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Optimizing network lifetime in wireless sensor networks: a hierarchical fuzzy logic approach with LEACH integration

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ABSTRACT

Wireless sensor networks (WSNs) are of significant importance in many applications; nevertheless, their operational efficiency and longevity might be impeded by energy limitations. The low energy adaptive clustering hierarchy (LEACH) protocol has been specifically developed with the objective of achieving energy consumption equilibrium and regularly rotating cluster heads (CHs). This study presents a novel technique, namely the hierarchical fuzzy logic controller (HFLC), which is integrated with the LEACH protocol to enhance the process of CH selection and effectively prolong the network's operational lifespan. The HFLC system employs fuzzy logic as a means to address the challenges posed by uncertainty and imprecision. It assesses many aspects, including residual energy, node proximity, and network density, in order to make informed decisions. The combination of HFLC with LEACH demonstrates superior performance compared to the conventional LEACH protocol in terms of energy efficiency, stability, and network durability. This study emphasizes the potential of intelligent and adaptive mechanisms in improving the performance of WSNs by improving the survivability of nodes by reducing the energy consumption of the nodes during the communication of network process. It also paves the way for future research that integrates soft computing approaches into network protocols.

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1. INTRODUCTION

"The main motto of any network, 'Harnessing intelligence for effortless success and enhanced comfort,' is increasingly evident as wireless sensor networks (WSNs) find applications in military spying, home automation, and environmental monitoring." By surveying the literature on [1] the authors talks about ways to handle energy, ways to collect green energy, problems that energy gathering WSNs face, as well as possible future study areas and new uses. The growing amount of information being sent and travel between networks is forcing network technologies to change quickly. Smart traffic control, smart towns, and home management all use connected smart gadgets internet of things (IoT). There is a mesh structure that can be used for these IoT devices to work as WSNs. Drawing upon a wide array of scholarly sources more speed, dependability, and power use can be gained by connecting these networks together, which can improve specific sensing skills. Not many studies and thorough reviews, though, have looked at linking methods. As it talks about the problems and chances in the area of mixed WMSNs, Nurlan *et al.* [2] looks at the ways that WSNs and WPNs are used now. In WSN, the coverage problem is how to schedule sensors' sleep and wake times so that the network lasts as long as possible. This essay looks into the maximum coverage sets scheduling (MCSS) problem, which is to find a way to schedule a group of coverage sets so that the network lasts as long as possible. Luo *et al.* [3] has been shown to be NP-hard and is written as an integer linear programming problem. It is suggested that a greedy algorithm called greedy-MCSS be used first, followed by an approximation algorithm called MCSS algorithm (MCSSA), which promises theoretical performance. There are also a lot of test results that show how well these methods work.

This study [4] looks at and the paper explores various transport techniques in WSNs, focusing on energy management and network longevity. It presents models of network setup, dividing protocols into uniform, mixed, static, and mobile subgroups, and discusses simulations and future work directions. A route system that uses less energy for WSNs is suggested in this study [5]. This would solve the problem of "hot spots." This system has a double cluster head (CH) strategy, a mixed CH rotating strategy, and uneven clustering technology. When compared to LEACH, DEBUC, and UCNPD, simulations show that this protocol improves network stability, speed, lifetime, and energy balance. Due to WSNs changing structure, limited resources, and spread-out nature, WSNs need routing algorithms that work well [6]. Efficacy depends on how long the network lasts and how much energy it uses. Supporting quality of service (QoS) is hard, and transport systems that are aware of QoS have gotten more attention. There are three types of WSNs that the piece talks about: flat networks, hierarchical networks, and QoS aware protocols. Protocols that work in flat networks are reactionary, proactive, and mixed. Protocols that work in hierarchical networks are chain-based, grid-based, tree-based, and area-based. Additionally, the paper [7] explores various transport techniques in WSNs, focusing on energy management and network longevity. It categorizes protocols into uniform and mixed, static and mobile, and discusses models and simulations. It concludes with future directions. Battery change, on the other hand, makes WSNs battle with limited power. For WSNs to last longer, energy-harvesting technology is needed along with an energy-efficient transportation system. Similarly in the article [8] suggests an adaptable hierarchical-clustering-based routing scheme (HCEH-UC) for EH-WSNs that updates data transmissions to maintain target coverage. Using energy-harvesting technology, simulations show that this technique can extend the maximum lifetime coverage of WSNs and secure continuous target coverage. Accordingly in the study [9] suggests an energy-efficient routing protocol (OEERP) method for WSN. The goal is to lower the amount of energy used and make the networks work better. For optimal energy use and longer network lifespan, the program puts idle nodes into a sleep state on a plan. OEERP does better than other algorithms in simulations when it comes to accuracy, speed, and extending the lives of devices. Jaffri *et al.* [10] that the threshold-based energy-aware zone efficiency measuring hierarchical routing protocol be used to make routing in next-generation wireless sensing networks more energy-efficient. To better handle data, this algorithm divides the network into several zones. It was designed for a network with no differences between nodes, but adding variation makes it use less energy.

