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An energy-efficient clustering approach for wireless sensor networks: green hybrid-LEACH

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ABSTRACT

Energy management is a key challenge in wireless sensor networks (WSNs), primarily due to the limited battery resources of sensors, which shorten the network lifespan. Uneven energy consumption and high routing overhead significantly reduce network longevity. In this paper, we present an energy-efficient clustering method called green hybrid-low energy adaptive clustering hierarchy (GH-LEACH). The proposed method selects balanced and energy-efficient cluster heads (CHs) during the setup phase by considering residual energy, node density, node centrality, and distance to the base station (BS). Additionally, an adaptive CH rotation mechanism and multi-hop communication among CHs are incorporated to reduce transmission energy and distribute the network load more effectively. Results demonstrate that GH-LEACH minimizes network overhead, extends the time until the first node dies (FND), improves overall network performance, and enhances throughput compared to existing protocols such as conventional LEACH, LEACH-C, TL-LEACH, and LEACH-F. This approach distributes the energy load among sensors more evenly, especially in denser networks.

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1. INTRODUCTION

WSNs have become a fundamental technology for a wide range of applications, including environmental monitoring [1], [2], precision agriculture [3], industrial automation [4], [5], healthcare [6], military surveillance [7], and smart cities [8]. A typical WSN consists of wirelessly interconnected, low-cost electronic devices called sensor nodes (SNs), which are randomly dispersed in an environment to monitor physical or environmental conditions and transmit the collected data to a central sink node called the BS [2]. Energy management plays a crucial role in WSNs because nodes are battery-operated, non-rechargeable, and often deployed in remote hazardous areas [9]. Consequently, many protocols have been proposed to reduce energy dissipation in these nodes. The main objective of routing research in WSNs is to maintain each node's energy consumption in order to increase the network's lifespan. In WSNs, routing protocols are essential because they dictate how sensed data is sent from SNs to the sink or base station (BS) [10]. Because SNs have limited energy, computing power, memory, and communication bandwidth, routing methods are mainly made to maximize energy consumption while guaranteeing dependable data transmission and prolonging network lifetime. Recent works and their limitation are presented in Table 1.

Based on their routing strategies, WSN routing protocols are generally classified into four main categories [11]. These include flat-based routing protocols, hierarchical (Cluster-based) routing protocols, location-based routing protocols, and quality of service (QoS)-based routing protocols [12]. LEACH [13]-[15] is a hierarchical routing protocol that offers significant improvements over direct communication; its CH selection relies mainly on random probability and ignores critical network factors such as residual energy, node distribution, communication distance, and local topology. To avoid these limitations, numerous improvements have been proposed over the past two decades. E-LEACH enhances the original LEACH by incorporating residual energy into the CH election process. Nodes with higher remaining energy are assigned a greater probability of becoming CHs, thereby balancing energy consumption more effectively than purely random selection. However, E-LEACH still relies on single-hop communication and reconstructs clusters during every round, limiting its scalability in large deployment areas [16]. LEACH-F introduces fixed cluster formation during the network initialization phase. Once clusters are established, only the CH role rotates among members of the same cluster. This approach eliminates the repeated clustering overhead associated with conventional LEACH and reduces control message exchanges. This fixed cluster architecture limits the system's ability to adjust to changes in network topology and uneven energy use, which ultimately causes clusters to become unbalanced and decreases routing efficiency [17].

TL-LEACH extends LEACH by introducing a two-level hierarchical routing architecture. In this approach, ordinary CHs forward aggregated data to higher-level CHs before transmission to the BS. The multi-level hierarchy decreases long-distance transmission costs and improves scalability compared with the original LEACH [18]. Despite these improvements, the protocol still depends on probabilistic CH selection without considering node density or spatial distribution, and it does not optimize relay selection according to energy-aware routing metrics. Several subsequent LEACH variants have incorporated additional optimization strategies, including fuzzy logic [19], evolutionary algorithms [20], swarm intelligence [21], machine learning, and energy-aware metrics. These methods generally improve CH selection by considering multiple parameters such as residual energy, distance to the BS, node degree, or communication cost. Nevertheless, most existing approaches continue to perform complete CH re-election in every round, which introduces unnecessary control overhead and increases energy consumption. In addition, many protocols rely exclusively on single-hop communication or employ relay selection methods that neglect the residual energy of intermediate CHs. Furthermore, redundant sensing among neighboring SNs remains largely unaddressed despite its significant impact on network lifetime.

