

Balancing Energy Consumption and Network Longevity: A Review of LEACH Protocol Enhancements through Computational Intelligence

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Abstract

Low Energy Adaptive Clustering Hierarchy (LEACH) is the most widely used protocol for clustering in wireless sensor networks (WSNs). These networks are composed of numerous Sensor Nodes (SNs) that are employed for data monitoring and collection from the environment. We utilized the Systematic Literature Review (SLR) approach to study a total of 960 papers from 2020 to 2025 using IEEE Xplore, Web of Science, Springer Link, Science Direct, and Scopus databases. Google Scholar was used as an additional database for verification purposes only. Research gaps and potential directions for hybrid model development were identified based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The study focused on LEACH protocol enhancements through computational intelligence associated with WSNs. Reviews indicate that 22% of the reviewed papers used artificial intelligence (AI) approach, 48% of the reviewed papers used fuzzy approach, and 30% of the reviewed papers used genetic approach based on adaptability and scalability. Each of the proposed approaches consistently outperforms traditional LEACH in energy balance but couldn't balance energy consumption and network longevity with optimal performance. The findings demonstrate the persistent challenges in communication overhead, scalability, and adaptability. The paper argued that hybrid computational intelligence frameworks offer the most promising direction for enhancing LEACH-based WSNs toward sustainable, energy-efficient, and scalable performance.

Keywords: Artificial Intelligence, Clustering Algorithms, Computational Intelligence, Data Aggregation, Energy Consumption, Fuzzy Logic, Genetic Algorithm, LEACH Protocol, Machine Learning, Network Lifetime, Protocol Optimization, WSNs

I. INTRODUCTION

Wireless Sensor Networks are the foundation of the technology used today for data collection and monitoring systems. These networks are ideal for more complex real-time systems due to their capabilities in basic data collection and monitoring. These networks make it possible to develop applications such as factory automation and smart homes by sensing the environment and collecting data from the environment using tons of sensor nodes [1]. However, these sensor nodes usually employ non-rechargeable batteries, and they have great limitations in energy, which causes intractable problems in terms of the network lifetime and efficiency [2].

LEACH protocol is preferred as a solution to address these challenges [3]. Moreover, LEACH's hierarchical structure groups sensor nodes into clusters, and designated Cluster Heads (CHs) aggregate data and send it to a Base Station (BS) [4]. This clustering technique lowers the energy usage related to data transfer by distributing the energy load evenly among nodes, and also

improves the overall network performance [5]. The LEACH protocol has drawbacks with regard to the random selection of the CH despite its numerous benefits. This can result in unequal energy consumption and the formation of hotspots in the network [6].

A. Challenges of Energy Consumption and Network Longevity in WSNs

WSNs face serious challenges related to energy consumption during the operation of the LEACH protocol which directly impacts their operational lifespan and overall longevity. Ensuring energy efficiency to extend the lifespan of a network is the main goal in WSNs [7]. WSN nodes rely on battery power which makes energy conservation necessary for prolonged operation. Without efficient management of energy consumption, there will be node failures and reduced network coverage reduction of battery power [8].

Furthermore, unequal energy consumption of nodes during operation of the LEACH protocol in WSNs can lead to reduction of energy. This leads to premature node failures, creating gaps in network coverage and reducing overall network resilience [9]. The overall lifespan of a WSN is directly connected to the energy efficiency of its individual nodes and the network's ability to manage energy consumption effectively. These challenges of the LEACH protocol in WSNs are serious in environments where battery replacement is difficult or impossible [10].

B. Challenges of LEACH Protocol Enhancements through Computational Intelligence

Several studies have suggested different improvements in an effort to find a solution to the problems of the LEACH protocol. Computational intelligence methods such as fuzzy logic, genetic algorithms, and machine learning were utilized in their research. The improvements aimed to maximize the choice of CHs by considering several factors, such as node density, distance to the BS, and residual energy [11]. Moreover, these enhancements were introduced to help improve the reliability of data transmission, network longevity, and energy efficiency by strategically adding computational intelligence features to the base LEACH approach. To evaluate performance enhancements to the LEACH protocol, key performance metrics including network lifetime, energy consumption, and scalability were measured [12].

C. Approaches to Enhance LEACH Protocol through Computational Intelligence

Table 1: Summary of Computational Intelligence to enhance LEACH Protocol

Method	Definition	Advantage(s)	Limitations
AI driven methods	Computational approaches that use artificial intelligence techniques to automate decision making, optimize processes, and adapt intelligently to complex problems	Complex tasks are automated saving human effort. Learns from data to make better, data informed decisions.	Requires large, high-quality datasets. Energy and performance intensive
Fuzzy Logic	A computational approach that handles reasoning with uncertainty, using degrees of truth (0 to 1) instead of strict binary values, enabling approximate reasoning	Improves the network lifetime by optimal selection of the cluster head. Takes care of ambiguous sensor	The additional processing may be a burden on sensor battery. It is challenging in dynamic WSNs to

	similar to human decision-making	data for trustworthy tracking and routing.	construct effective fuzzy rules.
Genetic Algorithms	Techniques, based on natural evolution, which use selection, crossover and mutation to approach near optimal solutions for complex problems such as routing and energy management in WSNs	It achieves near optimal selection of cluster head to balance the consumption of energy. Can easily cope with dynamic WSN characteristics, such as node failure or topology change	Iterative computations can quickly drain sensor nodes. Slow Convergence to reach optimal solutions in WSNs

