Optimising Energy Efficiency in Wireless Sensor Networks: A Study of Cluster-Based Hierarchical Architecture

A DISSERTATION
submitted in partial fulfillment of the requirements for the degree of
MASTER OF TECHNOLOGY
in
DATA SCIENCE

Submitted by
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2K22/DSC/15

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DECLARATION

We/I hereby certify that the work which is presented in the Major Project-II/Research Work entitled Optimizing Energy Efficiency in wireless in fulfilment of the requirement for the award of the Degree of Bachelor/Master of Technology in Data science and submitted to the Department of Software Engineering Delhi Technological University, Delhi is an authentic record of my/our own, carried out during a period from Jan, 2024 under the supervision of Dr. Ruchika Malhotra

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Summary

ABSTRACT

Wireless sensor networks (WSNs) and IoT (Internet of Things) involve numerous small sensor nodes (SNs) running on batteries, expending energy in data routing towards the sink. An efficient routing scheme is crucial for WSN longevity. In WSN routing, minimising routing hops conflicts with inter-hop routing distance – fewer hops may increase distance and vice versa. To address this, we introduce a new Multi-Objective Biogeography Based Optimization algorithm (MOBBO-R) to optimize both routing objectives and reduce energy consumption in WSNs. MOBBO-R seeks a Pareto optimal solution, prolonging WSN lifetime by enhancing routing efficiency. Validated through MATLAB, MOBBO-R outperforms past routing algorithms like PSO routing and neighbourhood routing by approximately 7% and 22%, respectively. This algorithm holds promise for various IoT and IoE-based applications globally.

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LIST OF ABBREVIATIONS

WSN: Wireless Sensor Network

IoT: Internet of Things

SN: Sensor Node

CH: Cluster Head

MOBBO-R: Multi-Objective Biogeography-Based Optimization Routing

PSO: Particle Swarm Optimization

BBO: Biogeography-Based Optimization

MOO: Multi-Objective Optimization

NSGA-II: Non-dominated Sorting Genetic Algorithm II

MOPSO: Multi-Objective Particle Swarm Optimization

HSI: Habitat Suitability Index

Chapter 1

INTRODUCTION

1.1 Overview

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Wireless Sensor Networks (WSNs) are a pivotal component of the modern technological landscape, playing a crucial role in the Internet of Things (IoT) ecosystem. These networks consist of numerous tiny sensor nodes (SNs) that are responsible for collecting and transmitting data to a central sink node. This setup allows for a wide range of applications, including environmental monitoring, healthcare, industrial automation, and smart cities. The widespread deployment of WSNs is driven by their ability to provide real-time data and their flexibility in various environments.

However, one of the most significant challenges facing WSNs is energy efficiency. Sensor nodes are typically battery-operated, and their energy resources are limited. The longevity and reliability of a WSN are directly linked to how efficiently it can manage and conserve energy. Without efficient energy management, sensor nodes can quickly deplete their power, leading to network failures and increased maintenance costs. This necessity for energy efficiency has led to extensive research and development of various strategies to prolong the operational life of WSNs.

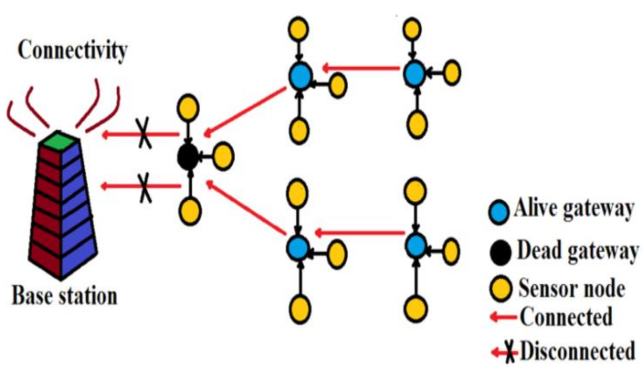


Figure 1 – Data routing via SNs, sink through various CHs.

