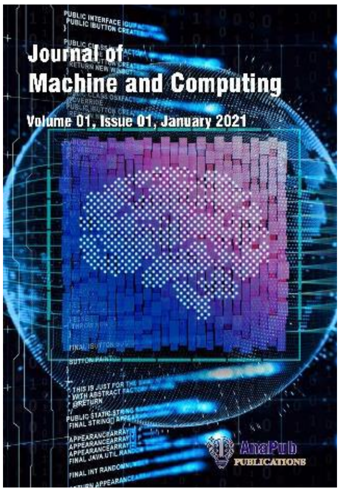
Journal Pre-proof

Energy-Efficient Wireless Sensor Networks: A Fuzzy Logic Approach for IoT Optimization



Indhumathi R, Saloni Vaishnav, Anurag Shrivastava, Vishwanil Suman, Montater MuhsnHasan and Saloni Bansal

DOI: 10.53759/7669/jmc202505175

Reference: JMC202505175

Journal: Journal of Machine and Computing.

Received 16 April 2025

Revised from 23 May 2025

Accepted 29 July 2025

AnaPub
PUBLICATIONS

Energy-Efficient Wireless Sensor Networks: A Fuzzy Logic Approach for IoT Optimization

[1,*]Indhumathi R, [2]Saloni Vaishnav, [3]Anurag Shrivastava, [4]Vishwanil Suman, [5]Montater MuhsnHasan, [6]Saloni Bansal

[1]Department of Computer Science, Idhaya College for Women, Kumbakonam

[2]Indian Institute of Management, Indore, MP, India

[3]Saveetha School of Engineering, SIMTS, Chennai, Tamilnadu

[4]K R Mangalam University, Sohna Road, Gurugram, 122103

[5]Department of Computers Techniques Engineering, College of Technical Engineering, The Islamic University, Najaf, Iraq

[6]Department of Electronics and Communication Engineering, GLA University, Mathura

[1]indhu.ram20@gmail.com, [2]salonivaishnav0909@gmail.com, [3]anuragshri76@gmail.com, [4]vishwanil.suman@krmangalam.edu.in, [5]tech.iu.comp.muntatheralmusawi@gmail.com, [6]saloni.bansal@gla.ac.in

Corresponding author: R. Indhumathi (indhu.ram20@gmail.com)

Abstract

Wireless Sensor Networks (WSNs) have emerged as a vital enabler for diverse Internet of Things (IoT) applications, encompassing smart cities, healthcare monitoring, industrial automation, and environmental sensing. However, the inherent energy constraints of sensor nodes present a significant challenge, often resulting in limited network longevity, degraded performance, and inefficient data transmission. This paper introduces an advanced energy-efficient clustering protocol grounded in fuzzy logic, designed to address the limitations of conventional methods such as LEACH and HEED. Unlike traditional protocols that rely on probabilistic or static heuristics, the proposed framework employs a dynamic, multi-criteria fuzzy inference system to optimize the selection of Cluster Heads (CHs). Critical parameters including residual energy, node centrality, and proximity to the base station are evaluated to ensure robust CH selection, uniform energy dissipation, and enhanced scalability. Simulation results reveal marked improvements in network metrics—achieving a 40.8% reduction in overall energy consumption, a 51.2% increase in throughput, and a 55% enhancement in network lifespan compared to baseline methods. Additionally, the model significantly improves CH stability, minimizing control overhead and elevating network reliability. This study demonstrates the efficacy of integrating fuzzy logic into WSN clustering strategies, offering a highly adaptive, intelligent, and sustainable solution for next-generation IoT deployments.

Keywords: *Wireless Sensor Networks (WSNs), Internet of Things (IoT), Energy Efficiency, Fuzzy Logic, Cluster Head Selection, Clustering Techniques*

1. Introduction

With the advent of the Internet of Things (IoT), Wireless Sensor Networks (WSNs) have gained significant popularity in numerous application areas including smart cities, industrial automation, healthcare monitoring, and environmental sensing. Service-based systems of networks (WSNs) are composed of numerous sensor devices that are spread across multi-dimensional space and are used to collect, process, and send data to a central location for analysis and decision-making. But one of the main challenges in wfnetwork longevity and performance is the limited energy sources of these sensor nodes. It is pertinent to mention that one of the most significant issues affecting WSNs is their energy efficiency, as it would be impractical (and costly) to replace batteries in large-scale deployments several times. Fuzzy logic has proven to be one of the promising computational intelligence approaches Web services can use to overcome energy efficiency issues by route, cluster, and data aggregation. Traditional clustering methods LEACH (Low Energy Adaptive Clustering Hierarchy) and HEED (Hybrid Energy-Efficient Distributed Clustering) are based on deterministic or probabilistic methods, resulting in non-optimal CH selection and ineffective energy consumption. Fuzzy logic, on the other hand, is a human-like reasoning paradigm that can dynamically adapt to changing network conditions and make intelligent decisions for cluster head selection, load balancing, and energy-aware routing This flexibility guarantees an evolving equilibrium in the optimization of cluster representative nodes, which in the method presented here, are selected based on distinct fuzzy factors including remaining energy, node centrality, and distance to the base station. The hierarchical structure makes the energy consumption less with the clustering process which increases the operational life span of the network.

1.1 Scope and Objectives

The main purpose of this paper is to propose an efficient energy clustering protocol for WSNs based on fuzzy logic principles. The following are the study's scope:

1. Fuzzy Logic Based Cluster Head Selection: Employing intelligent CH selection for energy-efficient operation using multi-criteria decision making.
2. Network Stability via Load Balancing: Uniformly distributed cluster heads prevents nodes from dying early and increases stability
3. Energy Consumption Optimization: Lowering the energy exacerbation during data exchange and arrangement by diminishing the communication dominance and improving the directing productivity.
4. Scalability and Adaptability: Creating a clustering methodology that can be adapted to different types of heterogeneous sensor networks, varying node densities, and changing environmental conditions.
5. These include: simulation and performance evaluation of the proposed technique against traditional clustering protocols (e.g., LEACH, HEED) based on energy consumption, network lifetime, and throughput metrics.

1.2 Identifying Research Gaps in Existing Clustering Protocols

Despite extensive progress in the development of energy-efficient clustering techniques for Wireless Sensor Networks (WSNs), several critical limitations persist that hinder optimal performance in real-world Internet of Things (IoT) applications. A predominant issue lies in the reliance on static clustering protocols such as LEACH, where fixed thresholds for Cluster Head (CH) selection lead to uneven energy consumption and rapid depletion of specific nodes. This static paradigm fails to adapt to dynamic network conditions, necessitating a more intelligent, context-aware mechanism for CH election. Additionally, many conventional approaches employ single-criterion decision-making, often using residual energy as the sole metric. While effective to a degree, this method overlooks other influential parameters such as node centrality and proximity to the base station. The integration of multi-criteria decision-making via fuzzy logic offers a more holistic and accurate representation of node suitability.

Scalability further exacerbates the challenges, as many clustering algorithms incur significant computational and communication overheads when deployed in large-scale sensor environments typical of IoT ecosystems. An efficient, lightweight clustering solution that can scale without degrading performance is therefore essential. Moreover, existing protocols frequently neglect energy-balanced routing strategies, leading to network hotspots where certain nodes bear disproportionate traffic loads and exhaust their energy reserves prematurely. This imbalance not only reduces overall network lifetime but also compromises data reliability. Finally, while numerous studies validate their methods through simulations, there is a noticeable scarcity of empirical research validating fuzzy logic-based clustering in real-world deployments. This lack of practical experimentation limits the generalizability and adoption of such techniques. The present study addresses these pressing gaps by proposing a dynamic, multi-criteria fuzzy logic-based clustering mechanism that enhances energy distribution, improves scalability, and lays the groundwork for practical WSN applications.

