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TECHNICAL ARTICLE

An Energy Efficient and Network Lifetime-Aware Routing Protocol for Wireless Sensor Networks

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ABSTRACT

In wireless sensor networks (WSNs), energy management is a major problem because of the sensors' limited battery life, which reduces the network's longevity. The Green Multi-Mechanism-Low Energy Adaptive Clustering Hierarchy (GME-LEACH) routing protocol presented in this paper combines four complementary mechanisms into a single clustering framework: adaptive CH rotation, sleep-awake scheduling, hybrid multi-hop communication, and multi-criteria cluster-head (CH) selection. To find energy-efficient and strategically placed cluster heads, the suggested CH selection method takes into account residual energy, distance to the base station (BS), local node density, and node centrality. While the hybrid routing system chooses relay-based or direct communication based on communication distance and energy circumstances, sleep-awake scheduling minimizes needless energy usage by alternatively turning on paired nodes. The communication load is further distributed via adaptive CH rotation. Adaptive CH rotation further distributes the communication burden among eligible nodes and helps prevent premature energy depletion. Using a MATLAB-based simulation with a typical WSN configuration, the suggested methodology was evaluated and compared with four ablated GME-LEACH variations and conventional LEACH. The results showed that the complete GME-LEACH achieved first-node-death (FND) at round 1220, half-node-death (HND) at round 1439, and last-node-death (LND) at round 1696 with 25,288 successfully sent packets to the BS. By demonstrating how removing specific mechanisms changes packet delivery behavior and network longevity, the ablation findings demonstrate that the integrated processes contribute differently to the overall performance of the proposed protocol. In particular, the entire design provides a well-balanced combination of early-node survivability, continuous network operation, and data transmission. These results indicate that GME-LEACH provides an integrated energy-aware clustering and routing framework for improving the operational lifetime and communication efficiency of WSNs.

KEYWORDS Wireless Sensor Networks, Energy-Efficient Clustering, Hierarchical Routing Protocols, LEACH, Routing Protocols, Distributed Network

1. Introduction

Environmental monitoring, precision agriculture, industrial automation, healthcare, military surveillance, and smart-city systems are just a few of the many uses for WSNs that have grown in importance (Bangotra *et al.* 2022; Rathinam *et al.* 2019; Yamaji *et al.* 2008; Gaj *et al.* 2013; Agarwal and Gupta 2024; Singla *et al.* 2023; Kaur *et al.* 2024). Many inexpensive SNs with sensing, processing, and wireless communication capabilities make up a WSN. These nodes are set up in a target area to gather data about environmental or physical conditions and send it to a sink or BS (Altaha and Al Ali 2025; Al-Sulaifanie *et al.* 2022). The operational effectiveness of WSNs is strongly influenced by the limited energy available at SNs. Since these nodes commonly rely on non-rechargeable batteries and may be deployed in locations where maintenance is difficult or impractical, efficient energy utilization is essential for sustaining network operation and prolonging its lifetime (Tian 2025). Consequently, energy efficiency has become a major consideration in the design of WSN routing protocols. Routing

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determines the communication paths through which sensed information is delivered from SNs to the BS. In addition to energy constraints, SNs operate with limited processing resources, memory, and communication bandwidth. Therefore, energy-aware routing strategies aim to utilize these constrained resources efficiently while maintaining reliable data transmission and extending the overall network lifetime (Hu *et al.* 2024). WSN routing protocols are typically divided into four primary groups according to their routing techniques (Gebyhu *et al.* 2026):

(a) Flat-Based Routing Protocols: These protocols lack specific functionalities and assign all SNs the same tasks and duties. (b) Hierarchical (Cluster-Based) Routing Protocols: To improve scalability and energy efficiency, hierarchical protocols group nodes into clusters. A CH is in charge of gathering data from member nodes in each cluster, combining it to remove redundancy, and sending the combined data to the BS. (c) Location-Based Routing Protocols: These protocols base their routing decisions on the geographic locations of nodes as determined by localization techniques or the Global Positioning System (GPS) (Gebyhu *et al.* 2026). (d) Quality of Service (QoS)-Based Routing Protocols: QoS-based protocols serve applications that need certain performance assurances, including guaranteed bandwidth, high dependability, or bounded delay (Prajapati *et al.* 2025).

LEACH, a hierarchical routing protocol proposed by Heinzelman et al. (2002), improves energy efficiency by organizing SNs into clusters. Despite this advantage, the conventional CH election process is largely probability-driven and provides limited consideration of factors such as the remaining energy of SNs, their spatial distribution, communication distance, and surrounding network topology. Low-energy nodes may therefore be chosen as CHs, which could result in uneven energy consumption, early node failures, and a shorter network lifetime. Furthermore, distant CHs find that direct communication with the BS requires more energy, which accelerates battery depletion and lowers network performance overall. To ensure a fair comparison with the traditional LEACH protocol, the suggested approach was constructed and assessed using simulations under identical network conditions. Standard criteria such network longevity, residual energy, throughput, and the FND, HND, and LND timings were used to evaluate performance. The results show that the suggested protocol is a promising solution for energy-constrained WSN applications since it increases load balancing, increases energy efficiency, and lengthens network lifetime when compared to the traditional LEACH.

The rest of the paper is organized as follows: Section 2 reports on related works. The network model is shown in Section 3. The suggested approach is covered in Section 4. Section 5 discusses the model's evaluation and simulation; Section 6 summarizes the findings and future directions.

2. Related work

WSNs be made up of distributed SNs that gather information from their surrounding environments and communicate the data that it sensed toward a BS. Energy consumption is still a major limitation in the design of WSNs since SNs usually have limited battery capacity, communication capabilities, and computational resources. In applications where SNs are isolated or hard to reach, frequent battery replacement or recharging is impossible. Therefore, increasing energy efficiency and maintaining data delivery are essential to network longevity and operation. Recent surveys of WSN routing research continue to identify energy consumption, clustering, and network lifetime as major design considerations in hierarchical routing protocols (Hussain *et al.* 2024).

Clustering is one of the established approaches for reducing communication overhead in WSNs. In a clustered architecture, SNs are grouped and a CH collects and aggregates data from associated members before sending it to the BS. This hierarchical organization reduces the need for every SN to communicate directly with the BS and consequently can improve energy utilization. Among the early and influential hierarchical protocols, LEACH introduced periodic cluster formation and probabilistic CH rotation to distribute the CH responsibility among SNs. Subsequent research has produced numerous LEACH successors that modify either CH selection, data transmission, or both in response to the limitations of the original protocol (Daanoune *et al.* 2021; Hussain *et al.* 2024).

Despite its simplicity and effectiveness, conventional LEACH does not explicitly evaluate the current energy condition and spatial characteristics of candidate CHs during probabilistic selection. Consequently, the CH role may be assigned to a node with relatively low residual energy or an unfavorable communication position. Due to this constraint, energy-aware and multi-criteria CH-selection methods that consider residual energy, distance, neighborhood features, and node distribution have been developed. This shift from probability-based CH election to more adaptable selection methods is reflected in the evolution of LEACH-based protocols shown in recent surveys (Daanoune *et al.* 2021; Hussain *et al.* 2024).

Computational intelligence and optimization techniques have been used in recent study to further expand CH selection (Raji *et al.* 2025). A hybrid metaheuristic strategy for energy-efficient cluster routing that combines Artificial Bee Colony and Ant Colony Optimization was presented by S. El Khediri et al. in 2024. This approach shows how optimization-based techniques may be used to simultaneously improve clustering and routing decisions. In the same year, Saadati et al. combined learning-based clustering with multi-hop communication to study energy-efficient clustering in dense WSNs using Graph Neural Networks and coverage measures. These studies demonstrate a recent trend away from traditional probabilistic CH election and toward data-driven and optimization-based decision methods.