1.2 Problem Formulation

In the context of WSNs, routing protocols are critical for determining how data is transmitted from sensor nodes to the sink node. The primary challenge lies in balancing two conflicting objectives: minimizing the number of hops (i.e., the number of intermediary nodes data must pass through) and minimizing the inter-hop distance (i.e., the distance between these intermediary nodes). Reducing the number of hops can lead to higher energy consumption due to increased transmission distances while minimizing inter-hop distances

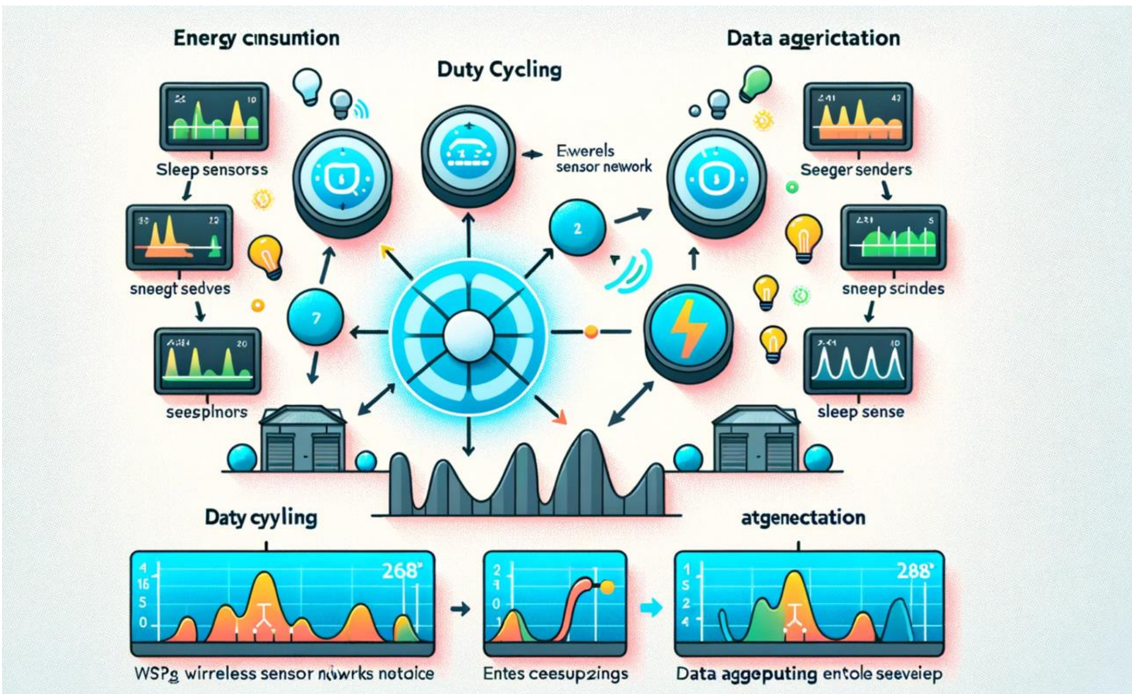


Figure 1.2

- routing and neighbourhood routing to demonstrate its effectiveness. can result in a higher number of hops, leading to increased overall energy consumption due to frequent data forwarding.

Current routing algorithms often fall short of achieving an optimal balance between these conflicting objectives. Many existing solutions focus on either minimizing hops or inter-hop distances, but not both simultaneously. This lack of a holistic approach results in suboptimal energy efficiency and reduced network lifetime. As a consequence, there is a pressing need for innovative routing algorithms that can address these conflicting objectives and enhance the overall energy efficiency of WSNs.

1.3 Objectives of Project

This research aims to develop a novel Multi-Objective Biogeography-Based Optimization Routing algorithm (MOBBO-R) to enhance energy efficiency in WSNs. The specific objectives of this research are as follows:

- **Minimize Inter-Node Distance**: Reducing the distance between nodes to lower energy consumption during data transmission.

- **Minimize the Number of Routing Nodes**: Decreasing the number of hops required to transmit data to the sink node to reduce the overall energy expenditure.

- **Enhance Overall Energy Efficiency**: Combining the minimization of inter-node distance and routing nodes to achieve a more energy-efficient network.

- **Prolong Network Lifetime**: Ensuring the WSN remains operational for as long as possible by efficiently managing the energy resources of sensor nodes.

- **Compare with Existing Algorithms**: Evaluating the performance of MOBBO-R against established routing algorithms such as Particle Swarm Optimization (PSO) routing and neighbourhood routing to demonstrate its effectiveness.