The 9-zone system is more stable and has a higher rate. It was tested against the stable election protocol, the low-energy adaptive clustering hierarchy, the modified low-energy adaptive clustering hierarchy, and the gateway-based OEERP. It did better, showing that it was more efficient. Few of the comparative analysis of our proposed approach is depicted in the form of Table 1: comparative analysis of the existing works inference which concludes various approaches based on the analysis we identied how each metric plays a vital role for efficient progress of WSNs. Likewise, the study [11] proposes a fuzzy logic model for selecting CHs in WSNs based on five criteria: residual energy, site suitability, density, compactness, and distance from the base station (BS). The model uses fuzzy logic to develop an energy-efficient clustering method, requiring minimum spacing between CHs. Simulation results show improvements in network lifespan and energy consumption distribution. Owing to the previous works in the article [12] presents a fuzzy-based cluster-head election algorithm for a two-step energy-efficient protocol. This algorithm, using fuzzy logics, selects CHs by considering node density, proximity to the BS, and battery capacity. The simulation findings show that the fuzzy-based CEATSEP network outperforms CEATSEP, improving stability and longevity. Moreover, Tagare and R. Narendra [13] presents a novel protocol created for a remote setting where sensor nodes are randomly positioned and have solar panel capabilities. The protocol utilizes a hierarchical clustering technique to send data to the nearest CH based on probability. The data is then sent to the BS. CHs use more energy levels than normal nodes. CHs will only be triggered when their energy drops below 5% of their initial capacity. The protocol improves energy efficiency and network lifespan, offering greater stability and reduced energy consumption compared to the MLHEED and LEACH methods. The protocol increases the number of packets transmitted to the BS. The energy-efficient distributed unequal clustering approach is a new clustering method designed to fairly share energy use across CHs in WSNs. Significantly in the approach used by Manikandan and Jeyakarthic [14] a centralized genetic-based clustering system using the onion approach is proposed to manage energy consumption in WSNs. The method adjusts cluster size based on input fuzzy parameters, selecting CHs based on sensor nodes with the highest likelihood. The technique is being evaluated against proven energy-efficient algorithms. Notably Hatamian *et al.* [15] a novel fitness function has been developed, allowing BS to designate chromosomes as appropriate CHs in a network. The onion approach reduces communication overhead by dividing the network into onion layers.