However, selecting appropriate CHs does not by itself eliminate energy imbalance. CHs undertake additional communication and aggregation responsibilities, and nodes located in unfavorable regions may experience faster energy depletion. When CHs far from the BS should provide aggregated data across great distances, this issue gets worse. Recent LEACH-based works have therefore studied energy aware clustering and routing mechanisms trying to define a more efficient distribution of the communication costs. For instance, Abose et al. (2024) has investigated improved LEACH variants by implementing residual energy mechanisms and optimal clustering probabilities. The relationship between CH selection, energy consumption and network lifetime is emphasized.

Reduce unnecessary node activity to conserve energy beyond CH selection. Sleep–awake scheduling lets some sensor nodes go low-power while others stay active. This strategy can reduce energy spent by redundant or inactive nodes, but it must be coordinated with clustering and data transmission to avoid cutting cluster connectivity or sensing availability. This limitation can be overcome by multi-hop communication where data can be forwarded through intermediate CHs or relay nodes. However, multi-hop routing itself does not guaranty lower energy consumption: an inappropriate relay may introduce additional forwarding traffic and drain its energy faster. As a result, recent studies have looked into routing strategies that simultaneously take forwarding cost, relay selection, and communication distance into account. Recent optimization-based protocols that combine inter-cluster routing and CH selection show this tendency in particular.

The development of multi-hop strategies has also encouraged research into adaptive communication rather than enforcing a single transmission mode for all CHs. Direct transmission is still suitable when the CH is close enough to the BS, while relay-based communication can be beneficial for larger transmission distances. This enables a hybrid routing mechanism to choose either direct or relay-based communication based on the current network conditions. In this manner, the basic structure of the LEACH clustering is preserved, but the inter-cluster data transmission is made more flexible.

CH rotation is essential to energy balance. Even though traditional LEACH rotates the CH role regularly, probability-based rotation does not always guaranty that the elected node has enough residual energy or advantageous network properties. Thus, energy-aware and adaptive rotation mechanisms have been studied recently. Zeng et al. (2025) proposed an intra-cluster multi-hop CH-rotation protocol that uses residual-energy thresholds to determine CH rotation, demonstrating continued interest in adapting CH responsibility to network energy state.

In 2025, Behzadi et al. proposed a multi-objective clustering protocol for CH selection using Improved Binary Dragonfly Algorithm, residual energy, node to BS distance, and neighborhood

degree. Data transmission uses multi-hop communication and cluster formation uses Mamdani fuzzy inference. Wang et al. (2025) created a Spider Wasp Optimizer-based framework to optimize CH selection and multi-hop path construction simultaneously using inter-cluster communication. These developments show a shift toward optimizing clustering and routing together rather than separately.

Although these approaches provide increasingly sophisticated solutions, many recent methods rely on metaheuristic optimization (Wilson *et al.* 2024; Yao *et al.* 2024), neural networks, fuzzy inference (Yao *et al.* 2024), or other computational techniques to determine clustering and routing decisions. In 2024, metaheuristic applications in WSNs focused on energy efficiency and clustering, but also noted the challenges of optimization-based WSN design. The methodological trade-off is improving decision quality or increasing algorithmic complexity.

Accordingly, there remains an opportunity to investigate a lightweight LEACH-based framework that integrates several complementary energy-management mechanisms without relying on computationally intensive optimization (Wilson *et al.* 2024) or learning models. GME-LEACH addresses this direction through four coordinated mechanisms: multi-criteria Clustered selection, sleep–awake scheduling, hybrid multi-hop communication, and adaptive CH rotation. The CH-selection stage evaluates remaining energy, distance to the BS, local node density, and node centrality to identify candidates that are suitable from both energy and spatial perspectives. Sleep–awake scheduling is then used to reduce unnecessary node activity, while the hybrid communication mechanism permits direct or relay-based transmission according to communication conditions. Finally, adaptive CH rotation regulates the distribution of the CH responsibility according to the current suitability and energy status of candidate nodes. Geerthik et al. (2026) proposed a hybrid optimization and deep-learning framework for WSNs that employs SLepBO for energy-efficient multi-objective routing and ConvXGB for intrusion detection, demonstrating the growing use of intelligent optimization and learning-based techniques in WSN routing and security.

The contribution of GME-LEACH is therefore not based on claiming that each individual mechanism is entirely new. Instead, the proposed framework investigates how these complementary mechanisms can be coordinated within a relatively simple and interpretable LEACH-based architecture. This integrated design provides a basis for examining the individual contribution of each mechanism through ablation analysis and for evaluating whether their combination can improve energy utilization and network lifetime under a common network model.

3. Network model and assumptions

GME-LEACH protocol suits homogeneous WSN in which SNs periodically monitor a predefined sensing area. The network consists of N SNs randomly deployed within a two-dimensional 100×100m sensing field. A single BS is located outside the sensing region, as illustrated in Figure 1, allowing the effect of communication distance and relay-based transmission to be considered in the network model. Following deployment, the SNs are assumed to remain at fixed locations throughout the network operation. The nodes have identical hardware characteristics and are initially assigned the same energy level (E_0), with comparable communication, processing, and sensing capabilities (Heinzelman *et al.* 2002). Each SN periodically acquires environmental measurements and participates in clustered communication to deliver the collected information to the BS. The BS is assumed to remain stationary during the entire simulation period, whereas the sensor nodes do not change their positions after deployment. Each node is assumed to know its own location and to obtain the distance to the BS and neighboring nodes. This information is used by the routing protocol when making clustering and communication decisions. In addition, every SN maintains its current residual energy throughout the network operation, enabling energy-aware decisions during CH selection and rotation.

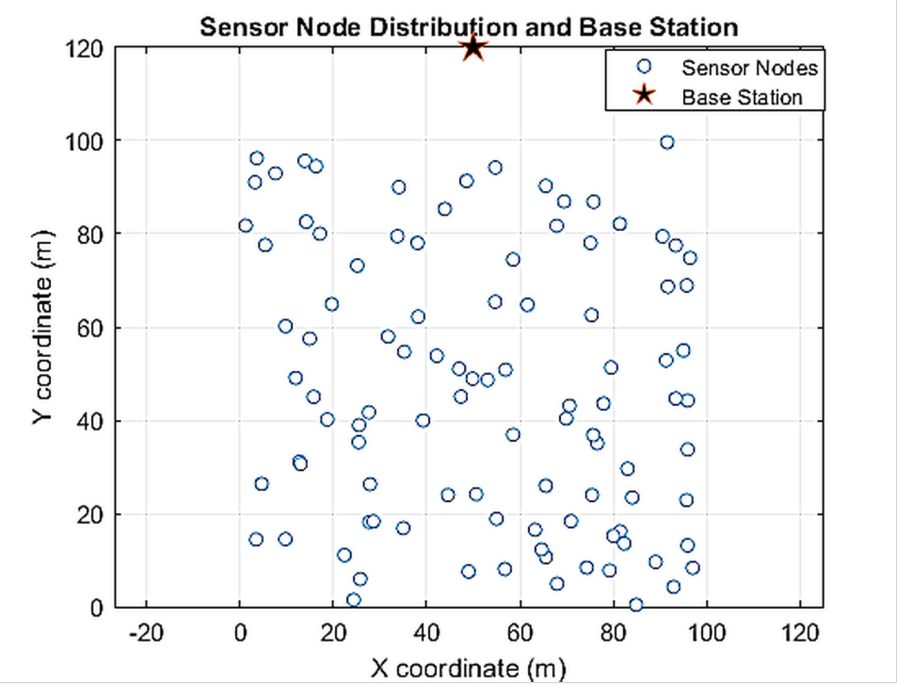

Figure 1. The base station outside the network.

