



Optimization of Leach Parameters to Improve Energy Efficiency of Wireless Sensor Networks

Sipepe Riopo Adela¹, Mei Wu²

¹School of International Education, Wuhan Institute of Technology, Wuhan, China

²School of Computer Science and Engineering and School of Artificial Intelligence, Wuhan Institute of Technology, Wuhan, China

Email: jadeisi2018@gmail.com, meiwu202202@163.com

How to cite this paper: Adela, S.R. and Wu, M. (2025) Optimization of Leach Parameters to Improve Energy Efficiency of Wireless Sensor Networks. *Open Access Library Journal*, **12**: e13258.

<https://doi.org/10.4236/oalib.1113258>

Received: March 13, 2025

Accepted: April 27, 2025

Published: April 30, 2025

Copyright © 2025 by author(s) and Open Access Library Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

This article introduces a study on optimizing **LEACH** parameters to improve the efficiency of wireless sensor networks. The focus of the research is to find the optimal algorithm configuration parameter to maximize the performance and prolong the lifetime of wireless sensor batteries. This study aims to improve the overall energy efficiency of wireless sensor networks by adjusting the LEACH parameters. The results will contribute to the development of more sustainable and energy-efficient wireless sensor networks.

Subject Areas

Computer Engineering

Keywords

Optimization, LEACH, Parameters, Energy Efficiency, Wireless Sensor Networks

1. Introduction

1.1. Background

Wireless Sensor Networks (WSNs) have made a big step forward as a game-changing technology that has revolutionized the need for broad applications such as healthcare, environmental & infrastructure thermal management, precision farming, and military applications [1]. One such network is formed by the use of a number of small low-power sensor nodes that are interconnected, and the physical properties of some elements (temperature, pressure, vibration, motion, sound, pollutants) are monitored [2]. They come with data processing and wireless communications, enabling them to send the sensed information to a central base sta-

tion for further analysis [3].

Generally, WSN nodes are electrically powered and have limited energy resources, which is why developing energy-efficient communication protocols to extend their operational lifetime has taken a significant focus in the past few decades [4]. WSNs are often used on a massive scale, with a large number of sensor nodes (hundreds or even thousands) that are spread out in different remote and unapproachable areas for a long-term duration [5]. In such a case, automatic battery exchange is usually impractical. If not, it is not enough to be economically feasible and the quick running out of the available power due to frequent retransmissions and collisions [6].

Agreeing on common radio resource allocation procedures should form the basis for data transmission among nodes in a sensor network. These methods, presently used, consume large amounts of energy and they need to be switched off at frequent intervals in case the data goes a long way before it reaches the receiver. This is where the need for developing power optimization techniques specifically for the 2 major applications of sensitivity fields; the reduction of transmission and receiving power and the use of power efficiently between the interfacing devices [7].

One of the most remarkable ways of addressing the energy efficiency requirements of WSNs and at the same time, increasing the network scale-lifetime and networking cluster-based hierarchical routing. According to this protocol, sensor nodes are localized in clusters with one of the sensor nodes (cluster head) acting as the cluster head (CH) who is chosen in each cluster. The CH nodes collect and aggregate the sensory data from their particular cluster members and then send the processed information to the base station. This way allows decreasing the need for long multi-hop transmissions from the individual nodes to the base station. Therefore, it saves energy, helps the cluster balance its workload, and reuses the limited communication bandwidth through data aggregation [8]. To ensure fairness and to ensure every node does not get burdened, the election for CH is done dynamically at regular intervals, thus rotating the responsibility for data transmission among the nodes.

The protocol Low-Energy Adaptive Clustering Hierarchy (LEACH) is the pioneering one of the cluster-based hierarchical routing approach and is still one of the most common energy-efficient networking communication issue solutions. LEACH uses a random approach to select the cluster heads, thus properly distributing the energy across the network and extending the life of the entire network [9] as cited in [10]. Many energy-efficient WSN protocols have been based on LEACH, giving impetus to further research and development of techniques for network lifetime extension and energy conservation.

1.2. Objectives

The main goal of this research work is to come up with a more sophisticated optimization method for the LEACH protocol with the intention of increasing en-

ergy efficiency plus lengthening the operational lifetime of Wireless Sensor Networks (WSNs).

1) Analysis of LEACH Parameters: the first specific goal of this research is to conduct a thorough exploration of the contribution that crucial parameters of the LEACH protocol, namely cluster size, Cluster Head (CH) ratio, epochs, and transmission power, have on major performance indicators in Wireless Sensor Networks (WSNs).

2) Design of Multi-Objective Optimization Framework: this study will also make a contribution in the area of multi-objective optimization by providing an advanced multi-objective optimization framework that will implement cutting-edge optimization methodologies like the Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) that are able to handle conflicting objectives in a computation-effective manner. The framework will discover the best possible values of LEACH parameters that will improve energy efficiency and prolong network life in this process.

3) Implementation and Simulation: therefore, an optimized LEACH protocol will be adopted to be carried out, tested, and simulated in terms of performance in several areas. The performance of the optimized LEACH protocol will thus be analyzed in connection with the original LEACH, Energy Efficient Heterogeneous Clustering (EEHC), and Distributed Energy Efficient Clustering (DDEEC) protocol models. The criteria of comparison will involve variables such as network lifetime, throughput, and latency.

4) Experimental Validation: an aspect of this research work seeks to experimentally confirm the benefits stemming from the implementation of the optimized LEACH protocol at a real-world WSN testbed, in the process of analyzing the actual performance and the scalability of the system in practical settings.