Table 1. Comparative analysis of the existing works

S. No	R.No	Proposed approach	Strong point	Liabilities
1	[19]	The proposed model optimizes power consumption, increases throughput, and enhances efficiency, surpassing the existing LEACH protocol.	The simulation research shows that the HROCF scheme effectively decreases network energy use and prolongs the lifetime of highly active sensors in comparison to current methods.	Implementing fuzzy logic and optimal clustering algorithms in resource-constrained WSN nodes might pose challenges in terms of memory, processing power, and energy consumption.
2	[20]	The study proposes an EECMHR method to improve data gathering in WSNs by dividing the network into regions and clusters.	The study explores the utilization of multi-hop communication in WSNs to improve energy efficiency and maintain connection by transmitting data via intermediary nodes over long distances.	The proposed routing method may not be suitable for evolving network conditions like node failures or traffic patterns, necessitating a discussion on strategies for managing these issues.
3	[21]	The EECHRP is an OEERP that divides a network into two hierarchical levels using CHs, reducing repetitive CH selection and improving network efficiency by designating one cluster node as a CH.	The suggested protocol might aid in load balancing by effectively distributing traffic across CHs, thereby avoiding network congestion and promoting consistent energy use among sensor nodes.	The protocol's efficacy in practical implementations relies on its capacity to adjust to changing network circumstances, such as node failures or changes in network architecture.
4	[22]	The model integrates a CS-based approach for WSN routing, using hierarchical techniques. The system examines network energy use and establishes functional connections to compute energy consumption at the conclusion of each sample interval.	Hierarchical and grid-based architecture optimizes load balancing by allocating data collection and transmission responsibilities, minimizing congestion, and promoting consistent energy usage across sensor nodes.	The integration of hierarchical compressive data collection with grid-based routing could enhance model complexity, making them challenging to execute, troubleshoot, and maintain in resource-limited WSN settings.
5	[23]	The FLEAC protocol uses fuzzy if-then rules and an enhanced grasshopper optimization algorithm to select CHs and relay nodes, enhancing energy efficiency and network lifespan in WSNs.	This work provides good results in terms of extending the network's lifetime.	The study demonstrates its practicality in identifying intrusions and defending against wireless network assaults, demonstrating its usefulness in real-world scenarios and paving the way for future research.
6	[24]	The FLEAC protocol uses fuzzy if-then rules and an enhanced grasshopper optimization algorithm to select CHs and relay nodes, enhancing energy efficiency and network lifespan in WSNs.	The protocol probably includes sophisticated optimization methods for WSNs, improving cluster formation, head selection, and data routing to minimize energy use and prolong network functionality.	Evaluating the protocol's ability to withstand changes in dynamic contexts, such as node failures, mobility, and developing network circumstances, is essential.
7	[25]	The EELTM method optimizes WSN longevity by creating energy-balanced clusters using a PSO algorithm and fuzzy-based approach. It minimizes overhead and manages energy threshold fluctuations for sensor nodes.	EELTM employs fuzzy-based uneven clustering to adaptively modify cluster sizes according to node characteristics, promoting equitable energy allocation across sensor nodes and extending network lifespan.	WSN applications in real-world scenarios must overcome problems such as reliability to achieve their full potential is not clear.
9	[26]	The study enhances the LEACH protocol in WSNs using a fuzzy approach, demonstrating superior stability, network survivability, and energy consumption.	Soft computing methods enhance several elements of wireless networks such as routing, resource allocation, power control, and handover management to enhance efficiency, throughput, and dependability.	It is applicable only for homogeneous networks.

The cancer genomics consortium (CGC) protocol improves efficiency in operational time, node survival, packet reception, and energy consumption. On the other hand, Kiamansouri *et al.* [16] suggests a two-tier clustering approach using fuzzy logic and content-based routing for data categorization, outperforming existing strategies in energy consumption, operational node number, network longevity, and packet delivery efficiency, particularly in the context of IoT. Notably in the paper [17] proposes a method to improve IoT connectivity security through a star structure, encryption, and authentication mechanisms. Simulations show improvements in energy efficiency, latency, flexibility, packet delivery rate, and active nodes compared to other methods. Likewise, Hatamian *et al.* [18] suggests congestion-aware routing and a fuzzy-based rate controller for WSNs, focusing on priority-based and queueing architectures.

The controller regulates congestion rate based on factors like input rate, forwarding rate, queue buffer size, and node size, reducing packet loss and energy consumption. The Table 1 is showing the comparative analysis of the existing works referring [19]-[26].

The research seeks to examine the operational lifespan of WSNs to ensure continued usefulness, particularly in distant regions. It enhances the robustness and efficiency of networks in situations like disaster response and industrial automation. By incorporating hierarchical fuzzy logic into protocols like as LEACH, the management of energy is improved, allowing for accurate decision-making and adaptable modifications to network behavior. The main objectives of this proposed approach is listed below:

The system aims to optimize network lifetime in WSNs using a hierarchical fuzzy logic approach with LEACH integration. It aims to preserve energy efficiency by evenly distributing consumption across nodes and prolonging network operational lifetime, enabling more informed energy management choices. By addressing these objectives, the proposed hierarchical fuzzy logic approach with LEACH integration can effectively optimize network lifetime in WSNs, enabling prolonged operation, improved reliability, and enhanced energy efficiency. Organization of the paper:

The organization of this paper is organized as follows section 2 discusses about proposed approach outlines the proposed methodology for integrating hierarchical fuzzy logic technique by using pipelinging between two fuzzy inference systems into the LEACH protocol followed by the simulation and results in section 3 presenting the simulation setup, performance metrics, and results obtained through simulations and experiments justifying the noteworthy findings of proposed approach compared to the existing state of art approaches. Finally, the section 4 addresses the conclusion by summarizing the key contributions, highlights the significance of the proposed approach, and suggesting the potential avenues for further exploration of the work.

2. PROPOSED METHOD

The approach optimizes WSNs effectiveness by selecting a cluster leader and using hierarchical routing to maximize network lifetime and reduce individual node energy consumption.

2.1. Network model

The proposed model, depicted in Figure 1, outlines a WSN with a central mote, efficient data transfer, and utilizes inter-clustering and intra-clustering techniques. The proposed method given as follows. The proposed approach has a procedural step as it has hierarchical fuzzy inference approach to extend the network life span and reduce the energy consumption of nodes during each phase of communication in WSN.

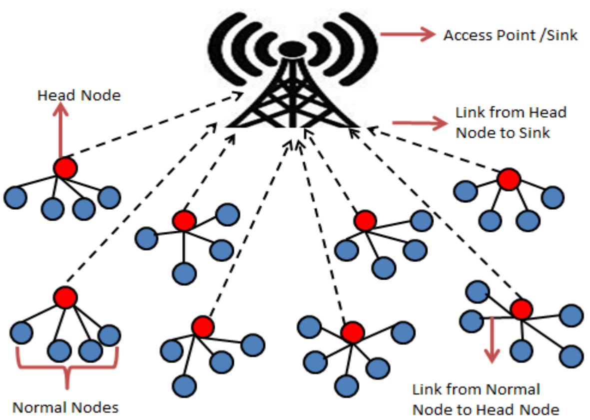

Figure 1. Network model

2.1.1. Initilization of the network setup

The receiving node sends control packets to all sensor nodes, storing well location information in memory. The recipient node then receives data on all sensor nodes within the WSNs.

2.1.2. Selection of head node or parental or master node

The protocol optimizes data transmission, reduces energy consumption, and improves network efficiency using multi-hop routing and fuzzy logic controllers, assessing residual energy, distance, and living node probability. shown in the Figure 2.

A HFLC is used in a multi-hop routing method, utilizing two FLCs. Fuzzified numbers are generated from space and energy left over, with rules for distance and extra energy using IF/THEN rules. Nine rules form the rule base, based on input and output factors shown in Table 2 and Table 3.

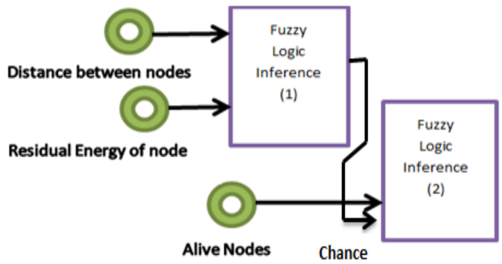

Figure 2. Proposed architecture of hierarchical fuzzy approach in LEACH protocol

Fuzzy logic controller-1

– Step 1: fuzzification:

Inputs like leftover energy, distance, and codes are converted into fuzzy values using fuzzification.

– Step 2: knowledge base:

A fuzzy rule base is established to determine the likelihood of a node being the next hop.

