A Fuzzy Logic Based Hierarchical Routing Protocol for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) are essential for a number of applications, including industrial automation and environmental monitoring. The sensor nodes' constrained energy supplies, however, present serious problems for their long-term functioning. The energy limits in WSNs have been addressed, and energy harvesting techniques have emerged as a feasible approach. In this research, fuzzy logic is used to introduce a unique method for energy harvesting in WSNs. The suggested method makes use of fuzzy logic to streamline the energy collection procedure and improve the network's overall energy efficiency. By constantly modifying the harvesting settings in response to the current ambient circumstances and the energy levels of the sensor nodes, fuzzy logic-based algorithms are used to intelligently regulate the energy harvesting process. The network lifespan is increased and energy is efficiently used thanks to this adaptive and intelligent control system.Energy harvesting modules, sensors, and fuzzy logic controllers are used to build the energy harvesting system. To verify the effectiveness of the suggested system, experimental assessments are carried out. The findings show that in terms of efficiency of energy and longevity of network, the fuzzy logic-based energy harvesting solution performs better than conventional approaches. The research also examines how numerous factors, including network structure, energy usage, and environmental factors, affect the energy harvesting process. The results demonstrate how well the fuzzy logic-based solution adapts to various conditions and optimises energy harvesting based on the dynamic network needs. In summary, this study proposes a unique fuzzy logic-based energy harvesting architecture for WSNs. The suggested strategy dynamically optimises the energy collecting process to efficiently handle the energy limits of sensor nodes. The experimental findings support the efficacy and superiority of the fuzzy logic-based method over more conventional ones. The results offer information on the use of fuzzy logic in energy harvesting systems and aid in the creation of WSNs that are energy-efficient.**

I. Introduction

Due to its numerous applications in various fields, such as environmental monitoring, healthcare, and industrial automation, Wireless Sensor Networks (WSNs) have attracted a lot of interest in the yester years. The constrained energy resources of the individual sensor nodes, however, are one of the main issues WSNs must deal with. The network's lifespan is constrained and its long-term functioning is hampered by its dependency on batteries for power delivery. Researchers have been investigating alternate energy sources and energy collecting strategies to address the energy limits in WSNs. A proposed method to increase network longevity and lessen reliance on batteries is energy harvesting, which involves gathering and transforming ambient energy into useable electrical energy. Numerous methods, including solar, wind, vibration, and thermal energy harvesting, have been studied. These methods collect environmental energy and store it for later use. However, there are still many obstacles to overcome before the captured energy can be used optimally in WSNs. Artificial intelligence's fuzzy logic field offers a potent tool for handling ambiguity and imperfect data. It is ideally suited for improving energy harvesting in WSNs because to its capacity for dealing with complicated and nonlinear interactions.

Fuzzy logic allows for intelligent decision-making and control by taking several variables into account at once and modifying system settings according to the situation. This study intends to investigate the use of fuzzy logic in energy collection for WSNs. Designing an intelligent and adaptable energy harvesting system that maximises energy usage and increases network lifetime is the goal. Fuzzy logic controllers are used in the proposed system to dynamically modify the energy harvesting settings in response to the environment and sensor nodes' energy levels at any given time. The purpose of this research is to examine the advantages of using fuzzy logic in energy harvesting systems and to assess how it performs in comparison to more conventional approaches. It will assess how well the fuzzy logic-based strategy performs in maximising energy efficiency and extending network lifetime. To learn more about the flexibility and effectiveness of the suggested strategy, it will be examined how several aspects, including network structure, energy consumption, and environmental factors, affect the energy harvesting process.

By selecting the routes for transmission of data from source nodes to the sink, routing protocols play a critical role in WSNs. Traditional WSN routing protocols like LEACH and AODV are built using hierarchical or centralised design principles. These protocols, however, struggle with problems including single points of failure, excessive energy usage, and lack of scalability. Researchers have suggested distributed routing protocols that spread the decision-making process among the sensor nodes themselves to solve these issues. A branch of artificial intelligence known as fuzzy logic provides a flexible and reliable method for decision-making and control in ambiguous and imprecise situations. It is feasible to improve the effectiveness, flexibility, and fault-tolerance of the routing protocol in WSNs by using fuzzy logic methods. The design and implementation of a distributed fuzzy logic-based routing system for wireless sensor networks are the main topics of this research article. The main aim is to create a routing system which makes intelligent and adaptable routing decisions depending on a variety of network characteristics, such as energy levels, link quality, and network congestion.

