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A Comprehensive Survey: Energy-Efficient, Cluster-Based Routing Protocol for Wireless Sensor Networks Using Fuzzy Logic

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Abstract: Wireless Sensor Networks (WSNs) are essential for many applications, such as smart cities, healthcare, and environmental monitoring. However, because sensor nodes have limited power resources, energy efficiency and network longevity continue to be major concerns. Fuzzy-based Routing and clustering protocols have been created to overcome these difficulties, using fuzzy logic to improve data transmission and cluster formation decision-making. This survey demonstrates the conventional methods as well as the cutting-edge hybrid approaches in WSN. In addition, it highlights the integration of fuzzy logic with other advanced techniques like machine learning, genetic algorithms, and swarm intelligence, which aim to further enhance energy efficiency, scalability, and overall network performance. By exploring the strengths and limitations of these hybrid models, the survey provides valuable insights into the future direction of WSN research, emphasizing the need for adaptive, intelligent systems capable of addressing the evolving challenges of real-world applications.

Keywords: WSN, Clustering, Fuzzylogic, Routing.

I. INTRODUCTION

Due to their numerous uses in industrial automation, healthcare, military surveillance, and environmental monitoring, wireless sensor networks, or WSNs, have attracted a lot of attention. Energy consumption is one of the main issues facing WSNs, as it has a direct impact on network performance and lifetime. Techniques for routing and clustering are essential for maximizing energy efficiency. This survey of the literature examines the current state of research on fuzzy logic-based methods for routing and clustering that use less energy.

A. Clustering in WSNs

To improve network scalability and lower energy usage, sensor nodes are categorized into groups using the clustering approach. A few clustering algorithms have been put forth, such as: A popular clustering approach called LEACH (Low-Energy Adaptive Clustering Hierarchy) chooses cluster heads (CHs) at random to distribute energy usage among nodes[1]. Nevertheless, it has an unequal distribution of energy. Hybrid Energy-Efficient Distributed Clustering, or HEED, adds computational effort but improves network stability by choosing CHs depending on communication cost and residual energy.

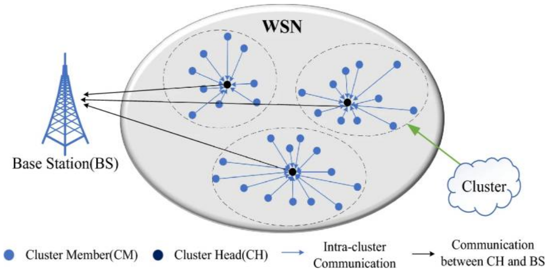

Fig:1 Cluster

Distributed Energy-Efficient Clustering, or DEEC, is a technique that ensures a longer network lifetime bydynamically electing CHs depending on residual energy levels.

B. WSN Routing Protocols

Routing is essential for energy efficiency since it determines the best routes for data transmission. Among the noteworthy routing protocols are: Sensor Information System Power-Efficient Gathering (PEGASIS): reduces transmission lengths using a chain-based method, but it adds a lot of latency The hierarchical routing protocol known as TEEN (Threshold-sensitive Energy Efficient Sensor Network) works well in reactive networks but might not be the best choice for collecting data on a regular basis. LEACH-C (LEACH-Centralized) is an enhanced LEACH variant that uses a centralized method to optimize CH selection, improving energy efficiency.

C. WSNs and Fuzzy Logic

An intelligent method for making decisions that addresses uncertainty in WSNs is fuzzy logic. It is Frequently used in routing and clustering the CH option is dependent on a number of factors, including distance toward the base station, node density, and residual energy. Adaptive load balancing decision-making increased network lifetime as a result of clever data aggregation. Dynamic CH Selection: QPSO optimizes the selection procedure, while fuzzy logic chooses CHs using a multi-criteria decision-making method. Energy-Aware Routing: Fuzzy logic improves the decision-making process while QPSO determines the best routing routes [3]. Load balancing: Network congestion is reduced and node lifetime is increased by combining the two strategies.

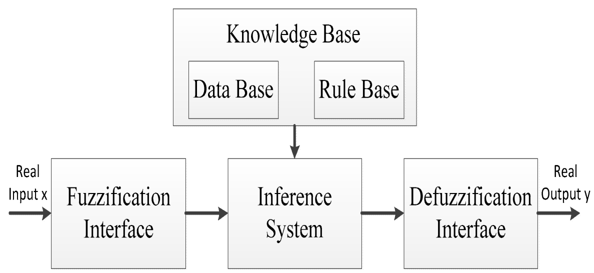

Fig:2 Fuzzy Logic

II. RELATED WORK

Energy-efficient routing and clustering in WSNs have been the subject of numerous studies. Due to their simplicity, traditional clustering protocols like LEACH (Low-Energy Adaptive Clustering Hierarchy) have gained a lot of traction; however, their restricted scalability and unequal energy distribution are drawbacks. By choosing cluster heads according to residual energy and node proximity, HEED (Hybrid Energy-Efficient Distributed Clustering) enhances LEACH; yet, it introduces computing complexity. Optimization of Particle Swarms (PSO) and Genetic Algorithms (GA), two recent developments in metaheuristic-based techniques, have been used to optimize routing and clustering. By dynamically choosing cluster heads, PSO-based clustering techniques increase energy efficiency; nevertheless, they frequently converge too soon. Optimization of Quantum Particle Swarms (QPSO), which improves search capabilities and offers better energy balancing, was introduced to get around this restriction.