Table 2. Input parameters and output parameters for fuzzy logic inference

Input parameters	Input	Membership				
	Distance	Low	Very low	Medium		
	Residual energy	High	Very high	Medium		
	Cost	Low	Very low	Medium		
Output parameters	Output	Membership				
	Chance	Very low	Low	Medium	High	Very high

Table 3. Rule base for fuzzy logic inference

Rule No	Residual energy (RE)	Distance (D)	Cost	Chance
1	RE_high	D_low	Cost_medium	Chance _low
2	RE_high	D_very low	Cost_low	Chance _very high
3	RE_high	D_medium	Cost_very low	Chance _high
4	RE_high	D_low	Cost_medium	Chance _medium
5	RE_high	D_very low	Cost_low	Chance _very high
6	RE_high	D_medium	Cost_very low	Chance _high
7	RE_high	D_low	Cost_medium	Chance _medium
8	RE_high	D_very low	Cost_low	Chance _high
9	RE_high	D_medium	Cost_very low	Chance _high
10	RE_very high	D_low	Cost_medium	Chance _medium
11	RE_very high	D_very low	Cost_low	Chance _very high
12	RE_very high	D_medium	Cost_very low	Chance _high
13	RE_very high	D_low	Cost_medium	Chance _low
14	RE_very high	D_very low	Cost_low	Chance _very high
15	RE_very high	D_medium	Cost_very low	Chance _very high
16	RE_very high	D_low	medium	Chance _medium
17	RE_very high	D_very low	Cost_low	Chance _high
18	RE_very high	D_medium	Cost_very low	Chance _very high
19	RE_medium	D_low	Cost_medium	Chance _low
20	RE_medium	D_very low	low	Chance _medium
21	RE_medium	D_medium	very low	Chance _medium
22	RE_medium	D_low	medium	Chance _high
23	RE_medium	D_very low	low	Chance _medium
24	RE_medium	D_medium	very low	Chance _very high
25	RE_medium	D_low	medium	Chance _high
26	RE_medium	D_very low	low	Chance _high
27	RE_medium	D_medium	very low	Chance _low

– Step 3: inference engine:

The likelihood of each node being the next hop is calculated by integrating the fuzzified values from each input with the rules in the rule base.

– Step 4: defuzzification:

The final decision on node selection is made using the centre of gravity (CoG) technique, evaluating all fuzzy values produced in the inference mechanism.

$$\text{Output 1}=\frac{\sum_{j=1}^{nr} yj*u(yj)}{\sum_{j=1}^{nr} u(yj)} \tag{1}$$

– Step 5: fuzzy logic controller -2

The output of the previous fuzzy logic controller 1 is considerd as one of the input to the next fuzzy logic controller -2. Rest all process is similar as in fuzzy logic controller -1.

i) Fuzzification:

- Inputs like output 1 or chance and number of alive nodes are converted into fuzzy values using fuzzification Table 4.

Table 4. Input parameters for fuzzy logic inference

Input parameters	Input	Membership				
	Chance (C)	C_low	C_very low	C_medium		
	Alive nodes (AN)	AN_high	AN_very high	AN_medium		
Output parameters	Output	Membership				
	Chance2 (C2)	C2_Very low	C2_Low	C2_Medium	C2_High	C2_Very high

– Step 6: knowledge base:

A fuzzy rule base is established to determine the likelihood of a node being the next hop shown in Table 5.

Table 5. Rule base for fuzzy logic inference

Rule No	Residual energy (RE)	Distance (D)	Cost	Chance (C2)
1	RE_high	D_low	Cost_medium	C2_low
2	RE_high	D_very low	Cost_low	C2_very high
3	RE_high	D_medium	Cost_very low	C2_high
4	RE_very high	D_low	Cost_medium	C2_medium
5	RE_very high	D_very low	Cost_low	C2_very high
6	RE_very high	D_medium	Cost_very low	C2_high
7	RE_medium	D_low	Cost_medium	C2_low
8	RE_medium	D_very low	Cost_low	C2_medium
9	RE_medium	D_medium	Cost_very low	C2_very high

– Step 7: inference engine:

The likelihood of each node being the next hop is calculated by integrating the fuzzified values from each input with the rules in the rule base.

– Step 8: defuzzification:

The final decision on node selection is made using the centre of gravity technique, evaluating all fuzzy values produced in the inference mechanism.

$$\text{CV (i)}=\frac{\sum_{j=1}^{nr} yj*u(yj)}{\sum_{j=1}^{nr} u(yj)} \tag{2}$$

The inference engine creates new data or values by comparing rules to input parameters, using fuzzed distance and extra energy numbers. The center of gravity method can be used to obtain clear new values. Eighteen rules are created based on input and output factors, and the process is repeated for all nodes, with the node with the highest cost function value chosen as the parent.

