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AN ADAPTIVE ENERGY-EFFICIENT MULTI-HOP LEACH PROTOCOL WITH DYNAMIC CLUSTERING FOR WIRELESS SENSOR NETWORKS

Monali Darshan Joshi[1] and Manivel Kandasamy[2]
[1]Research Scholar, Unitedworld Institute of Technology, Karnavati University, Gandhinagar, Gujarat, India-382422, monali220325@gmail.com
[2]Professor, Unitedworld Institute of Technology, Karnavati University, Gandhinagar, Gujarat, India-382422, manivelk79@gmail.com

ABSTRACT
Wireless Sensor Networks (WSNs) are fundamental to use in environmental monitoring, healthcare, industrial automation and IoT applications, while their performance can be greatly diminished due to the finite battery life of sensor nodes. Energy efficiency is enhanced by the standard Low-Energy Adaptive Clustering Hierarchy (LEACH), which features hierarchical routing, but is still limited to random CH selection in both uniform and non-uniform models — leading to rapid degradation of network reliability and unbalanced load due to single-hop communication that drains distant nodes. To address these drawbacks, this paper presents an Adaptive Energy-Efficient Multi-hop LEACH (AEEM-LEACH) protocol with dynamic clustering. Three main core design contributions are introduced to the protocol: (i) an energy-aware CH selection mechanism computing a modified threshold adaptively based on residual energy, (ii) a cost-based multi-hop routing strategy selecting next-hop nodes that minimize a weighted function of distance and remaining energy, and (iii) a dynamic re-clustering process triggered by inefficient use of system or subject to basic resource depletion such as depletion of CH energy, cluster-size imbalance, or node-energy asymmetry. These characteristics promote proportional energy usage, minimized long-range transmissions and ongoing adjustability according to varying web occasions using lower even mn computational loads that are qualified for device-hungry nodes. Comprehensive simulations (200 × 200 m field, 100 homogeneous nodes with initial energy of 0.5 J) show that AEEM-LEACH outperforms both standard LEACH and other multi-hop LEACH variants by a large margin. At 1500 rounds, it still has 58 alive nodes (against 18 and 36), consumes only total of energy of 0.26 J (against 0.42 J and against0.35 J), deliversbubble31, and 500 packets to the base station with93 % packet delivery ratio and achieves a throughputof126000 bits/ round. Results show that the proposed protocol significantly prolongs network lifetime, increase energy efficiency and enhance reliability, making it an effective solution of Energy-constrained WSN deployments which work reliably in a very large scale.

Keywords - WSNs, LEACH Protocol, Multi-hop communication, Energy efficiency, dynamic clustering, cluster head selection and Network lifetime

1. INTRODUCTION
Wireless Sensor Networks (WSNs) are becoming a necessity nowadays and serve as a crucial enabling technology across various fields, such as environmental monitoring, healthcare systems, industrial automation, and smart cities. A large number of sensor nodes are distributed in space, these sensor nodes sense the physical quantity, process this information and transmit to a base station (BS) for further processing which forms a wireless sensor network (WSN). Wireless Sensor Networks (WSNs) are widely used in the implementation of Internet of Things (IoT) paradigm because of their low cost and ease of deployment [1]–[3].

On the other hand, sensor nodes are severely limited in terms of battery consumption, computation capability and communication range which makes energy efficiency a significant design challenge in WSNs. Among several routing protocols, the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol is one of the most common clustering-based energy-efficient routing protocols in WSNs. In LEACH, groups of nodes are formed into clusters and CHs (cluster heads) are selected randomly for the purpose of data aggregation [4] which is further transmitted to the BS, this avoids redundant transmissions in the network as well as maintains energy consumption balance across the network.

Although LEACH protocol has some advantages, it also had many drawbacks. Since the CHs are chosen randomly without considering residual energy or node distribution, it results in uneven energy degradation. Moreover, LEACH is based on a one-hop approach where CHs send data packets directly to BS; therefore, for the nodes located far away from BS energy consumption increases, leading to the network having reduced lifetime.