Table 1 shows a summary of computational intelligence to enhance LEACH Protocol

D. Motivation

This systematic literature review (SLR) is motivated by the need to balance the energy consumption and network longevity through computational intelligence. There is the need to integrate computational intelligence in LEACH protocol to balance the energy consumption and network lifetime [13]. In addition, existing approaches for balancing energy consumption and network longevity in LEACH protocol were reviewed. In addition, this paper describes the importance of optimizing energy consumption and extending network lifespan in WSN.

E. Problem Statement

Balancing the amount of power utilized by the sensor nodes to prolong the lifespan of the network is a challenge for the existing techniques in data-gathering sensors [14]. A key design objective for WSNs is to balance energy consumption and increase the network longevity. Recent studies have shown the importance to manage battery power in WSNs [15]. Selecting heads and relay nodes is necessary to balance the energy among the sensor nodes by considering different metrics of WSNs [16]. WSNs support a great number of applications with changing environments which need adaptive and scalable communication protocols [17]. The design of protocols that accomplish high performance in data transmission and low energy consumption to balance the amount of power utilized by the sensor nodes is a challenge. The optimal deployment schedule of the network is very essential to reduce coverage holes and make full use of network energy. Poor deployment can result in energy waste and blind spots in monitoring [18].

F. Scope

This article presents a review of LEACH protocol techniques for balancing energy consumption and network longevity in WSNs using computational intelligence. A substantial part of the paper is focused on the energy efficiency which is a crucial factor, since nodes in a WSN are battery operated and they are often placed in changing environments. It discusses the use of computational intelligence in enhancing energy consumption in detail, and highlights the challenges in terms of flexibility and scalability. The paper aims at optimal balance of energy consumption and network longevity in WSNs.

G. Objective

The focus of this SLR is to provide a comprehensive overview about computational intelligence based enhancements in the LEACH protocol to upgrade energy consumption and network lifetime. This paper will discuss the various techniques applied in order to enhance a network's lifetime and energy consumption. In addition, it will consider the effectiveness and implications of such enhancements on future research and practical WSN deployment. By systematic review of the existing literature, this will increase understanding of how computational intelligence may be applied to enhance performance of LEACH based protocols in energy constrained environments.

II. RESEARCH METHODOLOGY

We followed the systematic approach to review the existing literature on energy consumption and network longevity enhancement through computational intelligence within the LEACH protocol in WSNs. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used for this review. It includes defining the research questions, selecting databases, developing search strings, establishing of inclusion exclusion criteria, and applying a quality assessment framework. The methodology is organized as follows:

A. Data Sources and Search Strategy

To ensure comprehensive coverage of relevant studies, the search was conducted across five (5) academic databases. These databases are IEEE Xplore, Web of Science, SpringerLink, ScienceDirect, and Scopus. Google Scholar was used as an additional database for verification purposes only.

Table 2: Selection of search keywords

Method	Keywords
AI driven method	('AI-Driven Energy Optimization in WSN' OR Intelligent Routing Protocols in WSN) AND (Network Lifetime Enhancement in WSN' OR 'Energy Consumption Minimization in WSN') ('Machine Learning-based Clustering in WSN' OR 'Reinforcement Learning Optimization in WSN') AND ('Data-Driven Network Management in WSN' OR 'Adaptive Energy Control Mechanisms using Computational Intelligence')
Fuzzy Logic	('Fuzzy Logic Optimization in WSN' OR 'Energy-Efficient Routing in WSN') AND ('Cluster Head Selection in WSN' OR 'Network Lifetime Enhancement in WSN') ('Energy Balancing Mechanism in WSN' OR 'Multi-criteria Decision Making') AND ('Adaptive Clustering Algorithm in WSN' OR 'Residual Energy Estimation using Computational Intelligence')
Genetic Algorithms	('Genetic Algorithm Optimization in WSN') OR ('Energy-Efficient Routing Protocol in WSN') AND ('Network Lifetime Maximization in WSN' OR 'Energy Consumption Balancing in Cluster Head Selection') ('Intelligence Computation in Adaptive Clustering Mechanism' OR 'Fitness Function Design in WSN')

Table 2 shows the keywords used for the search on the various databases

B. Inclusion and Exclusion Criteria

To filter search results, for relevant studies, we established the following inclusion and exclusion criteria:

1) Inclusion

- Studies that focused on energy consumption and network longevity enhancement through computational intelligence within the LEACH protocol in WSNs.
- Peer-reviewed journal articles, conference papers
- Studies that provide empirical results or evaluations using datasets relevant to energy consumption and network longevity enhancement through computational intelligence within the LEACH protocol in WSNs
- Publications written in English
- Propose novel methods and use of simulations

2) Exclusion

- Studies not related to intrusion detection algorithms designed to energy consumption and network longevity enhancement through computational intelligence within the LEACH protocol in WSNs
- Publication that provide theoretical models without empirical validation
- Non-peer reviewed sources such as thesis, white papers, and editorials.