The proposed approach seeks to boost data transmission reliability in WSNs, extend network lifetime, and enhance overall network performance. The article will present a thorough analysis of the current WSN routing protocols, highlighting their advantages and disadvantages. The idea of fuzzy logic and its use in decision-making will next be introduced. The distributed fuzzy logic-based routing protocol's design and implementation details will be discussed, with an emphasis on the crucial elements and underlying algorithms. Extensive simulations will be used to compare the proposed protocol's performance to that of other routing technologies. The assessment parameters will include end-to-end latency, network longevity, packet delivery ratio, and energy usage. The outcomes will show how well the distributed fuzzy logic-based routing protocol performs and overcomes the difficulties associated with WSNs.

Additionally, the paper will go through the proposed protocol's scalability and fault-tolerance features, emphasising how well they can manage large-scale networks and adjust to node failures or changes in network topology. The performance of the protocol will be examined in order to get insight into its sturdiness and adaptability. These factors include network density, traffic load, and node mobility. This study offers a distributed fuzzy logicbased routing system for wireless sensor networks as its conclusion. The proposed protocol makes use of fuzzy logic methods to provide intelligent and flexible routing decisionmaking. The simulation results show that the suggested protocol outperforms other established routing protocols in terms of performance and network resilience. The results illustrate the potential of fuzzy logic in overcoming the difficulties of dynamic and resource-constrained networks and enhance routing methods in WSNs. The rest of this essay is structured as follows: An overview of relevant research in the fields of energy harvesting and fuzzy logicbased control systems is given in Section 2. The approach and design of the suggested fuzzy logic energy harvesting system are presented in Section 3. The experimental setup, findings, and analysis are presented and discussed in Section 4. The research's conclusions and ramifications are discussed in Section 5. The study is concluded in Section 6, which also discusses potential future research paths in the field of energy harvesting in wireless sensor networks utilising fuzzy logic.

II. Literature Review

Energy harvesting techniques and fuzzy logic-based control systems have been extensively explored in the context of wireless sensor networks (WSNs). In the given literature survey, we present a comprehensive overview of existing research related to energy harvesting using fuzzy logic in WSNs, highlighting the key contributions and findings in the field.

A. Routing Protocols used in WSN:

In WSNs, routing techniques play a key role in both energy optimisation and network longevity. According to the network structure, there are three primary types for routing protocols in WSNs: data-centric flat routing, hierarchical routing, and location-based routing. To optimize the network lifetime of a Wireless Sensors Network, many routing protocols use hierarchical mechanisms and intelligent algorithms such as reinforcement learning, ant colony optimization, genetic algorithm, neural network, and fuzzy logic. The researchers use intelligent algorithms as they provide adaptive mechanisms that suit the complex and dynamic behavior of WSNs.

Hierarchical routing and intelligent algorithms that make use of the fuzzy logic (FL) module are of interest to us in this research. We think that these two methods offer potential improvements to the network lifetime and are appropriate for a WSN's constrained capacity.

B. A cluster-based routing protocol:

LEACH An established hierarchical routing protocol is LEACH. It is a cluster-based technique that distributes the energy load across network nodes equally by randomly rotating local cluster-heads. LEACH's progression is composed of rounds. Each round starts with a setup phase and then moves into a steady-state phase. The steady-state phase lasts longer than the setup phase in order to reduce overhead. During the clusters construction, each node decides whether or not to become a cluster-head for the current round. This decision is made by the node n choosing a random number between 0 and 1. If the number is less than a threshold T(n), the node becomes a cluster-head for the current round. The threshold is set as: LEACH's progression is composed of rounds. Each round starts with a setup phase and then moves into a steady-state phase. The steady-state phase lasts longer than the setup phase in order to reduce overhead. Where r is the current round, G denotes the set of nodes that have not been cluster-heads in the last 1P rounds, and P denotes the desired proportion of clusters (e.g., P = 0, 05 implies 5 percent of nodes are cluster-heads). Each node will become a cluster leader at some time during a 1P round using this threshold. Each node has a P probability of becoming a cluster head during round 0 (r = 0). The nodes that are cluster heads in round 0 are ineligible to lead clusters in subsequent 1P rounds. As a result, since there are fewer nodes that are eligible to become cluster leaders, the chance that the remaining nodes are cluster heads must grow. All nodes are again eligible to become cluster heads after 1P rounds, and after 1 1P rounds, T = 1 for those nodes that have not previously been cluster heads. To balance energy consumption and increase network lifetime, a special mechanism is needed for cluster-head election and cluster conservation.

