animal monitoring [34, 35]. WSNs facilitate the collecting of data in real time, allow for flexible allocation of energy, and enable quick identification of faults. These capabilities contribute to the development of a power infrastructure that is both sustainable and resilient [36, 37]. In addition, they improve the efficiency and dependability of wind turbines and solar panels by the continual monitoring of environmental conditions and operational parameters. WSNs offer detailed and reliable data for precision farming, empowering farmers to make well-informed choices that maximize resource utilization and enhance crop productivity. WSNs are used in livestock monitoring to monitor the health and movement patterns of animals. This allows for the timely detection of health issues and enables optimal management of the herd [38, 39]. The PDBAC-LEACH protocol aims to improve energy efficiency and reliability in WSNs by selecting cluster heads that have high residual energy and are close to the base station. This protocol improves the durability and efficiency of WSNs, hence enhancing their effectiveness in various applications. The adaptability and effectiveness of WSNs in these industries highlight their ability to bring about significant changes. Utilizing advanced protocols such as PDBAC-LEACH is crucial in fully utilizing the potential of WSNs, enabling vital applications, and fostering innovation in many industries.

2. RELATED WORKS

Recent advancements in Wireless Sensor Networks (WSNs) have emphasized the importance of energy-efficient clustering protocols to extend network lifespan and enhance performance. A comprehensive survey by Jones and Smith [40] explored various hierarchical clustering algorithms designed to improve the energy efficiency of WSNs. This study provides an extensive review of different clustering techniques and their impact on network longevity, establishing a foundational understanding of the strategies that have been developed to date.

In 2019, a novel energy-efficient clustering protocol was introduced, which focused on optimizing cluster head selection and enhancing data transmission reliability [41, 42]. This protocol aimed to significantly extend the network's lifespan by employing multi-hop communication and prioritizing energy efficiency. The proposed approach demonstrated notable improvements in network performance, highlighting the critical role of strategic cluster head selection in conserving energy.

Further advancements were made in 2020 with the enhancement of the traditional LEACH protocol using fuzzy logic [43]. This study incorporated fuzzy logic to make more informed decisions during cluster head selection, taking into account multiple parameters. The fuzzy logic-based enhancement resulted in improved energy efficiency and overall network performance, showcasing the potential of intelligent algorithms in refining existing protocols.

The focus on adaptive strategies continued with the introduction of an adaptive clustering protocol for energy-efficient WSNs in 2021 [44]. This protocol adjusted cluster sizes and cluster head rotation based on the energy levels of sensor nodes, aiming to balance energy consumption across the network. By dynamically adapting to the energy conditions of individual nodes, this approach effectively prolonged the operational life of the network, underscoring the importance of adaptability in energy management.

In 2022, research delved into dynamic clustering techniques that responded to changing network conditions and energy levels of sensor nodes [2]. These methods were designed to reduce energy consumption and enhance data transmission efficiency. The dynamic clustering approach highlighted the need for responsive and flexible protocols that can adjust to the evolving states of the network, ensuring sustained performance and energy conservation.

Based on such researches, a recent study introduced a probabilistic-based energy-efficient clustering protocol for WSNs [45]. This protocol selected cluster heads based on residual energy and their distance to the base station. By distributing energy consumption more evenly, this probabilistic approach aimed to improve network longevity. The study demonstrated the effectiveness of probabilistic methods in achieving balanced energy usage and extending network life.

The application of advanced techniques was further explored in 2024 with the use of machine learning algorithms to optimize clustering in WSNs [46]. This research investigated how machine learning could predict optimal cluster head nodes, leading to better energy management and an extended network lifespan. The integration of machine learning showcased the potential for predictive and intelligent systems to revolutionize clustering protocols, providing a robust solution for enhancing the efficiency and durability of WSNs.

These related works collectively highlight the evolution of energy-efficient clustering protocols in WSNs from 2018 to 2024. Each study contributes to a deeper understanding of how to optimize energy consumption, improve data transmission reliability, and ultimately extend the lifespan of WSNs through innovative approaches and advanced technologies. To highlight the advancements made by PDBAC-LEACH, Table 1 provides a comparison with existing clustering protocols such as LEACH, LEACH-C, and HEED. The comparison focuses on key aspects such as energy efficiency, reliability, and suitability for real-world applications, showing how PDBAC-LEACH addresses the limitations of these protocols.