C. Study Selection Process

Figure 3 shows the study selection process which followed the PRISMA framework using these three (3) phases:

- Initial Screening: All reviewed articles were screened by titles and abstract to exclude irrelevant studies and choose those meeting the inclusion criteria for full-text review
- Full-Text Review: Full text of selected articles were reviewed to determine their relevance and quality. Excluded articles that did not provide detailed information on energy consumption and network longevity enhancement through computational intelligence within the LEACH protocol in WSNs
- Data Extraction and Coding: A standardized form was used to extract data from the final set of articles including energy consumption and network longevity enhancement through computational intelligence within the LEACH protocol in WSNs.

Data Sources and Search Strategy

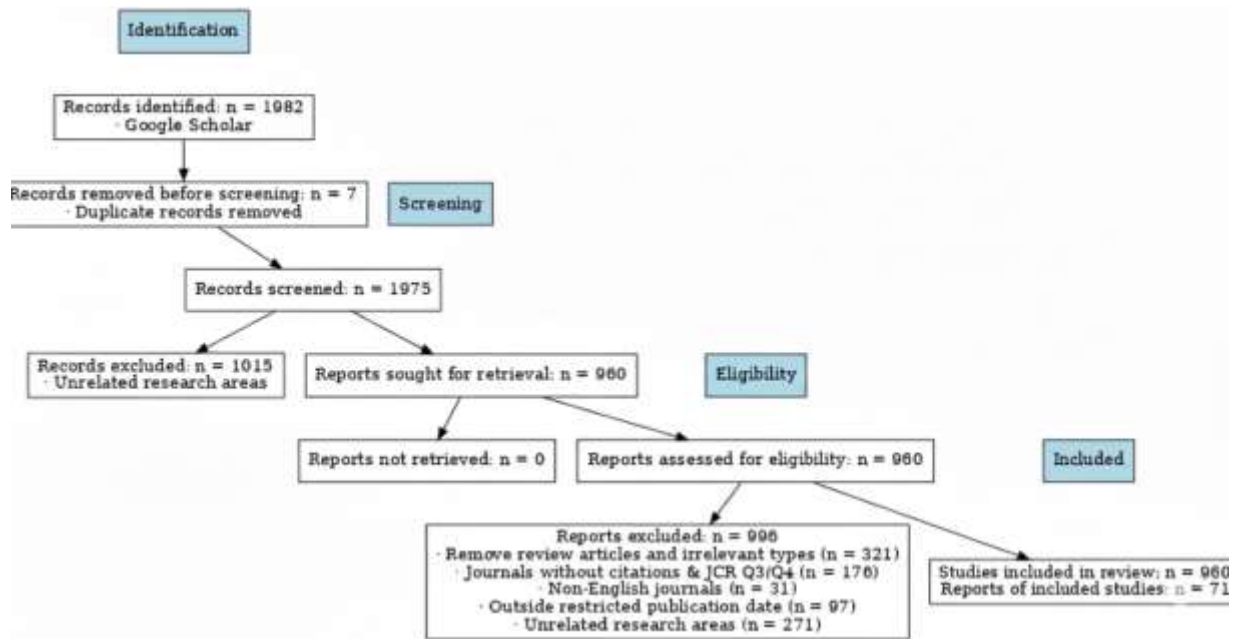


Figure 1: PRISMA flow diagram summarizing the study selection process

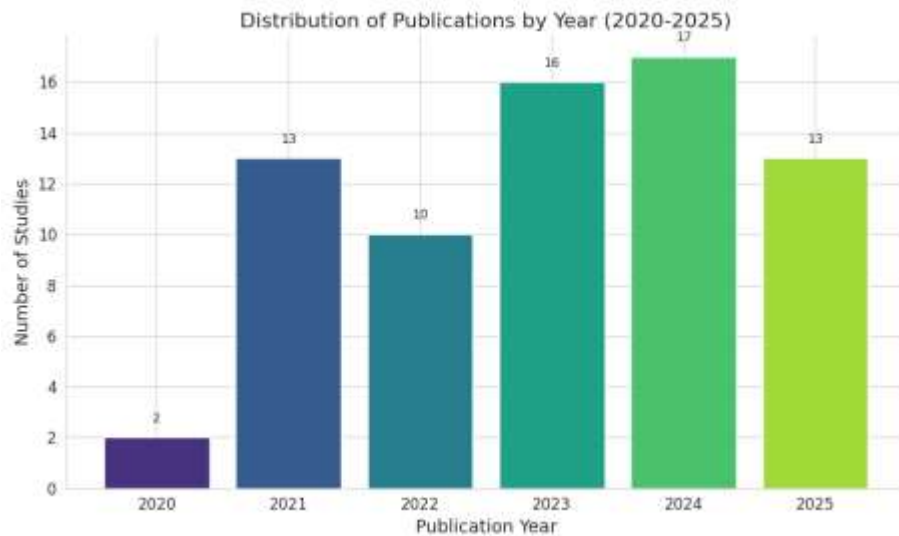


Figure 2: Distribution of publications included in the review based on year

Figure 1 shows a PRISMA flow diagram summarizing the study selection process and figure 2 shows a distribution of publications included in the review based on year.