$$T(n) = \begin{cases} \frac{P}{1-P\cdot(r\cdot\mathrm{mod}\left(\frac{1}{P}\right))} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases}$$

C. Fuzzy logic and routing protocols:

Fuzzy logic and routing protocols are two distinct concepts but can be related in the context of network routing. Fuzzy logic is a mathematical framework used to handle imprecise or uncertain information, while routing protocols are algorithms and protocols used to determine paths and forwarding decisions in computer networks. Here are a few ways in which fuzzy logic can be applied to routing protocols:

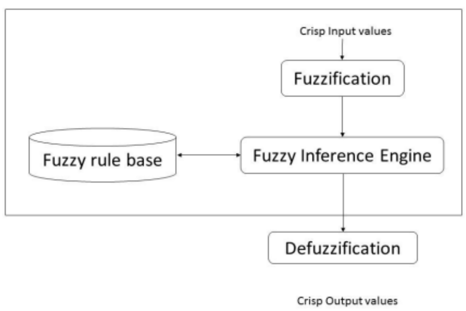

Fig. 1. Fuzzy Logic Controller Components

1) Quality of Service (QoS) Routing:: Fuzzy logic can be used in QoS routing protocols to make decisions based on multiple criteria, such as bandwidth, delay, and reliability. Fuzzy logic allows for the representation and handling of imprecise or subjective information, which is beneficial in determining the best path for routing traffic based on QoS requirements.

2) Traffic Engineering:: Fuzzy logic can be used in traffic engineering for routing decisions based on network congestion and load balancing. Fuzzy logic can take into account multiple factors, such as link utilization, packet loss, and delay, to dynamically adjust routing paths and optimize network performance.

3) Fault Tolerance:: Fuzzy logic can be used in fault-tolerant routing protocols to handle uncertainty and imprecision in network conditions. By considering various factors like link reliability, availability, and node failure probability, fuzzy logic can help determine alternative routes in the presence of failures or degraded network conditions.

4) Adaptive Routing:: Fuzzy logic can be employed in adaptive routing protocols to dynamically adjust routing decisions based on real-time network conditions. Fuzzy logic can consider factors such as link quality, traffic load, and network topology to adaptively select routes that are optimal for the current network state.

Overall, fuzzy logic can enhance routing protocols by providing a flexible and adaptable framework for decision-making in the face of uncertain or imprecise information. It allows routing protocols to incorporate subjective or non-binary factors into the decision-making process, leading to more efficient and effective routing in computer networks.

III. Preliminaries

A. Routing protocols in WSNs

Routing protocols play a crucial role in facilitating communication and data transmission in Wireless Sensor Networks (WSNs). These protocols are responsible for determining the paths and mechanisms through which data is carried by routing from source nodes to the destination or base station. Here are some commonly used routing protocols in WSNs:

1) LEACH (Low-Energy Adaptive Clustering Hierarchy):: The hierarchical routing technique LEACH (Low-Energy Adaptive Clustering Hierarchy) is frequently used in WSNs. By dynamically choosing cluster heads that collect and broadcast data towards the base station, it makes use of clustering to save energy. LEACH uses a probabilistic approach for election of cluster leaders in rounds, distributing energy usage across nodes equally.

2) AODV (Ad-hoc On-demand Distance Vector): : Adhoc On-Demand Distance Vector (AODV): AODV is a routing protocol used for on-demand networks, such as WSNs. By keeping a routing table with distance vectors, it creates routes between nodes as necessary. In a dynamic network environment, AODV establishes and maintains routes effectively using techniques for route discovery and management.