Table 1. The recent studies and their research gaps in WSNs

Ref	Key approach	Strengths	Research gap	How GH-LEACH addresses the gap
El-Sayed *et al.*, [22]	Combines the energy hole removing mechanism (EHORM) with an artificial neural network (ANN) to choose CHs intelligently.	Improves network lifetime, balances energy consumption, and enhances CH selection compared with conventional LEACH.	Requires a neural network to be trained and run, which increases computing complexity and makes it less appropriate for SNs with limited resources.	Employs lightweight multi-criteria decision-making (residual energy, distance, node density, and centrality) without AI training, reducing computational overhead while maintaining energy efficiency.
Raji *et al.*, [23]	Optimizes CH selection and routing decisions by combining AI approaches with CRT-LEACH.	Enhances energy efficiency, packet delivery ratio, and overall network lifetime.	Primarily focuses on CH selection and does not incorporate adaptive sleep scheduling or energy-aware CH rotation.	Integrates Sleep–Awake Pairing, Green Rotation, and Hybrid Multi-hop Routing to further reduce energy consumption and improve network stability.
Alshudukhi *et al.*, [24]	Introduces a deep recurrent Q-Learning framework for intelligent next-hop selection in 6G-enabled WSNs using residual energy and node proximity.	Improves network lifetime and throughput, and reduces latency through adaptive routing.	Requires high computational resources, continuous model training, and is unsuitable for low-cost SNs with limited memory and processing capability.	Achieves energy-efficient routing using lightweight multi-criteria CH selection, adaptive Green Rotation, and Hybrid Multi-hop Routing without relying on deep learning.
Chu *et al.*, [25]	Presents a comprehensive taxonomy of LEACH enhancements, including energy balancing, clustering optimization, security, and intelligent routing.	Provides a structured classification of LEACH variants and highlights current research trends.	It is a review paper and does not introduce or experimentally validate a new routing protocol. The survey also identifies the need for low-complexity and adaptive LEACH variants.	Proposes a complete routing protocol with MATLAB implementation, combining energy-aware CH selection, Sleep–Awake Pairing, Green Rotation, and Hybrid Multi-hop Routing to address these open challenges.
G. S. *et al.*, [26]	Combines a metaheuristic optimization algorithm with deep learning to optimize routing and energy efficiency in WSNs.	Enhances routing accuracy, network lifetime, and packet delivery by combining optimization and AI techniques.	High computational complexity, increased processing overhead, and dependency on optimization iterations reduce suitability for resource-constrained WSNs.	Avoids complex optimization algorithms while maintaining balanced energy consumption through lightweight multi-criteria decision-making and adaptive routing.

Based on the above observations, several research gaps remain unresolved. Existing clustering protocols rarely integrate residual energy, communication distance, neighborhood density, and node centrality into a unified CH selection mechanism. Likewise, few protocols exploit redundant node pairing through alternating sleep–awake scheduling to reduce unnecessary sensing while maintaining coverage. Moreover, adaptive CH retention based on residual energy has received limited attention, despite its potential to reduce cluster reconstruction overhead. Finally, energy-aware relay selection for multi-hop inter-cluster communication remains insufficiently explored in combination with adaptive clustering mechanisms.