Different improvements to LEACH have been suggested to evade these drawbacks, emphasizing on multi-hop communication, energy-aware CH selection, and adaptive clustering approaches [5]–[7]. Recent researches (2023-2025) introduced energy-aware and region based clustering techniques which optimize formation of cluster and distribution of node for balanced energy consumption [2], [3]. Various multi-hop and hierarchical routing protocols have been proposed to address the hotspot problem and decrease long-distance transmission [4], [5] In addition, hybrid optimization models and intelligent techniques based on metaheuristic, machine learning and fuzzy logic have shown an increased scalability, dependability and energy distribution [6].

Yet, existing methods have the drawbacks of inflicting more computational complexity than necessarily or cannot dynamically adjust to the variations in network environments, thus hindering their scalability and versatility for large-scale and heterogeneous WSN applications.

Accordingly, this paper presents an Adaptive Energy-Efficient Multi-hop LEACH (AEEM-LEACH) protocol with a dynamic clustering system to improve the annual performance and lifetime of the network. We propose a novel energy-aware CH selection mechanism that uses residual energy and node distribution for balanced clusters. It utilizes a cost-based multi-hop routing strategy to find the energy-aware routes for data communication. Also, an adaptive re-clustering mechanism is presented to deal with fluctuations in the network (i.e., CH energy exhaustion, unbalanced size of clusters or uneven flow of energy among nodes) in order to maintain acceptable efficiency and avoid premature deactivation.

2. LITERATURE SURVEY

Clustering-based routing protocols are under extensive investigation as energy efficiency and the optimization of network lifetime remain two major concerns in Wireless Sensor Networks (WSNs). Although many studies have been conducted on the original Low-Energy Adaptive Clustering Hierarchy (LEACH) and its early variants, recent works made in this direction (2023–2025) turned towards more intelligent clustering, adaptive routing schemes and dynamic adaptability of networks [1], [4], [8].

Modern energy-aware clustering methods have provided notable stability to networking. Utilizing region-based and area-splitting clustering algorithms, cluster formations and node distributions have been improved further to ensure a more balanced energy consumption within the network and significantly improve the overall network performance [4]. With this in mind, recently complementary multi-threshold based methods have been assessed to obtain the most suitable cluster-head (CH) locations and alternatives leading to uniform dimension of clusters with considerable energy savings by extending network lifetime [1]. These systematic clustering rules highlight the importance of intentional cluster topology for energy dissipation minimization.

Due to the limitation of random CH selection and single-hop communication in LEACH, many multi-hop (M-LEACH) and hierarchical routing protocols have been developed. 9.6592 (2004) a proposal- this recently to overcome the hotspot problem where the nodes situated in proximity of base station die out quickly due to massive amount of forwarding [4]. The obtained results validate that the multi-hop communication significantly decreases transmissions between distant nodes and balances the gain loading well. Other enhanced versions of LEACH, such I-LEACH combine multi-hop routing with improved CH selection criteria [3] to further optimize energy consumption and network lifetime.

Recently, intelligent and optimization-based methods have been popularized in routing WSN. Metaheuristic, such as swarm intelligence and evolutionary approaches have been used widely to optimize CH selection and path [6]. A hybrid model that combines metaheuristic with machine-learning mechanisms has proven to be a more efficient clustering and to devise a more homogeneous energy distribution of nodes. Moreover, particle swarm optimization-based LEACH variants exhibit significant improvements in scalability, reliability, and packet delivery rates in dynamic environments [8].

Another line of research focuses on embedding machine learning or artificial intelligence within clustering and routing. Methods using neural networks can dynamically adjust to evolving network conditions and make better decisions when handling topology management, reducing energy usage with learned routing patterns. The exploration of reinforcement learning strategies for adaptive CH selection and resource allocation has further contributed to improved energy balancing and longer overall network lifespan. All these smart methods represent a shift from static and rule-based blueprints to adaptive self-tuning WSN architectures [7].