Table 1. Comparison of PDBAC-LEACH with existing clustering protocols

Protocol	Selection Criteria	Energy Efficiency	Reliability	Application Suitability
LEACH	Random CH selection	Low – Random CH selection leads to uneven energy usage	Low – No consideration of node energy, leading to early node deaths	Limited – Suitable for small networks only
LEACH-C	Centralized CH selection based on energy and location	Moderate – Optimized cluster formation but centralized	Moderate – Centralized control limits scalability and introduces single-point failures	Limited – Requires centralized infrastructure
HEED	Residual energy and communication cost	Moderate – Improved over LEACH by balancing energy usage	Moderate – Focuses on intra-cluster cost minimization	Suitable for moderate-scale deployments
PDBAC-LEACH	Residual energy and distance to BS	High – Dual-criteria CH selection ensures balanced energy consumption	High – Multi-hop communication and adaptive cluster resizing improve robustness	Highly Suitable – Effective for large-scale networks and dynamic applications

3. METHODOLOGY

This section describes the methodology of the proposed PDBAC-LEACH protocol. Initially, we delineate the sequence of steps that conform with protocol, and subsequently, we illuminate the structure of our approach. Following that will discuss the particular details of the parameters related to the clustering and hierarchical approach that will be utilized in the analysis.

In WSNs, the random and dynamic selection of cluster heads (CHs) leads to specific nodes depleting their stored energy more quickly than others. The gathering of data and its transmission to the base station (BS) are exclusively performed by the cluster head (CH) in a cluster. Consequently, this function uses significantly more power than a typical sensor node.

PDBAC-LEACH selects cluster heads (CHs) based on residual energy and distance to the base station to ensure balanced energy usage and network longevity. The selection process involves a combination of energy and distance metrics, with nodes with higher residual energy and shorter distances to the base station given preference. This strategy prevents nodes with lower energy from being overburdened with CH responsibilities. The precise training approach of the suggested protocol is illustrated in Figure 8.

To quantify the CH selection process, the following equations are used:

(1). Threshold energy function for CH selection in Eq. (1):

$$Ti = P \cdot \frac{Eres(i)}{Eavg} \tag{1}$$

where, Ti is the threshold for node i; P is the probability of being selected as a CH; $Eres(i)$ is the residual energy of node i; $Eavg$ is the average energy of all nodes in the network.

(2). Distance-based weighting in Eq. (2):

$$Wi = \frac{1}{dBS(i)} \tag{2}$$

where, Wi is the weight assigned to node i based on its distance to the base station; Wi is the distance from node i to the base station.

(3). Combined metric for CH selection in Eq. (3):

$$Si=Ti\times Wi \tag{3}$$

where, a node i is selected as CH if Si is among the highest values in the network.

Simulation Setup:

The simulation of PDBAC-LEACH was conducted in MATLAB R2020a.

Key parameters include:

Number of nodes: 100.

Area of deployment: 100m×100m.

Initial energy level: 0.5 J per node.

Initialization, maintenance, and distribution are the three usual steps of a clustering process in a simulation model. As part of the group-up step, the cluster needs to be formed before the communication process can begin. During this period, which is sometimes called the "offline" or "passive" phase, the only packets being sent are control packets. In addition, the fixed as well as routing stages of operation are when data arrives at the network for aggregation and routing. As well as Figure 9 displays the above 3 steps.

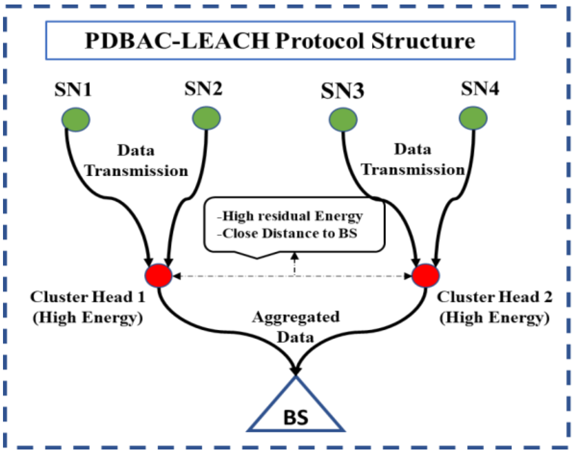

Figure 8. PDBAC-LEACH protocol structure

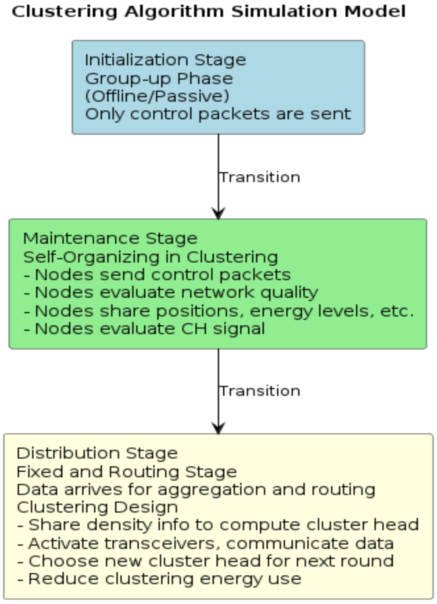

Figure 9. Clustering algorithm simulation model

A. Clustering algorithm simulation model

1) Initialization, maintenance, and distribution stages are 3 stages of clustering are (initialization, maintenance, as well as distribution).