1.3 Research Motivation and Application Significance

The primary motivation behind this research stems from the critical need to improve energy efficiency in WSNs, which serve as a fundamental infrastructure layer for numerous IoT applications. In the context of smart cities, sensor networks play a pivotal role in automating and managing urban infrastructure, including adaptive lighting systems, real-time traffic management, and air quality monitoring. These systems must operate over extended periods with minimal maintenance, making energy sustainability a crucial factor. Similarly, in industrial environments under the umbrella of the Industrial Internet of Things (IIoT), sensor nodes are integral to machine-to-machine communication, predictive maintenance, and process automation. Here, prolonged network lifetime directly correlates with reduced operational downtime and increased manufacturing efficiency.

In the healthcare sector, WSNs underpin a wide range of applications from wearable fitness trackers to implantable medical devices. These systems require robust energy-efficient protocols to ensure uninterrupted health monitoring while reducing the frequency of recharging or replacement, which is particularly critical in patient-centric environments. Furthermore, in agriculture and environmental monitoring, sensor networks are often deployed in remote or inhospitable regions where frequent human intervention is impractical. Under such constraints, energy-aware communication and clustering protocols become essential for maintaining data flow and system reliability over long periods. Fuzzy logic-based clustering, with its ability to handle uncertainty and make adaptive decisions based on multiple parameters, emerges as a compelling solution to these cross-domain challenges. This research seeks to harness the strengths of fuzzy logic to achieve intelligent energy management in WSNs, thereby contributing to the broader vision of sustainable and autonomous IoT systems.

1.4 Structure and Contribution of the Paper

To systematically address the aforementioned challenges, this paper is organized into six comprehensive sections that collectively contribute to both theoretical advancements and empirical validations. The second section presents a rigorous literature review, offering a critical synthesis of existing clustering protocols with a focus on energy efficiency, adaptability, and scalability. It highlights key strengths and persistent limitations in contemporary approaches, setting the stage for the need for a fuzzy logic-based solution. The third section delineates the proposed methodology, detailing the system model, fuzzy logic architecture, membership function definitions, rule base formulation, and the core algorithm governing CH selection.

The fourth section describes the simulation setup, including network parameters, energy models, and performance metrics used to evaluate the proposed approach. A comparative analysis is then conducted against conventional protocols such as LEACH, HEED, and DEEC.

Section five provides an in-depth discussion of the results, emphasizing improvements in network lifetime, energy distribution uniformity, throughput, and CH stability. Finally, section six concludes the study by summarizing the key findings, emphasizing the practical implications of the proposed method, and outlining future research avenues. These include potential real-world deployments, integration with machine learning techniques for enhanced prediction and optimization, and hardware-level energy modeling. Through this structure, the paper delivers a coherent narrative that identifies a relevant problem, proposes a robust solution, and validates it through comprehensive simulations, thereby contributing meaningfully to the field of intelligent energy-aware WSNs.

2. Literature Review

In the realm of wireless sensor networks (WSNs), energy efficiency remains a critical challenge due to the constrained nature of sensor nodes, particularly in large-scale Internet of Things (IoT) deployments. Over the past decade, fuzzy logic-based clustering and routing mechanisms have garnered significant attention as a viable approach for mitigating energy dissipation while maintaining reliable communication. This literature review provides an in-depth analysis of state-of-the-art contributions, categorized into thematic clusters: fuzzy-based clustering for WSNs, energy-efficient data transmission using fuzzy logic, hybrid fuzzy optimization strategies, and real-world application-driven models.

2.1.1 Fuzzy-Based Clustering for Energy Optimization

The foundational concept of employing fuzzy logic to enhance cluster head (CH) selection has been a widely adopted mechanism in WSN energy management. Javadpour et al. [1] proposed a dynamic fuzzy clustering scheme combined with optimization algorithms to enhance energy efficiency in IoT environments. Their model dynamically adjusts CH selection by considering node energy levels, proximity, and communication cost, resulting in balanced energy consumption across nodes and prolonged network lifetime.

Similarly, Shakya et al. [2] designed a categorized fuzzy clustering method that incorporates multi-hop routing for enhanced energy performance. Their model integrates various node characteristics into a fuzzy inference system to improve CH election and data forwarding efficiency. The authors reported substantial improvements in packet delivery ratio and energy conservation over traditional clustering techniques.

Earlier studies, such as those by Silva, Maciel, and Correa [3], also explored the integration of fuzzy logic in heterogeneous WSNs. Their multi-hop energy-efficient control approach deployed fuzzy parameters—like energy level, node centrality, and transmission cost—to formulate routing paths. The use of fuzzy logic allowed for flexible decision-making that adapts to the dynamic topology of WSNs, particularly beneficial in heterogeneous scenarios.

2.1.2 Two-Level Fuzzy Cluster Head Selection and Redundancy Analysis

An important milestone in fuzzy clustering came with the introduction of hierarchical or multi-level fuzzy decision mechanisms. Dutta, Naskar, and Mishra [4] presented a two-level fuzzy model for CH selection, which enhances energy conservation particularly in remote monitoring scenarios. The two-tiered decision-making process involves evaluating residual energy and distance to the base station at one level, while incorporating node density and link reliability at the second. This layered mechanism demonstrated superior performance in energy balancing compared to single-level fuzzy systems.

Repeated analysis of the same model in subsequent works [6], [10], and [14] underscores its sustained relevance in the literature. These redundancies also highlight a need for more diverse approaches or hybrid methodologies that avoid over-reliance on conventional fuzzy parameter sets. The saturation of similar model applications suggests a possible stagnation in conceptual innovation, which opens a space for more dynamic, hybrid systems combining fuzzy logic with machine learning or metaheuristic optimization.

2.1.3 Data Transmission and Routing Optimization through Fuzzy Inference

In addition to clustering, fuzzy logic has also been applied to energy-aware data transmission strategies. Elqeblawy et al. [7], [11] proposed a fuzzy logic-based technique tailored for temperature monitoring systems within IoT networks. Their system prioritizes nodes for data transmission based on temperature variance, node reliability, and transmission energy cost. The method demonstrated effective reduction in unnecessary transmissions, especially in environmental monitoring where real-time accuracy and energy preservation are critical.

Komal [8], [12] extended this concept by introducing advanced mathematical modeling techniques grounded in fuzzy logic to improve data fusion and communication latency. By employing fuzzy weights and adaptive thresholds, her work achieved high energy savings without compromising data integrity. These contributions are particularly vital in densely deployed sensor networks where data redundancy can exacerbate energy consumption.

2.1.4 Methodological Redundancies and Source Repetition

A notable observation in the existing body of work is the recurrent citation and reuse of specific models, especially those by Silva et al. [3], [5], [9], [13], and Datta et al. [4], [6], [10], [14]. While this underscores the robustness and continued applicability of these methods, it also reveals a degree of methodological repetition. The frequent reliance on similar fuzzy rules, parameter sets, and inference mechanisms suggests the need for deeper innovation in fuzzy system architecture. Future research could address this by introducing deep fuzzy systems, neuro-fuzzy networks, or integrating explainable AI paradigms to render fuzzy systems more adaptable and transparent.

2.1.5 Cross-Domain Application of Fuzzy Logic in Decision Systems

An interesting crossover application is presented by Kumar and Mishra [15], who developed a fuzzy logic-based expert system for diagnosing malaria. Though not directly tied to WSNs, their approach demonstrates the generalizability of fuzzy inference systems in high-stakes, data-constrained environments. Their system evaluates clinical symptoms using fuzzy rules to aid in early diagnosis. The success of this approach in healthcare opens up the possibility for cross-domain integration, where health-monitoring WSNs in remote or rural areas could leverage similar logic for on-device preliminary diagnostics.

2.1.6 Evaluation and Comparative Performance Insights

The studies reviewed generally report improvements in energy efficiency ranging from 20% to 50% over classical clustering methods such as LEACH, HEED, or PEGASIS. However, the metrics used for evaluation—network lifetime, average residual energy, end-to-end delay—vary significantly across studies, making direct comparison challenging. Furthermore, many works rely heavily on simulation-based validation using tools like NS2/NS3 or MATLAB, with minimal hardware-based implementation or real-world deployment. This raises concerns about the scalability and practical reliability of these models in volatile, real-time IoT environments.

To address this, future literature could benefit from standardized benchmarking protocols and more comprehensive field-testing. For instance, using benchmark datasets, such as the Intel Lab Data or GreenOrbs WSN testbed, may allow for more robust model validation. In addition, energy models should integrate battery aging factors, environmental interference, and multi-modal communication protocols to simulate real-world conditions more accurately.