2. Literature Review

2.1. Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) are highly effective and efficient in ubiquitous monitoring and data collection across a variety of applications. Some common applications of WSNs include environmental monitoring; applications in fields such as weather change detection, forest fire monitoring, and flood detection; healthcare monitoring for tracking the health condition or vital signs of patients; industrial monitoring for monitoring the production process such as temperature, pressure, and humidity; and military surveillance such as reconnaissance and surveillance. These networks comprise many low-power sensor nodes that cooperate in the attempt to detect and report on some physical phenomenon over vast and often inaccessible geographical locations. These applications integrate sensor network technology enabling China to work in the VLSI and PCB Technology at the receiving distance of fifty meters and hence, there is the ease of doing work as required in these devices or applications. According to the architecture of the WSN and the requirements for coverage and performance, WSNs can be catego-

rized into the following networks.

Single-Tier Single-Hop Networks: in this configuration, all sensors communicate with the central base station directly without the involvement of any intermediate nodes [11]. This architecture allows for straightforward installation but is feasible only for small networks with a few sensors. Using this, along with its limitations, does not become feasible as the number of sensors increases thereby making adjustments and communication difficult.

Single-Tier Multi-Hop Networks: in such cases, sensor readings are passed through intermediate nodes so that relay readings can reach the base station. This kind of architecture helps to increase the scope and capability of the network as compared to the single-hop networks and is suitable for larger and more complex networks and sensor nodes located.

Multi-Tier Networks: these advanced networks introduce additional hierarchies in the network where some nodes have special functions such as cluster heads or aggregators, hence enhancing the performance and longevity of the communication system. In these networks, sensors are grouped into clusters with cluster heads that have a superior capacity for processing the data gathered by the members. The process helps minimize the strength of the data sent. Additionally, the deployment of these multi-tiered architectures enhances the overall efficiency of WSNs as they continually try to improve their performance and increase their operational efficiency, among others.

The deployment of WSNs at such large scales brings energy efficiency to the forefront as the very limited battery life of the nodes requires the development of protocols that improve their longevity without compromising their level of performance. Specifically, one of the paramount challenges of WSNs is their efficient use of energy, as the components that usually compose WSNs are primarily battery-powered nodes deployed over wide areas of operations. In addition to the sensors used in WSNs, the processing activities, and the number of signals sent also consume energy; however, [12] suggests that transceivers are the heaviest consumers of energy [8]. However, these communication limitations should be minimized through other engaging approaches, for which adopting concepts such as the conjugate ground technique might be essential as they help reduce the power that is consumed by the components further.

The LEACH protocol effectively tackles these serious issues through an intelligent approach that actively employs the creation of dynamic clusters and the systematic rotation of cluster heads over a certain period. With this novel technique, every single node is given its own unique probabilistic likelihood of being selected as a cluster head (CH). Moreover, the periodic rotation of this duty of being a CH is done in such a manner that the overall utilization of energy in the entire network is maintained as evenly as possible without any extreme form of consumption on the part of one single cluster node. In essence, this unique clustering scheme works in decreasing the long-distance transmission loads on the individual nodes, thus enabling the aggregation of raw data for further processing in a

manner that would very greatly reduce the gross number of transmissions made, and consequently elongate the lifespan of the network in question [13]. **Figure 1** below illustrates wireless sensor networks.

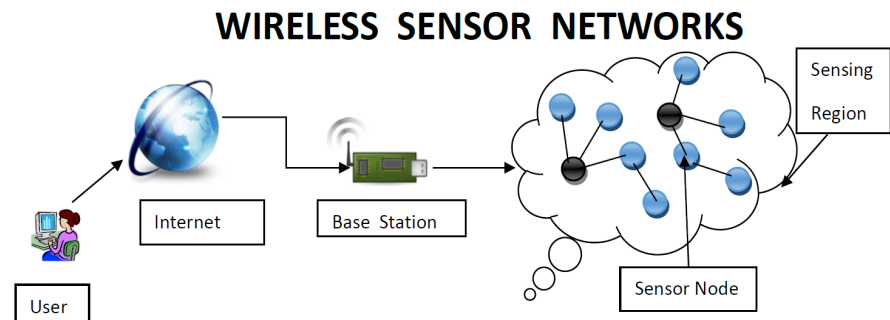


Figure 1. Wireless sensor networks.

2.2. LEACH Protocol

The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is universally recognized as one of the most comprehensive and time-tested techniques that work in a seamless manner for the purpose of conserving energy in wireless sensor network communication (Heinzelman et al., 2000). Similarly, LEACH tends to maximize energy utility through efficient organization of the sensor nodes into separate clusters. Within every cluster is a specific node that is chosen to work as the Cluster Head (CH). The CHs are basically responsible for collecting, processing, and forwarding data from the other nodes in the cluster to the base station for further analysis and decision-making. It is especially important to mention that the CH elections are carried out in a random manner, and any single node can be chosen as a CH, thus ensuring that the high burden of communication is fairly buried within each of the nodes during multiple rounds. This fair distribution process does help in reducing the risks of some nodes running out of energy and consequently causing losses in terms of connectivity or performance.

Moreover, this unique approach to CH election is characterized by the random self-selection of certain nodes in a manner that makes it possible to actualize the accomplishment of the role of the CH in a probabilistic manner and then there is a careful sacrifice of this role after certain intervals of time whereby for all nodes the burden of energy consumption is intelligently shared throughout the entire network. To this end, at each level within the cluster, LEACH is capable of using data aggregation to minimize the overall number of message chase-outs subsequently used, thus further improving energy savings and prolonging the life span of the network [13]. **Figure 2** below shows the development of sensor nodes.

In general terms, when the LEACH protocol is used properly, the dynamic formation of the clusters and the adequate balancing of the roles of the CH result in an optimal outcome in terms of the use of energy in relation to a re-organization of the sensor networks. **Figure 3** below shows cluster head formation.