To deal with uncertainty in sensor networks, fuzzy logic-based clustering has also been investigated. Fuzzy logic protocols create sensible CH selection decisions by considering many elements, such as distance to the base station, node density, and residual energy. Research integrating PSO and fuzzy logic has demonstrated encouraging outcomes in terms of increasing network lifetime and optimizing energy use [2]. Recently, hybrid techniques that combine fuzzy logic with QPSO have drawn interest because of their potential to improve WSN optimization and decision-making. By improving energy distribution, lowering communication overhead, and prolonging the life of the network, these approaches perform better than traditional clustering and routing strategies. However, there is still room for advancement in areas like computing efficiency and real-time adaptation. Optimization of Quantum Particle Swarms (QPSO)

A popular bio-inspired optimization method for routing and clustering is called particle swarm optimization (PSO). However, premature convergence is a problem with classical PSO. By applying the concepts of quantum physics to PSO, Quantum PSO (QPSO) improves it and produces: Enhanced ability to search globally quicker convergence Improved WSN energy balance Numerous studies have demonstrated that by improving CH selection and data transmission pathways, QPSO-based clustering and routing improve energy efficiency. *Scalability:* To facilitate extensive WSN deployments, future studies should examine the scalability of fuzzy logic-based techniques like QPSO. *Energy Harvesting*: Investigating integration with energy harvesting methods may help WSNs last longer.

Security Considerations: Future research must focus on integrating security procedures into QPSO-fuzzy logic models because WSNs are frequently used in important applications. *Hybrid Optimization Techniques:* Efficiency can be increased by combining QPSO and fuzzy logic with additional optimization techniques like machine learning and reinforcement learning. *Real-Time Adaptability:* More advancement in real-time decision-making techniques can facilitate dynamic adaptation to shifting network conditions.

TABLE 1: comparative analysis of various surveyed algorithms has been presented.

Reference	Approach	Description	Advantages	Disadvantages
[1]	ESO-LEACH ALGORITHM	The simulation result of the proposed ESO-LEACH algorithm depicts that the complete energy depletion for first hub is achieved around 650th round, and nearly all hubs lose all of their energy once the network has completed about 1000 rounds. In contrast to LEACH, which exhibits a sharp decline that results in the death of every node after roughly 2200 rounds, ESO-LEACH achieves the first-node dead condition after roughly 150 rounds, after which the curve's slope follows a consistent pattern.	(i)Improved Cluster Head Selection (ii)Longer Network Lifetime (iii)Load Balancing	(i)Increased Communication Overhead (ii)Not Ideal for Dynamic Networks
[2]	PSO-based routing	The routing algorithm builds a trade-off between energy efficiency and energy balancing, whereas the clustering takes care energy consumption of the gateways and the sensor nodes. We have presented NLP formulation for both the routing and the clustering algorithms.	(i)Efficient Cluster Head Selection. (ii)Global Optimization Capability	(i)Premature Convergence Issue (ii)increased Communication Overhead
[3]	EECF-PROTOCOL	EECF-protocol is based on a three-way message exchange between every sensor and its one-hop neighbors and ends up with a clustered network.	According to performance evaluation, EECF outperforms EESH, a recently released clustering protocol for wireless sensor networks, in terms of network longevity and the ratio "Number of CHs/Total number of sensors.".	(i)Average energy saving.

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Reference	Approach	Description	Advantages	Disadvantages
[4]	LPLL-LEACH	Developed a method that allows the caching of sensor data to the sink node so that only relevant data packets to be forwarded ahead in the network.	LPLL-LEACH optimizes cluster head (CH) selection by considering residual energy and node density, reducing unnecessary energy consumption.	(If nodes are sparsely distributed, LPLL-LEACH may struggle to maintain balanced cluster sizes, leading to uneven energy consumption.
[5]	MOFCA	MOFCA that addresses both hotspots and energy hole problems in stationary and evolving networks.	The suggested MOFCA technique uses fuzzy logic to overcome the uncertainties present in the WSN nature while taking into account the density characteristics, distance to the sink, and remaining energy levels when calculating the cluster head competition radius.	MOFCA requires more data exchange between nodes for decision-making, which can increase network trafficand energy consumption.
[6]	Using fuzzy logic for distributed unequal clustering	In order to balance the CHs' energy usage, DUCF creates uneven clusters. The residual energy, node degree, and distance to BS are input variables used by the fuzzy inference system (FIS) in DUCF for CH election.	DUCF improves the network lifetime by balancing the energy consumption among the nodes.	(i)Not in consideration the coverage redundancy, node centrality and related parameters.
[7]	FQA	the quantum annealing algorithm to select the optimal route from the CHs and the base station (BS).	the quantum annealing algorithm to select the optimal route from the CHs and the base station (BS).	(i) (i)Less improvement in cluster formation. (ii)Adaptability in relating to bio-inspired computing can be improved.
[8]	NPSOP	NPSOP, a novel clustering and routing protocol based on particle swarm optimization, is suggested to optimize the network lifetime while taking energy efficiency and load balancing into account.	In comparison to PSO-EEC, LDIWPSO, and OFCA, the network lifetime of NPSOP has increased by 29.94%, 24.16%, and 13.67%, respectively.	(i) (i)High Computational Complexity- (ii)ENERGY CONSUMPTIO N