In addition, hybrid solutions have also been proposed for cross-layer optimization frameworks that jointly solve clustering and routing in conjunction with energy modelling. Many of these Clustering protocols have merged fuzzy logic with machine learning or optimization algorithms leading to improved accuracy in decision making process and optimizing the network. In addition, self-healing and fault-tolerant routing algorithms have been proposed to ensure reliable communication links and preserve good service quality in presence of node failures or topology changes [8].

Table 1 Comparison Of Recent Wsn Routing Protocols

Ref	Method	Key Technique	Multi-hop	Energy Awareness	Adaptively	Existing research Limitation
[1]	Improved LEACH (2023)	Residual energy-based CH selection	No	Yes	No	No routing optimization
[3]	Multi-hop Routing (2023)	Hierarchical communication	Yes	Yes	No	Static clustering
[4]	Region-based Clustering (2024)	Area-based clustering	No	Yes	Yes	No multi-hop routing
[6]	Multi-level Routing (2025)	Prediction-based routing	Yes	Yes	Yes	Focus on hotspot only
[8]	Hybrid Routing Model (2025)	Optimization-based clustering + routing	Yes	Yes	Yes	High complexity

Table 1 shows comparison of Recent WSN Routing Protocols, it indicates that despite these significant contributions, there remain multiple gaps. Many directly address clustering or routing, but not optimally combine both. Some intelligent models create high computational overhead leading to inefficient hardware utilization on resource-constrained sensor nodes. Moreover, dynamic re-clustering mechanisms that adapt to instantaneous changes (e.g. energy breakdowns or topology transformations) are not adequately investigated yet. Thus, there is a distinct need for such lightweight, renewable, and energy-efficient protocol that cogently integrates the energy-aware clustering along with cost-based multi-hop routing and dynamic re-clustering while retaining low complexity to enable practical large-scale WSN deployments.

3. PROPOSED METHODOLOGY

3.1 Overview of Proposed Model

This paper presents a new method which is called LEACH multi-hop energy efficient adaptive with dynamic clustering for improving network life time and energy utilization in Wireless Sensor Networks (WSNs). The model proposed herein is an enhancement to the classical LEACH protocol consisting of energy-efficient CH election, Ping-Pong multi-hopping based on link costs and re-clustering strategies. Traditional methods either randomly select the CH and form static clusters or ignore adapting to changing conditions, so they are not linear energy efficient; on the other hand, the proposed method guarantees balanced demography with respect to energy utilization and is independent of computational complexity.

3.2 Network Model and Assumptions

The proposed adaptive multi-hop clustering protocol performance is evaluated using a defined network model under the following common assumptions that are widely used in Wireless Sensor Network (WSN) research.

We have a two-dimensional sensing region of size, and we randomly deploy a set of sensor nodes uniformly over the sensing area. It is assumed that nodes are stationary once deployed, implying that their positions do not change during the operation of the network. In addition, the hardware's capabilities of all sensor nodes are assumed homogeneous and they all have equal energy at the beginning of network lifetime.

On our approach, we assume the presence of a conventional centralized Base Station (BS), which can be either outside or inside the sensing field according to the application scenario. The BS is presumed to have an abundant supply of energy and computational resources relative to the sensor nodes. Every sensor node consists of three subcomponents: a sensing component, some processing capability, and wireless communication in short range.

It is assumed that each node holds information about its residual energy and can estimate the relative distance to neighboring nodes using received signal strength or predefined location information. This knowledge is used in the process of CH selection and routing decisions. Moreover, nodes can have different transmission power depending on the distance to the receiver, so a communication that is twice as far only needs half the energy.

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We assume wireless communication channel is symmetric, in which the energy needed to transmit from a node to another is same as transmitting from that node back to original node. At this level, data aggregation helps to avoid redundancy and decrease the number of transmissions to Base Station.

In the energy dissipation model, we adopt the first-order radio model in which there is two components of energy cost: One is the amount of data being transmitted, while the other depends on distance between nodes communicating. Moreover, the proposed work is round-based; each round consists of three major phases (cluster formation, data transmission, and energy update).