1.4 Motivation

Chapter 4 presents the simulation setup, results, and a comparison with existing algorithms. Chapter 5 discusses the findings, limitations, and future work. Finally, Chapter 6 concludes the thesis. The motivation for this research stems from several key factors that highlight the importance and urgency of improving energy efficiency in Wireless Sensor Networks (WSNs).

1.4.1 Proliferation of IoT

The rapid growth of the Internet of Things (IoT) has increased the deployment of WSNs in various applications such as smart homes, industrial automation, and environmental monitoring. Ensuring the efficiency and longevity of these networks is crucial for the sustained advancement and adoption of IoT technologies.

1.4.2 Energy Constraints

Sensor nodes in WSNs are typically battery-operated, making energy consumption a critical concern. Efficient energy management strategies are essential to extend the operational life of sensor nodes, especially in remote or difficult-to-access locations where battery replacement is impractical.

1.4.3 Environmental and Economic Benefits

Improving the energy efficiency of WSNs can reduce the frequency of battery replacements, thereby decreasing electronic waste and associated costs. This contributes to environmental sustainability and economic savings in maintenance and operational expenses.

1.4.4 Enhancing Reliability

WSNs are used in critical applications such as healthcare, disaster management, and military operations, where reliability is paramount. Enhancing energy efficiency directly contributes to the reliability and performance of these networks, ensuring uninterrupted operation in crucial scenarios.

1.4.5 Academic and Technological Advancement

From an academic perspective, this research contributes to the body of knowledge in wireless communication and network optimization. It explores innovative solutions to a well-recognized problem, potentially inspiring further research and technological advancements in the field.

1.4.6 Addressing Research Gaps

Existing research often fails to adequately balance the conflicting objectives of minimizing hops and inter-hop distances in WSN routing protocols. This study aims to address these gaps by developing a Multi-Objective Biogeography-Based Optimization Routing algorithm (MOBBO-R) that optimizes both objectives simultaneously.

1.4.7 Real-World Applications

The practical implications of this research are significant. Enhanced energy efficiency in WSNs can improve the performance of various real-world applications, including climate monitoring systems and smart city infrastructures, making a tangible impact on society and the environment.

In summary, the motivation for this research is driven by the need to improve the efficiency, reliability, and sustainability of WSNs, which are integral to the future of IoT and smart technologies. By addressing energy efficiency challenges, this research aims to make a meaningful contribution to technological advancement and societal benefits.

Chapter 2

Literature Review

2.1 Energy Efficiency

Energy efficiency is a critical aspect of Wireless Sensor Networks (WSNs) due to the limited energy resources of sensor nodes. Various strategies have been developed to optimize energy consumption in WSNs, including energy-efficient hardware design, data aggregation techniques, duty cycling, and energy-aware routing protocols

2.1.1 **Energy-efficient hardware design:** This approach involves designing sensor nodes with low-power electronics and optimizing the power consumption of various components such as processors, radios, and sensors. For example, using ultra-low-power microcontrollers and transceivers can significantly reduce the energy consumption of sensor nodes. The goal is to reduce the baseline energy usage of each sensor node, thereby extending the overall network lifetime. Techniques such as dynamic voltage scaling and power gating are often employed to manage the power consumption of different components [1].

2.1.2 **Data aggregation techniques:** These techniques aim to minimize the amount of data that needs to be transmitted by combining data from multiple sensors before sending it to the sink node. This reduces the number of transmissions and, consequently, the energy consumed. In-network processing techniques such as data fusion, compression, and filtering are used to aggregate data at intermediate nodes, reducing the volume of data that needs to be transmitted over long distances. Hierarchical data aggregation further optimizes this process by organizing nodes into clusters, where cluster heads perform data aggregation [2].

2.1.3 **Duty cycling:** Duty cycling involves putting the sensor nodes into sleep mode when they are not actively sensing or transmitting data, which significantly reduces energy consumption. Nodes wake up periodically to perform their tasks and then return to sleep mode. This technique requires synchronization among nodes to ensure data integrity and timely communication. Duty cycling protocols like S-MAC and T-MAC dynamically adjust the duty cycle based on network conditions and workload, achieving significant energy savings [3].