2) Clustering- up phase, is the "offline" or "passive" phase, which is the initial stage.

3) The fixed as well as routing step involves data arriving at the WSN for aggregated besides routed.

B. Self-organizing in clustering

1) To verify their existence to the sensor, nodes transmit control messages to the network.

2) The Nodes evaluate network quality and compute aids in decision-making.

3) Sharing node positions, energy levels, and other info enables the network to begin to self-organize.

4) Nodes evaluate a CH signal after broadcasting data.

C. Clustering design

1) Nodes collaborate by exchanging density data with node (dm) to calculate the cluster head.

2) Nodes activate transceivers and communicate data using maximum-information-density nodes.

3) Nodes choose their new cluster head by picking the next round's node density.

4) Reducing clustering energy use extends network lifespan.

The threshold energy function for cluster head generation determines if a node will take over as cluster leader in the subsequent cycle Eq. (1). It involves the fraction of nodes that should be cluster heads (P_e), the current round number (R), a set of nodes that have not been cluster heads in previous rounds (N, which is $1–P_e$), the initial energy of the node (E_i), and the current residual energy of the node at round R (E_{res}). The ratio of E_{res} to E_i evaluates which nodes have sufficient residual energy to be considered as cluster heads. The cluster head selection criteria compare the energy levels of nodes to select those with higher energy to become cluster heads (Eq. (4)). Nodes evaluate their energy levels against a threshold value $S(j)$; if a node's energy is less than $S(j)$, it becomes a cluster head in the next cycle. Root CH Selection Criteria are involved in Eq. (5). Once a cluster is finished, CHs construct TDMA tables according to the number of nodes and their distance from the base station. A root CH is selected if its residual energy is higher than the average energy of CHs and its distance to the base station is lower than the average distance of both CHs and BSs. Eq. (6) involves Node Density for Cluster Head Election, where nodes choose their cluster head based on the highest node density for the next round, helping to reduce clustering energy and prolong network lifespan. Figure 10 illustrates the architecture of the network model, showing how nodes organize into clusters and communicate. Key elements include node self-organization, where nodes authenticate with the sensor and send control packets to the network, arrange tables, and make decisions based on overheard communication. During the Cluster Head (CH) Election, nodes share density information to determine the cluster head, with nodes having higher residual energy being preferred. In TDMA Scheduling, once clusters are formed, CHs create TDMA tables based on node count and distance, allowing each sensor node to communicate with the CH during its assigned time slot. The communication process involves sending data via nodes with maximum information density, with clusters reducing energy consumption to prolong network lifespan. These elements work together to ensure efficient communication and energy utilization in the network.

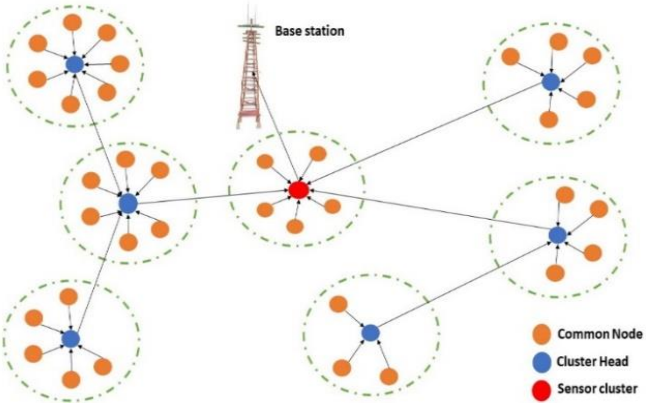

Figure 10. Suggested model of PDBAC-LEACH

$$S(j) = \left\{ \frac{P_e}{1-P_e * \left(R\% \left(\frac{1}{P_e} \right) \right)} * \frac{E_{res}}{E_i}, J \in N \right. \tag{4}$$

where, $E_{res} = E_0 - E_{cons}, E_{cons} = E_{Tx} + E_{Rx}$.

$$E_{ave} = \frac{\sum_{C=1}^{CL} E_{res}(C)}{CL} \tag{5}$$

$$d_{ave\ to\ BS} = \frac{\sum_{C=1}^{CL} d_{to\ BS}(C)}{CL} \tag{6}$$

Each CH's energy level at the end of the current round is shown by a sink. Basic Service (E_{res}) in a hierarchical network, regular nodes transmit data from their immediate environments to the next-level CH during communication. The CH is the sole device that can talk to the sink. Table 2 contains information about the transactions, Table 3 displays the parameters used in the simulation, and Figure 11 illustrates the flowchart of the proposed model.