III. LITERATURE REVIEW

A. Challenges in the Original LEACH Protocol

The Original LEACH has been a major progression for wireless sensor networks due to its energy efficient clustering methodology [19]. Nevertheless, there are some limitations which affect its efficiency and performance. There are several constraints of the original LEACH protocol, and one of them is energy [20]. Although it aims to reduce energy usage by rotating cluster heads, the overhead associated with this process can lead to increased energy consumption during the setup phase. Frequent re-clustering causes the batteries of the nodes to drain rapidly, and reduces their lifespan of operation and thereby affecting the network's lifetime [21].

LEACH suffers from scalability of the network as it grows with the number of node, and hence inefficient data transfer and bottleneck may occur with decrease in performance under heavy load [22]. In response to these problems, several improvements and new protocols are proposed for minimizing the energy consumption with more scalability structure and efficient communication among nodes in WSNs. However, fuzzy logic, genetic algorithm, and AI driven technique were proposed in previous studies to increase the lifespan of the batteries and improve network performance [23]. Although the existing techniques enhance the lifespan of the batteries in WSNs, the need for further enhancement is needed to maximize the lifespan of batteries in WSNs [24].

Moreover, these advancements not only allow efficiency to be enhanced, but make scalable solutions capable of facing the most pressing challenges in urban planning, resource allocation and public health interventions [25]. Furthermore, these scalable solutions will enable organizations to extract data driven insights, drive intelligent decision making and promote responsible practices throughout many sectors [26].

B. Computational Intelligence Techniques

An automated system proposed by Prithi and Sumathi [27] enhances energy consumption, network lifetime, throughput, end-to-end delay, routing, and intrusion detection in WSNs. The method aimed at creating a system that can learn, monitor, and control the changing behavior of the network environment while optimizing routing using computational intelligence techniques [28].

The proposed method was evaluated based on multiple performance metrics such as network lifetime, energy efficiency, throughput, end-to-end delay, accuracy, detection rate, computation time, and recall rate [29]. The technique can be applied in different areas that already use WSNs, including health for patient monitoring, environmental monitoring and home automation, and vehicular network security [30].

However, a novel approach which integrates Distributed Artificial Intelligence (DAI) and Adaptive Fish Swarm Optimization (AFSO) for resource allocation in WSNs with the aim of reducing energy consumption was introduced by Reddy et al. [31]. This approach reduces the challenges of efficient resource utilization in WSNs, which are constrained by computational

latency, communication range, bandwidth, storage, and battery power was improved [32]. The DAI focuses on inter-cluster power allocation by considering Quality of Service (QoS) and energy consumption. The proposed method improves network lifetime and throughput while minimizing computational delay and overhead in WSNs. A reduction in energy consumption by 7.86% which outperforms the existing methods was achieved by the proposed method. However, the integration of DAI and AFSSO lead to additional complexity in terms of implementation and computational requirements.

C. Enhancements to LEACH Protocol

Buvana et al. [33] presented an enhanced optimized LEACH protocol to enhance energy utilization of the network and prolong overall network lifetime, and the primary contributions include several modifications and additions to original standard LEACH protocol. The paper introduces a new method for calculating the 'fitting factor' of the next hop in multi-hop communication among clusters [34]. This formula takes into account factors such as angle, energy, and distance, aiming to optimize inter-cluster data transmission [35]. Furthermore, a technique which was included in the proposed approach divided the network area into adjusted cluster size in changing environments [36]. The technique takes into account the distance between the nodes and residual energy of a node and also embedded a sleep mechanism to intra cluster communication in WSNs [37].

The primary goal of the method used by Khan et al. [38] is to enhance the network lifetime and reduce energy consumption in WSNs. This is achieved by optimizing the cluster head (CH) selection process using a micro genetic algorithm (μ GA) integrated with the LEACH protocol. The μ GA is a variant of the genetic algorithm that operates with a smaller population size, which makes it suitable for real-time applications due to its faster convergence.

The structure of the proposed μ GA-LEACH protocol is based on improving the performance of conventional hierarchical routing protocols, such as LEACH, LEACH-C, LEACH GA and GADA LEACH. The strategy is designed to enhance the network energy efficiency and prolong its lifetime through an efficient CH selection. This is important since the CHs are in charge of coordinating internal communication within clusters and sending aggregated data to the base station.

Shen [39] proposed a fuzzy logic algorithm that enhances a cluster head selection in WSNs. This approach aims to enhance the classic LEACH protocol by integrating the fuzzy logic on node characteristics such as remaining energy, distance with base station and connectivity. The algorithm uses a fuzzy logic system to evaluate multiple parameters and this approach helps in selecting cluster heads based on a combination of factors rather than a single factor.