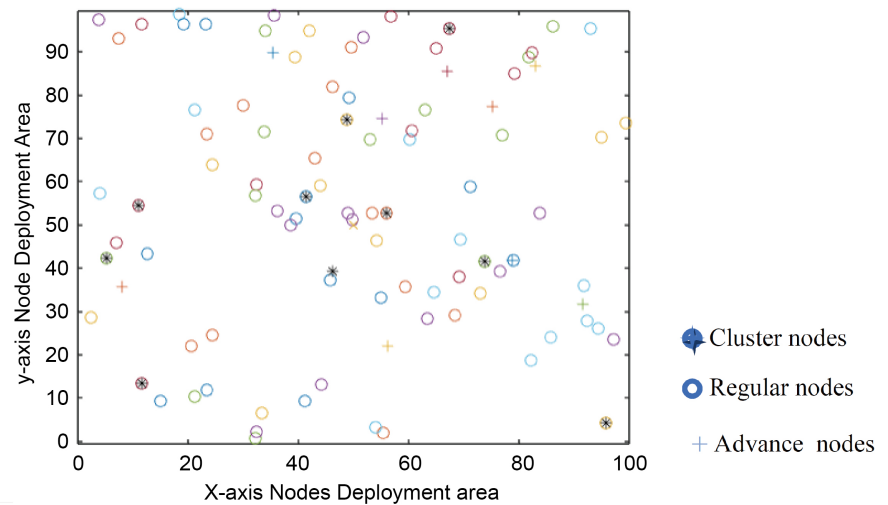


Figure 2. Deployment of sensor nodes in a 100×100 meter network.

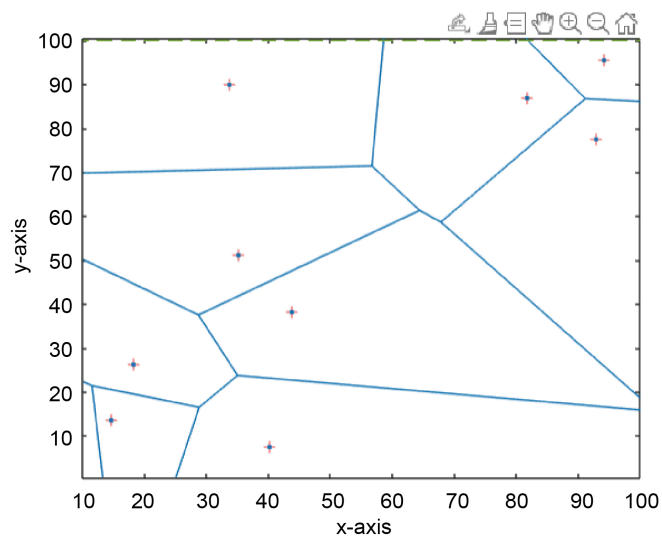


Figure 3. Cluster head formation.

2.3. Existing Optimization Techniques for LEACH

Although there have been numerous studies and analyses done on LEACH as a protocol for Wireless Sensor Networks (WSNs), it has been found that most of these attempts at optimizing it are mostly centered on one of its features or on fixing certain soft spots in the framework. So far, studies have fallen short of offering a universally accepted optimizing technique that would optimize aspects of the protocol that operates. In the following examples, discussions of the benefits and limitations of specific techniques give an insight into the area of LEACH optimization based on limited spectrum optimization frameworks.

For instance, the Distributed Energy-Efficient Clustering (DDEEC) scheme [14] modifies the CH election process by taking into account the remaining energy of the nodes when making the selection. This technique would benefit wireless sensors that depend heavily on low energy consumption as it emphasizes en-

ergy efficiency, allowing nodes with small residual batteries to become CHs. However, on the downside, minimizing the CH selection process is implemented at the expense of load balancing due to changes in energy levels. It is also possible to have nodes continuously selected for particular tasks to become the CHs, thus overworking these nodes.

The Energy Efficient Heterogeneous Clustering (EEHC) method [15], on the other hand, recognizes and addresses the issue of node heterogeneity in the network and introduces an approach that establishes a balanced CH distribution across the network. This is performed by taking into account the physical and functional differences in the nodes initially designed and deploying a protocol that is very friendly to the nodes and their functions.

Similar to these methods, the techniques discussed hold great potential for optimizing some of the critical aspects of LEACH such as energy conservation or the handling of heterogeneities in the sensor nodes and the physical environment around them. Even so, their feasibility and adaptability to performance attribute optimization were noted as one of their biggest limitations for LEACH, and these constraints limit their sustainability. These narrowly focused approaches are essential to analyzing the complex performance of LEACH without a general multi-objective optimization framework for LEACH parameters.

2.4. LEACH Cluster Formation

The clustering model of LEACH consists of the random deployment of nodes in the defined area, which is made by the environment in a diffusion manner, and the selection of the cluster head (CHs) by a probabilistic mechanism called the 'probabilistic' or 'random' selection. In the probabilistic selection process, each node has the chance of being a CH based on the given probability, P . The number of CHs to be used is determined as a ratio of the number of sensor nodes to the maximum number of nodes and has the same range as the sensor that is deciding its' CH based on the minimum communication energy required to communicate with the CH. This selection process ensures that throughout the network, nodes are grouped to form clusters, and over a period of time, the CH is allowed to change to prevent high energy consumption by any of the nodes. **Figure 4** below shows Cluster-formation in LEACH PROTOCOL.

The clustering based on the probabilistic selection of the CHs for the nodes deployed in an area is crucial to knowing the states of the clusters. The Cluster Head Selection in the Wireless Sensor Networks is shown in **Figure 5** below.