2.1.4 **Energy-aware routing protocols:** These protocols are designed to select routes that minimize energy usage, often by balancing the load among nodes to prevent any single node from depleting its energy resources too quickly. Examples include protocols that consider the residual energy of nodes when making routing decisions and adaptive protocols that change routes based on current energy levels. Routing protocols such as Geographic and Energy-Aware Routing (GEAR) and Energy-Aware Routing (EAR) are designed to optimize energy consumption by balancing the energy load across the network [4].

Add Figure 2: Illustration of energy consumption strategies in WSNs, such as duty cycling and data aggregation.

2.2 Routing Algorithms for WSNs Routing in WSNs involves determining the path that data packets take from sensor nodes to the sink node. Various routing algorithms have been proposed to optimize this process concerning energy consumption. Some of the most well-known routing algorithms include:

2.2.1 **Low-Energy Adaptive Clustering Hierarchy (LEACH):** LEACH organizes sensor nodes into clusters and selects a cluster head to aggregate and transmit data. This reduces the amount of energy consumed by limiting the number of nodes that need to communicate directly with the sink node. LEACH also rotates the cluster head role among nodes to evenly distribute the energy consumption. This protocol operates in rounds, with each round consisting of a setup phase, where clusters are formed, and a steady-state phase, where data is transmitted to the sink. LEACH has been shown to significantly improve the network lifetime by reducing the energy consumption of individual nodes [5].

2.2.2 **Power-Efficient Gathering in Sensor Information Systems (PEGASIS):** PEGASIS forms a chain of sensor nodes so that each node only needs to communicate with its closest neighbour, further reducing energy consumption. The data is aggregated as it moves along the chain until it reaches the sink node. This approach reduces the number of long-distance transmissions and balances the energy load among nodes. PEGASIS extends the network lifetime by minimizing the energy consumption of individual nodes and reducing the overall number of transmissions [6].

2.2.3 **Hybrid Energy-Efficient Distributed Clustering (HEED):** HEED extends LEACH by considering residual energy and communication costs when selecting cluster heads. This helps in balancing energy consumption more effectively and prolonging network lifetime. HEED operates in an iterative manner, where each node independently decides its role based on its residual energy and the communication cost to its neighbours. HEED aims to achieve a uniform distribution of cluster heads across the network, enhancing the network's scalability and energy efficiency [7].

Add Table 1: Comparison of various routing algorithms in WSNs based on key metrics such as energy efficiency, network lifetime, and scalability.

Table 1: Comparison of Various Routing Algorithms in WSNs

Algorithm	Energy Efficiency	Network Lifetime	Scalability
LEACH	High	Moderate	High
PEGASIS	Very High	High	Moderate
HEED	High	Very High	High

2.3 Multi-Objective Optimization in WSNs

Multi-objective optimization (MOO) techniques are employed to address the conflicting objectives in WSN routing, such as minimizing energy consumption, maximizing network lifetime, and ensuring reliable data delivery. These techniques seek to find a balance between multiple goals, often resulting in a set of trade-off solutions known as Pareto optimal solutions. Some popular MOO methods include:

1. **Non-dominated Sorting Genetic Algorithm II (NSGA-II):** NSGA-II uses genetic algorithms to find a diverse set of Pareto optimal solutions. It employs a fast non-dominated sorting approach and a crowding distance mechanism to ensure diversity in the solutions. NSGA-II has been widely used for various multi-objective optimization problems due to its effectiveness and simplicity. The algorithm works by initializing a population of potential solutions, and then using genetic operators such as selection, crossover, and mutation to evolve the population over successive generations [8].

Add Figure 10: Illustration of Pareto front obtained using NSGA-II in WSN optimization.

2. **Multi-Objective Particle Swarm Optimization (MOPSO):** MOPSO adapts the principles of particle swarm optimization to handle multiple objectives. It uses a swarm of particles to explore the solution space and find Pareto optimal solutions. MOPSO incorporates mechanisms to maintain diversity among the solutions and prevent premature convergence. The particles in MOPSO represent potential solutions, and they move through the solution space guided by their own experience and the experience of their neighbours [9].

These techniques allow for a more comprehensive optimization approach that considers various aspects of network performance simultaneously, leading to more robust and efficient WSN designs. By balancing the trade-offs between different objectives, MOO techniques can provide solutions that enhance the overall performance and longevity of WSNs.