To overcome these limitations, we propose GH-LEACH, an integrated clustering protocol that combines four complementary mechanisms in a unified routing framework. First, a multi-criteria Green CH Selection algorithm selects CHs based on a weighted score of residual energy, distance to the BS, neighborhood density, and node centrality. Second, a pairing-based sleep scheduling strategy identifies redundant neighboring SNs and alternates their active and sleep states to reduce sensing energy while maintaining coverage. Third, an energy-aware hybrid multi-hop routing algorithm allows distant CHs to forward aggregated data through intermediate CHs using a relay cost function that jointly considers transmission distance and residual energy. Lastly, an Adaptive Green Rotation mechanism maintains efficient CHs with residual energy above the network average, thus avoiding unnecessary CH replacement and reducing control overhead. The combination of these four mechanisms is expected to achieve balanced energy consumption, improved scalability, and extended network lifetime compared with conventional LEACH-based protocols. The rest of the paper is organized as follows: Section 2 reports on the method. In Section 3, the results and discussion are presented, and the conclusion and future directions are summarized in Section 4.

2. METHOD

The proposed GH-LEACH protocol is designed for homogeneous WSNs deployed to continuously monitor a sensing field while minimizing energy consumption and extending network lifetime. The network consists of N SNs randomly distributed within a two-dimensional sensing area of M × M meters. $X_{m,}Y_m$). All SNs are assumed stationary after deployment and possess identical hardware capabilities, including the same initial energy (E_0), processing capability, communication range, and sensing radius [13]. Figure 1 shows the layout of the WSN when the BS is inside the network. A single stationary BS, also referred to as the sink, is located inside the sensing field. SNs periodically collect environmental data and transmit the sensed information to the BS through cluster-based communication. The following assumptions are adopted for the proposed protocol: All SNs are homogeneous and initialized with equal energy.E_0). Nodes remain static after deployment, while the BS is fixed throughout network operation. Each SN is aware of its geographical location or can estimate its distance to neighboring nodes and the BS. Nodes continuously monitor their residual energy during operation. Data aggregation is performed only by CHs before forwarding aggregated packets. The wireless communication channel is symmetric; thus, the energy required for transmission from node *i* to node *j* equals that required for reverse communication. SNs operate in rounds, each consisting of a setup phase followed by a steady-state phase [2], [8]-[9], [13], [15]-[19].

As shown in Figure 2, the communication model is based on the radio energy dissipation model. The size of the message and the distance between nodes determine how much energy is needed for transmitting and receiving. In this model, the energy consumed is used for transmission.

A message of k bits over a distance d is given by (1),

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

The energy used per bit during transmission or reception, denoted as E_{elec}, depends on the electronic circuitry of the transmitter and receiver. Where: k is the packet size in bits, d is the transmission distance, ε_{fs} is the free-space amplifier parameter, ε_{mp} is the multipath amplifier parameter, d_0 is the threshold distance where $d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$.

Additionally, the energy consumed by the transmitter amplifier varies according to the chosen amplifier model, which affects the total transmission energy. This model captures the essential energy costs for communication in WSNs, allowing accurate estimation of energy expenditure based on message size and transmission distance [13], [15]-[18]. The proposed GH-LEACH is an energy-efficient clustering protocol designed to prolong WSNs' lifespan by minimizing unnecessary energy consumption and balancing the communication load among SNs. The proposed protocol consists of four sequential stages: Green cluster head (CH) selection, green sleep scheduling, hybrid multi-hop routing, and adaptive green rotation.