Table 2. Transactions details

Details	Illustration
BT	Range of broadcast transitions
RN Info	Information of the broadcast receiving node
Decision-Making Node	The ID of the DMN
NC	Count of neighbouring nodes
ID	The ID of the transition node
Seq. Number Postfix	Postfix counter of the packet sequence number

Table 3. Simulation parameters

Parameters	Values
Zone of sim	100m×100m
Simulator program	MATLAB
Time of sim	Three mints
WSN nodes	Random distribution
Node type	Heterogeneous
Number of the nodes	Ten in every cluster
Number of the (C)	One – Nin cluster
Max number of packets	One hundred
Probabilities of cluster	Ten per cent
Initial potential energy	0.5 J
DAE	Five n J/bit
E_{fs}	10 p J/bit/ m^2
E_{mp}	0.0013 p J/ bit/ m^4
The size of the packet	4000 bits
No. of round expending	1728

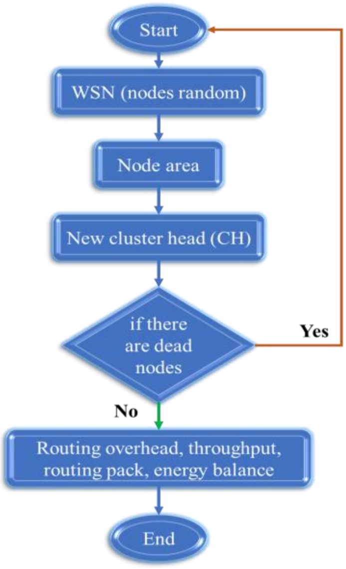

Figure 11. PDBAC-LEACH model

4. RESULTS AND DISCUSSION

The simulation results offer an approximate performance evaluation of the proposed protocol, PDBAC-LEACH. This simulation was carried out using the MATLAB programming environment. In this experiment, we simulated a wireless sensor network (WSN) composed of 100 nodes randomly distributed across the network. For each packet, source and destination IP addresses were generated randomly to mimic realistic network traffic. The simulation starts by tallying up all the nodes in the nine network regions. Figure 12 illustrates an example of the BS and CHs within a network. It provides insight into their role and behavior, highlighting their positions and connections within the network. The BS is centrally located, while CHs are distributed around it, representing a typical network setup.

While, Figure 13 depicts the spatial distribution of nodes and sensors, randomly deployed in a 100m×100m area. In this visual representation, black stars denote sensor positions, while circles represent node locations. The random deployment showcases the spatial dynamics and initial setup of the network components, aiding in understanding their distribution and interaction.

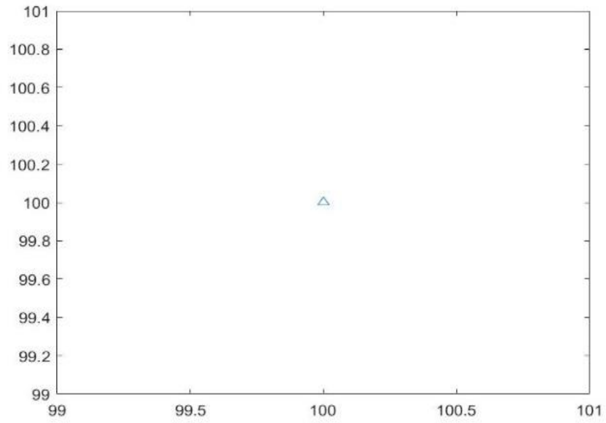

Figure 12. Sample of BS and CH

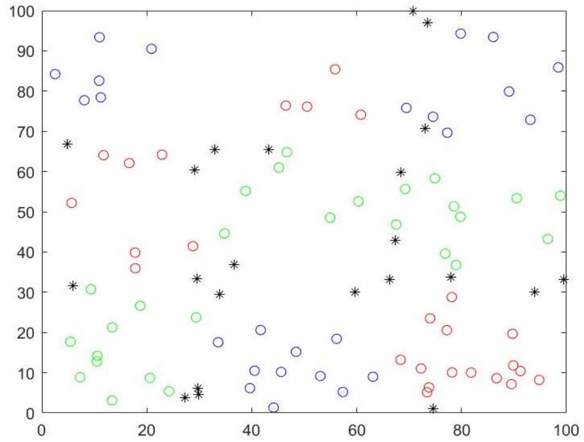

Figure 13. WSN sensors and nodes in random

The selection of CH from a pool of 100 nodes is the next stage after recognizing the sensors and their nearby nodes and creating the path tables for the suggested protocol (PDBAC-LEACH), the goal of which is to max the energy savings in the WSN. This protocol is designed to minimize energy depletion across the network. Table 4 provides details of the nine cluster heads selected within the network. This process ensures that the optimal paths are utilized, significantly reducing the overall energy consumption and enhancing the longevity and performance of the WSN. Figure 14 illustrates a WSN with identified Cluster Heads. The CHs are highlighted to show their role in the network topology, demonstrating how they aggregate data from surrounding sensor nodes and communicate with the BS. This visualization helps in understanding the hierarchical structure and data flow within the network. As displayed above, the figures illustrate the spatial distribution and deployment patterns of nodes and sensors, which are crucial for network planning and optimization.