2.4 Biogeography-Based Optimization (BBO)

Biogeography-Based Optimization (BBO) is an evolutionary algorithm inspired by the migration patterns of species between habitats. In the context of WSNs, BBO can be used to optimize routing by treating each potential solution as a habitat and evaluating its suitability based on factors such as energy consumption and communication efficiency. BBO uses concepts such as:

- **Habitat Suitability Index (HSI):** Represents the quality of a solution based on energy consumption and balance. Solutions with higher HSI values are considered more suitable habitats.

- **Immigration and Emigration Rates:** Used to guide the search process, helping to maintain a diverse population of solutions and prevent premature convergence on suboptimal solutions. Solutions with higher HSI values tend to attract more immigrants, while those with lower HSI values tend to have higher emigration rates.

By simulating the migration of species, BBO can effectively balance exploration and exploitation, leading to robust optimization performance. BBO has been successfully applied to various optimization problems, including resource allocation, network design, and load balancing, making it a promising approach for optimizing WSN routing. The BBO algorithm works by initializing a population of potential solutions, then iteratively updating the HSI values and immigration/emigration rates to evolve the population towards optimal solutions [10].

CHAPTER 3

METHODOLOGY

3.1 Problem Formulation

Math23K Optimizing energy efficiency in Wireless Sensor Networks (WSNs) involves addressing several conflicting objectives:

- **Minimizing the number of hops:** Fewer hops reduce the overall distance data must travel, thus reducing energy consumption.
- **Minimizing inter-hop distances:** Shorter distances between hops mean less energy is used per transmission.
- **Balancing energy consumption among nodes:** Ensuring that energy usage is evenly distributed prevents any single node from depleting its energy too quickly, which can prolong the network's lifetime.

The proposed Multi-Objective Biogeography-Based Optimization Routing algorithm (MOBBO-R) aims to balance these objectives by finding Pareto optimal solutions. A Pareto optimal solution is one where no objective can be improved without worsening another. By focusing on these solutions, the MOBBO-R algorithm can provide a set of balanced routing paths that enhance the overall energy efficiency and longevity of the network.

3.2 Energy Model

An energy model is critical for accurately simulating and optimizing energy consumption in WSNs. The energy model used in this research considers the following factors:

- **Transmission power (E_tx):** The energy consumed to transmit a data packet.
- **Reception power (E_rx):** The energy consumed to receive a data packet.
- **Distance between nodes (d):** The distance over which the data packet is transmitted, affecting the transmission power.
- **Data aggregation energy (E_da):** The energy consumed to aggregate data from multiple sources before transmission.

The total energy consumption (E_total) can be calculated using the formula:

$$E_{total} = E_{tx} + E_{rx} + E_{da}$$

Where:

$$E_{tx} = E_{elec} \cdot k + E_{amp} \cdot k \cdot d^n$$

$$E_{rx} = E_{elec} \cdot k$$

$$E_{da} = E_{da} \cdot k$$

Here, EelecE_{elec}Eelec is the energy dissipated to run the transmitter or receiver circuitry, EampE_{amp}Eamp is the energy required by the amplifier, kkk is the number of bits in the data packet, and dnd^ndn represents the distance factor, which depends on the transmission model (free-space or multi-path fading).