Member nodes send sensed data to the CH in each cluster, which aggregates it and sends it to the BS. Communication links are assumed to be symmetric; therefore, the transmission characteristics between two communicating nodes are considered equivalent in both directions. Network operation proceeds in successive rounds. Each round begins with clustering and network decisions, followed by sensing data transmission and aggregation in the steady-state stage. This round-based organization follows the general operational structure established by LEACH and subsequently adopted by several LEACH-based protocols (Heinzelman *et al.* 2002; Altaha and Al Ali 2025; Kaur *et al.* 2024; Tian 2025; Wang *et al.* 2026; El-Sayed *et al.* 2024).

The energy consumption is modeled with the classic first-order radio energy dissipation model. In this model the energy required for wireless transmission is a function of the packet size and the distance between the communicating nodes. The transmitter incurs an electronic processing cost in addition to a distance-dependent amplification cost, whereas the receiver consumes energy for receiving and processing the transmitted packet. Accordingly, communication over longer distances results in greater transmission energy expenditure, which provides the basis for evaluating the energy-saving effects of clustering and relay-based communication in GME-LEACH. A message of L bits over a distance $\mathbf{d}$ is given by Equation 1:

$$E_{TK}(L,\ d) = \begin{cases} LE_{elec} + k\varepsilon_{fs}d^2,\ d < d_0 \\ LE_{elec} + k\varepsilon_{mp}d^4,\ d \geq d_0 \end{cases} \quad (1)$$

The energy used per bit during transmission or reception, denoted as $\mathbf{E_{elec}}$, depends on the electronic circuitry of the transmitter and receiver. Where: $\mathbf{L}$ is size of the packet in bits, ε_{mp} is the multipath amplifier parameter, $\mathbf{d}$ is the transmission distance, ε_{fs} is the free-space amplifier parameter, d_0 is the threshold distance where $d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$. The overall transmission energy is also impacted by the transmitter amplifier's energy consumption, which varies depending on the amplifier model selected. This model accurately estimates energy consumption based on message size and transmission distance by capturing the important energy expenses for communication in WSNs (Heinzelman *et al.* 2002; Wang *et al.* 2026; Loscri *et al.* 2005; Raheem and Raheem 2026).

4. Methodology

4.1. LEACH protocol

LEACH is one of the most well-known hierarchical protocols designed to extend the lifespan of SNs deployed in clusters within WSNs. LEACH incorporates data fusion into the routing process to minimize the amount of data sent to the BS and employs localized coordination to improve scalability and robustness in dynamic networks. The main focus of LEACH is clustering, in which SNs are arranged into clusters under the direction of a CH. Before sending the processed data to the BS, CHs are in charge of gathering and combining data from the SNs that are connected to them. By greatly reducing the requirement for direct connection between individual SNs and the BS, this method increases network energy efficiency. LEACH incorporates a randomized rotation of the high-energy CH duty among the several sensors to prevent depleting the battery of a single sensor. A preparation phase and a steady-state phase make up each round of the LEACH protocol's operation. CHs are chosen at random during the setup phase using Equation (2) and their residual energy. At every given moment, sensors have a specific likelihood of choosing to be the heads of local clusters:

$$\mathbf{T(n)}=\frac{\mathbf{p}}{1-\boldsymbol{p}*\left(\boldsymbol{r}*\boldsymbol{mod}\frac{1}{\boldsymbol{p}}\right)\boldsymbol{if}\ \boldsymbol{n}\in\boldsymbol{G}} \tag{2}$$

where n is a random number between 0 and 1, p is the desired percentage of cluster heads, r is the current round, and G is the set of nodes that have not been cluster heads in the last 1/p rounds. The node becomes a CH if n < T(n). This guarantees that every node turns into a CH at least once per 1/p rounds. Cluster creation is also carried out during this phase: non-CH nodes choose the CH with the strongest received signal (often the shortest distance) and then send join requests to the CH they have chosen. Elected CHs broadcast advertisement messages to neighboring nodes. After then, each CH generates a Time Division Multiple Access (TDMA) schedule, disseminating the schedule to every cluster member and allocating transmission time slots to member nodes.

Data transmission is the main focus of the steady-state phase, which is usually longer than the setup phase. The CH receives sensed data from SNs, combines it, and sends it to the base station. This technique improves energy efficiency and lowers communication overhead. In this phase, transmission energy, reception energy, and data aggregation energy are all covered by the radio energy dissipation model. Equation (1) is used to compute the transmission energy, while Equation (3) is used to determine the receiving energy:

$$\mathbf{E}_{\boldsymbol{RX}}\mathbf{(k)}=\boldsymbol{k}*\boldsymbol{E}_{\boldsymbol{elec}} \tag{3}$$

Additionally, CHs consume energy for data aggregation according to Equation (4):

$$\mathbf{E}_{\boldsymbol{Data}}=\mathbf{E}_{\boldsymbol{DA}}*\boldsymbol{k} \tag{4}$$

Despite its advantages, LEACH's effectiveness in real-world applications may be constrained by a number of presumptions. It is better suited for small-scale networks since it implies that every SN can communicate directly with every other SN and reach the sink. LEACH assigns transmission slots based on the assumption that every node has data to send, which may result in inefficient use of resources if some nodes don't have any data. It also makes the assumption that nearby nodes provide correlated data, which might not always be the case. Lastly, LEACH makes the assumption that nodes are constantly listening to the communication channel, which could result in higher energy usage, particularly if cluster heads are situated near the network's edges (Heinzelman *et al.* 2002).

4.2. The proposed protocol GME-LEACH

By reducing needless energy usage and distributing the communication strain among SNs, the suggested GME-LEACH clustering technique aims to increase the lifespan of WSNs. Unlike the conventional LEACH technique, which chooses CHs at random in each round, the proposed protocol offers a multi-stage decision framework that considers the network's topology and energy level before selecting cluster heads. Additionally, redundant SNs are momentarily put into sleep mode and multi-hop communication between CHs is employed when direct transmission to the BS is inefficient. There are four consecutive steps in the suggested protocol: Adaptive Green Rotation, Green Sleep Scheduling, Multi-hop Hybrid Routing, and Multi-Criteria CH Selection

4.2.1. Stage 1: multi-criteria cluster-head selection

Instead of depending just on the probabilistic selection method used by traditional LEACH, the GME-LEACH protocol takes into account several aspects of the WSN to identify the best CHs. Four criteria are used to choose CHs for each living SN: energy, distance, density, and centrality. To evaluate each node's eligibility for CH selection, these elements are then combined into a single Green Score. Energy Factor: Residual energy is regarded as the main factor for CH selection since CHs require much more energy than regular SNs because of their added duties in data aggregation and communication. As a result, nodes with leftover energy greater than the current network average receive higher Energy Factor values, making them more suitable for taking on the extra energy load related to CH operation.