3) ZigBee Routing Protocol (ZRP):: ZRP is a hybrid routing protocol which combines the benefits of both reactive and proactive routing approaches. It employs proactive routing within a local neighborhood to provide fast and efficient routing. For longer distances, it switches to reactive routing, where route discovery occurs only when needed. ZRP is commonly used in WSNs based on the ZigBee standard.

B. Fuzzy Logic

Fuzzy logic is a mathematical approach that allows to represent and manipulate the imprecise or information that carries uncertainty. It uses fuzzy sets and membership functions to handle degrees of truth and ambiguity in decisionmaking processes. Fuzzy logic enables more flexible and nuanced reasoning in complex systems by capturing the vagueness and imprecision present in real-world scenarios.

C. Fuzzy logic and routing protocols

The term ”fuzzy logic implementation in routing protocols” refers to the incorporation of fuzzy logic methods into the Wireless Sensor Networks (WSNs) routing protocol decision-making process. Based on numerous network data and situations, it entails applying fuzzy logic controllers to create intelligent and adaptive routing decisions. Routing protocols often use clear, binary judgements to choose the pathways for data delivery. However, with WSNs, network circumstances are frequently unclear and imprecise due to changing energy levels, variable connection quality, and dynamic network topologies. By allowing for varying degrees of truth and ambiguity in decision-making, fuzzy logic offers a framework to manage this uncertainty.

There are various processes involved in fuzzy logic implementation in routing protocols. First, using the necessary membership functions, the relevant network parameters— such as energy levels and connection qualities—are fuzzified. The linguistic variables that reflect the network circumstances are given degrees of membership by these membership functions. The links between the linguistic variables and fuzzy rules are then defined. The information and experience about how various network situations ought to affect routing decisions is captured by these rules. The rules are presented as "if-then" sentences, where the "if" portion denotes the ambiguous conditions and the "then" part denotes the routing actions or judgements.

The fuzzy logic controller assesses the fuzzy conditions based on the input values collected from the fuzzified network parameters once the fuzzy rules have been formed. The input values are compared to the relevant fuzzy sets in this evaluation procedure, and the degrees of membership are calculated. To determine routing decisions, the fuzzy logic controller combines the fuzzy rules and calculated degrees of membership. The controller's output reflects the chosen routing procedures, such as choosing the next hop or modifying the transmission power level.

WSNs can gain from more intelligent and adaptable routing decisions by introducing fuzzy logic into routing protocols. A more effective use of network resources, increased energy efficiency, and higher network performance are all made possible by the fuzzy logic implementation, which takes into account the uncertainty and imprecision in network settings.

IV. System Model

A. Network Architecture:

1. The wireless sensor network (WSN) consists of a large number of sensor nodes deployed in a designated area.
2. Sensor nodes are responsible for sensing and collecting data from the environment.
3. Each sensor node is equipped with a wireless communication module for transmitting and receiving data.
4. Sensor nodes are organized in a multi-hop communication network, where data is transmitted through intermediate nodes towards a designated sink node or base station.

1) Sensor Node Characteristics:: 1. An exclusive identifier (ID) is used to identify each sensor node.
2. Sensor nodes have limited energy, memory, and computing resources.
3. Environmental variables like temperature, humidity, or light intensity can be measured and sensed by sensor nodes.
4. Within their range of communication, sensor nodes can talk to nearby nodes.

2) Fuzzy Logic-Based Routing Protocol:: 1. The suggested routing protocol decides where to go by using fuzzy logic.
2. Every sensor node has a routing database that contains details about nearby nodes, their connection characteristics, and their energy levels.
3. The best next hop for data transmission is determined using fuzzy logic methods that analyse routing criteria including signal strength, residual energy, and distance.
4. The fuzzy inference system uses these measurements as inputs and generates a clear output that illustrates how desirable each neighbouring node is as a potential future hop.
5. Based on the specified routing metric targets, the routing protocol uses the fuzzy outputs to choose the best next hop node.
6. The protocol continually modifies the rules and settings of the fuzzy inference system to dynamically adapt to network circumstances, such as node mobility and energy levels.