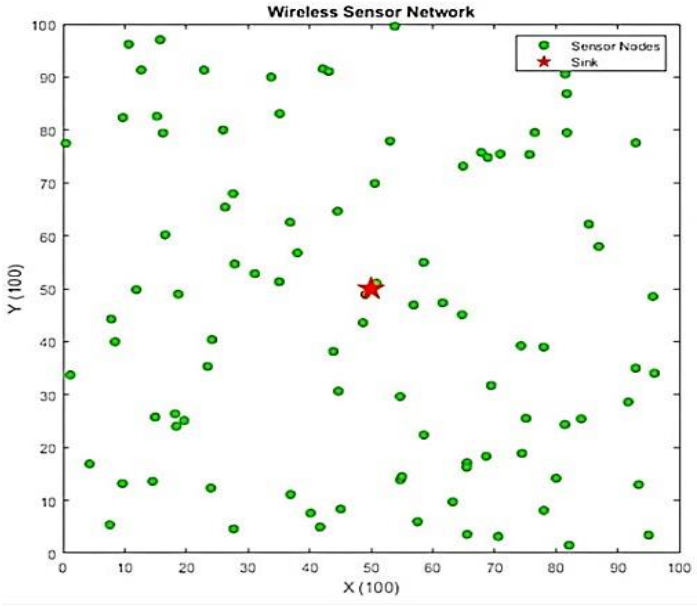

Figure 1. The BS inside the network

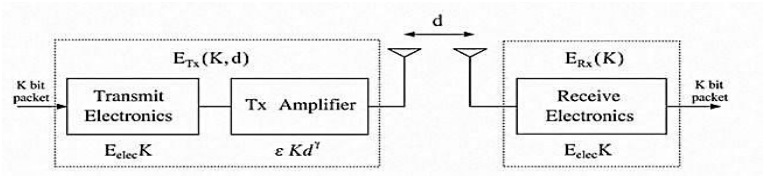

Figure 2. Radio energy dissipation model [13]

2.1. Green cluster head selection

The first stage focuses on selecting the most suitable CHs according to multiple network characteristics rather than relying solely on probabilistic selection as in the conventional LEACH. Each alive SN is evaluated using four decision factors (energy factor, distance factor, density factor, and centrality factor). Since CHs consume considerably more energy than ordinary nodes, the residual energy of each sensor is considered the primary selection criterion. The energy factor is computed as,

$$EF_i = \frac{E_i}{\overline{E}} \tag{2}$$

Where: E_i denotes the residual energy of node i,$(\overline{E})$ represents the average residual energy of all alive nodes. Nodes with energy higher than the network average receive higher scores. CHs located closer to the BS require less transmission energy. The normalized distance factor is defined as in (3),

$$DF_i = 1 - \frac{d(i,BS)}{d_{max}} \tag{3}$$

Where: $d(i, BS)$ is the Euclidean distance between node i and the BS. d_{max} is the maximum possible communication distance inside the sensing field. The Euclidean distance is calculated by,

$$d(i, BS) = \sqrt{(x_i - x_{BS})^2 + (y_i - y_{BS})^2} \tag{4}$$

Nodes located in dense neighborhoods are preferred because they can serve more nearby SNs while reducing intra-cluster transmission distances. The neighborhood density is calculated as,

$$Density_i = \frac{N_i}{N} \tag{5}$$

Where: N_i is the number of neighboring nodes within radius (R), N is the total number of SNs. The neighbor condition is $d(i,j) < R$. A CH should ideally be located near the geometric center of its neighboring nodes. The average distance to neighboring nodes is,

$$AvgDist_i = \frac{\sum_{j=1}^{N_i} d(i,j)}{N_i} \quad (6)$$

The centrality factor becomes,

$$CF_i = 1 - \frac{AvgDist_i}{R} \quad (7)$$

A higher centrality value indicates that the node is positioned closer to the center of its local neighborhood. The four factors are combined into a unified Green Score,

$$Score_i = w_1 EF_i + w_2 DF_i + w_3 Density_i + w_4 CF_i \quad (8)$$

Subject to $\sum_{l=1}^{4} w_l = 1$.

The node obtains a higher probability of becoming a CH when its green score increases. Instead of using the original LEACH threshold only,

$$\boldsymbol{T(n) = \frac{p}{1-p*\left(r*mod\frac{1}{p}\right) if\ n \in G}} \quad (9)$$

The proposed protocol employs

$$T_{Green} = T(n) * Score_i \quad (10)$$

Which integrates both probabilistic rotation and node quality.