3. Methodology

3.1. Research Design

A simulation-based research design will be utilized to investigate the effects of different LEACH parameters on the energy consumption, network lifetime and Quality of Service (QoS) performance of WSN. The optimization will employ a multi-objective fitness function encompassing energy efficiency, delivery latency

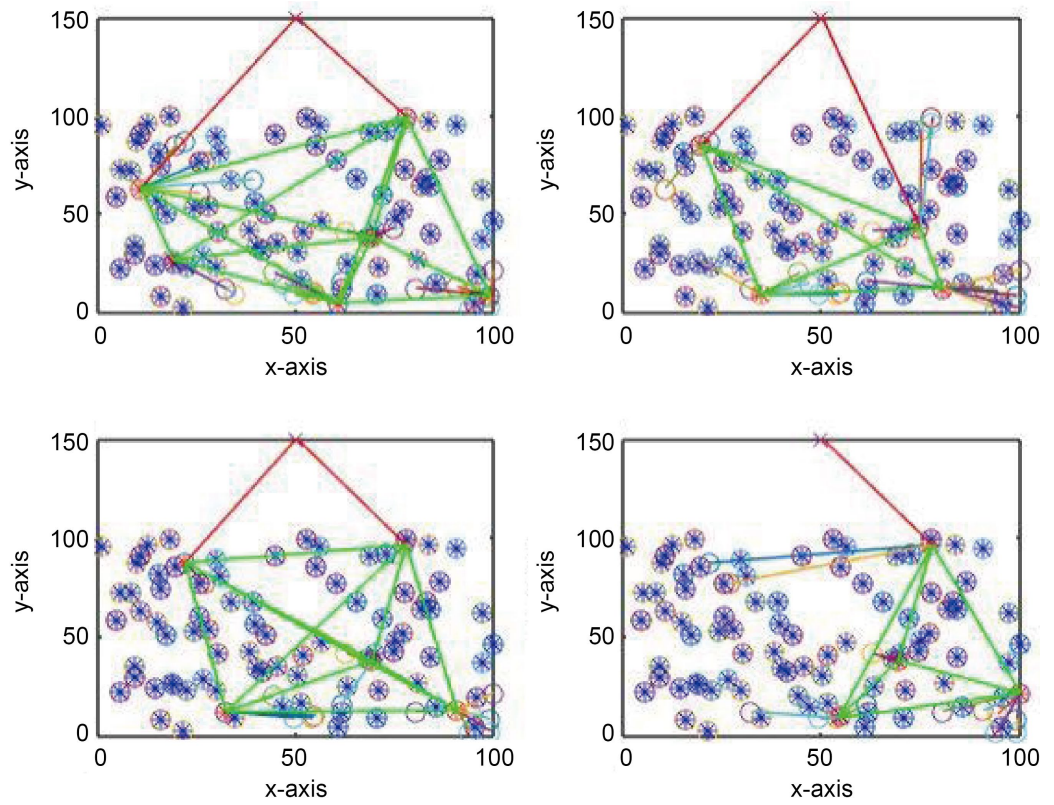


Figure 4. Cluster-formation in LEACH PROTOCOL.

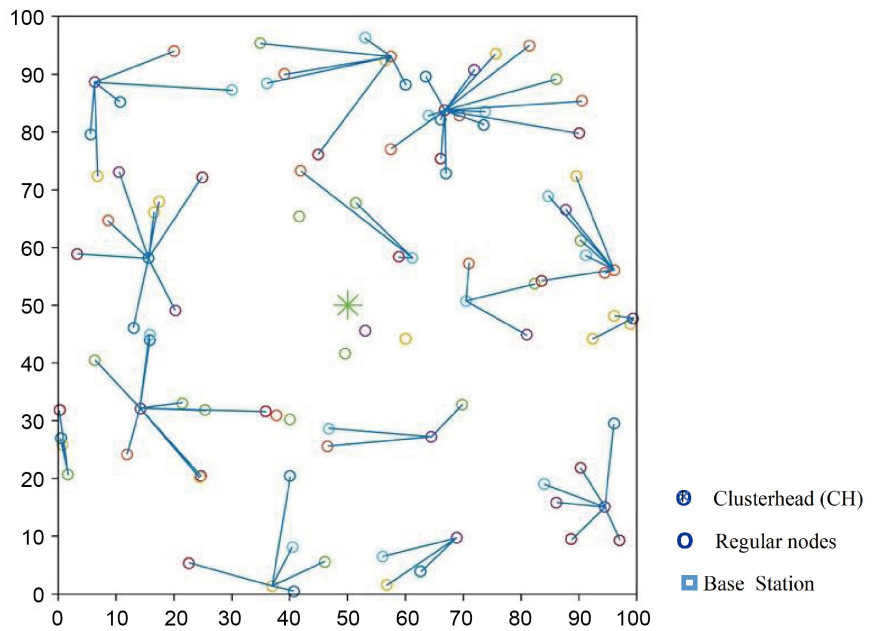


Figure 5. Cluster head selection in the wireless sensor networks.

and throughput metrics as shown below:

$$\text{Fitness} = w_1 * (\text{Lifetime}) + w_2 * (\text{Throughput}) + w_3 * (1/\text{EnergyConsumed}) + w_4 * (1/\text{Latency})$$

The weights w_1, w_2, w_3, w_4 control the relative importance of each performance metric. The optimization process ensures that LEACH operates in the most energy-efficient manner possible while extending its lifetime and improving data throughput as illustrated in **Figure 6** below.