3) Routing Process:: 1. A sensor node starts the routing procedure when it generates data by choosing the following hop according to the fuzzy logic-based routing protocol.
2. The chosen next hop node serves as the relay node in charge of transmitting the data to the sink node.
3. The procedure keeps on until the data reaches the base station or sink node.
4. By taking into account the network's shifting circumstances and choosing the most suitable next hop node at each intermediate hop, the routing protocol enables effective data delivery.

4) Performance Evaluation:: 1. Simulated experiments are used to assess the suggested routing scheme.
2. Measured performance indicators include packet delivery rate, end-to-end latency, network longevity, and energy use.
3. In order to show the protocol's efficacy in terms of routing efficiency, energy efficiency, and network longevity, its performance is contrasted with that of existing routing protocols.

V. Proposed Methodology

A. The proposed fuzzy logic based algorithm:

The proposed protocol is an enhancement to LEACH with the goal of extending network lifetime through enhanced LEACH clustering. The suggested protocol's network lifespan is separated into rounds, much like the LEACH protocol algorithm.
Being a homogenous network at first, the setup phase occurs at random. Five percent of all nodes are chosen to serve as LEACH-compliant cluster chiefs. As a result, the network includes both Clusterhead and Member nodes. On

their own, the nodes form clusters when they band together. Each cluster's member nodes start broadcasting sensed data to the heads of the clusters to which they are connected in accordance with their TDMA (Time Division Multiple Access) schedules. During the steady phase, cluster heads then transmit aggregated data to the base station. A clusterhead constantly checks his energy level. If the cluster head's value exceeds the Elimit energy (Relative Energy Level) according to the following equation, a fresh local round to reorganise the group of its members is started. In order to reorganise a cluster, member nodes must execute the fuzzy module and select a new cluster-head.
Each node maintains his job if the remaining energy of the current cluster head falls below Elimit. To deliver the detected data to their member nodes, the cluster heads send TDMA (Time Division Multiple Access) schedules. The Relative Energy Level determined by the following equation is called Elimit:

$$E_{\text{limit}} = \frac{E_{\text{node}} - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}}$$

Where Emax and Emin represent a cluster's highest and minimum energy levels, respectively. Enode is the remaining energy of the node.

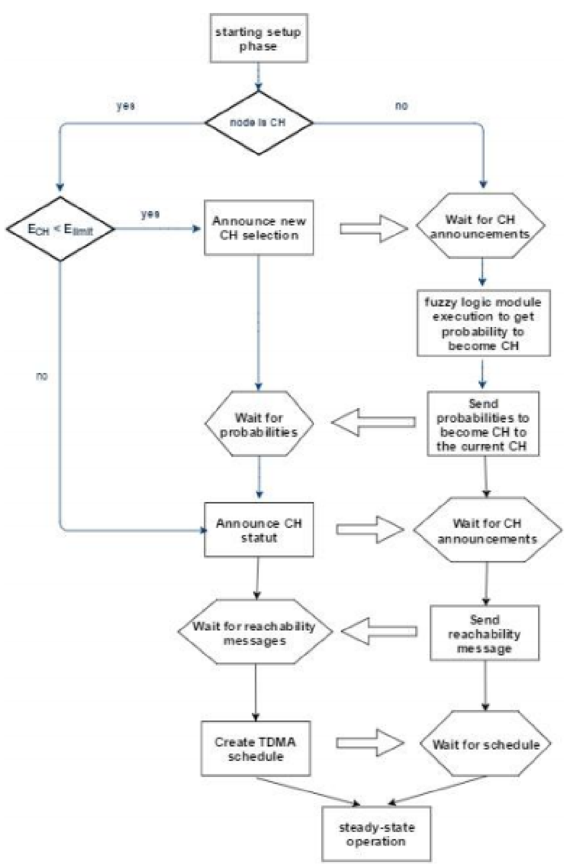

Fig. 2. Chartflow of the setup phase of the proposed algorithm

B. Fuzzy controller design:

The proposed fuzzy logic approach is a distributed algorithm that member nodes run over a number of rounds to determine the optimum cluster head. The method takes into account three parameters: Position (the distance between the node and the current cluster head), Node's remaining energy, and Current Cluster Head's remaining energy.
A cluster-head is allowed to remain in that place across following rounds if it seems to be the best choice given the characteristics of the suggested algorithm.