Reference	Approach	Description	Advantages	Disadvantages
			Additionally, the network's energy usage has dropped by 24.08%, 19.16%, and 10.95% in comparison to PSOEEC, LDIWPSO, and OFCA.	
[12]	ECUCF	algorithm namely as ECUCF (Energy Conserved Unequal Clusters with Fuzzy logic). Based on the distances of the nodes from the base station, the network is divided into three different sectors. For designing unequal clusters in each sector, a fuzzy logic approach is followed.	ECUCF has given improved results in maximizing the number of clusters, extending the total number of live nodes and increasing the lifetime of nodes on each round	(i) (i)Frequent Re-clustering. (i) (ii)uneven load distribution
[13]	EECHS	Throughput, dead node count, live node count, and residual energy (RE) all seem to be being utilized by the suggested method.	The EECHS algorithm increases the network lifetime of the WSN.	(i) (i)Unbalanced Energy Consumption (i) (ii)Failure recovery (i) (iii) limited scalability

Here's a comparison table -II of different Fuzzy Hybrid Approaches for Wireless Sensor Networks (WSNs) based on key factors like energy efficiency, scalability, and computational complexity.

Approach	Hybrid of	Advantages	Disadvantages	Best For
Fuzzy-LEACH (FLEACH)	Fuzzy Logic+ LEACH	- Improves cluster head selection using fuzzy rules. - Reduces energy consumption. - Extends network lifetime.	- Not optimal for large-scale networks. - May suffer from unbalanced clustering.	Small to medium-sized WSNs with dynamic conditions.
Fuzzy-Energy-Aware Clustering (FLEC)	Fuzzy Logic + Energy-Aware Routing	- Balances energy usage among nodes. - Reduces communication overhead. - Enhances stable cluster formation.	- Slightly higher computational complexity. - Performance depends on fuzzy rule optimization.	Large-scale WSNs needing energy balance.
Fuzzy-PSO (Particle Swarm Optimization)	Fuzzy Logic + PSO	- Intelligent cluster head selection. - Self-adaptive and efficient. - Reduces energy	- High computational cost. - Slower in large networks.	Networks with dynamic node mobility and load balancing needs.

Approach	Hybrid of	Advantages	Disadvantages	Best For
		consumption.		
Fuzzy-GA (Genetic Algorithm)	Fuzzy Logic + Genetic Algorithm	- Long-term optimization. - Adaptive clustering based on genetic evolution. - Improves network stability.	- High computational overhead. - Slower convergence time.	Large-scale WSNs requiring long-term energy efficiency.
Fuzzy-ACO (Ant Colony Optimization)	Fuzzy Logic + Ant Colony Optimization	- Intelligent routing based on fuzzy logic. - Improves data transmission efficiency. - Reduces delays in communication.	- Complex pheromone update mechanism. - May not be energy-efficient in all cases.	Delay-sensitive applications and real-time WSNs.

III. CONCLUSIONS

Clustering approaches utilizing fuzzy logic may be able to create optimal clusters that reduce total energy usage during operation. A number of researchers have been working for the past few years to build an efficient clustering algorithm for WSNs utilizing fuzzy logic after realizing this fact. In WSNs, fuzzy logic-based techniques increase scalability, adaptability, and energy efficiency. These techniques allow the network to handle dynamic conditions, such as node mobility and varying environmental factors, while maintaining high performance. By providing a more flexible and robust approach to clustering and routing, fuzzy logic can effectively balance energy consumption and network stability, leading to prolonged network lifespans. Furthermore, as technology continues to evolve, the integration of fuzzy logic with emerging technologies, such as machine learning and AI, holds great promise for developing even more sophisticated algorithms that can intelligently manage energy resources in real-time. This evolution could potentially revolutionize WSNs in a wide range of applications, from smart cities to healthcare, by ensuring that the networks are not only efficient but also capable of supporting the growing demands of the Internet of Things (IoT). Ultimately, the continued research and refinement of fuzzy logic-based techniques will be crucial in advancing WSNs to meet the challenges of next-generation applications.

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