2.2. Green sleep scheduling

The second stage reduces redundant sensing activity by identifying neighboring nodes that monitor nearly identical regions. During network initialization, nodes separated by less than a predefined radius R_S are paired, $d(i,j) < R_S$. Only one node in each pair remains active during a communication round, while the partner enters sleep mode. To avoid exhausting a single sensor, the active and sleeping roles alternate periodically. For two paired nodes,

Round 1: Node $_A$ = Awake, Node $_B$ = Sleep

Round 2: Node $_A$ = Sleep, Node $_B$ = Awake

This rotation balances sensing energy between neighboring sensors while preserving sensing coverage. Unlike static sleeping strategies, the proposed scheduling guarantees fairness and extends network lifetime.

2.3. Hybrid multi-hop routing

In conventional LEACH, every CH communicates directly with the BS: CH→ BS. This approach becomes inefficient when CHs are located far from the BS. The proposed protocol introduces adaptive multi-hop communication. Whenever$d(CHi, BS) > d0$, The CH searches for another CH that is closer to the BS, has sufficient residual energy, and minimizes the routing cost. The routing becomes: $CHi \rightarrow CHj \rightarrow BS$ instead of $CHi \rightarrow BS$. Each candidate relay is evaluated using (11),

$$\boldsymbol{RelayScore = \alpha\left(\frac{d_{CH}}{d_0}\right) + \beta\left(\frac{d_{RelayBS}}{d_{BS}}\right) + \gamma\left(\frac{\bar{E}}{E_{Relay}}\right)} \quad (11)$$

Where: d_{CH} is the distance between two CHs, $d_{RelayBS}$ is the relay distance to the BS, E_{Relay} is the relay residual energy. The relay with the minimum routing cost is selected. The weighting coefficients satisfy: $\alpha + \beta + \gamma = 1$.

2.4. Adaptive green rotation

The original LEACH protocol rotates CHs periodically regardless of their remaining energy. This often replaces efficient CHs unnecessarily. The proposed protocol introduces adaptive rotation. A current CHs continues serving if: $Ei > \Gamma\bar{E}$. WhereΓ is the rotation threshold, $\bar{E}$ is the average residual energy. Otherwise, Ei ≤ ΓĒ a replacement CH is elected using the Green Score. This adaptive strategy reduces

cluster reformation overhead, minimizes control packet transmission, and preserves stable clusters for longer periods.

Algorithm 1. Green hybrid - LEACH

```
Initialize the sensor network and deploy N SNs randomly
Set the initial energy E0 for all nodes
Define weighting coefficients w1, w2, w3, and w4
for each round r do
Compute the average residual energy of all alive nodes
for each alive node n do
Compute the Energy Factor (EF), the Distance Factor (DF), the Density Factor (DenF), the
Centrality Factor (CF)
Calculate the Green Score
 Score_i = w_1 EF_i + w_2 DF_i + w_3 Density_i + w_4 CF_i
end for
Select the optimal CHs according to the highest Green Score
Associate each non-CH node with the nearest CHs
Form sleep-awake pairs among neighboring member nodes
Activate one node in each pair and switch the paired node to sleep mode
for each CHs do
if Distance (CH, BS) ≤ d0 then
Transmit aggregated data directly to the base station
else
Forward aggregated data through the best relay CHs
end if
end for
Perform adaptive CHs rotation according to the residual energy threshold
Update the residual energy of all SNs
end for
End Algorithms
```

3. SIMULATION RESULTS AND PERFORMANCE EVALUATION

The proposed GH-LEACH protocol was implemented in MATLAB R2024a and evaluated under the same simulation environment used for the benchmark routing protocols. A square sensing field of 100 m × 100 m containing 100 randomly deployed SNs was considered. The BS was located in the middle of the sensing field at coordinates (50, 50). Each SN was initialized with 0.5 J of energy. The first-order radio energy model was adopted for all communication operations to ensure a fair comparison among the evaluated protocols. Table 2 provides a summary of the simulation parameters.