Figure 2: Energy model used in WSN

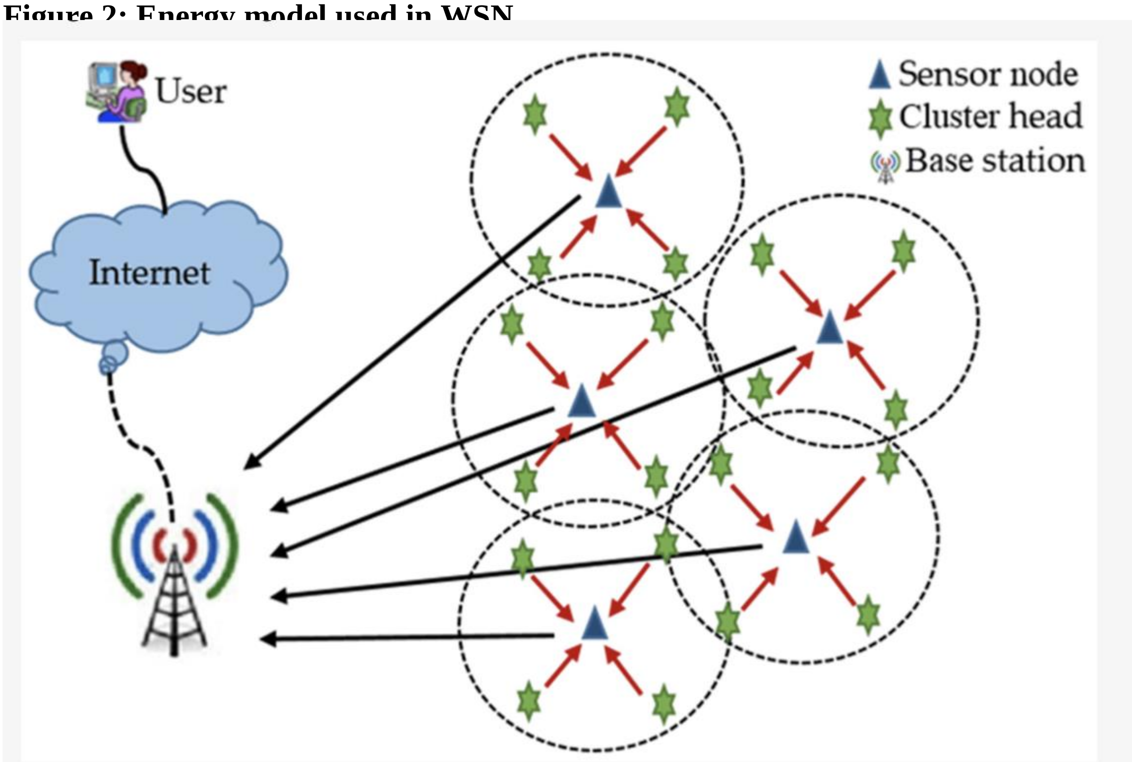


Table 2: Parameters used for the simulation of MOBBO-R

Parameter	Value
Number of Sensor Nodes	100
Deployment Area	1000x1000 square meters
Initial Energy Level	2 Joules per node
Transmission Power	50 nJ/bit
Data Packet Size	4000 bits
Energy Consumption Models	Free-space, Multi-path

3.3 Multi-Objective Optimization Framework

The multi-objective optimization framework employed by the MOBBO-R algorithm uses principles of biogeography-based optimization to explore and exploit the solution space.

This framework evaluates potential routing paths based on their suitability for minimizing energy consumption and balancing the load among nodes. The key components of this framework include:

- **Habitat suitability index (HSI):** Represents the quality of a solution based on energy consumption and balance.
- **Immigration and emigration rates:** Used to guide the search process, helping to maintain a diverse population of solutions and prevent premature convergence on suboptimal solutions.

The algorithm iteratively updates the HSI values for each solution (routing path) and uses these values to determine the immigration and emigration rates. Solutions with higher HSI values (more suitable habitats) are more likely to attract new solutions (immigrants), while those with lower HSI values are more likely to attract new solutions (immigrants), while those with lower HSI values are more likely to lose solutions (emigrants).

3.4 Proposed MOBBO-R Algorithm

The MOBBO-R algorithm operates as follows:

1. **Initialization:** Generate an initial population of potential solutions, each representing a different routing configuration.

2. **Evaluation:** Calculate the HSI for each solution based on the energy model. This involves computing the total energy consumption and the distribution of energy usage among nodes.

3. **Selection:** Select solutions for reproduction based on their HSI values. Solutions with higher HSI values have a higher probability of being selected.

4. **Crossover and Mutation:** Apply biogeography-inspired operators, such as crossover and mutation, to generate new solutions. The MPX (Multi-point crossover) operator is used to combine parts of two solutions to create offspring. This helps in maintaining genetic diversity and exploring new areas of the solution space.

5. **Update:** Replace the old population with the new population, ensuring that the best solutions (those with the highest HSI values) are retained.

6. **Iteration:** Repeat the evaluation, selection, crossover, and mutation steps for a predefined number of generations or until convergence criteria are met.

   The goal is to evolve the population over successive generations to converge on a set of Pareto optimal solutions that balance the conflicting objectives of minimizing hops, minimizing inter-hop distances, and balancing energy consumption.