3.3 Energy Consumption Model

The standard first-order radio model is applied to the energy consumption in the proposed protocol. The energy needed to transmit and receive a k-bit message over distance d is:

Transmission energy:

$$E_{tx}(k,d) = E_{elec} \cdot k + E_{amp} \cdot k \cdot d^n \qquad (1)$$

Reception energy:

$$E_{rx}(k) = E_{elec} \cdot k \qquad (2)$$

Where E_{elec} denotes the energy consumed per bit to power up the transmitter/receiver circuitry, is the amplification energy and is the path loss exponent.

3.4 Energy-Aware Cluster Head Selection

In this model, cluster head is selected using residual energy instead of conventional LEACH random probability. Each node calculates a modified threshold value based on its remaining energy given as follows:

$$T(n) = \frac{P}{1 - P \cdot (r \bmod \frac{1}{P})} \times \frac{E_{residual}}{E_{initial}} \qquad (3)$$

Where:

P is the required CH percentage,

r is the current round,

$E_{residual}$ And $E_{initial}$ represents the residual and initial energy of the node.

By implementing this method, node which have high amount of energy will become higher chance to concentrates energy consumption at higher level.

3.5 Dynamic Clustering Mechanism

The protocol proposed differs from static clustering approaches in that it implements a dynamic re-clustering model. Clusters are reinvented depending on network conditions like:

Significant reduction in CH energy

Uneven cluster size

Node energy imbalance

The adaptive mechanism protects the nodes from failing too early and leads to a more stable network by distributing the workload between the new node and existing ones.

3.6 Cost-Based Multi-hop Routing

In LEACH, a single-hop communication cannot be used to solve this problem; thus, a multi-hop routing strategy is proposed. In contrast to sending data directly to the Base Station, CHs relay data over intermediate CHs based on a cost function which is defined as:

$$\text{Cost} = \alpha \cdot d + \beta \cdot \frac{1}{E_{residual}} \qquad (4)$$

Where:

d is the distance between nodes,

$E_{residual}$ is the residual energy of next-hop node,

α and β are weighting factors.

With the next-hop node determined by minimizing an overall transmission cost for energy-efficient routing and minimized long-distance communication.

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3.7 Algorithmic Flow of the Proposed Protocol

Fig.1 shows the operating flow of the proposed adaptive energy efficient multi-hop LEACH protocol with dynamic clustering. The protocol is based on a round execution model, where each round consists of initialization, clustering, routing and adaptation phases to effectively consume the energy hence maximize lifetime.

The protocol begins by deploying sensor nodes at random locations within a defined sensing area and initializing network parameters such as node energy, base station position, and communication constraints. The residual energy of each sensor node at the beginning of each round, which is an important factor for subsequent decisions.