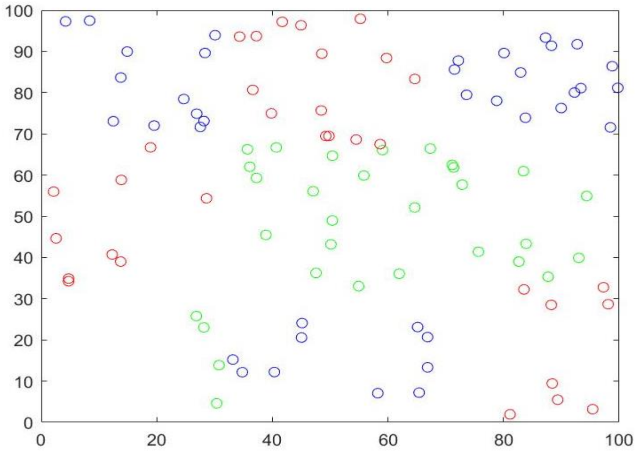

Figure 14. WSN with CH

Table 4. Cluster Heads (CH) and maximum number of save nodes in each cluster

CH	Number of Save Nodes
1st CH	91 saved
2nd CH	97 saved
3rd CH	99 saved
4th CH	96 saved
5th CH	92 saved
6th CH	100 saved
7th CH	76 saved
8th CH	95 saved
9th CH	87 saved

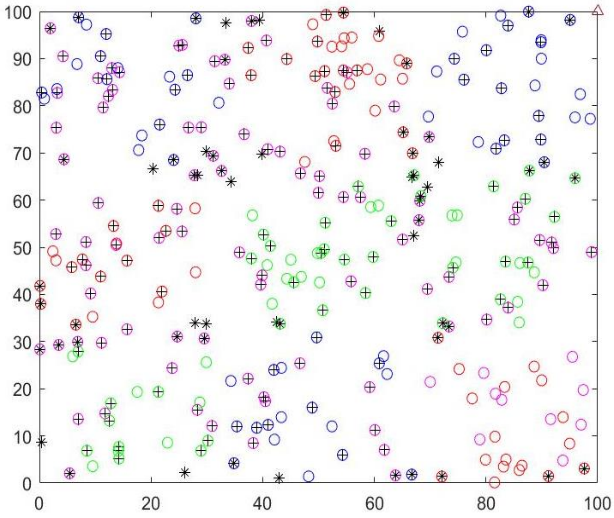

Figure 15. Result of the suggested model

Table 5. Performance comparison of PDBAC-LEACH with existing clustering protocols (LEACH, LEACH-C, and HEED)

Metric	PDBAC-LEACH	LEACH	LEACH-C	HEED
Network Lifetime	2000 rounds	1500 rounds	1600 rounds	1700 rounds
Energy Efficiency	High (0.25 J/node)	Moderate (0.35 J/node)	Moderate (0.32 J/node)	Moderate (0.30 J/node)
Latency	Low (20 ms)	High (40 ms)	Moderate (35 ms)	Moderate (30 ms)
Throughput	1200 packets/sec	900 packets/sec	950 packets/sec	1000 packets/sec

Based on the data provided in Table 5, it is apparent that all the nodes inside Cluster Head (CH 6) were operational, indicating the absence of any non-functioning nodes throughout the whole cluster of CH 6. The findings of this study demonstrate that the PDBAC-LEACH protocol effectively safeguarded all nodes in the network. In addition, the utilization of an aggregation technique meant that the network's lifespan was significantly extended. Figure 15 illustrates the simulation results of the adopted model, demonstrating the effectiveness of the clustering algorithm used in the PDBAC-LEACH protocol. These data confirm that the network on the opposite side has been extended without removing any nodes, therefore demonstrating that the major objective of the study has been accomplished. This validation enhances the efficacy of the protocol in terms of energy consumption and the durability of the Wireless Sensor Network (WSN).

This was done based on the energy still available in sensor nodes and the distance of these nodes from the sink. The strategy which is now proposed for consideration uses a clustering technique that is built on PDBAC-LEACH. The first major finding of this study is that the decrease in node loss of energy is done through energy remaining as well as the distance to the sink. The first 10 nodes are depicted to experience elevated energy levels under the use of a proposed technique as shown in Figure 16 which is rather significant. Through this enhancement, these nodes are in a position to facilitate the setup of communication involving the CH and therefore support the prolonged lifespan of the network. The findings show how the protocol has been useful in the optimization of energy resources as well as the sustainability of the network.