The enhanced algorithm performed better than the traditional LEACH protocol in network lifetime, energy consumption and overall stability of the network as confirmed by extensive simulation and statistics analysis [40]. The algorithm enhances energy consumption by taking residual energy into account, but is more complex to implement [41]. The enhanced fuzzy logic based method optimally combines the multiple criteria of energy efficiency and network lifetime along with stability without complex implementation.

Jukuntla and Dondeti [42] discussed an enhancement to the LEACH protocol, a method for optimizing energy consumption in WSNs. The work proposed uses a fuzzy controller in the LEACH protocol so that the energy consumption and selection of nodes are improved in making decisions, which contribute to the enhancement of network lifetime [43]. One of the major contributions of this approach is the concept of Rendezvous Nodes (RNs). These nodes serve as relays that allow data to be sent directly from the sink to specific data collecting nodes through a Base Station (BS). This method aims to save energy which is one of the crucial issues in WSNs [44].

Contrary to the original LEACH protocol, the proposed protocol explicitly takes longevity into account as a constraint. Furthermore, the RNs and fuzzy controller are incorporated to enhance the performance of LEACH protocol greatly [45]. The technique provided an efficient power utilization and prolong network lifespan by using less energy to acquire data, which is desirable for a number of applications including environmental monitoring and industrial automation.

Sivaraman [46] focused on increasing the network lifetime and reducing energy utilization in WSNs using Advanced LEACH (A-LEACH) protocol. The approach includes data aggregation, a traditional method to limit the redundancy of the individual node [47]. The A-LEACH protocol is used to perform the routing to assist WSN nodes in finding the best path from source to destination.

The approach improves the energy consumption problem of WSN, which is an important challenge in the network lifetime [48].

The SRN-LEACH protocol used by Sanapala and Duggirala [49] aimed at enhancing energy efficiency in wireless sensor networks (WSNs) by stabilizing the random number generation used in cluster head (CH) selection. The method introduces a stable random number-based approach to improve the efficiency of CH selection. The average node energy (ANE) of the network is multiplied by a random number that is dependent on the nodes' energy levels. This approach helps in stabilizing the CH selection process, which is a critical factor in reducing energy dissipation [50]. However, a minimum average delay of 0.136 ms, a packet delivery ratio (PDR) of 0.95%, a throughput (TP) rate of 148 kbps, and a network lifetime (NLT) of 95% were achieved by the SRN-LEACH protocol.

The approach proposed by Ampratwum and Nayak [51] was to prolong the network lifetime of WSNs. A nested genetic algorithm (GA) scheme is proposed in the paper as an optimization technique based on natural selection. This approach can optimize the sink node location that is important for network data collection and energy consumption [52]. It chooses cluster heads that process data information of sensor nodes and forward it to the sink node. This selection is important in order to make the energy load uniform through the nodes [53]. The proposed method was compared with four approaches in the field and demonstrated an average improvement of 15% in network performance under normal conditions and a 30% improvement in more changing environments. This indicates the robustness and effectiveness of the method in enhancing network lifetime [54].

D. Energy Consumption Analysis

Rathee et al. [55] adopted a method to enhance energy balancing for WSNs and it deployed multiple sinks. This resolved the problem of sensors having an uneven energy consumption, which is fundamental for improving the network lifetime. The use of multiple sinks helped to alleviate the bottleneck problem, but also added complexities such as changing network topologies and uneven path lengths [56]. A quantum inspired genetic algorithm for multi-sink deployment in WSNs was proposed and this approach minimized the locations of sinks so that they can forward data to most sensors with only one sink. In addition, the proposed method attempted to achieve equal route length for each sink, which is a routing problem in large WSNs [57].

The Q-GEMS approach is unique in its dual focus on minimizing energy consumption and reducing path length, unlike other methods that concentrate on one aspect [58]. It incorporates resilience to adapt to changes in network topology, such as sensor failures or external influences, which enhances the robustness of the network. Novel heuristics were proposed for sink positioning, sensor-to-sink binding, solution quality evaluation, and updating the Q-bit population [59], which are critical for achieving energy balance and reducing the number of sinks needed. Experimental results demonstrate that Q-GEMS outperforms existing methods, achieving a network lifetime that is 5.1%, 21%, and 24% longer than EEMS, EESS, and DPSO+PSO, respectively. This indicates a significant improvement in energy efficiency and network longevity.

E. Network Longevity Improvement Strategies

The proposed approach by [60] aimed at providing energy efficiency in WSNs by refining cluster head selection mechanism in the LEACH protocol. This is essential because sensor nodes in WSNs are equipped with limited energy supply, and more advanced data aggregation scheme could affect the lifespan of the network. The proposed work uses a Genetic Algorithm (GA) to optimize the cluster head selection. In this way, selected head nodes are viewed as solutions of the genetic model. The viability of these solutions is tested in terms of energy consumption [61]. The results demonstrated an 80% improvement in network lifespan compared to several routing protocols, a 54% improvement over ED-LEACH, and a 28% improvement over GADA-LEACH. This indicates that the LEACH-GA algorithm significantly outperforms the baseline LEACH algorithm and other algorithms in terms of energy efficiency, network lifetime, and data aggregation [62].