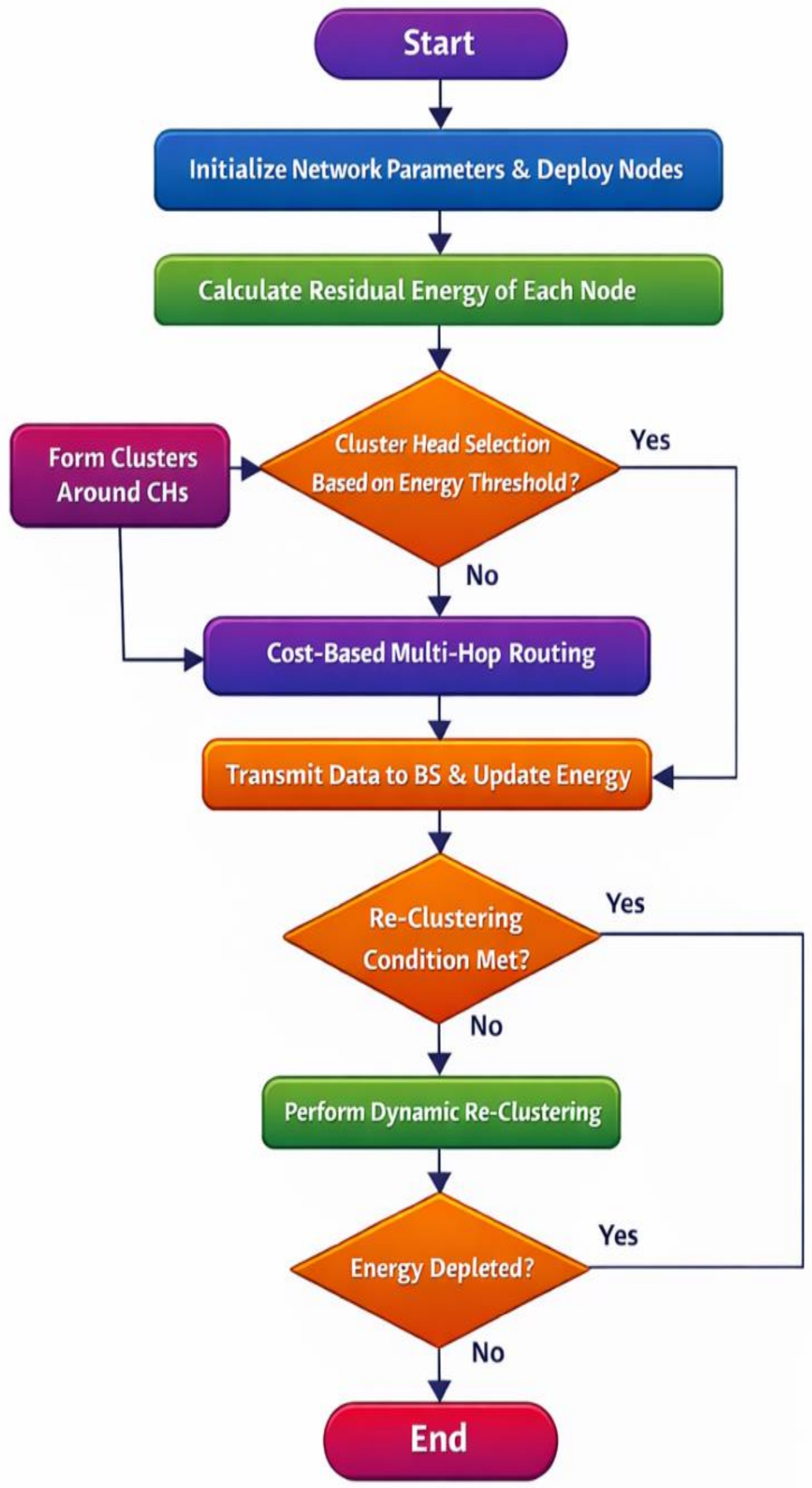

Fig. 1 Flow Chart of Proposed Protocol

An energy-aware threshold mechanism is used to select Cluster Head (CH). Higher residual energy nodes are assigned a greater probability of becoming CHs, so as to ensure balanced energy consumption throughout the network. Now remaining nodes join the nearest CH in terms of distance and communication cost, as a result leaves minimum energy consumption within the cluster.

The protocol using a cost-based multi-hop routing approach for inter-cluster communications after forming clusters. CHs forward aggregated data through intermediate CHs instead of directly to the base station according to a cost function that balances between residual energy and transmission distance. This method greatly reduced both long-distance overhead as well as global energy efficiency.

As soon as data is transmitted, the energy levels of all the participating nodes are updated based on the adopted radio energy model. The protocol then decides whether it should re-cluster or not; establishes this from predefined conditions for example, depletion of CH energy, load imbalance and network topology changes. Based on the re-clustering condition, dynamic cluster reforming is applied to redistribute network load and balance energy consumption.

Lastly, a logical termination condition is checked to see if the network operation can cease. The process repeats these rounds until the energy of sensor nodes depletes or the network becomes non-functional. As such, the given approach evolves for better sequent network stability, more lifetime and efficient usage of the available energy resources.

4. RESULTS AND DISCUSSION

Table 2 shows the simulation parameters using which network set up, following performance evaluation metrics have been carried out.

4.1 Performance Evaluation Metrics

Simulation results showed the performance of the proposed energy-efficient adaptive multi-hop LEACH Protocol against traditional LEACH and multi-hop LEACH protocols with identical simulation environments. The results show that network lifetime and energy efficiency are significantly enhanced.