$$EF_i = \frac{E_i}{\overline{E}} \tag{5}$$

Where: E_i denotes the residual energy of node i, $(\overline{E})$ represents the average residual energy of all alive nodes. In term of Distance Factor, The energy needed for data transmission is directly impacted by the distance between a candidate CH and the BS. Because they can send aggregated data with less transmission energy, nodes that are closer to the BS are typically chosen. The definition of the normalized distance factor is:

$$DF_i = 1 - \frac{d(i,\ BS)}{d_{\max}} \tag{6}$$

Where: $d(i, BS)$ is the Euclidean distance between the BS and node i, $d_{\max}$ is the farthest distance inside the sensing field at which communication is feasible. The Euclidean distance between node i and the BS is calculated as:

$$d(i,\ BS) = \sqrt{(x_i - x_{BS})^2 + (y_i - y_{BS})^2} \tag{7}$$

This normalization produces a higher Distance Factor for nodes that are geographically closer to the BS. To find nodes that can effectively service a sizable number of neighboring SNs, the local neighborhood density is taken into account. A node in a crowded area may be able to facilitate more efficient cluster formation and shorten intra-cluster communication distances. The formula for calculating the Density Factor is:

$$Density_i = \frac{N_i}{N} \tag{8}$$

Where: N_i is the quantity of nearby nodes within radius (R), N is the total number of SNs. Two nodes are considered neighbors when their Euclidean distance satisfies the following condition: $d(i,j) < R$. In addition to neighborhood density, the geographical position of a candidate CH relative to its neighboring nodes is considered. Ideally, a CH needs to be situated close to the neighborhood's geometric center. so that the communication distances between the CH and its member nodes can be reduced. The average distance between node i and its neighboring nodes is calculated as:

$$AvgDist_i = \frac{\sum_{j=1}^{N_i} d(i,\ j)}{N_i} \tag{9}$$

Based on this average distance, the Centrality Factor is defined as:

$$CF_i = 1 - \frac{AvgDist_i}{R} \tag{10}$$

A candidate node with a greater Centrality Factor is better suited for reducing intra-cluster communication distances since it is situated nearer the center of its immediate neighborhood. Energy, Distance, Density, and Centrality, the four decision-making criteria, are combined into a single metric referred to as the Green Score. The Green Score provides a comprehensive measure of the suitability of each alive node for CH selection and is calculated as:

$$Score_i = w_1 EF_i + w_2 DF_i + w_3 Density_i + w_4 CF_i \tag{11}$$

$$\sum_{i=1}^{4} w_i = 1$$

Where the weighting coefficients determine the relative contribution of the four decision factors to the overall Green Score. A higher Green Score indicates a more suitable candidate for CH selection because the node simultaneously exhibits favorable energy availability, BS proximity, neighborhood density, and local centrality. To preserve the probabilistic CH rotation mechanism of LEACH while incorporating the proposed node-quality assessment, the conventional LEACH threshold is first defined as Equation (2).

Instead of relying exclusively on this conventional threshold, GME-LEACH protocol modifies the CH-selection probability by incorporating the Green Score as follows:

$$T_{Green} = T(n) * Score_i \tag{12}$$

This formulation combines the probabilistic rotation principle of LEACH with the multi-criteria assessment of node quality. Thus, nodes with better network characteristics have a better chance of becoming CHs while maintaining the rotational nature of the original LEACH protocol.

4.2.2. Stage 2: green sleep scheduling

By locating nearby nodes that keep an eye on roughly comparable areas, this step minimizes duplicate sensing activity. Nodes that are less than a certain radius R_S apart are coupled during network startup. $d(i,j) < R_S$ To ensure continuous sensing coverage without depleting individual sensors, only one node in a paired set remains active per communication round while its counterpart enters a low-power sleep state. These active and sleeping roles alternate periodically—for instance,

Node A is awake and Node B is asleep in Round 1, whereas Node A sleeps and Node B activates in Round 2. The energy consumption of neighboring sensors is distributed uniformly by this rotation. Unlike static sleep schedules, the proposed approach ensures fair energy distribution and significantly extends network lifetime.

4.2.3. Stage 3: hybrid multi-hop routing

In a typical LEACH with multi-hop hybrid routing, every CH speaks with the BS directly. When CHs are far from the BS, the LEACH technique becomes less effective. Adaptive multi-hop communication is introduced by GME-LEACH. The CH looks for another CH that is closer to the BS, has enough residual energy, and reduces the routing cost when (CHi,BS)> d0. The routing becomes CHi→CHj→BS instead of CHi sending its data straight to BS. Equation (13) is used to assess each candidate relay:

$$\boldsymbol{RelayScore} = \alpha\left(\frac{\mathbf{d}_{CH}}{\mathbf{d}_0}\right) + \beta\left(\frac{\mathbf{d}_{RelayBS}}{\mathbf{d}_{BS}}\right) + \gamma\left(\frac{\overline{\mathbf{E}}}{\mathbf{E}_{Relay}}\right) \tag{13}$$

The distance between two CHs is represented by $\mathbf{d_{CH}}$, the relay distance to the BS by $\mathbf{d_{RelayBS}}$, the relay residual energy is $\mathbf{E_{Relay}}$. The relay with the lowest routing cost is selected, subject to the constraint that the sum of the three weighting coefficients equals one.

4.2.4. Stage 4: green rotation adaptation

Regardless of CHs' leftover energy, the LEACH technique rotates them on a regular basis. This frequently replaces effective CHs needlessly. GME-LEACH represents adaptive rotation. A current CH continues serving if:

$$\boldsymbol{Ei} > \boldsymbol{\Gamma}\overline{\mathbf{E}}$$

Where

- $\boldsymbol{\Gamma}$ is the rotation threshold,
- $\overline{\mathbf{E}}$is the mean residual energy.

Otherwise, $\mathbf{Ei} \leq \boldsymbol{\Gamma}\overline{\mathbf{E}}$ a replacement CH is elected using the Green Score. This adaptive approach minimizes control packet transmission, lowers cluster reformation overhead, and maintains stable clusters for extended periods of time. The proposed GME-LEACH routing protocol's operational flowchart is displayed in Figure 2.