1) Fuzzification of the input variables:: The proposed approach considers the distance between a node and the current cluster-head, as well as the remaining battery levels of the node and the current cluster-head. The first step is to map the crisp inputs to the appropriate fuzzy sets.

2) Membership functions:: According to the accompanying figures, the design employs triangular or trapezoidal membership functions for each input and output.

Parameters	Linguistic parameters
Node Remaining Energy	Low, Medium, High
C-H Remaining Energy	Low, Medium, High
Distance node-CH	Far, Medium, Near
Probability	VWeak,Weak,LWeak,Medium,LStrong, Strong, VStrong

Fig. 3. The parameters and their possible values

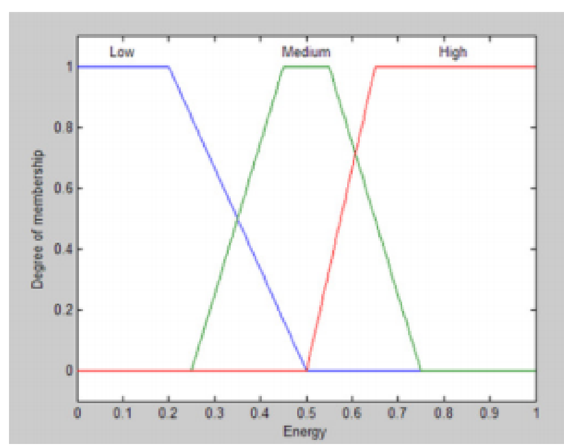

Fig. 4. Input fuzzification function 1(Energy)

3) Fuzzy Rules:: Rules are IF-THEN statements, as was previously mentioned. For instance, if the energy is low, the energy CH is high, the position is medium, and the probability is very weak. There are 27 of them.

4) Fuzzy Inference Engine:: Mamdani and Sugeno are two distinct fuzzy inference systems offered by the Fuzzy Logic Matlab Toolbox. The first approach is employed in this work since it is logical, precise, and well-liked.

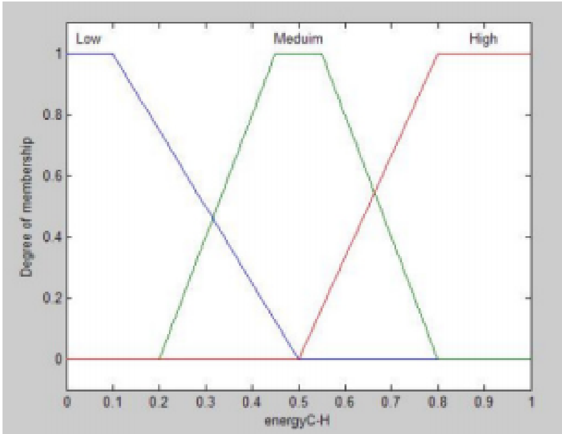

Fig. 5. Input fuzzification function 2(Energy-CH)

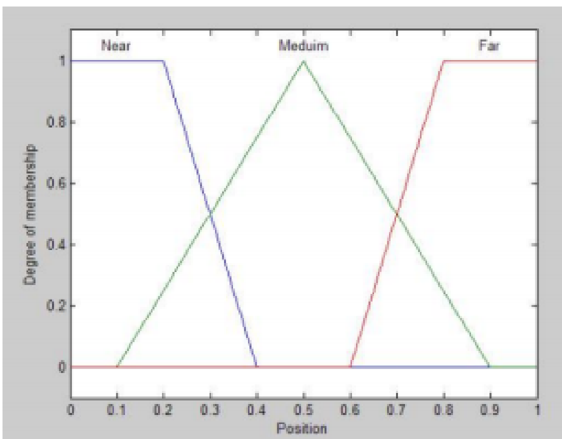

Fig. 6. Input fuzzification function 3(position, distance node-CH)