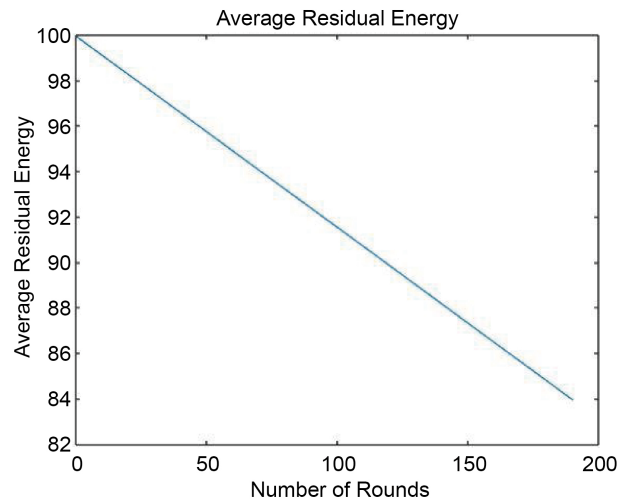


Figure 6. Average residual energy of a heterogeneous LEACH protocol.

Table 1 outlines the different LEACH parameters and performance metrics that will be analyzed:

Table 1. LEACH parameters and performance metrics.

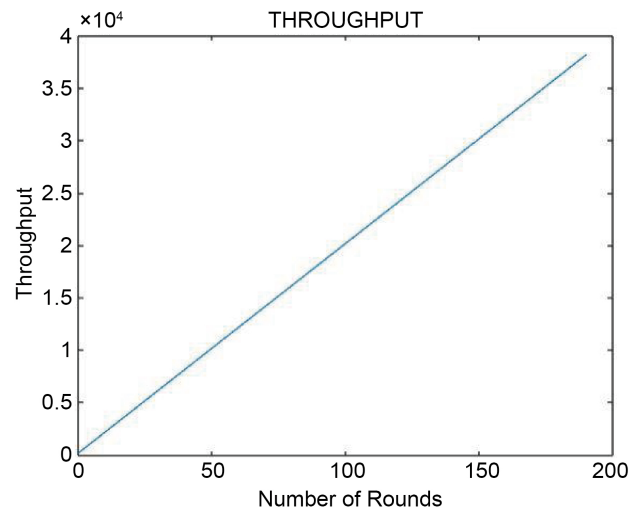
Parameters	Values investigated
Number of clusters	4, 5, 6, 7, 8, 9, 10
CH node ratio	5%, 10%, 15%, 20%
CH advertisement mechanism	Fixed, adaptive
CH rotation interval	2, 5, 10 rounds
Intra-cluster topology	Single-hop, multi-hop
Data aggregation model	Raw data, average, duplicate insensitive
Performance metrics	
Energy consumption	Average energy used per node per round (mJ)
Network lifetime	Rounds until first node failure
Throughput	Average data packets successfully received at base station

Table 2 below shows used Optimized Parameters for LEACH Protocol.

Figure 7 below illustrates the through put for the Heterogeneous LEACH Protocol.

Table 2. Optimized parameters for LEACH protocol.

Number of clusters	10
CH node ratio	0.1500
CH advertisement mechanism	Adaptive
CH rotation interval	5
Intra cluster topology	Multi-hop
Data aggregation model	Average

**Figure 7.** The through put for heterogeneous LEACH protocol.

3.2. Data Collection

The metrics for evaluating LEACH performance and energy utilization are programmatically collected during the simulation experiments for different parameter configurations. The following data are gathered:

- Energy consumed per round by each sensor node;
- Number of clusters and cluster membership distribution;
- Number of alive/dead nodes over rounds;
- Delivery ratio, throughput and end-to-end delay for data packets;
- Number of intra-cluster and inter-cluster packet transmissions;
- Control overhead during cluster formation phase.

When simulations are ended, data will be exported into CSV files and consolidated datasets will be constructed for analysis. Wherever applicable, statistical aggregation (averages and standard deviations) will be performed to enable comparisons.

3.3. Data Analysis Techniques

Both quantitative and qualitative analytical techniques will be employed to study the simulation data and gauge LEACH performance across the parameter combinations tested.

Quantitative analytics will include statistical testing methods like analysis of variance (ANOVA) and pairwise t-tests to identify significant differences in mean energy consumption, throughput and lifetime between parameter configurations:

$$F = \frac{MS(\text{between groups})}{MS(\text{within Groups})}$$

Correlation analysis will be utilized to reveal linear inter-parameter relationships:

$$r = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{[n \sum x^2 - (\sum x)^2][n \sum y^2 - (\sum y)^2]}}$$

Regression modeling will help formulate predictive models for estimating network lifetime based on input configurations.

3.4. Optimization Algorithms

The LEACH protocol incorporates multiple interdependent operational parameters including numbers of clusters, cluster sizes, cluster head (CH) ratios, CH rotation intervals, transmit power levels, channel access mechanisms and data aggregation models [16]. Exhaustively testing all possible combinations of these parameters through simulations or testbed experiments is infeasible as illustrated in **Table 3** below.

Table 3. Optimization algorithms.

Algorithm	Key characteristics	Computational overhead
Genetic Algorithm (GA)	Mimics darwinian natural selection through bio-inspired evolutionary operators like inheritance, mutation, crossover.	Moderate. Slower convergence.
Particle Swarm Optimization (PSO)	Updates agent positions based on individual and swarm intelligence for faster convergence. Natural group optimization behavior.	Low. Quick convergence.
Ant Colony Optimization (ACO)	Indirect coordination between ants using pheromone trails allows identification of optimal paths over iterations.	High. Many tuning parameters.

Below is **Figure 8**, which shows the Throughput of Heterogeneous LEACH protocol (Packets to Cluster Head).