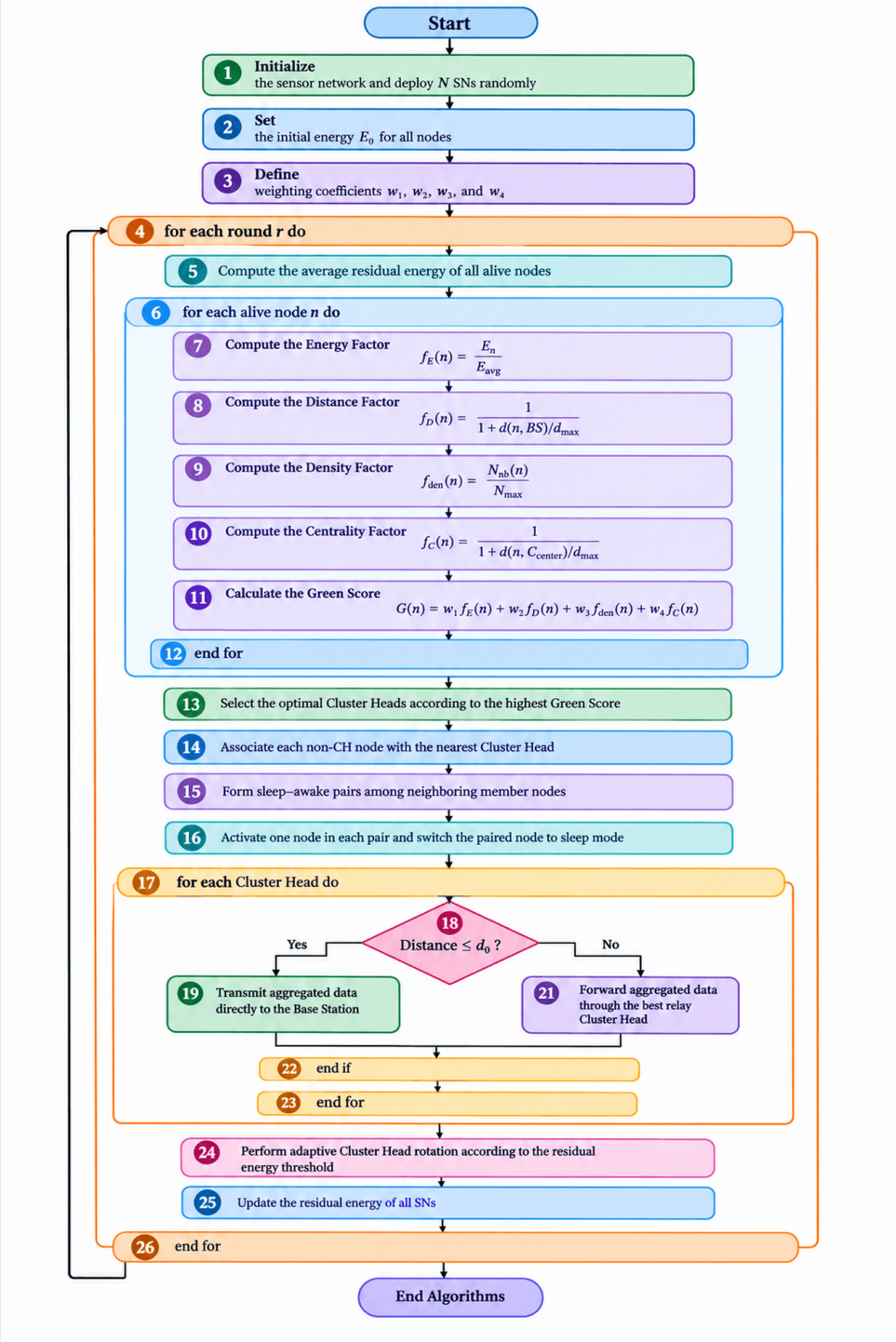

Figure 2. Operational flowchart of the proposed GME-LEACH routing protocol.

5. Performance evaluation and simulation results

The suggested protocol is tested in the same simulated environment as the benchmark routing protocols using MATLAB R2024a. 100 SNs are dispersed at random inside a 100 m × 100 m square sensing area. Because multi-hop requirements must be taken into account, the BS was situated outside the sensing field. At first, the energy of each SN was 0.5 J. For all communication operations,

the first-order radio energy model was employed to ensure a fair comparison of the evaluated protocols. The simulation parameters are summarized in Table 1:

Table 1. Simulation parameters

Parameters	Value
Initial energy	0.5 J
Base Station	(50,120)
Packet Size	4000 bit
ETX	50 nJ/bit
ERX	50 nJ/bit
EDA	5nJ/bit/signal
Efs	10 pJ/bit/m^2
Emp	0.0013 pJ/bit/m^4
CH probability	0.1
Density Radius	20
Pair Radius	8
W1	0.40
W2	0.25
W3	0.20
W4	0.15
γ	0.3
α	0.4
β	0.3
Adaptive Rotation Threshold (Γ)	1.0

The performance of the proposed routing protocols was evaluated using the following metrics: FND, HND, LND, and Throughput. Where the throughput represents the total number of packets that are successfully delivered to the BS. Table 2 performs a systematic ablation analysis in addition to comparison with the conventional LEACH protocol. This ablation design makes it possible to examine the effect of each mechanism separately and to determine how their combination influences the overall behavior of the proposed protocol. The main contributions of this study can be summarized as follows:

Table 2. Ablation study of GME-LEACH

Protocol	FND	HND	LND	Throughput
LEACH	922	1090	1391	11165
No Green CH (A1)	1038	1213	1896	36959
No Sleep (A2)	928	1102	1445	34814
No Multi-hop (A3)	1198	1498	1759	36848
No Adaptive Rotation (A4)	1147	1521	1898	15559
Full GME-LEACH	1220	1439	1696	25288

A multi-criteria CH-selection mechanism is created by taking into account remaining energy, node centrality, local node density, and distance between nodes to the BS. A sleep–awake scheduling mechanism is incorporated into the clustering framework to reduce unnecessary energy consumption. A hybrid communication mechanism is employed to support direct and multi-hop CH-to-BS transmission according to communication conditions and relay suitability. An adaptive CH-rotation mechanism is introduced to distribute CH responsibility while considering the current

energy and suitability of candidate nodes. A systematic ablation study is conducted to isolate the contribution of the four mechanisms and evaluate their effects on FND, HND, LND, and packet delivery. The proposed protocol is evaluated against conventional LEACH under a common simulation environment to provide a consistent assessment of network lifetime and communication performance.

The ablation study was conducted to evaluate the individual contribution of the four principal mechanisms integrated to propose GME-LEACH protocol: green multi-criteria cluster-head (CH) selection, sleep–awake scheduling, multi-hop routing, and adaptive CH rotation. The Full GME-LEACH configuration achieved an FND of 1220 rounds, an HND of 1439 rounds, an LND of 1696 rounds, and 25,288 packets successfully delivered to the BS. These results demonstrate that GME-LEACH provides a balanced performance across the four evaluation criteria—early node survival, half-node survival, overall network lifetime, and data delivery—rather than optimizing a single metric at the expense of the others.

The most significant observation is the FND improvement achieved by the complete GME-LEACH configuration. Compared with conventional LEACH, the proposed complete configuration increases FND from 922 to 1220 rounds, corresponding to an improvement of approximately 32.3%. This result indicates that the combined mechanisms are particularly effective in protecting the weakest-energy nodes during the early and middle stages of network operation. In WSNs, FND is an important indicator because the first node failure marks the beginning of network degradation and can affect sensing coverage and connectivity. The higher FND obtained by the complete configuration therefore suggests that the proposed combination provides more balanced initial energy consumption than conventional LEACH.

The ablation result for No Green CH (A1) provides evidence of the contribution of the proposed green CH-selection mechanism. Removing the green CH-selection mechanism increases FND to 1038 rounds, HND to 1213 rounds, and LND to 1896 rounds, while the throughput reaches 36,959 packets. Although these values may appear favorable for HND, LND, and throughput, they should not be interpreted as evidence that removing green CH selection improves the overall protocol. Instead, they indicate a different energy-consumption distribution. Without the green multi-criteria CH selection, some nodes can remain operational for a longer period, producing a higher LND, but FND occurs earlier than in the GME-LEACH protocol. The increase in FND from 1038 to 1220 when green CH selection is restored demonstrates that the green selection mechanism primarily contributes to early energy balancing and protection of vulnerable nodes. This is consistent with its use of multiple node and topology characteristics rather than relying on a single criterion.

For No Sleep (A2), the results show FND = 928, HND = 1102, LND = 1445, and throughput = 34,814 packets. The FND is only slightly higher than conventional LEACH, whereas the complete GME-LEACH increases FND substantially to 1220 rounds. This difference demonstrates the importance of the sleep–awake mechanism for reducing unnecessary energy expenditure by non-critical nodes. The reduction in LND from 1696 in the complete protocol to 1445 rounds when sleep scheduling is removed further suggests that continuously active nodes consume their limited energy more rapidly. Therefore, the sleep–awake mechanism contributes primarily to energy conservation and extension of network operation, particularly by preventing unnecessary participation of paired nodes in every communication cycle.

The No Multi-hop (A3) configuration provides an especially important result. Its FND, HND, and LND are 1198, 1498, and 1759 rounds, respectively, while throughput reaches 36,848 packets. Removing multi-hop therefore reduces FND only slightly, from 1220 to 1198 rounds, but produces higher HND and LND values. This indicates that multi-hop routing does not necessarily maximize the lifetime of every individual node under the investigated topology. Instead, its main role is to control the communication distance between cluster heads and the BS, particularly for CHs located relatively far from the BS. The complete GME-LEACH sacrifices some later-stage lifetime compared with A3, but provide a slightly higher FND, indicating better protection of early vulnerable nodes. This result

highlights an important energy-routing trade-off: multi-hop communication can redistribute communication costs, but relay participation introduces additional transmission and forwarding energy consumption.

