Babylonian Journal of Networking
Vol.2025, **pp**. 175–184
DOI: https://doi.org/10.58496/BJN/2025/016; ISSN: 3006-5372
https://mesopotamian.press/journals/index.php/BJN

Research Article

Enhancing Wireless Sensor Network Lifetime through Fuzzy-Based Execution of the LEACH Protocol

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ARTICLE INFO

Article History

Received 20 Sep 2025
Revised 22 Oct 2025
Accepted 27 Nov 2025
Published 13 Dec 2025

Keywords
Wireless Sensor Networks (WSN),
LEACH Protocol,
Fuzzy Logic,
Network Lifetime,
Energy Efficiency,
Cluster Head Selection.

ABSTRACT

Introduction Wireless Sensor Networks Wireless Sensor Networks (WSNs) consist of a number of physically disperse sensor nodes which use wireless communication to do sensing and retrieving information from the physical world. In a network of battery driven and energy limited nodes, the network lifetime is an important concern. Driven by the above mechanism, as a cluster of nodes is frustrated, the function of the entire network drops dramatically or even becomes inefficient. Low-Energy Adaptive Clustering Hierarchy (LEACH) LEACH is one of the most well-known energy-efficient clustering protocols for making wireless sensor networks more sustainable by grouping nodes and moderating the group head. However, in LEACH protocol, the operation of cluster head is selected randomly, which might lead to the waste of energy in the node. Here, this paper proposes an enhanced LEACH that integrates fuzzy logic-based decision-making with cluster head selection. The fuzzy-centric LEACH versions improve significantly in terms of energy consumption and network lifetime through the involvement of some parameters such as residual energy, distance to BS, and the density of sensor nodes. Simulation results confirms that the proposed fuzzy implementation of LEACH outperforms the existing classical variant and gives a feasible solution for WSN deployment environment.

1. INTRODUCTION

Introduction WSN consist large number of small nodes with sensing, computation and communication capabilities, which is deploy installed sensing field togethering communicate labelled information (event). Such networks can operate on the far natural area or urban infrastructure for environmental change detection, structural condition monitoring, traffic condition monitoring etc. Because of the flexibility and scalability of WSNs, WSNs are applied in varieties of fields, such as environmental monitoring, healthcare, agriculture, military surveillance, etc. Yet, beyond the attractive features, WSNs present severe constraints—mostly the restricted energy resources per sensor node, generally battery-operated [1]. In contrast to wired networks, which nodes are having infinite energy as it were their energy consumption is not a major concern and system lifetime is not a problem, the nodes in WSNs are subjected to finite power, which means that when a node's battery is drained, it no longer works, and this may cause a degradation or a failure in the network. Thus, the optimal utilization of power is indispensable for extending network lifetime. A number of WSN energy-aware routing approaches have been proposed in the literature which could be applied for this purpose [2,3]. The Low-Energy Adaptive Clustering Hierarchy (LEACH) is one of the earliest cluster-based protocol, every round Cycle a probabilistic model is used to elect a Cluster Head (CH) so that, it can minimize the power dissipated. But the original LEACH algorithm fails to take into account important parameters at the time of forming cluster such as, the residue energy of nodes or their distance to the Base station

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– indicating wastage in the energy consumption of nodes. Recently fuzzy logic-based CH selection enhancements have been offered for better energy balancing and lifetime [4]. In [5] routing protocols in WSN were categorized as: Network Structure-Based, Topology-Based, Communication Model-Based and Reliable Routing Schemes. In addition, WSNs use flat topology or hierarchical topology. Flat routing protocols such as Flooding [6], Directed Diffusion [7], Rumor Routing [8], SPIN [9] can work well in small size networks, however, they are not scalable. Therefore, the hierarchical routing protocol such as LEACH is generally used in large-scale WSN due to its energy efficiency and scalability. In hierarchical routing, the network is partitioned into clusters where specific nodes serve as Cluster Heads (CHs). This CHs are the nodes that are responsible for aggregating and compressing data from member nodes before forwarding it to the BS. As CHs perform extra tasks, they consume more energy than normal nodes. In order to avoid early energy death CHs are rotated periodically. [10-15], LEACH was presented as the first hierarchical protocol that uses the clustering technique with signal strength. This paper extends LEACH algorithm by using fuzzy logic in CH selection with the objective to improve network lifetime and efficiency.