Table 2. Simulation parameters

Parameters	Value
Network area	100*100 m^2
Number of SNs	100
Initial energy	0.5 J
Base station	(50,50)
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
W_1	0.40
W_2	0.25
W_3	0.20
W_4	0.15
γ	0.3
α	0.4
β	0.3
Adaptive rotation threshold (Γ)	1.0

The following metrics were used to assess the routing protocols' performance: First node dies (FND): The round in which the energy of the first SN runs out. Half of nodes die (HND): The round in which half of the SNs have run out of energy. Last node dies (LND): The round that represents a total failure of the network. Residual energy: The sum of all living SNs' residual energy. Alive nodes: The total number of

nodes that are active during the simulation. Dead nodes: The total number of nodes that fail over time. Network throughput: The total number of packets sent to the BS successfully. Table 3 shows a comparison of the network lifetime among the evaluated protocols.

The proposed GH-LEACH significantly delays the first node failure by employing an energy-aware cluster-head selection mechanism. Its pairing-based sleep scheduling reduces unnecessary sensing energy consumption, while adaptive cluster-head retention minimizes control overhead from repeated cluster reconstructions. Additionally, the hybrid multi-hop routing strategy lowers long-distance transmission costs, resulting in more balanced energy distribution throughout the network. Figure 3 illustrates the residual energy of all protocols throughout the simulation. The proposed GH-LEACH exhibits the slowest energy depletion rate. Unlike LEACH, which drains energy quickly due to random CH selection and direct communication with the BS, GH-LEACH distributes energy consumption more uniformly by incorporating residual energy, node density, centrality, and communication distance into the CH selection process. As a result, total residual energy remains higher throughout most simulation rounds.

Table 3. Evaluation of network performance

Protocol	FND	HND	LND
LEACH	981	1,174	1,446
LEACH-C	1,109	1,205	1,272
LEACH-F	1,107	1,209	1,261
TL-LEACH	1,091	1,301	1,574
GH-LEACH	1,502	1,672	1,988