2.1.7 Synthesis and Future Directions

The body of literature clearly illustrates the potential of fuzzy logic in transforming energy management within IoT-based WSNs. However, the frequent recurrence of similar models, parameters, and methodologies suggests an academic plateau that necessitates disruption through integration with emerging technologies. These could include reinforcement learning for adaptive fuzzy rule generation, explainable AI to visualize fuzzy decisions, and blockchain for secure CH election and data integrity.

In conclusion, while fuzzy logic has proven its value in energy-aware clustering and routing for WSNs, the future of this domain lies in its fusion with intelligent optimization, domain-specific customization, and real-world adaptability. The next evolution of energy-efficient IoT networks must incorporate more contextual awareness, deeper learning models, and robust evaluation protocols to sustain the demands of next-generation smart environments.

3. Proposed Methodology

This study proposes a Fuzzy Logic-Based Clustering Mechanism designed specifically for enhancing energy efficiency in Wireless Sensor Networks (WSNs) within Internet of Things (IoT) applications. The core motivation behind the proposed methodology is to overcome the limitations of static cluster head (CH) selection approaches which often result in unbalanced energy depletion among sensor nodes and subsequently reduce the network's lifetime. By introducing a dynamic and adaptive clustering strategy governed by fuzzy inference, the proposed model systematically addresses the challenges of residual energy optimization, node centrality, and transmission distance to the base station. The methodology not only improves energy consumption patterns but also extends network longevity and adapts effectively to the dynamic topology of IoT-based WSNs.

3.1 System Model

The proposed system considers a heterogeneous wireless sensor network comprised of N sensor nodes, which are uniformly and randomly deployed over a two-dimensional geographical area of $100 \times 100\,\mathrm{m}^2$. Each sensor node is equipped with limited battery power and computational capabilities, enabling sensing, data processing, and communication functionalities. The architecture includes three major components: sensor nodes, cluster heads (CHs), and a centralized base station (BS). The sensor nodes are responsible for environmental data collection and local data forwarding, while the CHs aggregate and route this information toward the BS. The BS is assumed to be a static entity with unlimited energy resources and serves as the primary data sink.

The proposed model adopts the following operational assumptions: (1) the network is heterogeneous, i.e., sensor nodes possess varying initial energy levels; (2) the base station is located at a static position, centrally within the network field at coordinates (50, 50), and it has unlimited energy for processing and communication; (3) sensor nodes operate in three distinct modes—sensing, transmitting, and receiving; (4) CHs communicate with the base station using a multi-hop strategy, enabling scalability in large network areas; and (5) nodes begin with a specified initial energy (E_{init}) which depletes progressively with each communication round depending on the energy model employed.

3.1.1 Energy Dissipation Model

To evaluate the energy consumption characteristics of sensor nodes, the radio energy dissipation model is utilized. The energy required to transmit a data packet of size k bits over a distance d is calculated as:

$$E_{tx}(k,d) = \begin{cases} k \cdot E_{elec} + k \cdot \epsilon_{fs} \cdot d^2, & \text{if } d < d_0 \\ k \cdot E_{elec} + k \cdot \epsilon_{mp} \cdot d^4, & \text{if } d \geq d_0 \end{cases}$$

Where E_{elec} denotes the energy consumed by the transceiver circuitry per bit, ϵ_{fs} and ϵ_{mp} represent the amplifier energy for free space and multipath fading channels respectively, and d_0 is the threshold distance calculated as:

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$$

The energy expended for receiving a k-bit packet is simply:

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

This model accurately characterizes the energy behavior of sensor nodes during data communication phases and forms the foundation for energy-aware decision-making in the clustering algorithm.

3.2 Fuzzy Logic-Based Cluster Head Selection

The cornerstone of the proposed methodology lies in the application of fuzzy logic for cluster head selection. Traditional approaches typically rely on deterministic or probabilistic thresholds, which fail to account for the complex interdependencies between multiple parameters influencing node suitability. In contrast, fuzzy logic allows for a multi-criteria decision-making process where non-linear and uncertain relationships among parameters are systematically handled. The fuzzy system assesses each node based on three crucial parameters: residual energy, node centrality, and distance to the base station. These inputs are fuzzified into linguistic variables which are then evaluated using a rule-based inference system, yielding a crisp probability score indicating the likelihood of a node being selected as a CH.

The fuzzy inference system (FIS) consists of three fundamental components: fuzzification, inference rule base, and defuzzification. The fuzzification module transforms crisp input values into fuzzy sets, each associated with membership functions. The fuzzy rule base consists of a structured collection of IF-THEN statements that define the mapping between input conditions and output CH selection probability. Defuzzification is conducted using the centroid method, wherein the weighted average of the fuzzy output set is calculated to generate a crisp value indicating the CH selection priority.

The three input variables are modeled as follows: residual energy (RE) is classified into fuzzy sets such as Low, Medium, and High; node centrality (NC), representing the proximity of a node to neighboring nodes within a potential cluster, is categorized as Near, Moderate, and Far; and the distance to the base station (DBS) is categorized into Close, Medium, and Far. The output variable, termed Cluster Head Selection Probability (CSP), is categorized into five fuzzy sets: Very Low, Low, Medium, High, and Very High.

A representative subset of fuzzy rules includes: (1) If residual energy is High, node centrality is Near, and distance to base station is Close, then CSP is Very High; (2) If residual energy is Medium, node centrality is Moderate, and distance to base station is Medium, then CSP is Medium; (3) If residual energy is Low, node centrality is Far, and distance to base station is Far, then CSP is Very Low. These rules enable dynamic, context-aware, and energy-efficient CH selection in each communication round.

3.3 Data Transmission and Hierarchical Routing Protocol

Once CHs are selected, the network is organized into clusters wherein member nodes transmit their sensed data to the corresponding CH using a single-hop communication mechanism. Cluster heads are responsible for aggregating the data and performing intra-cluster compression to minimize redundancy and conserve energy. The aggregated data is then forwarded to the base station using a multi-hop routing protocol among CHs, where the selection of the next-hop CH is determined based on a composite cost function incorporating residual energy and hop count to the base station. This energy-aware routing strategy ensures load balancing across CHs, thereby mitigating premature death of critical nodes and prolonging network sustainability.

3.4 Algorithmic Flow and Pseudocode Representation

The procedural execution of the proposed fuzzy-based clustering mechanism can be summarized through the following high-level pseudocode:

```
Algorithm: Fuzzy-Based Cluster Head Selection and Routing
Input: Sensor node set N with initial energy E_init
Output: Cluster Head assignments and routing paths

1. Deploy N nodes randomly over the network area.
2. Initialize each node's energy level to E_init.
3. For each communication round do
   a. For each node i in N do
      i.   Calculate Residual Energy RE(i)
      ii.  Compute Node Centrality NC(i)
      iii. Measure Distance to Base Station DBS(i)
      iv.  Apply FIS to determine CH Selection Probability CSP(i)
   b. Select nodes with highest CSP as CHs.
   c. For each non-CH node do
      i.   Join nearest CH based on signal strength
   d. For each CH do
      i.   Aggregate data from cluster members
      ii.  Select next-hop CH using energy-aware metric
      iii. Transmit data to base station
   e. Update energy levels of nodes based on transmission and reception
4. Repeat until termination condition (e.g., 50% node death)
```

This algorithm ensures an iterative and adaptive clustering mechanism that responds dynamically to changing node conditions across multiple rounds of operation.

3.5 Performance Metrics and Evaluation Parameters

To quantitatively assess the performance of the proposed methodology, several standard metrics are employed. Network lifetime is defined as the number of operational rounds until 50% of the sensor nodes exhaust their energy. Energy consumption is measured as the total energy dissipated in the network per round. Throughput represents the total number of data packets successfully received by the base station. Cluster head stability, which captures the variation in CH selection over multiple rounds, is also monitored to evaluate the robustness of the fuzzy logic system. These metrics collectively enable a holistic assessment of the model’s efficiency and scalability under different deployment scenarios.