2. METHODOLOGY

2.1 Low Energy Adaptive Clustering Hierarchy (LEACH) Protocol

For WSNs, the LEACH algorithm is one of the most well-known and essential kinds of hierarchical routing protocol. It is based on the structure of Cluster Routing in Secure LEAP (CL-SECLE), where a CH runs a smaller number of clusters and all clusters attain the whole network. The CH collects the sensed data from the sensor nodes (or member nodes), processes the data, and forwards it to the BS [16-23]. LEACH operates in two main stages: the setup and steady-state. While in the deployment stage, CHs are elected with probability based on a predetermined threshold function. the steady-state phase which consists in data delivery in a dual hop fashion from the member nodes to the respective CHs and then from the CHs to the BS. In order to have the energy consumption fairly distributed among all sensor nodes, LEACH uses a rotating CH mechanism. In every round, dynamic CHs are elected so that the initial nodes do not run out of energy prematurely. The threshold function T(n) to decide whether the nodes become a CH is denoted by equation (1).

$$T(n) = \begin{cases} \frac{P}{1-p\,(r \bmod 1/P)} & if\ n \in G \\ 0 & outherwise \end{cases} \tag{1}$$

Where:

- P is the desired percentage of CHs,
- r is the current round number,
- G is the set of nodes that have not been CHs in the last 1/p rounds.

Each node generates a random number between 0 and 1 in each round. If this value is less than T(n), and the node belongs to set GGG, then it becomes a CH for that round. After the CHs are selected, the other nodes associate themselves with the nearest CH based on received signal strength. Figure 1 illustrates the operational flow of the LEACH protocol, covering both CH selection and data transmission phases.

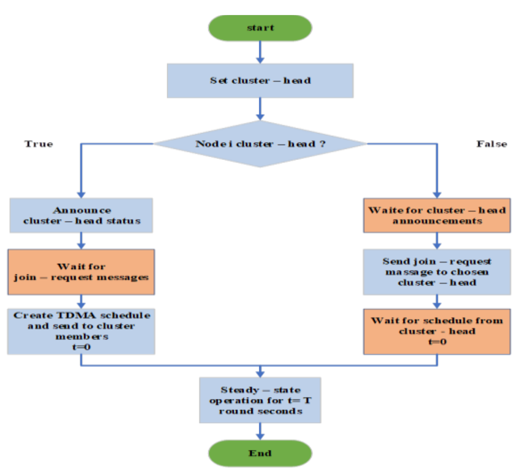

Fig 1. LEACH Protocol Flowchart

2.2 Fuzzy Logic

Fuzzy Logic (FL) is a more developed form of logic based on the fuzzy or imprecise truth rather than classical binary logic, in which variables may take any value in the range of 0 and 1. This is especially advantageous in those circumstances when there is ambiguity and vagueness related to the problem due to its application in the Sensor networks. Whereas Boolean Logic only recognizes an object as either a member of a set or a non-member of a set, Fuzzy Logic distinguishes between three possible types of objects that a given object can be: a. Banned b. Accepted to a degree, less than full association c. Fully accepted mapped by set enabled Person with at least some degree of Boat association whose grade ranges from zero to one. The basic idea was proposed by [6]. Figures 2 and 3 show that the classification of a human's height achieved with a binary logic representation differs from that achieved with a fuzzy logic representation.

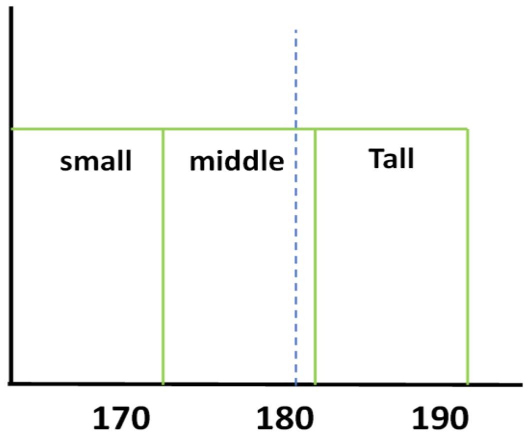

Fig. 2. Height intervals represented using Binary Logic.