IV. DISCUSSION OF LITERATURE REVIEW

WSNs are fundamentally composed of numerous sensor nodes (SNs) that rely on non-rechargeable batteries, leading to significant limitations in energy. This causes intractable problems concerning network lifetime and efficiency, especially in inaccessible environments where battery replacement is difficult or impossible. The limited power resources of sensor nodes make energy efficiency a critical factor for prolonged operation and overall network longevity. A major drawback of the LEACH protocol is the random selection of Cluster Heads, which can lead to unequal energy consumption and the formation of 'hotspots' in the network. However, the traditional LEACH intend to reduce energy consumption through the rotation of CHs, but overhead is incurred during the setup phase by frequent re-clustering and result in high energy consumption and a quick battery depletion, reducing the network lifespan. LEACH protocol suffers from

scalability problems as the number of node increases in WSNs, and results in inefficient data transfer and bottlenecks, leading to decreased performance under heavy loads.

Furthermore, LEACH protocol enhancement techniques that focus on improving energy consumption and prolonging the network lifespan in WSNs were discussed. The improvements deal with the effective selection of cluster heads in each data transmission round, which is crucial to balance energy among nodes and provide great benefits on network longevity [63]. Several methods used by previous researchers to minimize the energy consumption in WSNs such as energy-efficient data aggregation, cluster construction, sleep scheduling and energy efficient MAC protocols were discussed [62].

These techniques used by previous researchers reduce the data redundancy and classify the nodes into clusters, and determine their active and sleep slots to conserve energy [64]. The traditional LEACH protocol which uses an energy-efficient clustering approach had drawbacks such as additional energy consumption during set-up period due to higher operation of re-clustering [65]. This can result in battery power depletion of nodes and reduce the network lifespan [58]. The literature review on many computational intelligence techniques to the energy consumption and network lifespan. Machine learning approaches are used for CH selection based on energy as well as hybrid protocols and these methods significantly improved network performance and reliability.

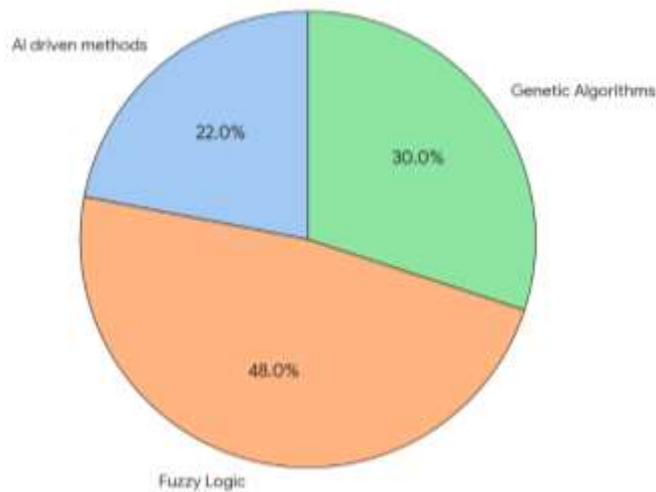


Figure 3: Distribution of techniques used in the studies

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Table 3: Summary of Literature Review

Author(s)	Year	Approach	Scope	Dataset	Metrics Results
Zhang et al.	2024	Modifications to the LEACH protocol's	Evaluation of a modified LEACH protocol specifically tailored to improve energy	Simulation results	Improves energy efficiency and extends the network's

		operational logic	efficiency and prolong the life of wireless sensor networks		operational lifespan compared to the original LEACH protocol
Daanoune, Baghdad, et al.	2021	Self-organizing, adaptive, and optimization-driven routing protocols for WSNs	Addressing the limitations of the traditional LEACH protocol, particularly its random Cluster Head (CH) selection and energy imbalance issues, through a new LEACH-based routing protocol	MATLAB simulation	Improves network lifetime and optimizes energy consumption in WSNs, outperforming the traditional LEACH protocol under the simulated conditions
El-Sayed et al.	2024	Neural networks	Enhancing the energy efficiency and longevity of WSNs through the development of a novel routing protocol	Simulation results	Optimized energy usage and maintained network stability within the simulated WSN environment
Jaleel et al.	2025	Ant Colony Optimization (ACO)	Enhancing the performance and longevity of WSNs through the development and evaluation of an energy-efficient hybrid LEACH protocol.	MATLAB simulation	A substantial improvements in network lifetime, data throughput, and energy efficiency, making it a more robust solution for WSNs
H El-Sayed et al.	2024	LEACH protocol that integrates multi-hop communication and neural networks	Evaluation of a modified LEACH protocol, with a central goal of improving energy efficiency and extending network lifetime	MATLAB simulation	Achieved superior energy efficiency and extend the operational lifetime of wireless sensor networks in IoT applications.
Salman, Mohammed, et al.	2023	An improved version of the LEACH protocol	Energy efficiency in WSNs algorithms that aim to minimize power consumption by optimizing the selection of cluster heads during data transfer rounds.	MATLAB simulation	A 14.5% increase in network lifetime and a 16.8% improvement in network throughput compared to the original LEACH algorithm.