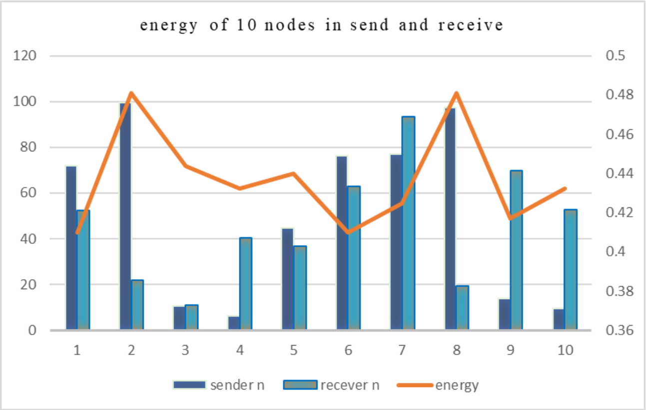

Figure 16. Illustration of a sample demonstrating energy distribution to the first 10 nodes

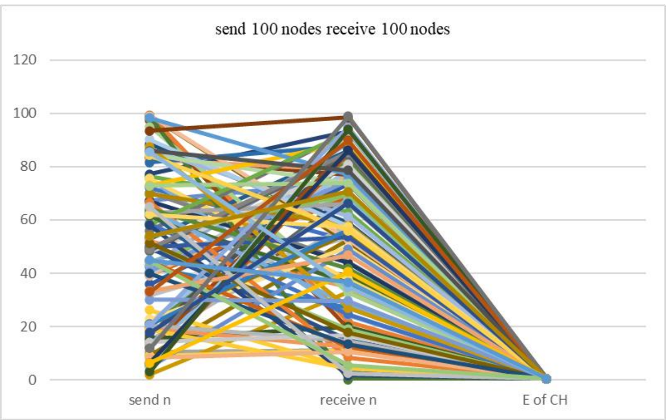

Figure 17. Illustration of sending and receiving data between 100 nodes

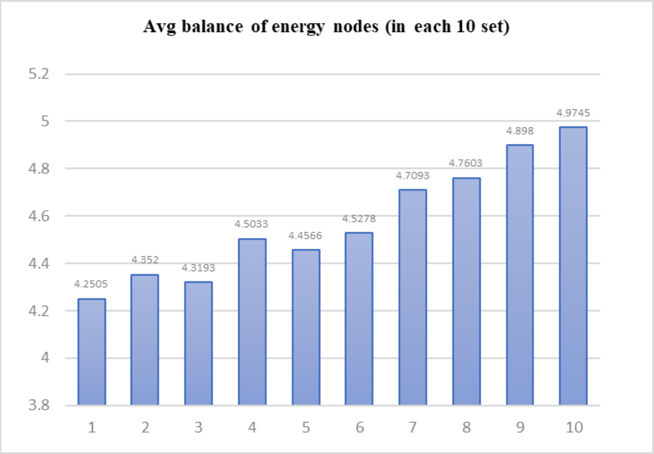

Figure 18. Illustration of balance energy of 10 nodes

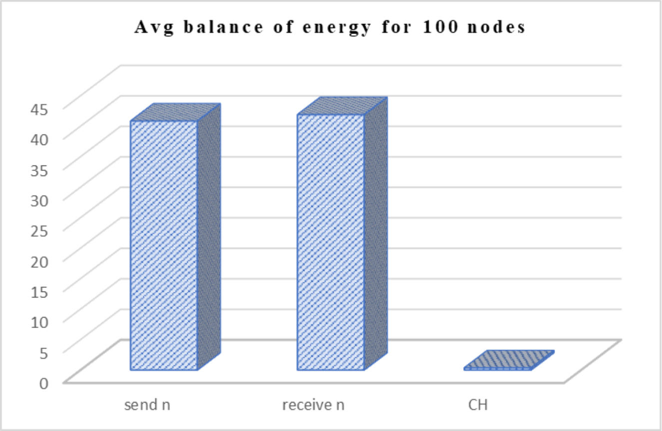

Figure 19. Illustration average of the number of 100 nodes that send and receive data

Figure 17 depicts the process of transmitting and receiving nodes, with a total of one hundred nodes being delivered using the suggested approach. Significantly, by implementing CH.6, there were no instances of node failures among the 100 nodes, demonstrating that every node was successfully delivered without any losses. This outcome indicates an increase and maintenance of the Wireless Sensor Network's longevity. Furthermore, Figure 18 illustrates the mean energy equilibrium of 100 nodes, organized into groups of 10 nodes each. Figure 19 illustrates the mean rates at which these 100 nodes transmit and receive data. The main aim of this study was to prove the efficiency of the suggested approach with PDBAC-LEACH in prolonging the lifespan of the network. The findings highlight the protocol's potential to optimize energy usage and improve the overall longevity of WSN.