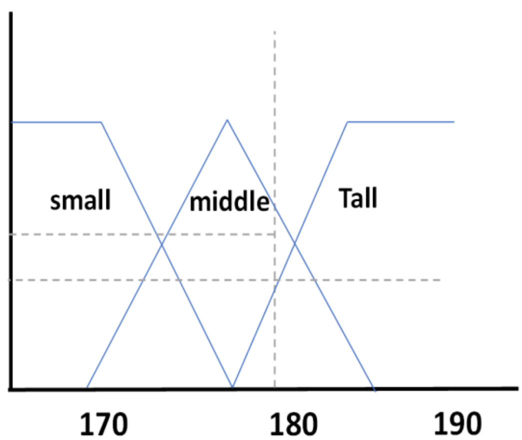

Fig 3. Height intervals represented using Fuzzy Logic

For example, a person 179.9 cm in height should not consider themselves Tall if 180 cm is the cutoff point in binary logic. But in fuzzy logic, this person can be "Tall" to some extent or "Middle" to some extent, and that depends on the values of the association functions.

2.3 Gupta's Fuzzy Logic-based LEACH Protocol

proposed an improved LEACH protocol with use of fuzzy logic technique in CH selection. The authors of their approach are not randomized, rather relies on three important metrics: residual energy, node density, and centrality. Such inputs are fuzzified and then go through a Mamdani inference engine to obtain a CH probability score. There are four main steps to the process:

a) Fuzzification: The crisp input factors—residual energy, node density and centrality—are transformed to fuzzy sets after applying suitable association functions.

b) Rule Evaluation: A rule base with fuzzy rules is employed to evaluate the fuzzy inputs.
c) Aggregation: Outputs of all the active rules are aggregated into one fuzzy set.
d) Defuzzification: The fuzzy result is then transformed into a crisp value by the use of Center of Gravity (COG), expressed by (2).

$$COG = (\sum \mu_A(X) * X) / \sum \mu_A(X) \qquad (2)$$

Where μA(X) is the association function of variable X. The input variables with their fuzzy set definition are listed in Table I. Figures 4–7 show the association functions of the input and output variable quantity.

TABLE I: INPUT VARIABLES IN GUPTA'S FUZZY LOGIC MODEL

Input Variable	Fuzzy Set Values
Energy of Residual (E)	Little, Medium, High
Concentration of Node	Sparse, Medium, Dense
Centrality of Node	Near, Adequate, Far