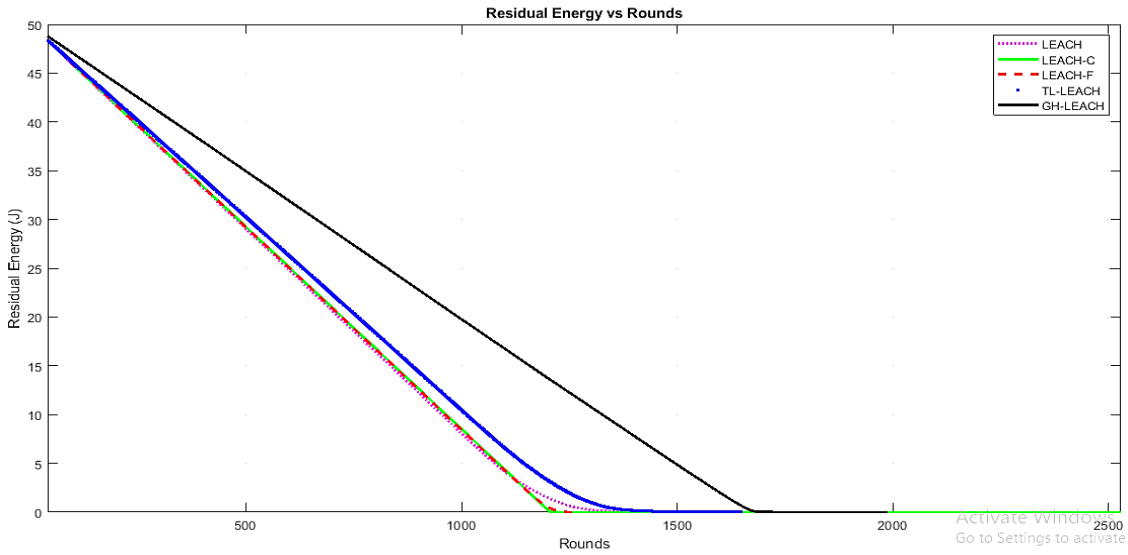

Figure 3. The residual energy of all protocols throughout the simulation

The combined impacts of sleep-pairing, multi-hop CH-to-CH transmission, and adaptive CH rotation are attributed for the observed shape of Figure 3. Throughout a significant amount of the network lifetime, these methods spread the communication load and lower energy usage. The greater reduction seen near the end of the network lifetime may be caused by the remaining nodes having higher communication costs as the number of surviving nodes drops and the network becomes more sparse. Figure 4 presents the number of alive nodes as the simulation progresses. GH-LEACH maintains a higher number of active SNs throughout the network lifetime. Its sleep-awake pairing mechanism effectively reduces redundant sensing, while adaptive CHs rotation minimizes unnecessary changes in cluster structure. As a result, node failures occur more gradually compared to benchmark protocols.

The distinct delayed-plateau behavior observed in the GH-LEACH alive-nodes curve can be attributed to its more balanced energy distribution compared with the baseline protocols. In conventional LEACH-based approaches, the probabilistic CH selection may result in an uneven distribution of the communication burden among SNs, causing some nodes to deplete their energy earlier. Since the FND marks the beginning of node failures, early energy depletion can subsequently accelerate the decline in the number of alive nodes. In LEACH-C, although CH selection is centrally optimized, the resulting communication

structure may still lead to unequal energy consumption among nodes. In LEACH-F, the relatively fixed cluster structure can cause repeated communication responsibilities to be concentrated on particular CHs, potentially accelerating their energy depletion. In contrast, GH-LEACH integrates energy-, distance-, density-, and centrality-aware CH selection with sleep-pairing, adaptive CH rotation, and multi-hop communication. These mechanisms redistribute the communication workload and reduce unnecessary energy consumption, allowing a larger proportion of SNs to remain operational for a longer period. Consequently, GH-LEACH delays both the onset of node deaths and the subsequent accelerated decline in network activity, resulting in the delayed-plateau behavior observed in Figure 4 and contributing to improvements in FND and LND. Figure 5 compares the cumulative packets successfully received at the BS. GH-LEACH achieves higher throughput than benchmark protocols due to its energy-efficient multi-hop routing strategy. By enabling CHs closer to the BS to relay packets from distant CHs, it reduces long-distance transmissions, resulting in more successful packet deliveries before network failure.