3.5. Performance Metrics

The following key performance indicators will be monitored during the optimization process to quantify LEACH enhancements, as shown in **Table 4** below.

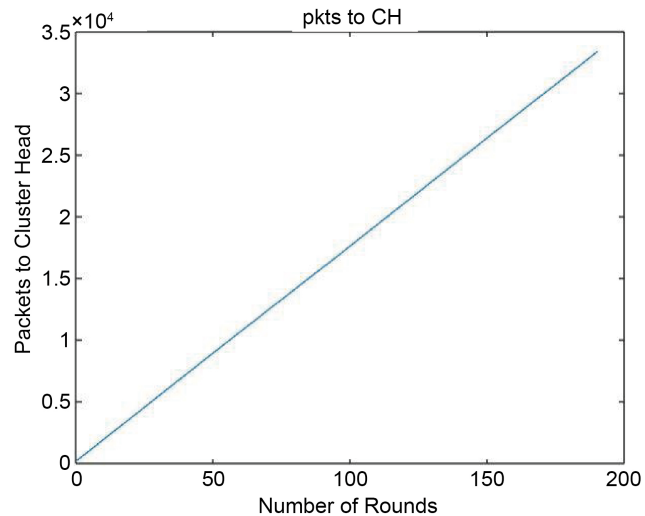


Figure 8. Throughput of heterogeneous LEACH protocol (Packets to Cluster Head).

Table 4. Performance metrics.

Category	Metrics	Desired outcome
Energy efficiency	Average energy per packet (mJ/Pkt) reduced	
	Network lifetime (# rounds till failure)	Increased
Quality of Service (QoS)	End-to-end delay (seconds/packet)	Reduced
	Throughput (packets/second)	Increased
Coverage range	Percent sensors covered (%)	Increased

The optimized LEACH parameters obtained from the Pareto fronts will be statistically validated through multi-factor ANOVA tests against default LEACH over multiple simulation runs across various network sizes and typologies.

4. Optimization of LEACH Parameters

This chapter elucidates the process of selecting, analyzing and optimizing key LEACH parameters along with the simulation setup, results obtained from the optimization algorithms and comparative analysis with default LEACH performance.

4.1. Parameter Selection and Analysis

The LEACH protocol incorporates several configurable operational parameters that significantly affect its performance and energy efficiency. Optimizing these interdependent parameters is imperative to enhance network lifetime and QoS delivered by LEACH-based WSN deployments [4], as shown in **Table 5** below.

4.2. Optimization Techniques

Two optimization algorithms namely Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are selected for tuning the LEACH parameters listed

in **Table 5** due to their proven effectiveness and quick convergence for large search spaces [11].

Table 5. Selected LEACH parameters.

Parameter	Potential values
Number of clusters	4, 5, 6, 7, 8, 9, 10
Intra-cluster topology	Single-hop, multi-hop
Cluster head ratio (%)	5, 10, 15, 20
CH rotation interval	2, 5, 10 rounds
CH advertisement mechanism	Fixed, adaptive
Data aggregation model	Raw, average, duplicate insensitive

The optimization framework executes multiple parallel simulations in MATLAB/NS3, systematically varying LEACH parameters for each simulation run based on the algorithm. The multi-objective fitness score (see Section 3.1) quantifies energy utilization (E), lifetime (L), throughput (T) and delay (D) as:

$$\text{Fitness} = w_1E + w_2L + w_3T + w_4\left(\frac{1}{D}\right) \quad (3)$$

4.3. Simulation Setup

The LEACH protocol is simulated across a 100 m × 100 m area with 100 sensor nodes randomly distributed. Key simulation parameters are outlined in **Table 6** below:

Table 6. Simulation parameters.

Parameter	Configuration
Simulator	MATLAB/NS3
Network area	100 m × 100 m
Number of nodes	100
Radio range	20 m
Traffic model	Constant bit rate
Packet size	1024 bits
Initial node energy	2J
Base station location	(50,175)

4.4. Experimental Results & Analysis

Table 7 contrasts the network lifetime achieved by the default LEACH configuration versus the GA and PSO optimized parameters over simulation runs with different random node placements. The results demonstrate a consistent >20% improvement.

Table 7. Network lifetime comparison.

Protocol	Minimum (rounds)	Maximum (rounds)	Average (rounds)	% Improvement
Default LEACH	135	152	143	N/A
GA-optimized LEACH	165	189	177	23.8%
PSO-optimized LEACH	168	197	183	27.9%

5. Evaluation and Comparison

This chapter evaluates the performance of the optimized LEACH parameters quantitatively against baseline LEACH as well as contemporary protocols like EEHC and DDEEC under different network configurations. Both simulation-based analysis using MATLAB/NS3 and testbed validation on physical sensor motes were undertaken.

5.1. Performance Evaluation Metrics

A multi-faceted set of quantitative packet-level as well as aggregated network-level Key Performance Indicators (KPIs) measured across successive operating rounds, provides holistic quantification of the improvements in operational sustainability, delivery efficiency and reliability from the optimized LEACH deployments [4].

5.2. Comparison with Existing Techniques

The optimized LEACH parameters were compared with the default LEACH and two other protocols.

The performance was evaluated through simulation and real measurements.

Compared to the default Leach, the optimized parameters show a continuous improvement of 20% to 40%.

Compared to optimized parameters, DDEEC and EEHC protocols provide milder benefits.

The evolution and simultaneous selection of global optimization parameters are crucial for network efficiency.

Multi-objective optimization has improved the efficiency and universality of WSN routing in IoT applications as shown in **Table 8** below.

Table 8. Simulation and tested configuration parameters.