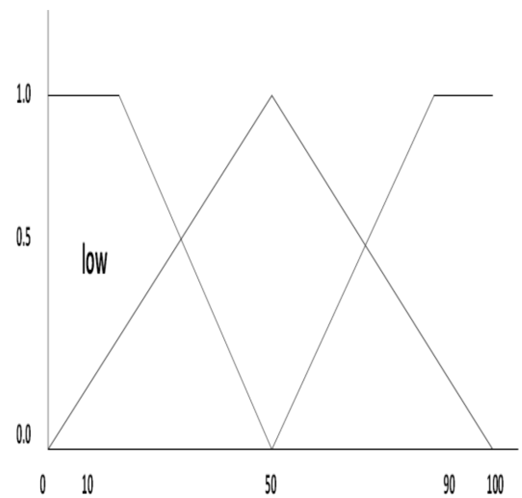

Fig 4. association function for Node Energy

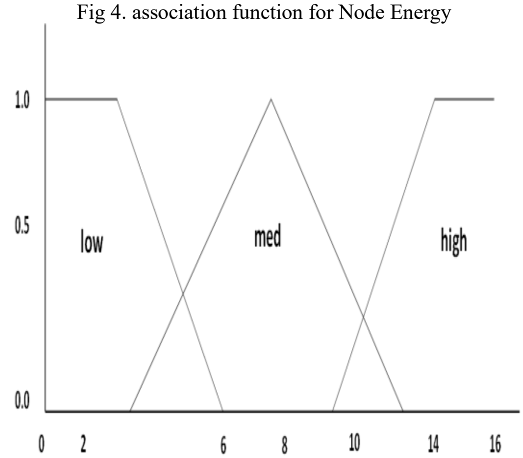

Fig 5. association function for Node Concentration

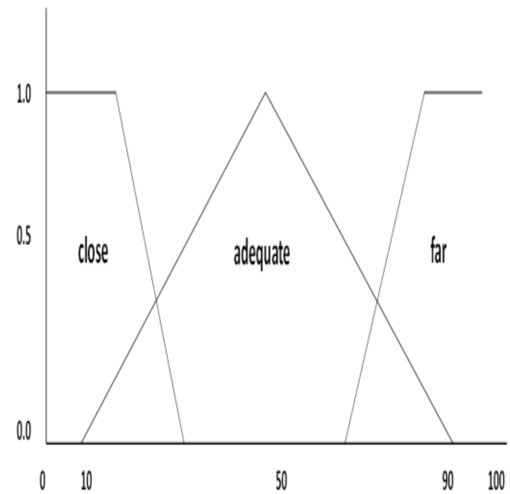

Fig 6. association function for Node Centrality

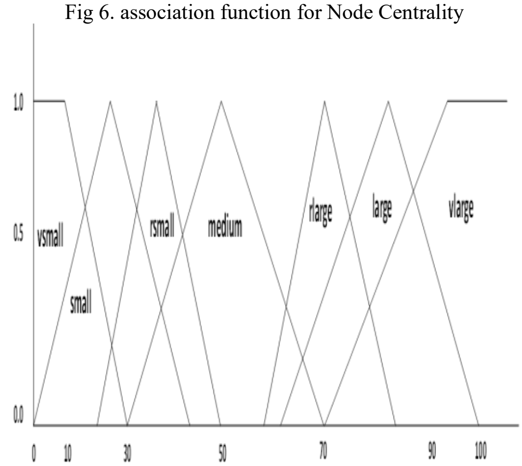

Fig 7. Association function for Output Possibility

At the beginning of each round, this algorithm calculates the possibility value for every node. As a result, CHs are chosen from among the nodes with the best probability ratings.

2.4 CHEF: Cluster Head Election using Fuzzy Logic

CHEF is another enhancement of the LEACH protocol that utilizes fuzzy logic to determine CHs based on two parameters: residual energy and node centrality. Node centrality is computed based on the distance from a node to its neighbors within a defined sensing radius r, given by Equation (3):

$$r = \sqrt{\frac{M}{\pi\, n\, P}} \tag{3}$$

Where:

- M is the area of the sensor field,
- n is the total number of sensor nodes,
- P is the desired CH probability.

Table II outlines the input parameters for the CHEF model, and Figure 8 visualizes node distances used in calculating centrality.

TABLE II: INPUT VARIABLES IN CHEF MODEL

Input Variable	Fuzzy Set Values
Residual Energy	Low, Medium, High
Node Centrality	Near, Medium, Far

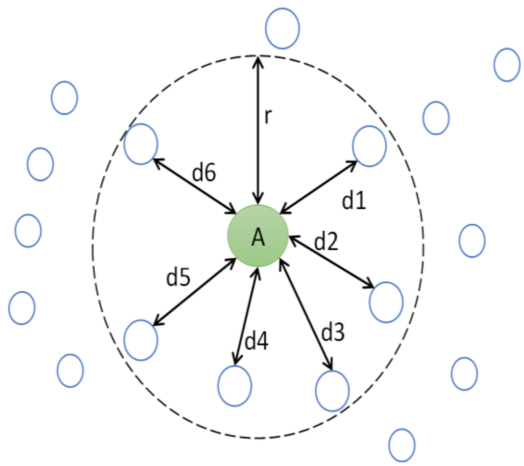

Fig 8. Sensing radius for centrality calculation in CHEF

In CHEF, nodes calculate their fuzzy-based CH probability, and the node with the highest score in each cluster is elected as the CH.