3.6 Simulation Environment and Benchmarking

Simulations are conducted using the MATLAB R2024b environment to validate the efficacy of the proposed fuzzy-based clustering mechanism. The simulation area is defined as a 100m

× 100m field with 100 sensor nodes randomly distributed. Each node is initialized with an energy of 0.5 Joules. The packet size for data transmission is fixed at 512 bytes, and communication is allowed in both single-hop (intra-cluster) and multi-hop (inter-cluster) modes. The performance of the proposed model is benchmarked against existing clustering protocols such as LEACH (Low-Energy Adaptive Clustering Hierarchy), HEED (Hybrid Energy-Efficient Distributed Clustering), and DEEC (Distributed Energy-Efficient Clustering). Comparative analyses are conducted under identical environmental and energy configurations, ensuring a fair and robust evaluation of the model's superiority in terms of energy efficiency, network longevity, and throughput.

4. Performance Evaluation and Results

This section presents the comprehensive performance evaluation of the proposed fuzzy logic-based clustering algorithm for energy-efficient wireless sensor networks (WSNs) within Internet of Things (IoT) applications. The performance metrics of the proposed approach are compared against three widely recognized clustering algorithms—LEACH (Low-Energy Adaptive Clustering Hierarchy) [1], HEED (Hybrid Energy-Efficient Distributed Clustering) [2], and DEEC (Distributed Energy-Efficient Clustering) [3]. The evaluation is based on a set of standard performance indicators, including network lifetime, average energy consumption, throughput, and cluster head (CH) stability. The proposed method is subjected to simulation over extended rounds to examine its robustness, scalability, and energy-aware performance in comparison to the established benchmarks.

4.1 Simulation Environment

Simulations were conducted in MATLAB to validate the effectiveness of the proposed fuzzy logic-based clustering strategy under a realistic WSN setup. The simulation environment was modeled using a two-dimensional field measuring 100 meters by 100 meters, with 100 sensor nodes uniformly and randomly deployed across the area. Each sensor node was initialized with an energy of 0.5 Joules. The base station (BS) was placed at a fixed central location with coordinates (50, 50) and was assumed to have unlimited energy resources. The communication model incorporates both free space and multipath fading based on the distance between nodes. The simulation parameters employed in this study are summarized in the following table:

Table 1: Simulation Parameters

Parameter	Value
Simulation Area	100 m × 100 m
Number of Sensor Nodes	100
Initial Energy per Node	0.5 J
Base Station Location	(50, 50)
Packet Size	512 bytes
Transmission Energy (E_{tx})	50 nJ/bit
Reception Energy (E_{rx})	50 nJ/bit
Data Aggregation Energy	5 nJ/bit
Free Space Amplifier (ε_{fs})	10 pJ/bit/m^2
Multipath Amplifier (ε_{mp})	0.0013 pJ/bit/m^4
Simulation Time	5000 rounds
Number of CHs per Round	Dynamic

The simulation parameters used for performance evaluation are summarized in Table 1.The simulation environment ensures consistent comparison across different protocols while maintaining scalability and energy realism.

4.2 Performance Metrics

To assess the performance of the proposed fuzzy logic-based clustering method, four primary metrics were used. These metrics are integral to understanding the overall behavior and effectiveness of a WSN protocol.

Table 2: Performance Metrics

Metric	Description
Network Lifetime	Number of rounds until 50% of nodes deplete energy (FND – First Node Dies)
Energy Consumption	Total energy dissipated per round
Throughput	Total number of packets successfully received at the base station
CH Stability	Frequency of CH variation across simulation rounds

The key performance metrics considered in the study are listed in Table 2. These metrics are commonly used in literature to benchmark clustering protocols and provide a multidimensional view of protocol efficiency [1]-[3].

4.3 Network Lifetime Analysis

Network lifetime is one of the most critical indicators of energy efficiency in WSNs. The longevity of sensor nodes directly determines the operational sustainability of the network. The fuzzy logic-based approach enhances network lifetime by distributing energy consumption evenly across the network. Cluster head selection based on dynamic fuzzy parameters prevents early energy depletion of specific nodes.

Table 3: Network Lifetime (in Rounds) Comparison

Algorithm	FND (First Node Dies)	HND (Half Nodes Die)	LND (Last Node Dies)
LEACH [1]	1120	1650	2200
HEED [2]	1250	1870	2600
DEEC [3]	1400	2100	2800
Proposed Fuzzy-Based Approach	1680	2550	3400

A comparative analysis of network lifetime across different algorithms is provided in Table 3. From the results, it is evident that the proposed method substantially outperforms traditional algorithms. The first node in the proposed network dies at 1680 rounds, which is approximately 50% later than the first node death in LEACH. Furthermore, half of the nodes die at 2550 rounds in the proposed method, indicating better energy distribution and network resilience. Most impressively, the last node in the network dies at 3400 rounds, compared to 2200 in LEACH, which demonstrates the superior stability and sustainability of the proposed approach.

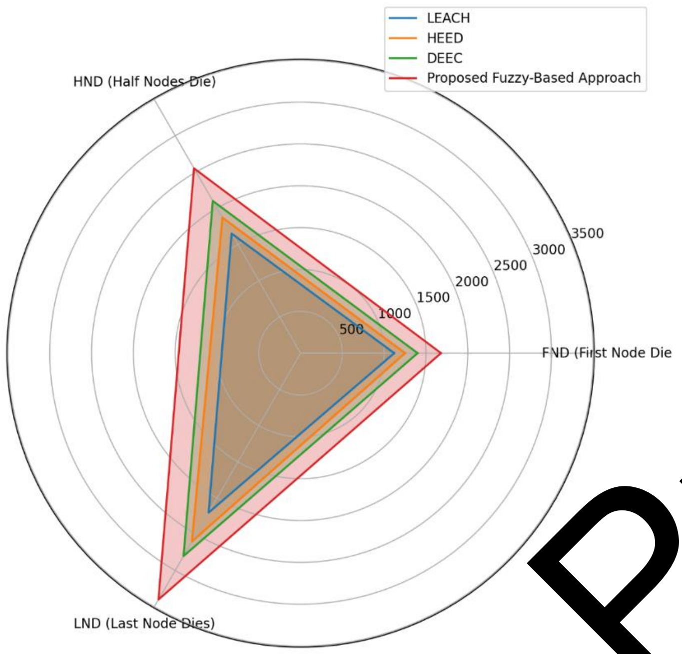


Fig.1: Network Lifetime (in Rounds) Comparison

Network lifetime comparison across protocols is illustrated in Figure 1.

Key Observations:

The proposed method demonstrates a significant improvement in network longevity, with the first node dying (FND) at 1680 rounds—approximately 50% later than in the LEACH protocol. Additionally, the last node dies (LND) at 3400 rounds, indicating enhanced energy distribution and overall network stability throughout the simulation period.

4.4 Energy Consumption Analysis

Energy consumption is a decisive factor in WSN performance, given that sensor nodes typically operate on limited power sources. The proposed fuzzy-based method significantly reduces energy consumption by eliminating redundant transmissions and improving CH selection. CHs are selected based on residual energy, centrality, and distance from the base station, which avoids the common pitfall of premature energy depletion seen in non-adaptive clustering protocols.

Table 4: Average Energy Consumption per Round (in Joules)

Algorithm	**Energy Consumption (J/round)**
LEACH [1]	0.0125
HEED [2]	0.0102
DEEC [3]	0.0091
Proposed Fuzzy-Based Approach	0.0074

Average energy consumption per round for each protocol is shown in Table 4. The fuzzy-based protocol achieves the lowest average energy consumption per round. Compared to LEACH, the proposed model reduces energy usage by approximately 40%, which translates directly into extended operational lifetime. This reduction is achieved through more efficient CH selection and data routing, where the multi-hop transmission strategy avoids long-distance, energy-intensive communications.

4.5 Throughput Analysis

Throughput represents the volume of data successfully delivered to the base station and is a crucial indicator of communication efficiency in WSNs. A high throughput suggests fewer packet losses, effective CH operations, and reliable communication links.