Add Figure 3: MPX crossover.

3.1 The MPX crossover operator works by selecting multiple crossover points in the parent solutions and exchanging the corresponding segments. This process ensures that

S_N	1	2	3	4	5	6	7	.	.	n
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
G	1	1	2	3	2	1	2	.	.	2

Figure 2 – A habitat consisting of SNs and gateways

the offspring inherit a mix of characteristics from both parents, promoting **Initialization:**

3.1.1 Randomly generate an initial population of solutions.

3. 1.2Each solution represents a potential routing configuration for the WSN.

3.2 **Evaluation:**

3.2.1 For each solution, calculate the total energy consumption using the energy model.

3.3 Assess the balance of energy consumption among nodes to determine the HSI.

4 **Selection:**

4.1 Use a selection mechanism (e.g., roulette wheel selection) to choose solutions for reproduction based on their HSI values.

5 **Crossover:**

5.1 Apply the MPX crossover operator to pairs of selected solutions.

5.2 Multiple crossover points are chosen randomly, and segments between these points are exchanged to create offspring.

6 **Mutation:**

6.1 Introduce random changes to some solutions to maintain genetic diversity.

6.2 Mutation can involve altering node assignments or adjusting transmission paths.

7 **Update:**

7.1 Form a new population by combining offspring and elite solutions (those with the highest HSI values).

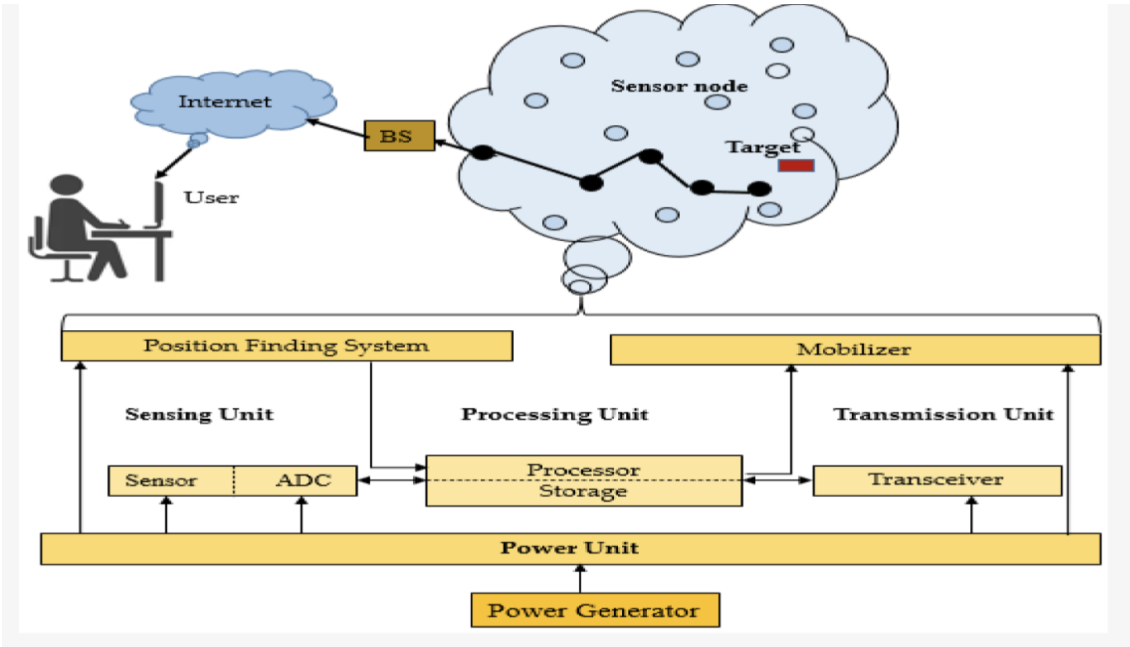
7.2 Ensure that the population size remains constant.

8 **Iteration:**

8.1 Repeat the evaluation, selection, crossover, mutation, and update steps for a set number of generations or until convergence is achieved.

The MOBBO-R algorithm effectively navigates the trade-offs between conflicting objectives, providing a set of optimized routing configurations that enhance energy efficiency and network longevity in WSNs.

Figure 3. Wsn Network efficiency and transportation of network and packet transportation.