2.5 LEACH-FL: LEACH with Enhanced Fuzzy Logic

LEACH-FL is an alternative to the LEACH model in which several fuzzy indicators are added in order to improve the CH choice. It takes four input parameters: the distance, node density, battery energy, and the centrality to calculate the CH selection probability. The CH probability of fuzzy-based approach is defined as follows:

$$Prob.value = (N.Energy) * 2 + (N.\ density) + (2 - N.\ Centr)$$

Table III describes the fuzzy sets used for the input variables, and Figures 9–12 show the membership functions for each variable.

TABLE III: INPUT VARIABLES IN LEACH-FL

Input Variable	Fuzzy Set Values
Energy of Node	Low (zero), Medium (one), High (two)
Density of Node	Low (zero), Medium (one), High (two)
Centrality of Node	Near (zero), Medium (one), Far (two)

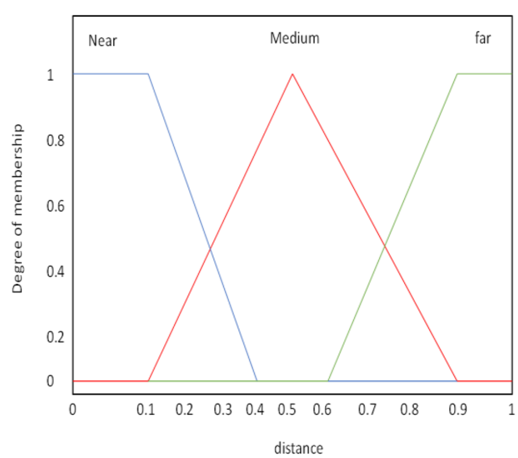

Fig 9. association function for Node Distance

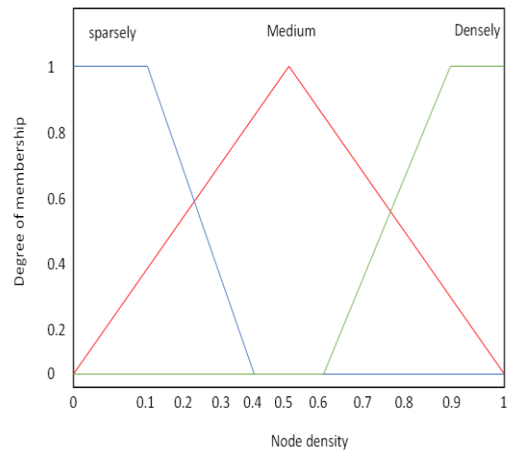

Fig 10. association function for Node Density

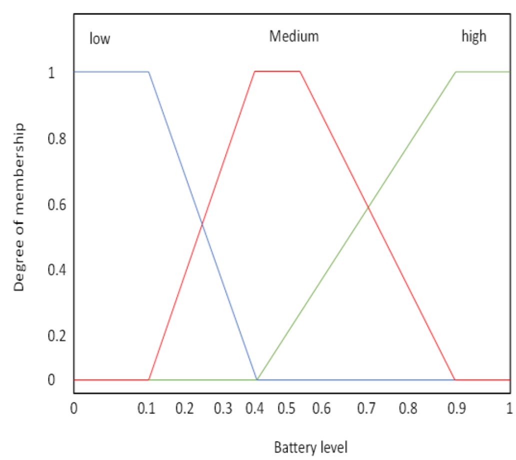

Fig 11. association function for Battery Level

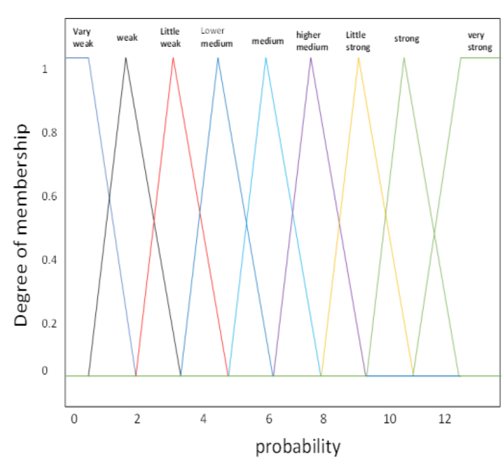

Fig 12. association function for CH Probability

In LEACH-FL, after obtaining the CH possibility through fuzzy reasoning, the CHs are selected by comparing them with a threshold T (n). This technique offers a better energy-based and smart method of cluster-head selection than the classical LEACH.