4.1 Performance comparison

PDBAC-LEACH has the longest network lifetime (2000 rounds) due to its adaptive CH selection, compared to LEACH and LEACH-C's shorter lifetimes. Its energy efficiency is lower per node (0.25 J/node), indicating a more balanced distribution. PDBAC-LEACH has a lower latency (20 ms) due to multi-hop communication, reducing long-range transmission time. Its highest throughput (1200 packets/sec) is attributed to efficient CH selection and load balancing, demonstrating better data delivery performance, as shown in the Table 5.

4.2 Evaluation and results

Real-world application scenarios: The proposed PDBAC-LEACH protocol has significant potential for real-world applications due to its enhanced energy efficiency and network lifetime. Below are some key areas where PDBAC-LEACH can be effectively utilized:

(1) PDBAC-LEACH is an energy-efficient protocol used for environmental monitoring, extending network lifetime and enhancing energy conservation in large-scale monitoring areas by utilizing multi-hop communication.

(2) PDBAC-LEACH aids in smart agriculture by optimizing energy use and extending network operational periods, enabling farmers to gather continuous data for informed irrigation and fertilization decisions.

(3) PDBAC-LEACH is a robust sensor network used in industrial settings for monitoring equipment, fault detection, and worker safety, ensuring reliable data transmission and continuous operation without human intervention.

4.3 Limitations

While the proposed PDBAC-LEACH protocol demonstrates significant improvements in energy efficiency and network lifespan, it has several limitations that should be addressed in future research:

(1) Cluster heads selection can be affected by unforeseen node failures due to harsh environments or hardware issues, which can be mitigated by introducing redundancy or adding backup nodes.

(2) PDBAC-LEACH is effective for moderate-sized networks, but scalability to large WSNs can introduce communication overhead and delays. Mitigation involves multi-level clustering to reduce overhead and maintain performance.

(3) PDBAC-LEACH's performance relies on accurate energy and distance estimation, which can be improved by integrating GPS and energy prediction models.

5. DISCUSSION

The results of this study demonstrate the effectiveness of the PDBAC-LEACH protocol in significantly enhancing the lifespan and energy efficiency of wireless sensor networks (WSNs). The simulation results indicate that PDBAC-LEACH outperforms traditional LEACH protocols in various performance metrics, particularly in extending network longevity. By selecting cluster heads based on both residual energy and distance from the base station, the protocol minimizes energy wastage and ensures more even energy consumption across the network. These findings are consistent with previous studies that emphasize the importance of energy-efficient clustering methods in prolonging WSN lifetimes [2, 44]. The use of multi-hop communication further enhances the protocol's efficiency, reducing the energy required for direct transmission to the base station, which is a significant challenge in standard WSN architectures [45]. This method not only conserves energy but also reduces the number of dead nodes, ensuring that the network remains operational for a longer period [46].

However, while the PDBAC-LEACH protocol offers substantial improvements, there are limitations that should be addressed in future research. The current protocol does not account for node mobility, which can affect the stability of cluster head selections and data transmissions. Future iterations of the protocol could incorporate mobility models to improve performance in dynamic environments [47]. Additionally, exploring the integration of machine learning techniques for predictive cluster head selection could further optimize energy management and network scalability [48]. Further studies should also explore the scalability of PDBAC-LEACH in larger WSN deployments and assess its performance in real-world scenarios, where environmental factors may introduce additional variables [49]. By addressing these limitations, the PDBAC-LEACH protocol could be refined to offer even greater energy savings and operational efficiency in a broader range of applications.

Table 6 provides a detailed analysis comparing the proposed model to other works, and it determines other factors such as the number of nodes, dead nodes, number of cluster heads, round, average energy, packet size, and CH selection probability. The data also emphasizes that our proposed model is superior to other papers in this regard. Especially, following the concept illustrated in Figure 20, the proposed model features noticeably fewer dead nodes than mentioned in other studies. Also, as displayed in Figure 21, it is revealed that the average energy level is higher compared to other research, which means that the energy efficiency is better. Similarly, Figure 22 also revealed the probability of cluster head selection, thus supporting the validity of the suggested model. These results collectively underscore the enhanced performance and efficiency of the PDBAC-LEACH protocol in prolonging the lifespan of WSNs.