Buvana et al.	2021	Sleep Mechanism for Intra-Cluster Transmission, and an introduction of a Barycenter Node.	An optimized LEACH-focused protocol aimed at improving network energy usage and extending the network's life cycle	Simulation results	The network life cycle was increased by 54% and significantly reduces the remaining total energy consumption by 32.6% compared to the traditional LEACH
Rathee et al.	2024	Use of quantum-inspired techniques and genetic algorithms	Energy balancing in Wireless Sensor Networks (WSNs) by deploying multiple sinks	Simulation results	Q-GEMS outperforms existing methods, achieving a network lifetime that is 5.1%, 21%, and 24% longer than EEMS, EESS, and DPSO+PSO, respectively
Saadallah et al.	2024	A Genetic Algorithm (GA) to optimize cluster heads selection.	Enhancing the energy efficiency of Wireless Sensor Networks (WSNs) by improving the cluster head selection process in the LEACH protocol	Simulation results	Improvement in network lifespan compared to several routing protocols, a 54% improvement over ED-LEACH, and a 28% improvement over GADA-LEACH
Shinde and Bichkar	2023	A genetic algorithm	Extending the lifetime of Wireless Sensor Networks (WSNs) by efficiently scheduling sensor nodes	Simulation results	A schedule with a minimal number of active sensor nodes, within just 3-5 iterations
Saadallah and Alabady	2023	Genetic Algorithm and Particle Swarm Optimization (PSO)	Enhancing energy efficiency and extend the network lifetime in Wireless Sensor Networks (WSNs)	Simulation results	A significant improvements in both energy efficiency and network lifetime
Salman et al.	2023	An improved version of	The focus is on optimizing network operations to reduce energy consumption and	MATLAB simulation	A 14.5% increase in network lifetime and a 16.8%

		LEACH protocol	extend the network's operational lifetime.		improvement in network throughput compared to the original LEACH algorithm
Ampratwum and Nayak	2023	A nested genetic algorithm (GA) approach	Reducing energy consumption and extend the through a nested genetic algorithm	Simulation results	Improvement of 15% in network performance under normal conditions and a 30% improvement in more changing environments.
Gayathri et al.	2023	A novel routing protocol that balances energy usage among nodes.	A thorough analysis of wireless data transmission fundamentals, including the positioning of sensor nodes and other vital components of WSNs	Simulation results	The new routing protocol significantly reduce the network's overall energy consumption while maximizing throughput
Sivaraman	2022	Advanced LEACH (A-LEACH) protocol	Enhancing the network lifetime and minimizing energy consumption in WSNs by using the A-LEACH protocol	Simulation results	reduces energy consumption and extends the network's operational life
Sanapala and Duggirala	2023	The SRN-LEACH protocol	Enhancing energy efficiency in WSNs by stabilizing the random number generation used in cluster head (CH) selection	Simulation results	Average delay of 0.136 ms, a packet delivery ratio (PDR) of 0.95%, a throughput (TP) rate of 148 kbps, and a network lifetime (NLT) of 90%

Table 4: Limitations and Contributions of Literature Review

Ref	Contribution	Limitation
[66]	An energy-saving routing protocol that enhances LEACH through specific criteria for cluster head selection and multi-hop transmission	The improvements is based on modifications to the LEACH protocol's operational logic rather than the integration of distinct computational intelligence paradigms
[67]	Optimize energy consumption and extend network stability through intelligent	The need for further enhancements, particularly regarding comprehensive QoS

	decision-making processes within the network	considerations and broader comparative analysis with other advanced protocols
[68]	NN_ILEACH significantly improves upon existing protocols in terms of network lifetime, throughput, and energy efficiency	The potential for more advanced machine learning integration to further boost its adaptability and overall performance in complex WSN environments
[69]	An enhanced LEACH protocol strategy to achieve superior energy efficiency, extended network longevity, and improved data throughput in WSNs	Challenge of energy distribution among CHs and the potential for data loss due to CH failure remain critical areas that warrant continuous research and improvement
[70]	Development and validation of NNMH_LEACH, a modified LEACH protocol that integrates multi-hop communication and neural networks	Absence of an explicit discussion of the study's constraints, potential drawbacks of the NNMH_LEACH protocol
[71]	An improved version of the LEACH protocol, specifically designed for WSNs.	Reliance on the current energy levels of the sensors for selecting cluster heads.
[33]	An optimized LEACH designed to improve network energy usage	Its current iteration has limitations regarding its long-term operational reach
[55]	An improved Dijkstra algorithm which uses energy consumption as its primary optimization objective for path planning.	Ability to quickly re-plan paths in response to unforeseen obstacles or changing conditions.
[60]	Improved Energy efficiency and network longevity	Computational cost, implementation complexity, and parameter sensitivity.
[62]	An enhanced energy efficiency of WSNs through improved genetic algorithm techniques	Focused on a specific set of metrics such as energy consumption, network lifetime, and data throughput.
[61]	A robust optimization framework that can adapt to various network scenarios.	The complexity of implementing a mobile sink and hybrid optimization strategy increased the computational overhead.
[47]	Improved cluster formation process by prioritizing nodes that are closer to the base station. This strategy reduces the energy required for data transmission, as shorter distances typically consume less power.	This is a practical enhancement over the traditional LEACH protocol, which does not explicitly consider distance in cluster formation
[51]	The method optimizes the placement of the sink node, which is crucial for efficient data collection and energy consumption in the network.	Focuses on optimizing the placement of the sink node
[52]	The new routing protocol can significantly reduce the network's overall energy consumption while maximizing throughput	Focuses on throughput to reduce the overall energy consumption
[46]	Effectively combines advanced routing techniques with data aggregation to improve energy efficiency and extend the network lifetime in WSNs	It concentrates on the method's advantages and its potential to address energy challenges in Wireless Sensor Networks.