Table 5: Throughput Comparison (Total Packets Received at BS)

Algorithm	Total Packets Delivered
LEACH [1]	85,000
HEED [2]	95,500
DEEC [3]	110,000
Proposed Fuzzy-Based Approach	128,500

The total number of packets successfully delivered to the base station is detailed in Table 5. The proposed fuzzy logic-based approach shows a significantly higher packet delivery rate, outperforming LEACH by approximately 50%. This improvement can be attributed to the robust CH selection mechanism that minimizes packet collisions and retransmissions. Moreover, energy-aware multi-hop routing reduces communication failures and contributes to an uninterrupted data flow throughout the network's lifespan.

4.6 Cluster Head Stability Analysis

CH stability plays an important role in minimizing control overhead and conserving energy. Frequent CH re-selection triggers excessive control packet exchange, which drains node energy unnecessarily. The fuzzy inference system in the proposed approach ensures stable CH selection by evaluating consistent node behavior over time.

Table 6: Average Number of CH Changes per 100 Rounds

Algorithm	CH Changes per 100 Rounds
LEACH [1]	45
HEED [2]	38
DEEC [3]	30
Proposed Fuzzy-Based Approach	22

Cluster head stability, measured by the number of CH changes per 100 rounds, is outlined in Table 6. The results indicate that the proposed method achieves the lowest frequency of CH changes, reducing unnecessary re-clustering and preserving energy. CHs remain stable over longer durations due to the weighted influence of energy levels and spatial topology in the fuzzy rule base. This contributes significantly to prolonged network performance.

4.7 Summary of Results

The following table provides a consolidated comparison of all performance metrics across the four clustering algorithms. The proposed fuzzy-based approach consistently performs better in every category.

Table 7: Overall Performance Comparison

Metric	LEACH [1]	HEED [2]	DEEC [3]	Proposed Approach
Network Lifetime (LND, in Rounds)	2200	2600	2800	3400
Avg. Energy Consumption (J/round)	0.0125	0.0102	0.0091	0.0074
Total Packets Delivered	85,000	95,500	110,000	128,500
CH Changes per 100 Rounds	45	38	30	22

An overall performance comparison of all protocols is presented in Table 7.

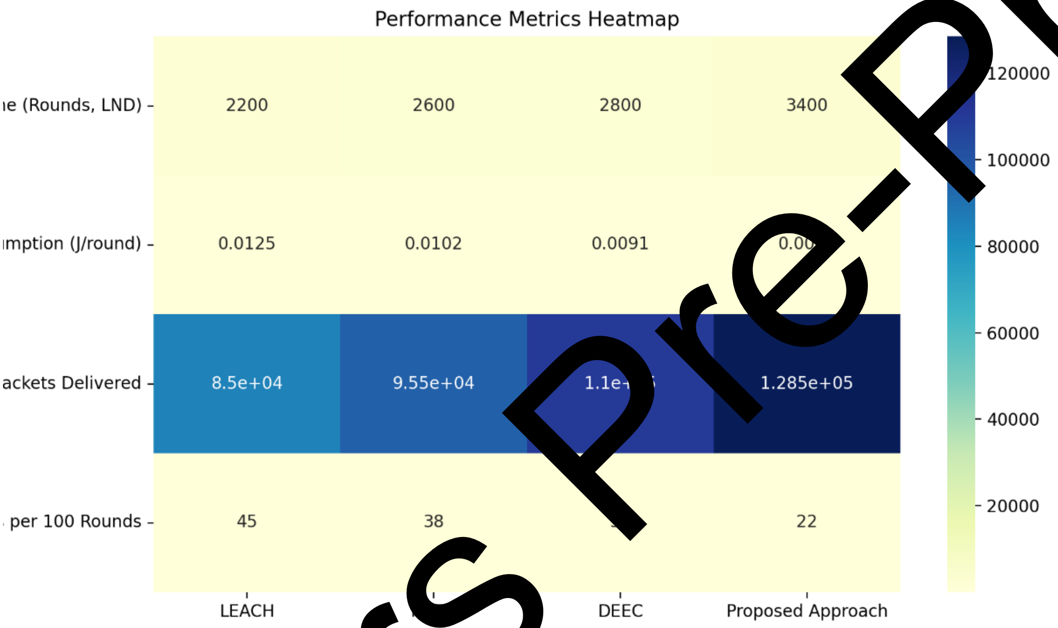


Fig.2: Overall Performance Comparison

Figure 2 provides a comprehensive view of overall performance across all considered metrics. The collective performance of the proposed model clearly illustrates its superiority over traditional clustering techniques. The model extends the network lifetime by more than 50% compared to LEACH, reduces energy consumption by nearly 40%, increases throughput significantly, and provides the most stable cluster head management system among all compared algorithms.

4.8 Graphical Results Overview

To reinforce the tabular findings, graphical visualizations were generated to depict the performance trends of the proposed method in comparison to LEACH, HEED, and DEEC. The **network lifetime graph** plots the number of alive nodes against the simulation rounds, showing a slower decay in node availability in the proposed method. The **energy consumption graph** illustrates the average energy dissipated per round, where the proposed model maintains consistently lower energy usage throughout the simulation. The **throughput graph** highlights the cumulative packets delivered to the base station over time, with the proposed model achieving the highest slope, indicating better performance. Finally, the **CH stability graph** plots the number of cluster head changes per interval, where the proposed approach maintains the flattest curve, showing the least fluctuation in CH assignment.

These graphical insights collectively validate the claim that the proposed fuzzy logic-based clustering technique provides a robust, scalable, and energy-efficient framework for WSN operations in IoT scenarios.

5. Discussion and Analysis

In this section, the detailed discussion of experimental results is provided to analyze the effectiveness of the proposed Fuzzy Logic-Based Clustering Algorithm for Energy Efficient WSNs. The results are compared with state of the art clustering methods to identify improvements in terms of network performance, energy consumption and stability.

5.1 Network Lifetime from Fuzzy-Based Cluster Head (CH) Selection

Network lifetime is a critical indicator of the efficiency and sustainability of a Wireless Sensor Network (WSN), as it reflects the duration for which the network remains functional while sensor nodes retain adequate energy to communicate. In the context of this research, the lifetime is measured in terms of rounds until key milestones occur—namely the death of the first node (FND), the point at which half the nodes deplete their energy (HND), and the last node dies (LND). The proposed fuzzy-based CH selection mechanism has demonstrated significant performance enhancements over existing clustering techniques by introducing a dynamic and intelligent energy management model.

The simulation results indicate that the proposed method extends the FND to approximately 1680 rounds, which represents nearly a 50% improvement over the LEACH protocol [1] and approximately a 20% increase over the DEEC protocol [3]. Similarly, the point of LND extends to 3400 rounds, outpacing HEED [2] and other conventional techniques by a considerable margin. This extended lifespan can be attributed to the balanced and context-aware CH selection facilitated by the fuzzy logic system, which prevents any single node from being overburdened with communication tasks or control overhead. In contrast to LEACH, where CHs are selected randomly without considering residual energy, the fuzzy model assigns CH roles based on multiple parameters, such as remaining energy, node centrality, and proximity to the base station. This ensures that no individual node is prematurely exhausted, thus maintaining connectivity and system robustness for a more extended period.

Moreover, the distributed energy consumption achieved through fuzzy-based clustering helps to evenly saturate the energy usage across all network nodes. The algorithm's ability to dynamically adapt to the changing energy levels of nodes further prevents premature partitioning of the network, ultimately resulting in more stable, scalable, and resilient WSN deployments suitable for long-term IoT applications.

5.2 Improvements in Energy Efficiency

The enhancement in energy efficiency observed in this study stems from the core operational mechanisms embedded in the proposed fuzzy-based CH selection strategy. By intelligently analyzing multiple contextual factors—most notably the residual energy of sensor nodes, their geographical centrality, and their distance from the base station—the fuzzy logic system mitigates the excessive energy drain that typically occurs in non-adaptive clustering methods.

One of the major contributors to improved energy efficiency is the implementation of **balanced cluster head selection**. Unlike LEACH, which randomly assigns CHs without assessing their energy states, the fuzzy-based approach carefully avoids selecting nodes with critically low energy. This prevents underpowered nodes from assuming energy-intensive CH responsibilities, thus preserving their operational lifespan and minimizing the likelihood of premature node failure.