The No Adaptive Rotation (A4) configuration produces FND = 1147, HND = 1521, LND = 1898, and throughput = 15,559 packets. The reduction of FND from 1220 to 1147 after removing adaptive CH rotation demonstrates that CH rotation contributes to protecting nodes from repeated CH responsibilities. In contrast, the high LND of 1898 indicates that some nodes remain alive for a considerable number of rounds even without adaptive rotation. The most striking feature, however, is the substantial reduction in throughput to 15,559 packets. This represents approximately a 38.5% reduction compared with the complete GME-LEACH configuration. Therefore, adaptive CH rotation appears to play an important role not only in lifetime balancing but also in maintaining effective data delivery to the BS. By redistributing the CH role among eligible nodes, the mechanism can reduce excessive energy depletion at frequently selected CHs and maintain more stable communication over the network.

The comparison between the complete protocol and the ablation configurations also demonstrates that network lifetime should not be evaluated using LND alone. For example, A1 and A4 both achieve LND values of 1896 and 1898 rounds, respectively, which are higher than the 1696 rounds obtained by the complete GME-LEACH. However, their FND values are considerably lower than the complete configuration. This means that a small subset of nodes can survive for a long time while other nodes have already died much earlier. Such behavior can lead to an unbalanced network in which sensing coverage and connectivity deteriorate despite the existence of some remaining nodes. The complete protocol instead achieves the highest FND, indicating a more favorable early-stage energy balance. A similar trade-off can be observed in throughput. A1, A2, and A3 produce higher packet-delivery totals than the complete configuration, with A1 reaching 36,959 packets and A3 reaching 36,848 packets. This does not necessarily indicate superior energy efficiency. Higher throughput may result from keeping more nodes continuously active or transmitting over more communication cycles, which can simultaneously accelerate energy depletion. Consequently, throughput should be interpreted jointly with FND, HND, and LND rather than as an isolated performance indicator. Overall, the ablation results demonstrate that the four mechanisms affect different aspects of network behavior. Green CH selection primarily improves early energy balance; sleep–awake scheduling reduces unnecessary energy consumption; multi-hop routing manages long-distance CH-to-BS communication; and adaptive CH rotation distributes the CH burden among nodes. Their interaction is more important than the effect of any individual mechanism in isolation. The complete GME-LEACH configuration achieves the highest FND of all evaluated configurations, increasing network protection against early node failures while maintaining intermediate HND and LND values. Therefore, the results support the methodological argument that the proposed protocol is not merely a combination of independent LEACH modifications; rather, the mechanisms address complementary sources of energy imbalance at different stages of network operation. Importantly, the ablation study also reveals that the proposed protocol involves an inherent multi-objective trade-off between early network stability, overall node survival, and data delivery. The complete GME-LEACH favors a higher FND, whereas some individual ablations produce higher HND, LND, or throughput. This behavior is expected in energy-constrained WSNs because aggressively maximizing one metric can redistribute energy consumption in a way that negatively affects another metric. Thus, the ablation results should be interpreted as evidence of complementary functional contributions rather than as a claim that the complete protocol maximizes every individual performance metric. Figures 3–8 present the ablation study results in terms of network lifetime, residual energy, dead nodes, alive nodes, and throughput, respectively.

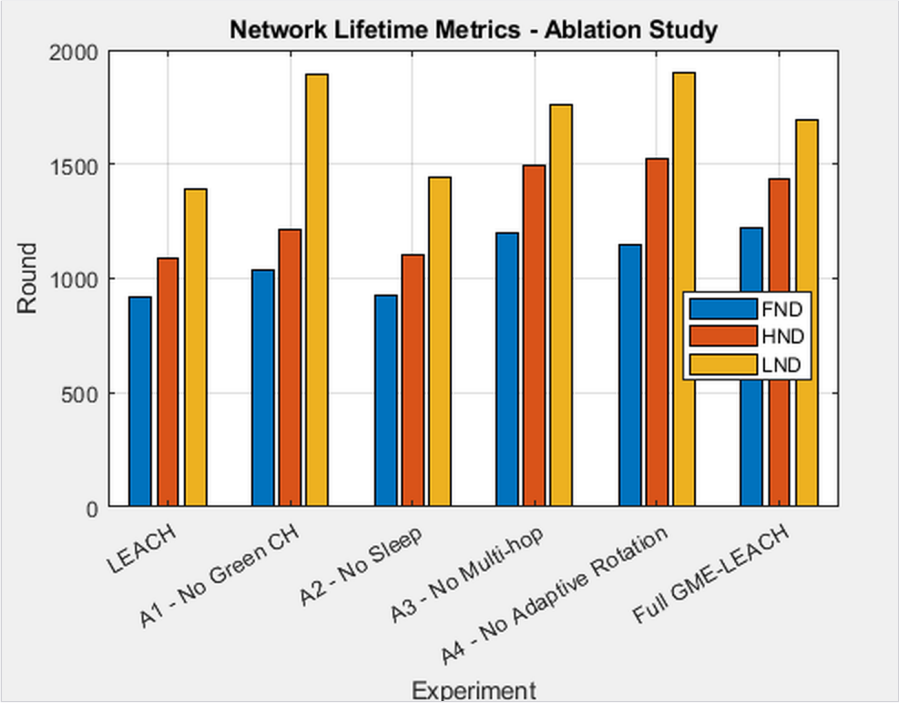

Figure 3. Network lifetime metrics for the ablation study.

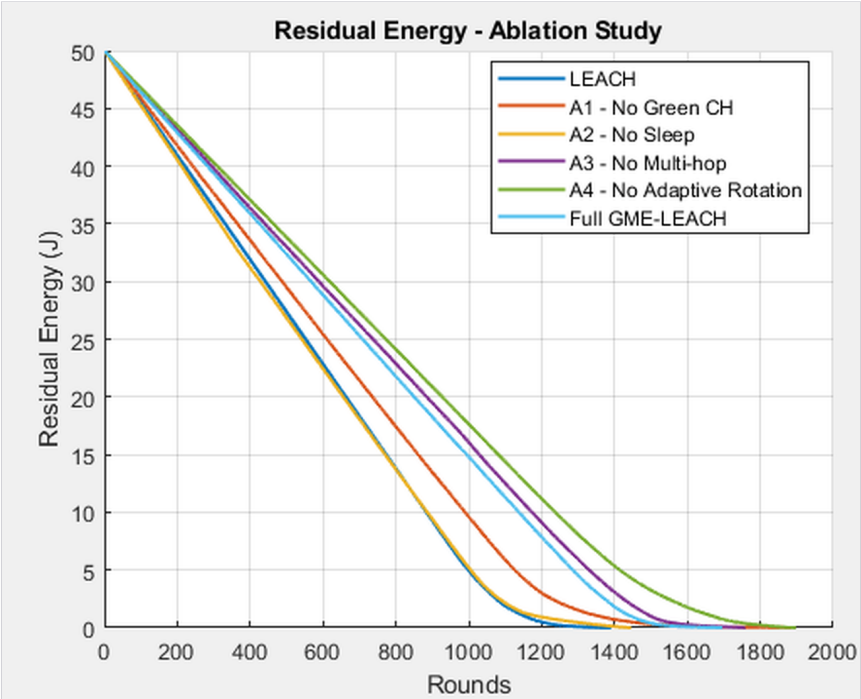

Figure 4. Residual energy for the ablation study.