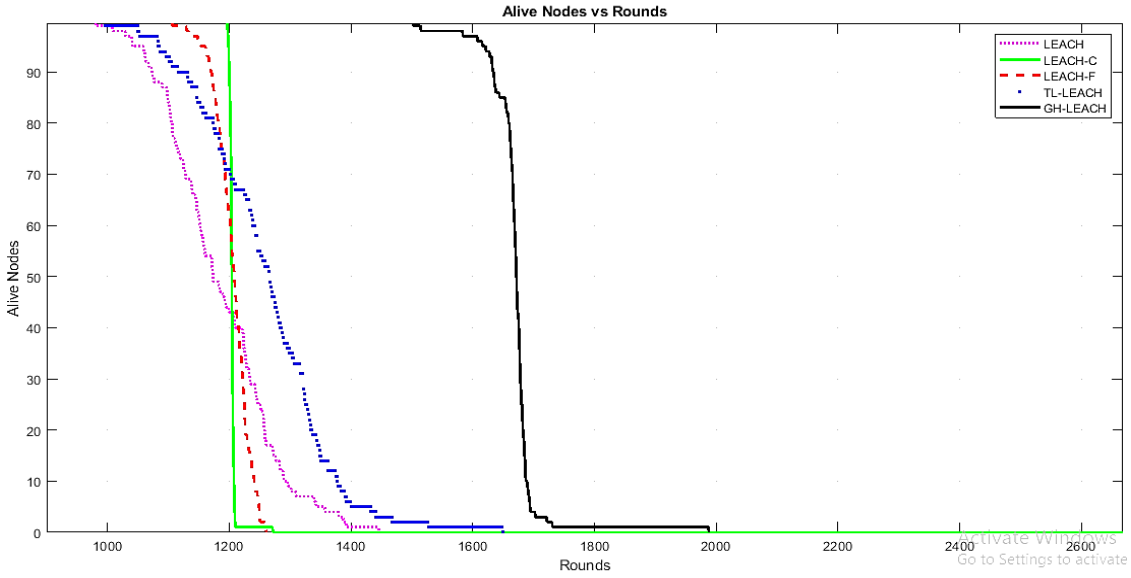

Figure 4. The number of alive nodes as the simulation progresses

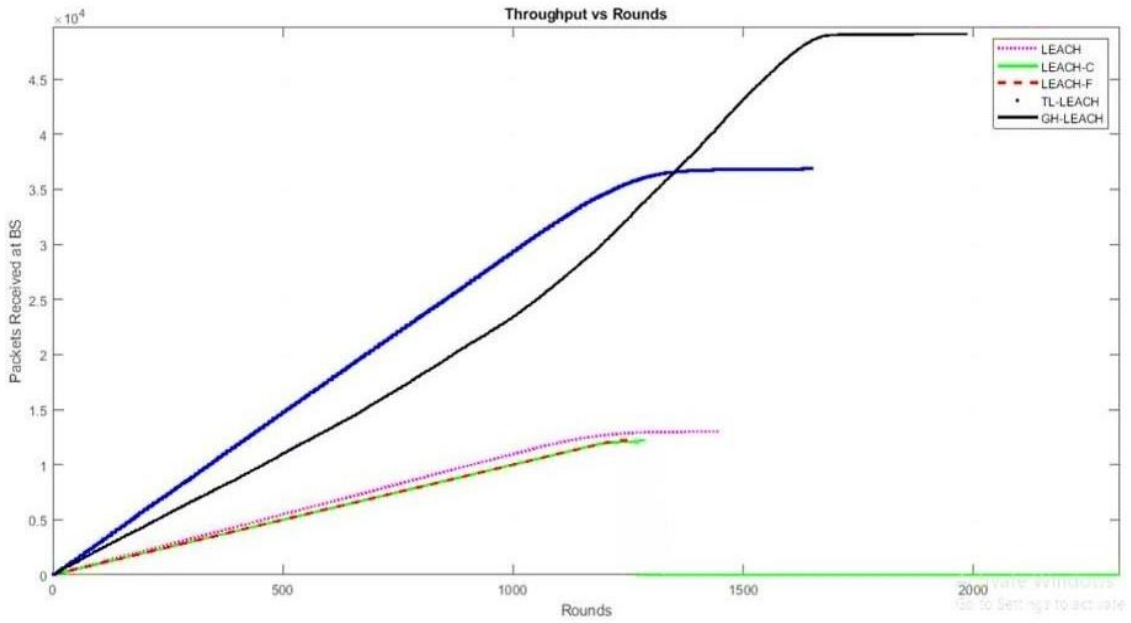

Figure 5. Compares the cumulative packets successfully received at the BS

4. CONCLUSION

The simulation results demonstrate that combining multiple complementary energy-saving mechanisms significantly enhances network performance. Unlike previous LEACH variants that optimize only one aspect of routing, the proposed GH-LEACH protocol addresses cluster-head selection, redundant sensing, relay routing, and cluster stability simultaneously. Specifically, GH-LEACH offers the following advantages: Higher network stability through energy-aware cluster-head selection, lower sensing energy consumption via pair-based sleep scheduling, reduced transmission energy using hybrid multi-hop communication, lower control overhead thanks to adaptive cluster-head retention, improved energy balancing across the entire network, and extended network lifetime compared to LEACH, LEACH-C, LEACH-F, and TL-LEACH. Overall, the proposed protocol achieves superior energy efficiency and network longevity while maintaining higher throughput and a larger number of active SNs throughout the simulation period.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Mazin Ismael Raheem	✓		✓				✓			✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state 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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