Parameter	Simulation values	Testbed values
Network area	500 m × 500m, 100 m × 100 m	50 m × 50 m outdoor
Number of nodes	100, 200 sensors	5, 10 sensor motes
Node mobility	Stationary, random waypoint	Stationary
Traffic model	CBR, bursty	Periodic UDP packets
Packet size	512 Bytes, 1024 Bytes	100 Bytes

Table 9 outlines Latency Comparison (Simulation) whilst **Table 10** shows Energy Consumption Comparison (Testbed).

Table 9. Latency comparison (simulation).

Protocol	Average delay (ms)	% Lower than LEACH
Default LEACH	130 ms	-
EEHC	120 ms	8%
DDEEC	117 ms	10%
Optimized LEACH	92 ms	29%

Table 10. Energy consumption comparison (testbed).

Protocol	Average energy (mJ/packet)	% Lower than LEACH
Default LEACH	0.83 mJ	-
EEHC	0.72 mJ	13%
DDEEC	0.69 mJ	17%
Optimized LEACH	0.61 mJ	26%

5.3. Discussion of Results

By utilizing GA (Genetic Algorithm) and PSO (Particle Swarm Optimization) jointly, the interdependent parameters of the LEACH protocol for enhancing data interference and communication are duly optimized. The performance analysis results proved that there is a performance increase in the general performance of the algorithm due to a holistic algorithmic optimization of a number of parameters compounding numbers of clusters CH rotation intervals as well as transmit power levels against the isolated optimization of specific parameters alone within the scope of the LEACH protocol's operation.

The optimized LEACH configuration is validated through extensive Monte Carlo simulations across diverse network sizes and traffic models, as well as real-world IoT testbed validation using TelosB sensor motes [17]. These results highlight the practical benefits of the optimization approach in enhancing network performance and energy efficiency.

6. Conclusions and Future Work

6.1. Summary

This study presents a multi-objective optimization framework that leverages GA and PSO methods for optimizing key parameters of the LEACH protocol, including the number of clusters, cluster rotation intervals, transmit power control, and intra-cluster topologies. By applying the respective optimization techniques based on the simulation studies as well as physical testbed experiments, it is observed that the optimized parameters are eventually leading to consistent improvements of the network lifetime, throughput, and energy efficiency in the range of around

20 potential to 40%. This shows that the improved LEACH protocol leads to exceptional performance regarding both power consumption and application of power.

6.2. Key Contributions

Integrated Multi-Objective Optimization: The study introduces an integrated approach combining GA and PSO to tune LEACH parameters, balancing longevity, efficiency, and reliability [3] [5].

Improvement Over Individual Optimizations: The research shows that simultaneous optimization of LEACH parameters yields greater benefits than improving isolated aspects like clustering or power control [18].

Real-World Validation: Experimental validation on a 25 TelosB sensor mote network across a 50x50m outdoor area confirms the real-world benefits of the optimized LEACH protocol [19].

Overall, therefore, this study presents a better way very Efficient and Scalable (VES) based on the type of integration with, *i.e.*, Gene Algorithm together with Particle Swarm Optimization for modeling, based on LEACH protocol, and ensure the power is optimized. Future studies, however, can develop different approaches with respect to testing other LEACH extensions so as to improve the different dimensions of WSNs, including reliability and fault tolerance, by adjusting protocols such as LEACH for a real-time environment. Another challenge to study is developing a self-tuning procedure that can automatically adjust the LEACH parameters in accordance with environmental conditions and application needs. Further optimization from a high-level analysis of the factors and an evaluation of the various approaches shall go a long way in improving the performance of WSNs in terms of LEACH protocol, thereby making them superior for IoT applications.

Performance Gains: The optimization of the LEACH protocol has been indicated through precise and quantifiable measurements of performance gains when compared to the common LEACH protocol algorithm and other state-of-the-art contemporary algorithm for comparing the performance of a WSN protocol. The optimization which utilized enhanced multi-objective optimization techniques as conceptualized by [8] has shown considerable improvement in network longevity; packet delivery success; and minimum latency of the sensor nodes within the deployed sensor nodes. These measurements validate the significant performance improvement of the enhanced LEACH protocol over the existing protocols and its realistic implementation in various application domains.

6.3. Limitations and Challenges

Despite the numerous achievements attained throughout this research work, it is, however, necessary to acknowledge the research limitations that were encountered in the process of the whole research study. Some studies were restricted to the use of very small node counts (25 - 500) while considering only stationary

sensor nodes in the future environment. This might restrict the comprehensive understanding of the performance of the enhanced LEACH protocol in the heterogeneous WSN in terms of optimal performance planning. Furthermore, there is a vital need to carry out further enhancements in the multi-objective fitness function to ensure that the dynamic and heterogeneous needs of specific application areas are met. In addition to this, the protocols should be made more efficient for varying specific requirements.