[49]	The SRN-LEACH protocol effectively addresses the challenge of energy efficiency in WSNs	It does not explicitly state any limitations or drawbacks
[27]	A comprehensive approach to enhancing the performance and security of WSNs through the use of an automaton system and computational intelligence techniques	It does not detail any specific constraints, challenges, or areas where the proposed method might fall short or require further development.
[41]	Integration of fuzzy logic into the LEACH protocol represents a promising method for enhancing the energy efficiency of WSNs. By improving cluster head selection, the network can potentially achieve a longer lifespan	The paper does not detail how these parameters were determined or if their optimal configuration is universally applicable across changing WSN environments and application scenarios
[38]	A comprehensive approach to addressing energy efficiency in IoT networks by integrating AI and digital twin simulations, thereby enhancing the traditional LEACH protocol	Lack of detailed experimental conditions, potential computational overhead, and a narrow focus on energy efficiency over other performance metrics.
[31]	A robust framework for resource allocation in WSNs, leveraging the strengths of DAI and AFSSO to enhance network performance and efficiency	Considerations regarding complexity and scalability should be addressed in future research
[38]	The μ GA-LEACH protocol enhances the efficiency of CH selection and contributes to the overall sustainability of the network by reducing energy wastage and prolonging the operational period of the sensor nodes	Complexity of implementing genetic algorithms in resource-constrained WSN nodes, and the potential overhead introduced by the genetic algorithm
[39]	The improved fuzzy logic-based method offers a balanced approach by enhancing energy efficiency and network stability	Complexity and scalability should be addressed in future research

Table 3 shows a summary of literature review, and table 4 limitations and contributions of literature review.

V. CHALLENGES AND OPEN DIRECTIONS

Although there are remarkable improvements in balancing the energy consumption and network lifespan of LEACH protocol in WSNs due to the integration of computational intelligence, new challenges have emerged such as computational overhead, algorithm complexity and parameter validation in automatic WSN. AI driven methods, rely on large scale high quality datasets and also consumes more energy. While fuzzy logic enhances the network lifetime and deals with uncertain data, it may cause extra computation load on sensor. Although genetic algorithms can achieve near-optimal CHs selection in addition to adapting to dynamic WSNs, the iterative computations can be a high drain on the sensor nodes and slow down the convergence of optimal solutions.

Implementation of complex techniques such as Distributed Artificial Intelligence (DAI) or Adaptive Fish Swarm Optimization (AFSO) can increase the complexity and computational demands. Also, GA with a mobile sink might be robust but may introduce computational complexity and requires experimental verification in real world.

Despite improvements, the issue of load balancing among nodes, which is crucial to prolonging the network lifespan, still remains. Some complex models and mobile sinks, can however to be hampered in terms of practical applicability and deployment by the added complexity as well as the testing required after validating solely via simulations. Future research should focus on a hybrid technique that utilizes energy-efficient protocols to better extend the network lifetime and guarantee robust performance in a hybrid fashion.

VI. CONCLUSION

We conducted a systematic review of improvements to the LEACH protocol, especially using computational intelligence to solve energy consumption problems in WSNs. The main objective was to balance the energy consumption and network lifetime effectively using computational intelligence. The review emphasized the significance of energy efficiency for WSNs on account of resource constrained sensor nodes, especially in changing environments. It also investigated several computational intelligence approaches such as fuzzy logic, genetic algorithms and AI based techniques to improve the energy consumption of LEACH protocol.

In summary, although the traditional LEACH protocol had made some effort in balancing the energy consumption using energy-efficient clustering, further development is still needed because balancing the energy consumption in WSNs cannot be handled by a single computational intelligence technique. However, using a hybrid computational intelligence technique will provides a strong approach for addressing these issues, and can contribute to the development of WSNs that are more reliable with reduced energy consumption and provide longer lifetimes.

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CONFLICT OF INTEREST

All authors declare no conflict of interest.

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