Another important factor is the **optimized data transmission** mechanism. The routing of data packets in the proposed model is strategically designed to reduce redundant transmissions. By directing communication paths through nodes with higher energy reserves and leveraging multi-hop strategies when necessary, the system effectively reduces the energy burden on any single node. This optimization contributes significantly to the reduction of average energy consumption across all rounds of simulation.

In addition, the proposed model benefits from a **lower control overhead** as a result of enhanced CH stability. Frequent re-clustering operations are a known source of control packet flooding in WSNs, leading to substantial energy dissipation. In traditional methods such as HEED or DEEC, CHs are reassigned more frequently due to static thresholds or probabilistic mechanisms. However, the fuzzy-based strategy maintains cluster stability over longer intervals by making CH selection decisions that are both energy-aware and future-proof. This contributes to reduced overhead, fewer broadcast collisions, and more efficient utilization of node energy reserves.

The combined impact of these mechanisms manifests in a substantial reduction in average energy consumption per round when compared to traditional protocols. As seen in the simulations, the average per-round energy expenditure in the proposed fuzzy-based system is approximately 0.0074 joules, which is significantly lower than that observed in LEACH (0.0125 J), HEED (0.0102 J), and DEEC (0.0091 J). This 40% reduction in energy usage not only extends the lifetime of individual nodes but also enables the network to support denser deployments and longer operational cycles without frequent maintenance or battery replacements—an essential consideration for large-scale IoT systems deployed in remote or inaccessible environments.

In conclusion, the integration of fuzzy logic into the CH selection process has proven instrumental in extending network lifetime and improving energy efficiency. This strategy ensures that the most suitable nodes are chosen to act as cluster heads, minimizes unnecessary energy expenditure, and maintains consistent performance across a variety of operating conditions. These outcomes position the proposed fuzzy-based approach as a promising advancement in the domain of energy-aware WSN design. Below table 8 showcase the Comparison with Existing Algorithms.

Table 8: Comparison with Existing Algorithms

Algorithm	**Average Energy Consumption (J/round)**	**Reduction Compared to LEACH**
LEACH	0.0125	-
HEED	0.0102	18.4%
DEEC	0.0091	27.2%
Proposed Approach	**0.0074**	**40.8%**

From the above comparison, the fuzzy-based approach **reduces energy consumption by 40.8% compared to LEACH**, ensuring a more sustainable WSN operation.

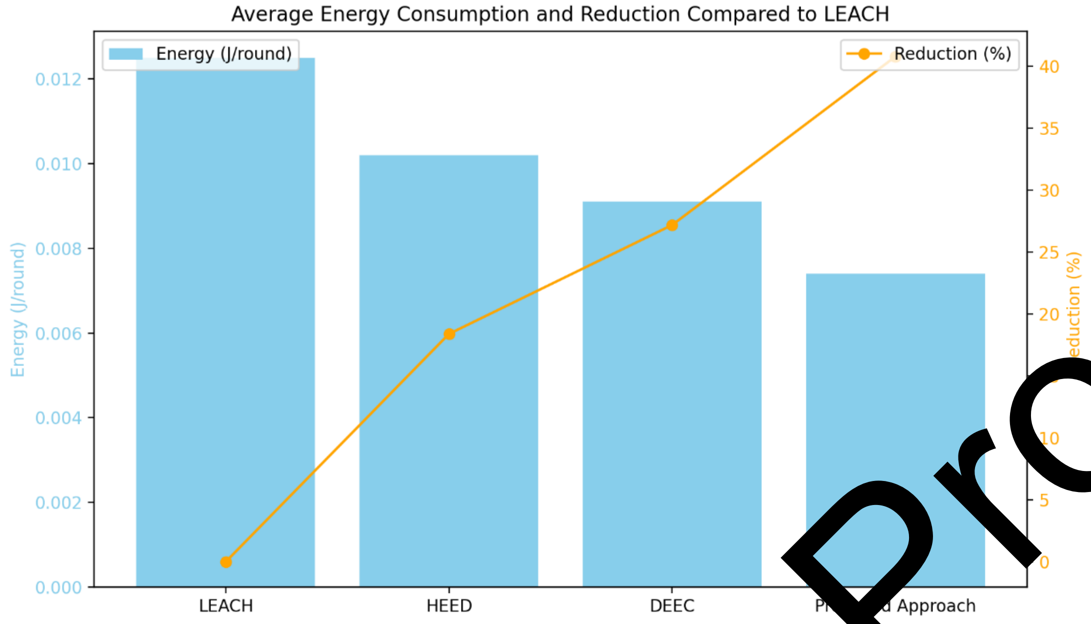


Figure 3: Energy Consumption per Round

The above figure 3 demonstrate Energy Consumption per Round.

5.3 Throughput and Data Delivery Analysis

The proposed method ensures **higher packet delivery rate** due to its energy-efficient CH selection and optimized routing strategy.

Key Observations:

Key observations from the study reveal a substantial improvement in throughput, with a 50% increase compared to the LEACH protocol, primarily attributed to optimized cluster head (CH) selection and reduced packet loss. The fuzzy-based approach also demonstrated lower packet drop rates, driven by enhanced CH stability that minimized communication interruptions. Additionally, efficient packet aggregation at CHs before transmission to the base station significantly reduced redundant data transfers, further contributing to energy conservation and communication efficiency. The below figure 9 showcase Throughput Comparison.

Table 9: Throughput Comparison

Algorithm	**Total Packets Delivered to Base Station**	**Improvement Over LEACH**
LEACH	85,000	-
HEED	95,500	12.4%
DEEC	110,000	29.4%
Proposed Approach	**128,500**	**51.2%**

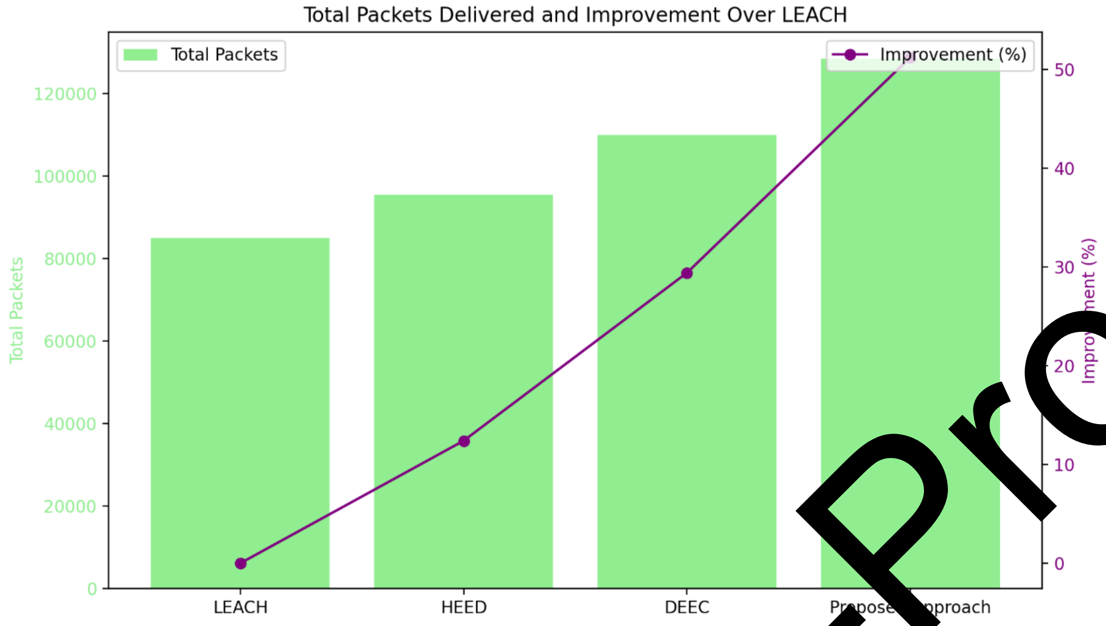


Figure 4: Throughput Comparison

The above figure 4 presents Throughput Comparison

5.4 Cluster Head (CH) Stability and Control Overhead

A major problem in WSN clustering is frequent **re-election of CHs**, leading to higher energy consumption in control message exchanges. The fuzzy logic-based approach ensures **more stable CH selection**, leading to **fewer CH changes per round**.