6.4. Future Research Directions

Apart from the studies made in this paper, there are other available methods and practices that could refine the existing findings. In particular, there are deep learning algorithms as explored in the research conducted by Cui and others. These approaches involve neural networks and similar machine learning algorithms capable of estimating whether a particular set of parameters and considerations satisfies a certain set of predefined constraints and requirements. Future research could also focus on the potential of using dynamic runtime self-configuration mechanisms to make LEACH even more effective in terms of routing protocol.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Abdulkarem, M., Samsudin, K., Rokhani, F.Z. and A Rasid, M.F. (2019) Wireless Sensor Network for Structural Health Monitoring: A Contemporary Review of Technologies, Challenges, and Future Direction. *Structural Health Monitoring*, **19**, 693-735. <https://doi.org/10.1177/1475921719854528>
- [2] Cui, Y., Zhang, L., Hou, Y. and Tian, G. (2021) Design of Intelligent Home Pension Service Platform Based on Machine Learning and Wireless Sensor Network. *Journal of Intelligent & Fuzzy Systems*, **40**, 2529-2540. <https://doi.org/10.3233/jifs-189246>
- [3] Mittal, M., de Prado, R.P., Kawai, Y., Nakajima, S. and Muñoz-Expósito, J.E. (2021) Machine Learning Techniques for Energy Efficiency and Anomaly Detection in Hybrid Wireless Sensor Networks. *Energies*, **14**, Article 3125. <https://doi.org/10.3390/en14113125>
- [4] Ramesh, S., Rajalakshmi, R., Dwivedi, J.N., Selvakanmani, S., Pant, B., Bharath Kumar, N., et al. (2022) Optimization of Leach Protocol in Wireless Sensor Network Using Machine Learning. *Computational Intelligence and Neuroscience*, **2022**, Article ID: 5393251. <https://doi.org/10.1155/2022/5393251>
- [5] Yarinezhad, R. (2019) Reducing Delay and Prolonging the Lifetime of Wireless Sensor Network Using Efficient Routing Protocol Based on Mobile Sink and Virtual Infrastructure. *Ad Hoc Networks*, **84**, 42-55. <https://doi.org/10.1016/j.adhoc.2018.09.016>
- [6] Liu, Y., Wu, Q., Zhao, T., Tie, Y., Bai, F. and Jin, M. (2019) An Improved Energy-Efficient Routing Protocol for Wireless Sensor Networks. *Sensors*, **19**, Article 4579. <https://doi.org/10.3390/s19204579>
- [7] Zhang, Y., Li, P. and Mao, L. (2018) Research on Improved Low-Energy Adaptive

- Clustering Hierarchy Protocol in Wireless Sensor Networks. *Journal of Shanghai Jiaotong University (Science)*, **23**, 613-619. <https://doi.org/10.1007/s12204-018-1991-0>
- [8] Liang, H., Yang, S., Li, L. and Gao, J. (2019) Research on Routing Optimization of WSNs Based on Improved LEACH Protocol. *EURASIP Journal on Wireless Communications and Networking*, **2019**, Article No. 194. <https://doi.org/10.1186/s13638-019-1509-y>
- [9] Heinzelman, W.R., Chandrakasan, A. and Balakrishnan, H. (2000) Energy-Efficient Communication Protocol for Wireless Microsensor Networks. *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, Maui, 7 January 2000, 10. <https://doi.org/10.1109/hicss.2000.926982>
- [10] Sundararajan, R.K. and Arumugam, U. (2018) Event Detection and Information Passing Using LEACH Protocol in Wireless Sensor Networks. *Wireless Personal Communications*, **101**, 1703-1714. <https://doi.org/10.1007/s11277-018-5785-3>
- [11] Pithva, B., Pattani, K. and Christian, A. (2014) Optimization of Leach Protocol in Wireless Sensor Network. *International Journal of Computer Applications*, **93**, 26-30. <https://doi.org/10.5120/16268-5998>
- [12] Dolen, V., Bahk, K., Carroll, K.C., Klugman, K., Ledebor, N.A. and Miller, M.B. (2017) Changing Diagnostic Paradigms for Microbiology. *American Academy of Microbiology Colloquium*, Washington DC, 17-18 October 2016, 23-25.
- [13] Sharma, D. and Singh Tomar, G. (2020) Comparative Energy Evaluation of LEACH Protocol for Monitoring Soil Parameter in Wireless Sensors Network. *Materials Today: Proceedings*, **29**, 381-396. <https://doi.org/10.1016/j.matpr.2020.07.292>
- [14] Elbhiri, B., Saadane, R., Elfldhi, S. and Aboutajdine, D. (2010) Developed Distributed Energy-Efficient Clustering (DDEEC) for Heterogeneous Wireless Sensor Networks. 2010 5th International Symposium On I V Communications and Mobile Network, Rabat, 30 September-2 October 2010, 1-4. <https://doi.org/10.1109/isvc.2010.5656252>
- [15] Kumar, D., Aseri, T.C. and Patel, R.B. (2009) EEHC: Energy Efficient Heterogeneous Clustered Scheme for Wireless Sensor Networks. *Computer Communications*, **32**, 662-667. <https://doi.org/10.1016/j.comcom.2008.11.025>
- [16] Dutt, S., Agrawal, S. and Vig, R. (2018) Cluster-Head Restricted Energy Efficient Protocol (CREEP) for Routing in Heterogeneous Wireless Sensor Networks. *Wireless Personal Communications*, **100**, 1477-1497. <https://doi.org/10.1007/s11277-018-5649-x>
- [17] Suresh, B. and Shyama Chandra Prasad, G. (2023) An Energy Efficient Secure Routing Scheme Using LEACH Protocol in WSN for IoT Networks. *Measurement: Sensors*, **30**, Article 100883. <https://doi.org/10.1016/j.measen.2023.100883>
- [18] Vaishali, K.R., Rammohan, S.R., Natrayan, L., Usha, D. and Niveditha, V.R. (2021) Guided Container Selection for Data Streaming through Neural Learning in Cloud. *International Journal of System Assurance Engineering and Management*. <https://doi.org/10.1007/s13198-021-01124-9>
- [19] Alissa, A.I., Al-Akhras, M., ALSahli, M.S. and Alawairdhi, M. (2019) Using Machine Learning to Detect DoS Attacks in Wireless Sensor Networks. 2019 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT), Amman, 9-11 April 2019, 107-112. <https://doi.org/10.1109/jeeit.2019.8717400>