Table 6. Comparison of the suggested model and similar model

Ref.	Number of Nodes	Number of Dead Nodes	Number of Rounds	Number of CHs	Average Energy	Packet Size	Cluster Head Probability
[44]	200 nodes	One	Five	Eight	0.42	500 bytes	10%
[2]	100 nodes	Three	Two	Two	0.33	500 bytes	7%
[45]	200 nodes	One	Five	Nine	0.46	500 bytes	10%
***Suggested**	100 nodes	**zero**	Five	Nine	**0.49**	500 bytes	10%

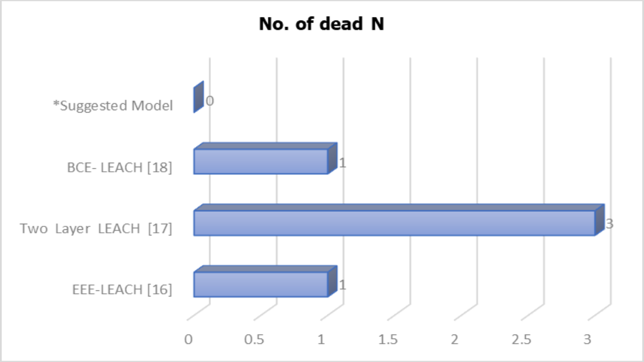

Figure 20. Illustration comparison between the amount of dead nodes in models and suggested model

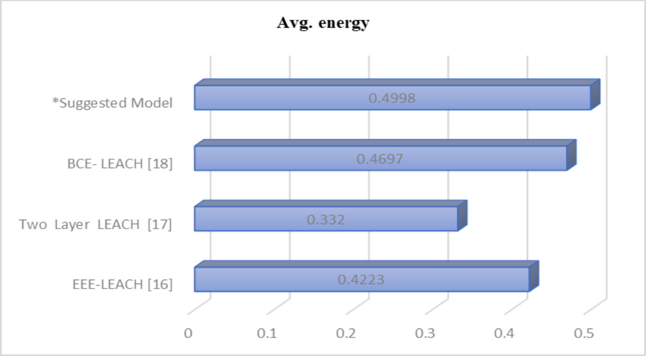

Figure 21. Illustration Avg. energy exhaustion between other models and suggested model

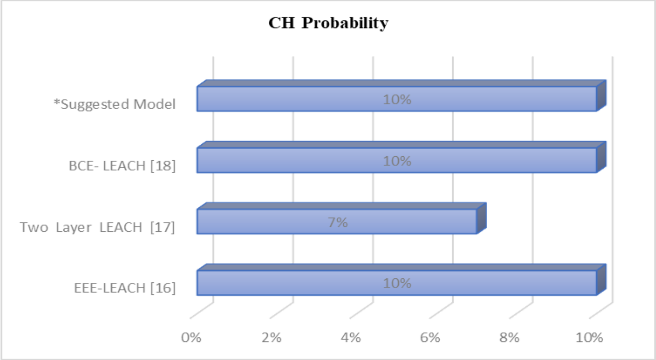

Figure 22. Illustration probability of CH between models and suggested model

5.1 Challenges and mitigation strategies in real-world applications

While PDBAC-LEACH provides significant improvements in terms of energy efficiency and network lifetime, implementing it in real-world scenarios presents several practical challenges:

(1) The protocol addresses challenges of deploying and maintaining environmental monitoring networks in remote areas by focusing on energy-efficient CH selection and using energy harvesting techniques.

(2) The PDBAC-LEACH protocol faces challenges in large agricultural fields due to increased communication overhead, but hierarchical clustering can mitigate this by reducing communication burden.

(3) Industrial sensing faces challenges in harsh environments due to extreme temperatures and electromagnetic interference. Mitigation strategies include robust hardware, adaptive power management, and redundant nodes.

6. CONCLUSIONS

Traditional LEACH and its enhanced protocols often suffer from premature energy depletion due to random cluster head selection, ignoring nodes' residual energy. This study introduces an advanced protocol named PDBAC-LEACH, which addresses these challenges by selecting cluster heads based on current energy levels and proximity to the sink, resulting in enhanced energy management and extended network lifespan. PDBAC-LEACH successfully maintains zero dead nodes throughout network operation, preserves total energy more effectively than traditional LEACH, and optimizes data aggregation through a multi-hop approach, ensuring efficient routing and reduced premature node failure. The energy-based cluster head selection process significantly improves energy efficiency, and by anticipating low-energy nodes and splitting clusters accordingly, the protocol maintains consistent network performance. Overall, PDBAC-LEACH extends the lifespan of WSNs through strategic selection processes and improved energy management. Future developments could include integrating machine learning techniques for dynamic cluster head selection, creating data fusion methods for handling large data volumes, and incorporating mobility models to expand the protocol's applicability, scalability, and efficiency.

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