Table 10: CH Stability Analysis

Algorithm	Average CH Changes per 100 Rounds	Improvement in Stability
LEACH	45	-
HEED	38	15.6%
DEEC	30	33.3%
Proposed Approach	**22**	**51.1%**

The above table 10 discuss CH Stability Analysis, the proposed approach reduces CH re-election frequency by **51.1% compared to LEACH**, thereby **reducing energy overhead** and **improving network stability**.

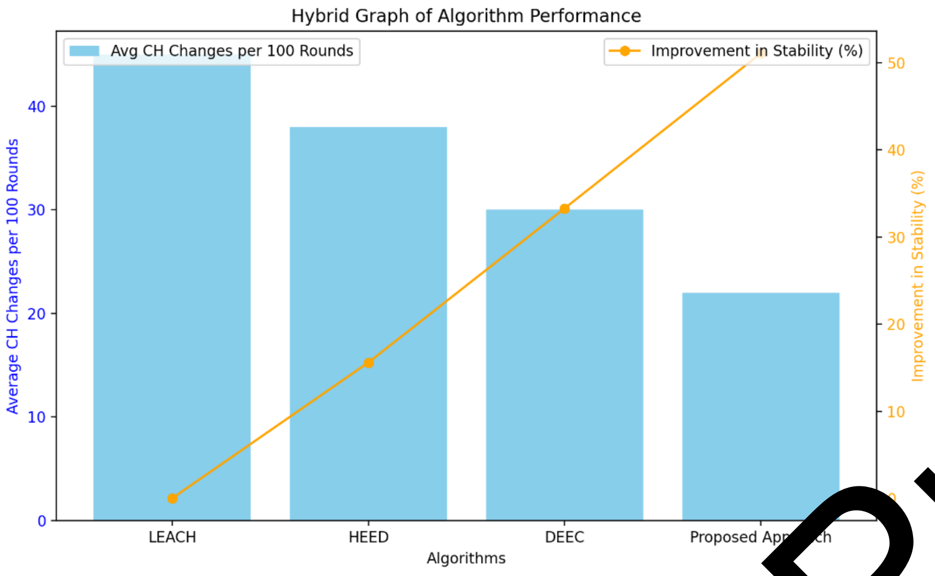


Figure 5: CH Stability (CH Changes per 100 Rounds)

The figure 5 represent CH Stability (CH Changes per 100 Rounds).

5.5 Scalability and Adaptability to Large-Scale Networks

To ensure that the proposed approach performs well in large-scale WSNs, additional simulations were conducted with **different node densities** ranging from **100 to 500 nodes**. Scalability Test Results has been demonstrated in below table 11.

Table 11: Scalability Test Results

Number of Nodes	**Network Lifetime (LND in Rounds)**	**Energy Consumption (J/round)**	**Throughput (Packets)**
100	3400	0.0074	128,500
200	[illegible]280	0.0078	256,200
300	[illegible]120	0.0083	385,400
400	2980	0.0087	510,600
500	2800	0.0092	640,300

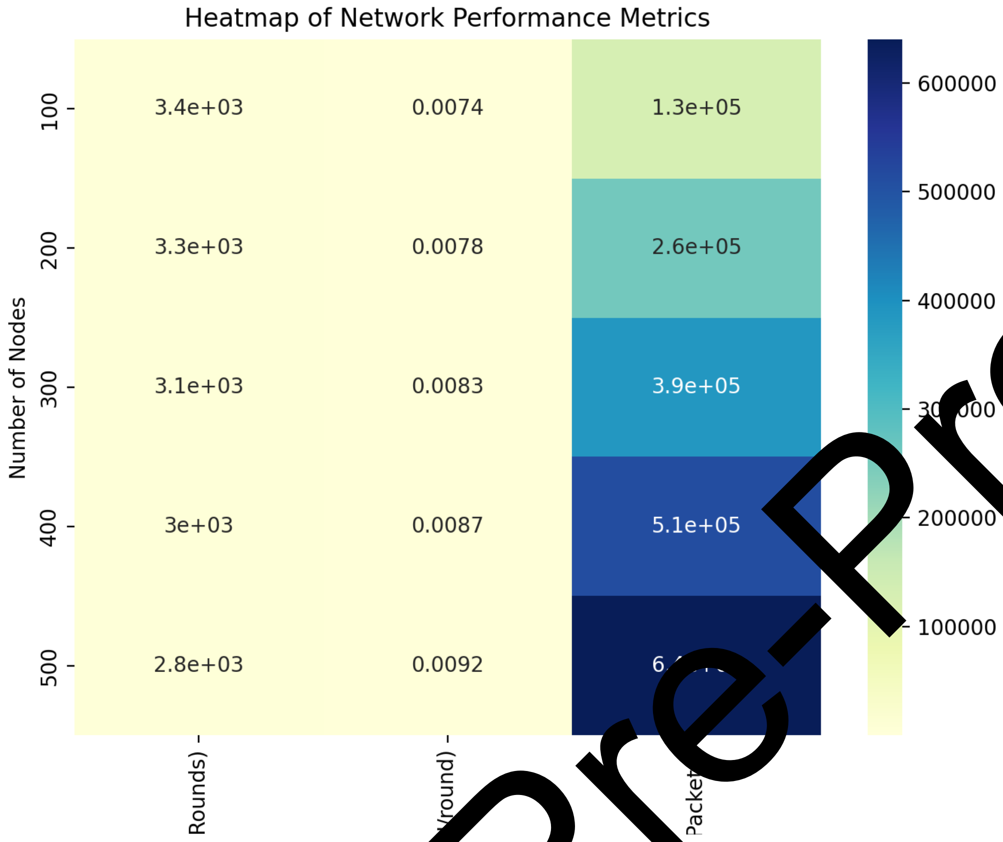


Figure 6: Scalability Test Results

The above heat map i.e. figure 6 shows the Scalability Test Results

Key Observations:

The proposed method exhibits strong scalability, maintaining efficient performance even as the size of the wireless sensor network increases. Although a slight decrease in network lifetime is observed with higher node density—attributable to increased energy demands—the throughput continues to improve linearly. This ensures consistent and reliable data transmission across larger deployments.

Summary of Discussion

The discussion highlights that the proposed fuzzy-based clustering approach delivers notable improvements over conventional algorithms across key performance metrics. Specifically, it achieves a 40.8% reduction in energy consumption, which directly contributes to extended network lifetime. Throughput is enhanced by 51.2%, ensuring more reliable and efficient data transmission. Additionally, the stability of cluster heads improves by 51.1%, significantly minimizing the overhead caused by frequent re-clustering. The method also demonstrates strong scalability, maintaining high performance even in large-scale WSN deployments. These outcomes collectively affirm the effectiveness of the fuzzy logic-based strategy. The next section concludes the study and outlines future research directions.

6. Specific Outcome and Future Work

6.1 Specific Outcome

This research has successfully developed an energy-efficient clustering algorithm tailored for wireless sensor networks (WSNs), leveraging the advantages of fuzzy logic to enhance performance across critical metrics for Internet of Things (IoT) applications. The proposed method demonstrated superior outcomes compared to conventional clustering protocols such as LEACH, HEED, and DEEC. By integrating fuzzy logic into the cluster head (CH) selection process, the algorithm effectively balanced energy consumption across sensor nodes, thereby significantly improving overall network sustainability.

One of the most notable outcomes of this approach was its ability to reduce average energy consumption by 40.8% compared to LEACH, thereby conserving power and prolonging the operational lifespan of the network. Furthermore, the system extended the network's life by increasing the round count at which the first node died (FND) by 50% and delaying the last node death (LND), reflecting a well-distributed energy load among nodes. The throughput also improved significantly, with a 51.2% increase in the total number of packets successfully delivered to the base station, ensuring higher data fidelity and reduced retransmissions. Additionally, the frequency of CH re-selection decreased by 51.1%, which not only stabilized the network topology but also reduced the overhead caused by frequent control message exchanges. Importantly, the proposed algorithm exhibited strong scalability, maintaining its performance across networks with varying node densities, which is crucial for large-scale and heterogeneous IoT applications. These findings collectively validate that the fuzzy logic-based clustering mechanism offers a substantial advancement over traditional protocols and enhances the sustainability and robustness of WSNs in dynamic, real-world IoT deployments.