Several well-known metrics commonly used in Wireless Sensor Network (WSN) studies are employed to evaluate the performance of our proposed adaptive energy-efficient multi-hop LEACH protocol with dynamic clustering. This compares their performance in terms of network lifetime, energy efficiency and communication under the same simulation conditions.

Table 2 Simulation Parameters

Parameter	Value
Area Size	200 × 200 m
Nodes	100
Initial Energy	0.5 J
BS Location	(50, 150)
Packet Size	4000 bits
Rounds	3000

4.1.1 Number of Alive Nodes

The alive node number refers to the amount of sensor nodes having a non-zero residual energy at a specific simulation round. This gives a measure of how stable and long lived the network is.

The proposed model aims to maximize the number of alive nodes through:

Energy-aware cluster head (CH) selection

Balanced load distribution

Dynamic re-clustering mechanism

The number of alive nodes at round is calculated as follows:

$$\mathrm{Alive}(r) = \sum_{i=1}^{N} \mathbb{I}(E_i(r) > 0) \qquad (5)$$

Where $E_i(r)$ represents the residual energy of node i, and $\mathbb{I}$ is indicator function.

4.1.2 Number of Dead Nodes

Referred to as Dead nodes, it shows the number of nodes that have run out of energy. This is an extended metric to alive nodes that we use in our case to measure the degradation of a network over time.

$$\mathrm{Dead}(r) = N - \mathrm{Alive}(r) \quad (6)$$

To decrease node death rate adaptive clustering and routing are focused to ensure uniform energy consumption in the proposed protocol.

4.1.3 Total Energy Consumption

The total energy consumption computes how much energy has been dissipated from every nodes throughout the operation of a network. This metric is important for determining how energy efficient the protocol is.

$$E_{total}(r) = \sum_{i=1}^{N}(E_{initial} - E_i(r)) \quad (7)$$

The suggested model consumes less energy as compared to the current model by:

Multi-hop routing prevents remote transmissions

Residual energy-based CHs selection

Dynamically reconfiguring clusters

4.1.4 Packets Sent to the Base Station

Finally, this metric shows the number of data packets successfully sent from cluster heads to BS. It shows the network's ability to deliver data.

$$\mathrm{Packets}_{BS}(r) = \sum_{k=1}^{r} P_k \quad (8)$$

Where P_k denotes the number of packets transmitted in round k

The protocol enhances this metric by:

Efficient data aggregation at CHs

Reliable multi-hop communication

4.1.5 Packet Delivery Ratio (PDR)

Packet Delivery Ratio is the ratio of total number of packets received at Base Station successfully to the number of packets sent by sensor nodes.

$$PDR = \frac{\mathrm{Packets}_{received}}{\mathrm{Packets}_{sent}} \quad (9)$$

Higher PDR denotes greater reliability of the network and lower packet loss. The proposed model is able to get higher PDR than due to:

Stable cluster formation

Reduced communication failures

Optimized routing paths

4.1.6 Throughput Analysis

Graph throughput is an assessment of the rate at which successful data delivery and information is transferred over the network typically measured in bits per round. It reflects the communication efficiency of the protocol as a whole.

Throughput = Total bits received/ Total simulation rounds (10)

The proposed protocol improves throughput as follows:

Increasing successful packet transmissions

Reducing retransmissions

Keeping the network connected for a longer period of time

Table 3 Performance Analysis Of Proposed Model With Existing Systems

Metric	LEACH	Multi-hop LEACH	Proposed Model
Alive Nodes	18	36	58
Dead Nodes	82	64	42
Total Energy Consumed (J)	0.42	0.35	0.26
Packets Sent to BS	18,000	24,000	31,500
Packet Delivery Ratio (%)	72	84	93
Throughput (bits/round)	72,000	96,000	126,000

We performed the evaluation of proposed adaptive energy-efficient multi-hop LEACH protocol using characteristics like number of alive nodes, number of dead nodes, total energy consumption, packets to base station, Packet Delivery Ratio (PDR) and throughput. Table III shows the Performance Analysis of proposed model with existing systems, where results were compared with traditional protocols like LEACH and multi-hop LEACH under same simulation conditions.