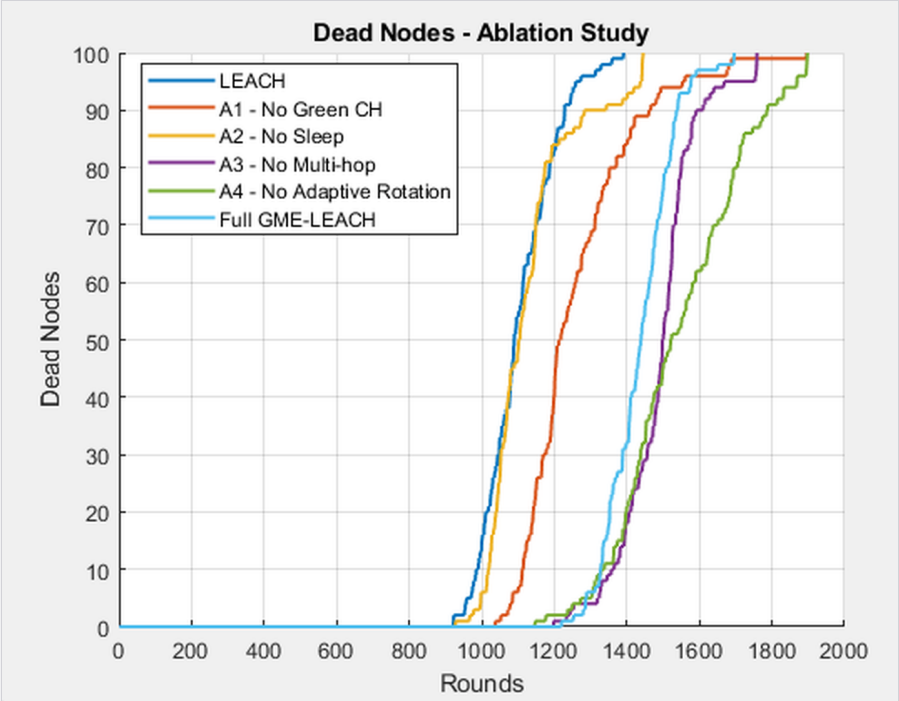

Figure 5. Dead nodes for the ablation study.

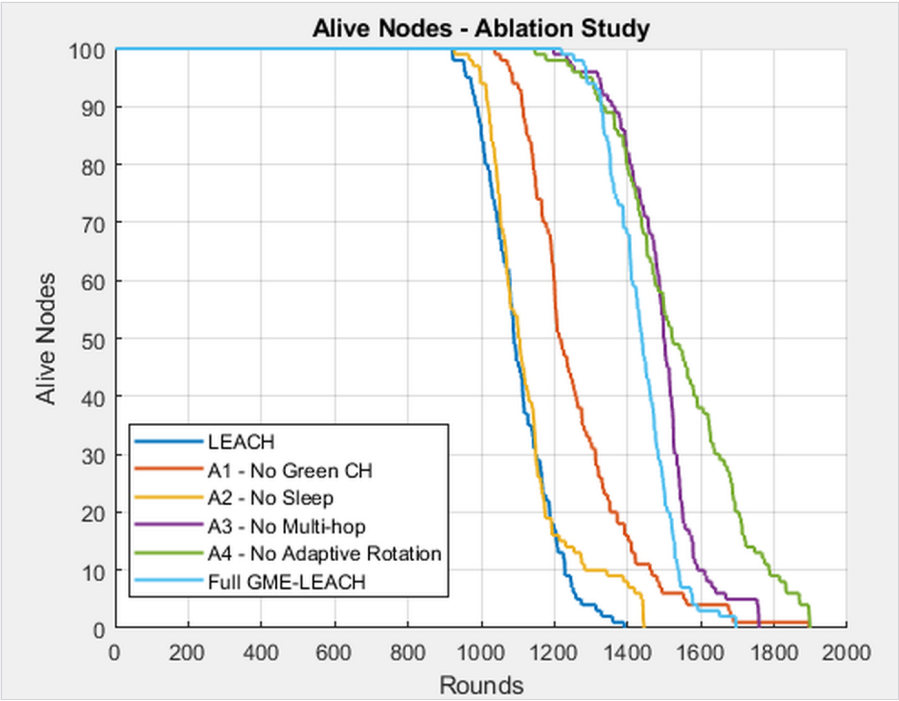

Figure 6. Alive nodes for the ablation study.

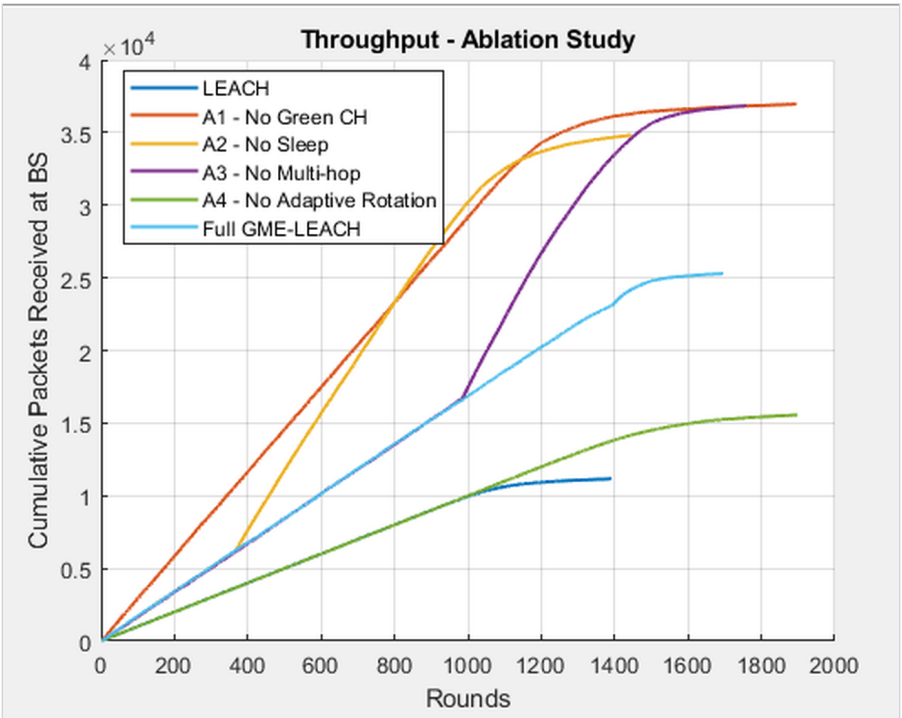

Figure 7. Throughput for the ablation study.

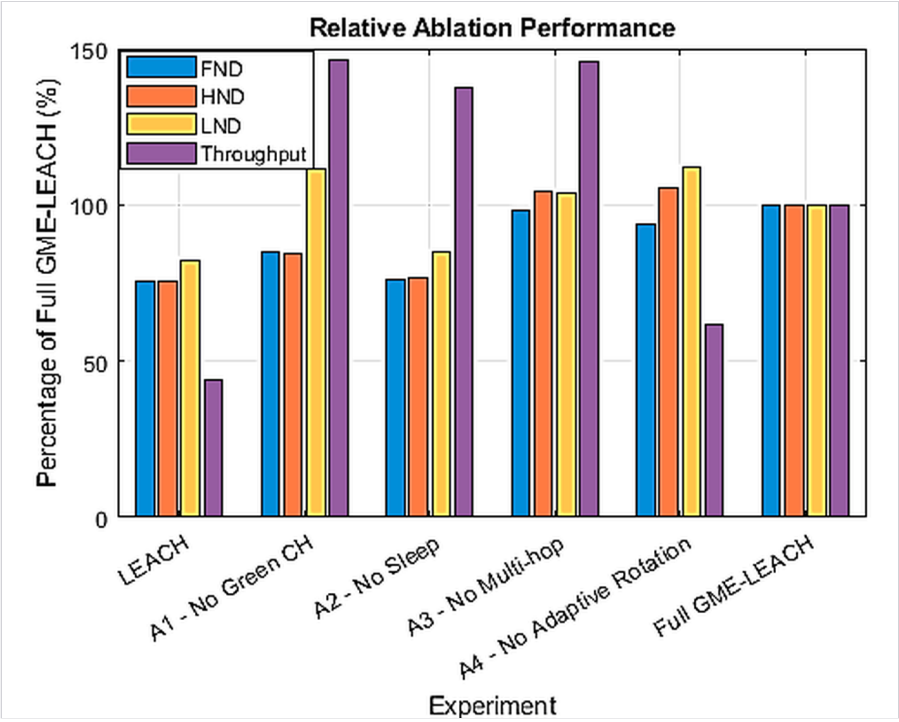

Figure 8. Relative ablation performance.