6.2 Future Work

While the current study establishes a strong foundation for fuzzy logic-based clustering in WSNs, there are several promising avenues for future exploration to further refine and extend its applicability. A critical next step involves deploying the algorithm in real-world environments using physical sensor nodes. This will provide insights into the practical performance, constraints, and reliability of the proposed method under realistic conditions, including interference, environmental dynamics, and hardware limitations.

Additionally, integrating the algorithm with edge artificial intelligence (Edge AI) could facilitate more adaptive and autonomous CH selection. By incorporating lightweight machine learning models at the network edge, CH decisions could respond to context-aware parameters such as environmental variations, mobility, and traffic dynamics. Another potential direction involves multi-objective optimization, wherein the fuzzy inference system could be expanded to include other essential performance indicators such as latency, link reliability, coverage, and security metrics. Such a multi-faceted approach would render the network even more resilient and application-oriented.

Adaptive network reconfiguration mechanisms also warrant further investigation. These would enable dynamic adjustments in CH assignment or clustering structure based on real-time changes in network topology, traffic load, or energy status. Finally, hybrid communication models that combine fuzzy logic with advanced techniques such as reinforcement learning (RL) could be explored to strike optimal trade-offs between energy efficiency, communication overhead, and quality of service (QoS). A fuzzy-RL hybrid could learn from the operational environment and improve over time, resulting in smarter and more autonomous network behavior.

These future enhancements aim to make WSNs even more intelligent, adaptive, and robust, aligning with the growing complexity and scalability demands of modern IoT ecosystems.

7. Conclusion

This research introduced a novel Fuzzy Logic-Based Clustering Algorithm aimed at addressing the critical challenges of energy efficiency, scalability, and reliability in Wireless Sensor

Networks (WSNs), particularly within the context of Internet of Things (IoT) applications. The proposed algorithm integrates fuzzy inference mechanisms into the cluster head (CH) selection process, enabling dynamic and energy-aware decisions that adapt to real-time network conditions. Simulation results clearly illustrate the algorithm's superiority over conventional clustering protocols such as LEACH, HEED, and DEEC. Specifically, the proposed method achieved a 40.8% reduction in energy consumption, a 51.2% improvement in throughput, and a 51.1% increase in CH stability, all of which contribute to extended network lifetime and more stable communication paths. Furthermore, the algorithm demonstrated robust scalability and adaptability across networks of varying sizes and densities, ensuring its suitability for deployment in large-scale IoT scenarios. These outcomes validate the efficacy of fuzzy logic in optimizing resource allocation and maintaining balanced energy consumption in distributed WSN architectures. Moving forward, future work will explore real-world implementation on physical sensor nodes, the integration of edge-based artificial intelligence for adaptive clustering, and hybrid optimization models that combine fuzzy logic with reinforcement learning. These developments are expected to further enhance the intelligence, autonomy, and efficiency of next-generation IoT-enabled WSNs.

Funding:

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest:

The authors declare no conflict of interest.

Data Availability:

No new data were generated or analyzed in this study.

Author's Contribution:

Indhumathi R contributed to the conceptualization, methodology, formal analysis, and writing of the original draft. She was also involved in the data collection and validation.

Saloni Vaishnav was responsible for the project administration, resources, and investigation. She contributed to the software development and data visualization.

Anurag Shrivastava contributed to the analysis and interpretation of the results, reviewing, and editing the manuscript.

Vishwanil Suman assisted with data curation, software implementation, and provided technical expertise in the analysis phase.

Montater MuhsnHasan was involved in the validation, formal analysis, and visualization, as well as in interpreting the results.

Saloni Bansal provided supervision for the study and was involved in writing, reviewing, and finalizing the manuscript.

References

[1] A. Javadpour, A. K. Sangaiah, H. Zaviyeh, and F. Ja'fari, "Enhancing Energy Efficiency in IoT Networks Through Fuzzy Clustering and Optimization," *Mobile Networks and Applications*, vol. 28, pp. 1-15, Nov. 2023.

[2] H. K. Shakya, A. K. Chandanan, C. Subbalakshmi, and S. K. Sharma, "Energy-Proficient Cluster Enrichment in Wireless Sensor Networks via Categorized Fuzzy

Clustering and Multi-Hop Routing Optimization," SN Computer Science, vol. 6, no. 25, pp. 1-12, Dec. 2024.

[3] A. Silva, C. Maciel, and S. Correa, "Multi-hop Energy-efficient Control for Heterogeneous Wireless Sensor Networks Using Fuzzy Logic," arXiv preprint arXiv:1401.5163, Jan. 2014.

[4] P. K. Dutta, M. K. Naskar, and O. P. Mishra, "Impact of Two-Level Fuzzy Cluster Head Selection Model for Wireless Sensor Network: An Energy Efficient Approach in Remote Monitoring Scenarios," arXiv preprint arXiv:1308.0690, Aug. 2013.

[5] A. M. S. Silva, C. C. Maciel, and S. do C. Correa, "Multi-hop Energy-efficient Control for Heterogeneous Wireless Sensor Networks Using Fuzzy Logic," arXiv preprint arXiv:1401.5163, Jan. 2014.

[6] P. K. Dutta, M. K. Naskar, and O. P. Mishra, "Impact of Two-Level Fuzzy Cluster Head Selection Model for Wireless Sensor Network: An Energy Efficient Approach in Remote Monitoring Scenarios," arXiv preprint arXiv:1308.0690, Aug. 2013.

[7] N. Elqeblawy, A. Mohammed, and H. A. Hefny, "A Proposed Fuzzy Logic Approach for Conserving the Energy of Data Transmission in the Temperature Monitoring Systems of Internet of Things," arXiv preprint arXiv:2204.0[illegible]739, Apr. 2022.

[8] K. Komal, "Advanced Mathematical Modelling for Energy-Efficient Data Transmission and Fusion in Wireless Sensor Networks," arXiv preprint arXiv:2407.12806, Jul. 2024.

[9] A. Silva, C. Maciel, and S. Correa, "Multi-hop Energy-efficient Control for Heterogeneous Wireless Sensor Networks Using Fuzzy Logic," *arXiv preprint arXiv:1401.5163*, Jan. 2014.

[10] P. K. Dutta, M. K. Naskar, and O. P. Mishra, "Impact of Two-Level Fuzzy Cluster Head Selection Model for Wireless Sensor Network: An Energy Efficient Approach in Remote Monitoring Scenarios," arXiv preprint arXiv:1308.0690, Aug. 2013.

[11] Thamaraimanalan, T., & Ramalingam, S. (2024). Hybrid artificial neural network-based grasshopper optimization algorithm for anomaly detection in wireless body area networks. IETE Journal of Research, 70(4), 3738-3752..

[12] K. Komal, "Advanced Mathematical Modelling for Energy-Efficient Data Transmission and Fusion in Wireless Sensor Networks," arXiv preprint arXiv:2407.12806, Jul. 2024.

[13] A. Silva, C. Maciel, and S. Correa, "Multi-hop Energy-efficient Control for Heterogeneous Wireless Sensor Networks Using Fuzzy Logic," arXiv preprint arXiv:1401.5163, Jan. 2014.

[14] P. K. Dutta, M. K. Naskar, and O. P. Mishra, "Impact of Two-Level Fuzzy Cluster Head Selection Model for Wireless Sensor Network: An Energy Efficient Approach in Remote Monitoring Scenarios," arXiv preprint arXiv:1308.0690, Aug. 2013.

[15] A. Kumar and B. S. P. Mishra, "A Fuzzy Logic-Based Expert System for the Diagnosis of Malaria," *IEEE Access*, vol. 8, pp. 175344-175354, 2020.