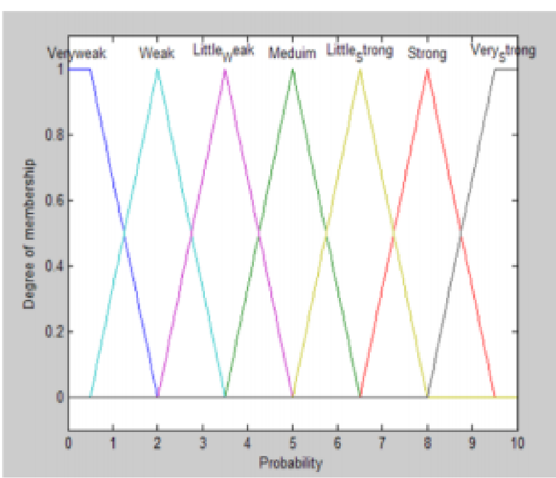

Fig. 7. Output fuzzification function(probability)

5) Defuzzifacation and fuzzy Control:: Several techniques, such the centroid of the area, the area's bisector, or the mean of the maximum, can be used to the defuzzification module. The centroid of area (COA) is the defuzzification technique employed in the suggested module. It gives back the centre of the region covered by the fuzzy set that was acquired by conclusion aggregation. The fuzzy logic controller determines the geometric centre of a region using the following equation:

$$COA = \frac{\int_a^b f(x) \cdot x \, dx}{\int_a^b f(x) \, dx}$$

VI. Results

Position (distance between a member node and its matching C-H), the chance that a node will develop into a cluster head, and the energy that is still available to both the node and the cluster head. The graphs shown below show that the LEACH protocol's improvements result in the longest-lasting networks. Compared to nodes that utilise the LEACH protocol, nodes that communicate using the modified LEACH (F-LEACH) protocol degrade more gradually. In fact, LEACH elects cluster heads with inadequate energy to gather data from members and transfer it to the base station since it does not take into account the elected cluster head's remaining energy when picking a new cluster head.

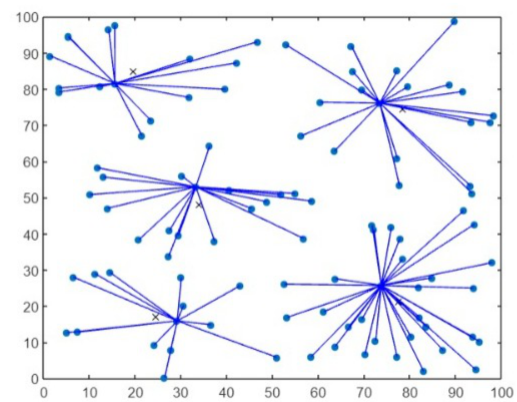

Fig. 8. Simulation result(MATLAB)

VII. Conclusion

The result of this study proposes a distributed fuzzy logic-based routing scheme for wireless sensor networks (WSNs). The objective of the project was to design and implement a routing protocol that use fuzzy logic techniques to make intelligent, adaptive routing decisions based on various network parameters. To solve the problems of energy efficiency, scalability, and flexibility in WSNs, the proposed protocol integrates fuzzy logic into the routing process. The protocol dynamically modifies routing decisions to enhance network performance and extend network lifetime by taking into account elements like energy levels, connection quality, and network congestion.

The distributed fuzzy logic-based routing protocol's usefulness has been shown through in-depth simulations and performance assessments. In comparison to conventional routing protocols, the results have showed improvements in important performance measures such network lifespan, energy usage, packet delivery ratio, and end-to-end latency. The research results emphasise the potential of fuzzy logic in overcoming the difficulties of dynamic and resourceconstrained networks, which helps to develop routing protocols in WSNs. The resilience and adaptability of the protocol are demonstrated by its capacity to manage massive networks, respond to changing network circumstances, and provide fault tolerance. Future research paths can concentrate on improving the protocol by including more optimisation methods or taking security and privacy concerns into account. Additionally, real-world deployments and implementations can be investigated to confirm the protocol's functionality and efficacy in realistic circumstances. Overall, the distributed fuzzy logic-based routing protocol described in this study offers a promising strategy for enhancing the reliability and efficiency of data transmission in WSNs. It adds to the body of knowledge in the area and offers useful information for designing and putting routing protocols into practise in WSNs.

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