The remaining energy of every procedure during the simulation is shown in Figure 9 below. The slowest rate of energy depletion is shown by the suggested GME-LEACH. By integrating remaining energy, node density, centrality, and communication distance into the CH selection process, GME-LEACH distributes energy consumption more evenly than LEACH, which rapidly depletes energy owing to random cluster head selection and direct connection with the BS. As illustrated in Figure 9, total remaining energy continues to deliver superior throughput across the majority of simulation rounds.

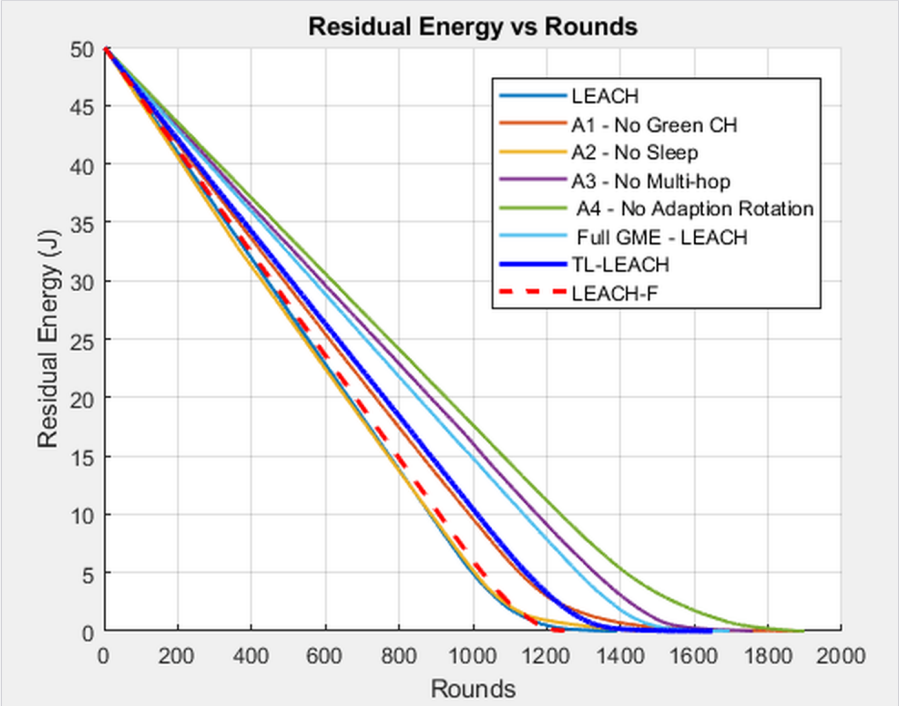

Figure 9. The residual energy of all protocols throughout the simulation.

The number of nodes that remain active during the simulation is shown in Figure 10. Among LEACH, TL-LEACH, and LEACH-F, GME-LEACH sustains a greater number of active SNs during the course of the network lifetime. Its adaptive cluster head rotation avoids needless changes in cluster structure, and its sleep-awake pairing technique efficiently decreases redundant sensing. Node failures thus happen more slowly than with benchmark protocols. Table 3 shows FND, HND and LND for LEACH, TL-LEACH, LEACH-F and GME-LEACH.

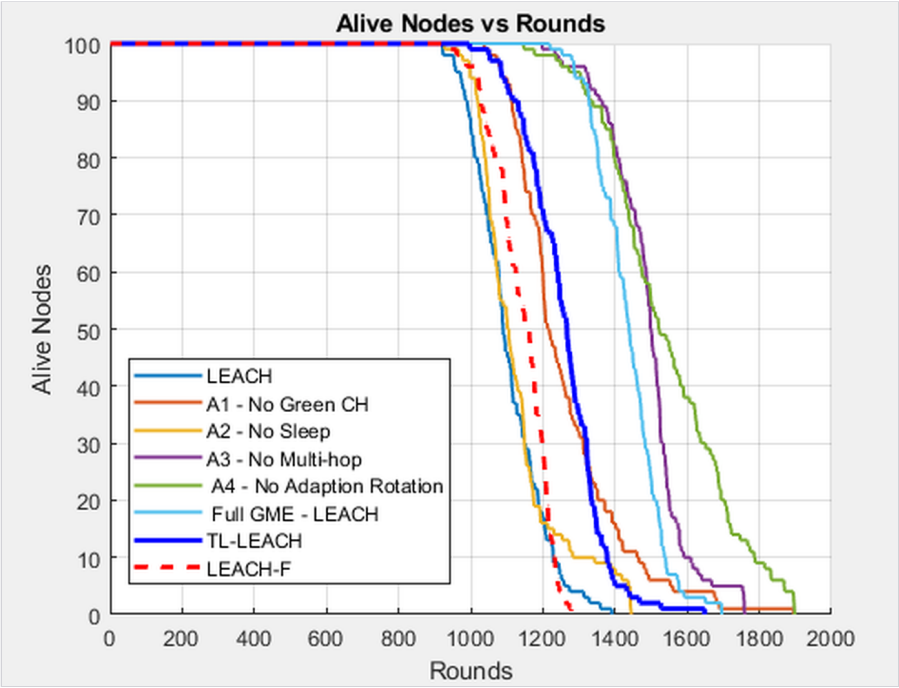

Figure 10. The number of alive nodes as the simulation progresses.

Table 3. FND, HND and LND for the different routing protocols

Protocol	FND	HND	LND
LEACH	922	1090	1391
TL-LEACH	997	1267	1649
LEACH-F	943	1160	1279
Full GME-LEACH	1220	1439	1696

6. Conclusion

This study presented GME-LEACH, an energy-efficient WSN protocol that integrates multi-criteria green cluster-head selection, adaptive cluster-head rotation, sleep–awake scheduling, and hybrid multi-hop communication. The ablation study showed that the complete GME-LEACH configuration achieved an FND of 1220 rounds, an HND of 1439 rounds, an LND of 1696 rounds, and 25,288 packets delivered to the base station. Compared with conventional LEACH, these results represent improvements of approximately 32.3%, 32.0%, 21.9%, and 126.5%, respectively.

The results indicate that the combined mechanisms provide a balanced improvement in energy management and early network stability rather than maximizing a single performance metric. The simulations were conducted for a 100 × 100 m sensing field with the base station positioned at (50, 120) m, i.e., outside the sensing area. This configuration introduces longer CH-to-BS communication distances and therefore provides a relevant setting for evaluating energy-efficient routing and multi-hop communication. Future work will evaluate GME-LEACH under multiple network sizes, base-station locations, and independent random deployments to further assess its robustness.

Declarations

Author contributions. Maha I. Raheem: Conceptualisation: Developed the overarching themes and objectives of the study. Methodology: Designed the proposed routing protocol and defined the criteria for its performance evaluation. Writing – Original Draft: Wrote the initial manuscript draft, including key sections.

Conflicts of interest. The author states no conflict of interest.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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