3. SIMULATION AND RESULTS

A thorough simulation was conducted, to evaluate the performance of the proposed Fuzzy-based modifications of the LEACH protocol, and compared with four major protocols: William Heinzelman's traditional LEACH protocol, Gapping and Zeng's Fuzzy Logic based LEACH, CHEF Logic and LEACH-FL: LEACH with Fuzzy Logic (in the network provided for simulation). The extension of the WSN lifetime was the main performance evaluation metric and was measured using several metrics, including the number of rounds check-out FND, the number of rounds till 80% of the nodes die, and 50% of the nodes die, respectively. The simulation was conducted under an assumption that the BS is at geometric center of the sensor field to minimize the average transmission distance for a fair comparison among the protocols. We executed all protocols in the same environment and with the same kind of hardware to ensure they ran under the same set of circumstances. The simulation parameters employed in the detailed simulations are provided in Table 4.

TABLE IV. PARAMETERS OF THE SIMULATION

Parameter	**Description**
Number of Sensor Nodes (N)	100 nodes deployed in the network
Deployment Area	General layout of 100m × 100m
Special Deployment Scenario	Road-based scenario: 50m × 50m (base) and 50m × 150m (road)
Initial Energy per Node	Each sensor node starts with 0.5 joules of energy
Radio Electronics Energy Consumption	50 nanojoules consumed per bit
Transmission Energy Requirement	10 picojoules consumed per bit per square meter
Transmit Amplifier for Multi-path Fading	0.013 picojoules consumed per bit per square meter
Data Aggregation Energy	5 nanojoules consumed per bit per signal

The performance results of the four protocols are detailed in **Table V**, which lists the number of rounds corresponding to the following key events:

a) **FND (First Node Dies)**: Indicates the onset of network degradation.
b) **80% Alive**: Shows the round where 80% of the nodes remain operational.
c) **50% Alive**: Represents the round where half of the nodes are still functioning, serving as a mid-point performance indicator.

TABLE V. RESULTS OF SIMULATION (NETWORK LIFETIME IN ROUNDS)

Protocol	**FND**	**80% Alive**	**50% Alive**
LEACH Protocol	338	374	407
Gupta's FL	258	375	410
CHEF	365	404	428
LEACH-FL	302	376	406

Figure 13 depicts the compared outputs for the three FL based protocols according to the number of alive nodes with time and demonstrates how the FL enhancements result in better and more durable performances. Significantly, we put up a performance beyond that of other methods by retaining a higher number of alive nodes for a prolonged time.

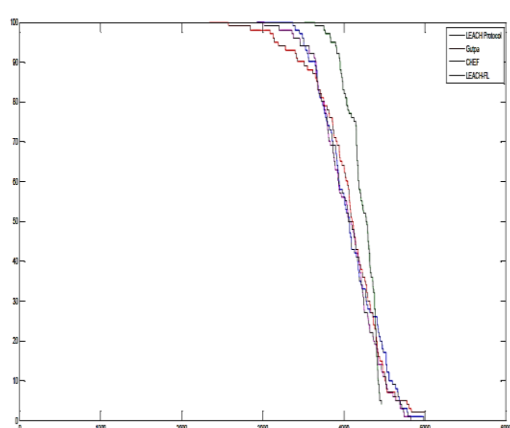

Fig 13. Performance Comparison of Three Fuzzy Logic Protocols (Alive Nodes vs. Rounds)

In addition, **Figure 14** offers a focused view of the LEACH protocol compared to its fuzzy logic counterparts, further reinforcing the superior performance of fuzzy-enhanced methods in WSN environments.