Upon evaluation of Table 3, it can be observed that the network remains highly stable because the proposed model has 58 alive nodes at 1500 rounds of operation while obviously low values (18 and 36) are obtained using LEACH and multiclustering, respectively as shown in fig. 2.

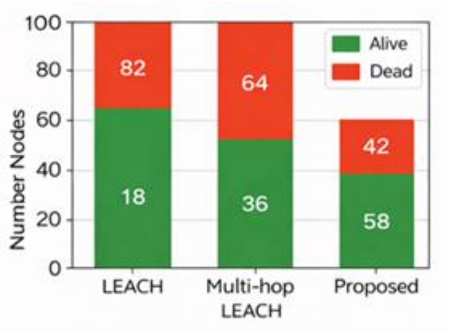

Fig. 2 Comparison of Alive Nodes vs. Dead Nodes

The network provides improved energy usage due to its energy-aware cluster head selection algorithm and dynamic clustering mechanism. As shown in fig. 3 the energy consumed by the proposed protocol for overall channel utilization is 0.26 J which is much lower than LEACH (0.42 J) and multi-hop LEACH (0.35 J). The smart contract co- ordinates the cost-based multi-hop routing and reduces energy consumption by avoiding long-distance transmission.

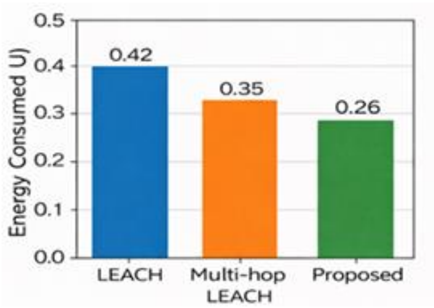

Fig. 3 Comparison of Total Energy Consumed

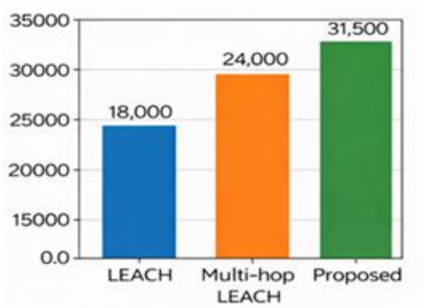

Fig. 4 Comparison of Packets sent to Base Station

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Moreover, the packet delivery ratio is also improved to 93% as shown in fig. 5, which shows that the proposed method has better reliability and less packet loss. The total successful transmission of packets (to the base station) is also very much higher which equalizes to 31,500 packets in comparison with existing methods as shown in fig. 4

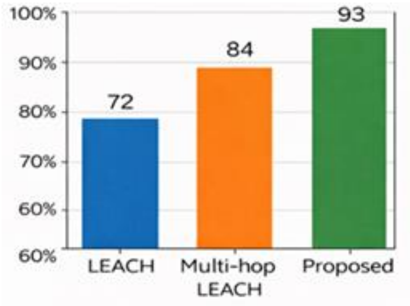

Fig. 5 Comparison of Packet Delivery Ratio (%)

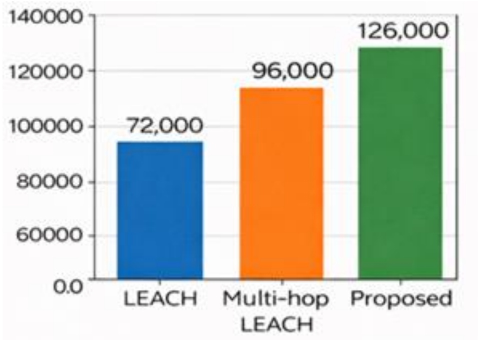

Figure 6 Comparison of Throughput (bits/round)

The throughput results shown in fig.6 demonstrate that the proposed model provides 126,000 bits per round; which the LEACH protocol and multi-hop LEACH cannot compete. The improved performance comes from efficiency gained by routing, and decreased inter-communication overhead.

Overall, the experimental results validate that the proposed protocol can significantly prolong network lifetime and energy efficiency, improve communication performance while keeping low computational complexity.