3. RESULTS AND DISCUSSION

The study demonstrates that a proposed protocol with the highest residual energy outperforms existing six WSNs in terms of network lifetime, using a forwarder node selection process using FIS. The network lifetime is calculated using four sub metrics, including first node die occurs when the first sensor node in WSNs runs out of energy, quarter node die occurs when a quarter of a sensor node's energy runs out, as demonstrated in Table 6, half node die half node die occurs in WSNs when a quarter of the nodes run out of energy, as demonstrated in a performance evaluation of the proposed HFLCLEACH approach, and number of nodes alive after 5,000 rounds The phenomenon known as "number of nodes alive" occurs in WSNs when the total of the count of considered sensor node are alive shown in Table 6: performance criteria evaluation for half node die after 5,000 rounds of proposed approach HFLCLEACH with few existing works. The proposed HFLCLEACH approach demonstrated a significant increase in active sensor nodes in wireless networks after 5,000 rounds, as shown in Figure 3.

Table 6. Performance criteria evaluation for first node die after 5,000 rounds of proposed approach

Performance criteria	LEACH	FUZZY LEACH	MUCH	FEECA	Fuzzy type 1	Fuzzy type 2	HFLCLEACH
FND	179	358	183	1009	1599	1779	2237
QND	279	548	261	1141	2344	2228	3058
HND	455	915	419	1201	2798	2562	4399
Nodes alive	1	1	1	1	7	19	39

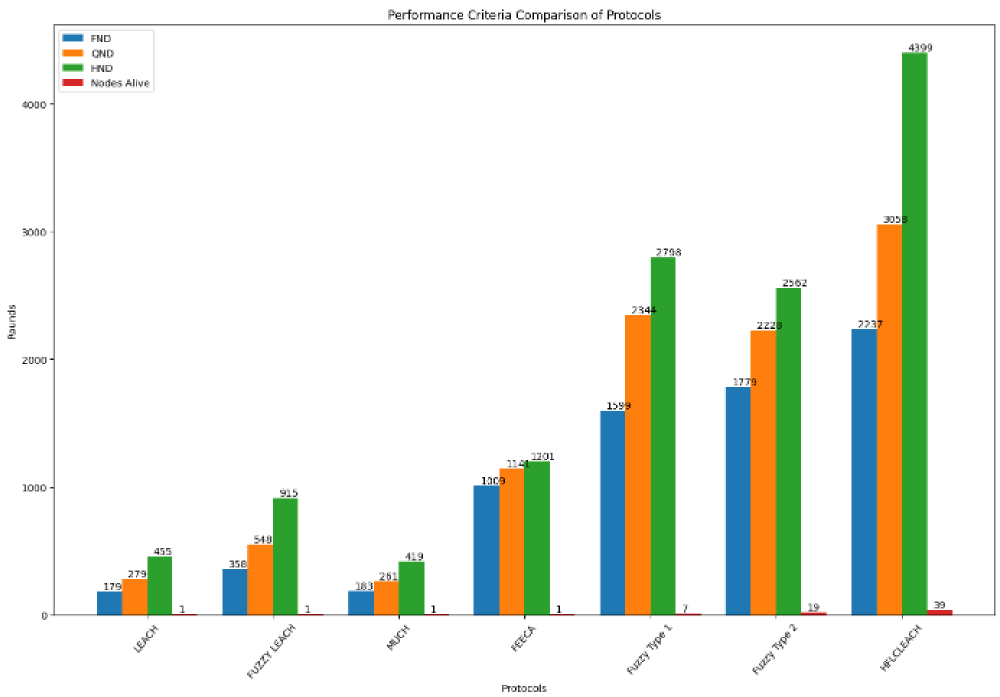

Figure 3. Performance metrics of the proposed HFLC LEACH after completion of 5,000 stipulated rounds

4. CONCLUSION

By integrating HFIS with the LEACH protocol, the performance of WSNs can be enhanced through the optimization of limited resources and the reduction of energy wastage. This methodology has the potential to extend the lifespan of the network and enhance the efficiency of data transmission, resulting in a more dependable and robust network.

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