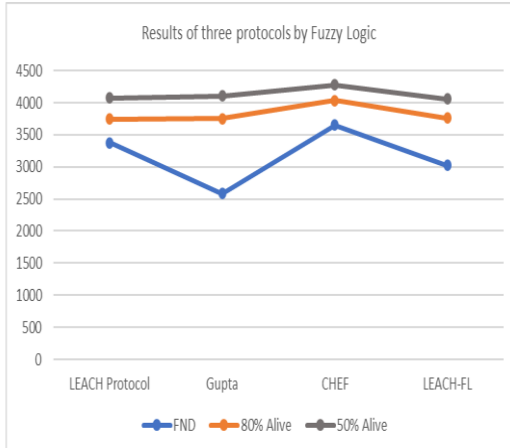

Fig 14. Comparative Performance of LEACH vs. Fuzzy Logic Protocols

The observed enhancements are due to the fuzzy inference rules which make the CHs selection more intelligent through a multi-criteria decision-making, and subsist the node energy, the node centrality, and the nodes status in the network, rather than a random threshold as in the conventional LEACH. The defuzzification, based on the centroid method, gives us crisp CH selection probabilities that are dynamically updated every round. The approach is based on Madman's inference system [11] wherein each sensor node computes a value called Prob and nodes with the values lower than a dynamic threshold T(n) are selected as CHs. This method can give the network a more balanced energy and longer lifetime. Figure 15 summaries the comparison in FND and round 50% of the nodes still alive, providing a simple visualization of the advantages brought by the new model.

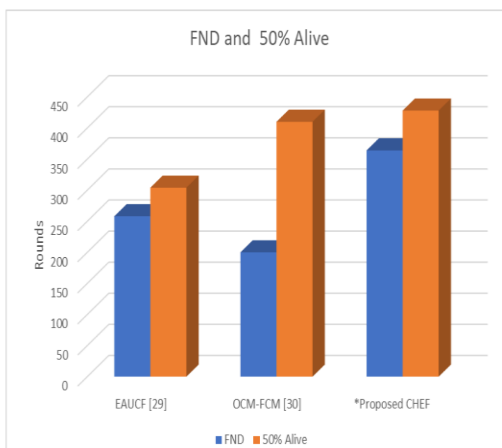

Fig 15. Comparison of FND and 50% Alive for Different Protocols (100 Sensor Nodes)

In summary, the simulation results demonstrate that incorporating fuzzy logic into CH selection—particularly with protocols like CHEF—can significantly enhance the performance of WSNs by delaying node deaths and maintaining higher network stability over time. These findings validate the effectiveness of intelligent routing approaches in energy-constrained wireless environments.

4. CONCLUSIONS

In recent years, research in wireless sensor networks (WSNs) has concentrated on minimising overall energy usage while simultaneously maximising the network's operational lifespan. In this study, the authors have suggested and analyzed a method to improve the classical LEACH protocol using the Fuzzy Logic (FL) based clustering approach. It considers intelligent decision making to enhance the selection of CHs that determines an extremely formidable role in balancing the energy load of network. Among all the fuzzy logic approach simulated, CHF (Cluster Head Election with Fuzzy/Hybrid) has been adopted from five similar approaches and all comparisons illustrate the performance and superiority of the CHEF over the other fuzzy protocol, for example, Gupta's Fuzzy Logic, LEACH-FL, and CHEF. Chef aggressively increased network lifetime better compared to other schemes by maximizing the capacity of the location of the BS with a dynamic usage of the LEACH threshold equation T(n). However, the resilience of the individual fuzzy protocols is dependent on the BS location. Although that CHEF performs well with centralized BS placement, both Fuzzy Logic of Gupta and LEACH-FL have limitation in cases centralized placement of BS that is located in high exposed sites or far distances. In such arrangements the clustering process may become less efficient and unbalanced promoting the network´s lifetime. In our future work, we will also investigate the scalability of such fuzzy based clustering algorithms, by increasing the number of sensor nodes and enlarging the complexity of the fuzzy inference system. Furthermore, we have the intention to explore the fusion of other smart optimization algorithms (like, genetic algorithms, particle swarm optimization, DL models) in order to optimize the process of selecting the cluster head. These improvements will be compared to the current proposed strategy and to each other to identify the best approach to extend the WSN lifetime for various network and environmental settings.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

Acknowledgment

Non.

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