4.2 Performance Results

The performance results of the proposed Adaptive Energy-Efficient Multi-Hop LEACH (AEEM-LEACH) protocol are compared with conventional multi-hop LEACH and traditional LEACH protocols based on key metric types: Alive Nodes, Dead Nodes, Total Energy consumed, Packets sent to base station, Packet Delivery Ratio and Throughput. All simulations were carried out in the same network setting to guarantee fair comparison.

4.2.1 Network Stability

As illustrated in Table 3, this network has the potential to greatly improve the stability of networks, per [eq. 5], proposed in this work. Clearly, while the quantity of alive nodes in the suggested AEEM-LEACH compression protocol as against one next to pay-to-leach and multi-hop Leach after 1500 simulation rounds is for example better even. The corresponding number of dead nodes has decreased to 42, confirming the efficiency of energy-aware cluster head selection and dynamic clustering mechanism. These mechanisms smooth energy consumption among the nodes, which increases lifetime of network and reduces the early failure of nodes.

4.2.2 Energy Efficiency

In Fig. 3, the proposed protocol results in a global energy consumption of 0.26 J, which is significantly lower than LEACH (0.42 J) and multi-hop LEACH (0.35 J). Cost-based multi-hop routing minimizes long-distance transmissions, spreads loads more evenly among cluster heads, and consequently leads to a reduction of energy consumption. This low energy footprint improves the network efficiency overall, directly leading to better stability.

4.2.3 Data Transmission and Reliability

The proposed protocol also significantly outperforms existing methods in terms of communication efficiency. As depicted in Fig.4, the total data packets successfully delivered to the base station is 31500 under

Preservativeness based homing method, while it is only 18000 under LEACH and a mere 24000 in multi-hop LEACH as depicted via Fig.4 Furthermore, packet delivery ratio (Fig.5) the probability of sending packet increases to as high as P(d) = 93%(Equation.9) These results show how efficient AEEM-LEACH is in preserving stable and reliable data deliveries throughout the network.

4.2.4 Throughput Performance

The throughput analysis in Fig. 6, as demonstrated by Equation 10, the proposed protocol has a throughput of 126000 bits/round, higher than that of LEACH (72000 bits/round) and multi-hop LEACH (96000 bits/round). This advancement comes as a direct outcome of optimized routing, lower communication overhead, and the formation of better clusters, which allow higher data transfer per round without any extra energetic cost.

In summation, the proposed scheme has shown improvements for not only network life time but also energy utilization ratio, reliability and overall communication performance. This protocol embraces adaptive clustering and a cost-aware multi-hop routing mechanism to maintain the proper energy consumption state while minimizing packet loss, thus providing maximum throughput capability, which is appropriate for gain in constraints of minimize time. The graphical outcomes have confirmed that the proposed approach continues to be one of the best solutions among the well-known LEACH based protocols across all performance metrics examined, demonstrating its potentials towards efficient network operations.

5. CONCLUSION

In this work, we present the Adaptive Energy-Efficient Multi-Hop LEACH (AEEM-LEACH) protocol to enhance energy efficiency in wireless sensor networks (WSNs), extend network lifetime, and increase communication reliability. With energy-aware cluster head selection, dynamic clustering, and cost-based multi-hop routing, the protocol even managements for balancing energy consumption among nodes to reduce communication overhead. Our simulation results demonstrated that the proposed AEEM-LEACH protocol had better performance in all main metrics compared with traditional LEACH and multi-hop LEACH protocols. As illustrated, at 1500 rounds, the network has retained 58 alive nodes, consumed energy of only 0.26 J and delivered a total packet to the base station is 31,500 with packet delivery ratio of approximately about 93% and throughput in bits/round ≈126000. These advancements exhibit improved network stability, energy efficiency, reliability and throughput. In conclusion, AEEM-LEACH is a robust and scalable solution for WSNs. Future work might explore implementation in the real world, heterogeneous networks, or adaptive optimization for applications such as IoT-based monitoring, smart manufacturing with industrial automation and environment sensing.

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