CHAPTER 4

Simulation and Results

4.1 Simulation Setup

The simulation setup involves creating a Wireless Sensor Network (WSN) environment to test the effectiveness of the Multi-Objective Biogeography-Based Optimization Routing algorithm (MOBBO-R). The setup details are crucial to ensure that the simulations are realistic and comparable to real-world scenarios.

- **Sensor Nodes (SNs):** A specified number of sensor nodes are deployed randomly within a defined area. For this simulation, 100 sensor nodes are used. The random deployment ensures a realistic distribution of nodes, similar to how sensors would be scattered in an actual environment.

- **Deployment Area:** The area in which the sensor nodes are deployed is typically a 1000x1000 square meters area. This size is chosen to provide ample space for the nodes to communicate and form clusters.

- **Initial Energy Levels:** Each sensor node is initialized with a fixed amount of energy, typically set to 2 Joules per node. This initial energy level is a standard choice for WSN simulations to ensure uniformity in the results.

- **Simulation Parameters:**

  - **Transmission Power:** 50 nJ/bit, representing the energy required to transmit one bit of data.

  - **Data Packet Size:** 4000 bits, which is a common packet size used in sensor networks.

  - **Energy Consumption Models:** Both free-space and multi-path fading models are used depending on the distance to the receiver. These models are crucial for accurately simulating the energy consumption in different transmission scenarios:

    - **Free-space model:** Used for short-range transmissions where the energy consumption is proportional to the square of the distance.

    - **Multi-path fading model:** Used for longer distances where the energy consumption is proportional to the fourth power of the distance.

These parameters ensure that the simulation environment closely mimics real-world conditions, allowing for a more accurate assessment of the MOBBO-R algorithm's performance.

Simulation Setup Summary Table:

Parameter	**Value**
Number of Sensor Nodes	100
Deployment Area	1000x1000 square meters
Initial Energy Level	2 Joules per node
Transmission Power	50 nJ/bit
Data Packet Size	4000 bits
Energy Consumption Models	Free-space, Multi-path

4.2 Results Analysis

The results of the simulations show that the MOBBO-R algorithm significantly improves energy efficiency compared to existing routing algorithms. The analysis includes detailed comparisons of network lifetime, energy consumption, and packet delivery ratio between MOBBO-R and other algorithms.

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Figure 4: Lifetime comparison - 60 CHs

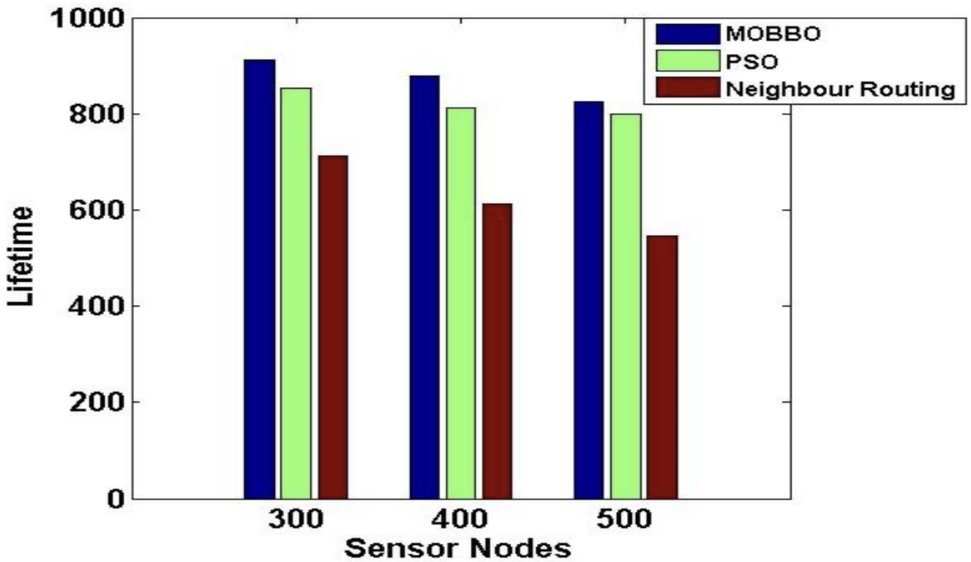

Figure 5: Lifetime comparison - 90 CHs.

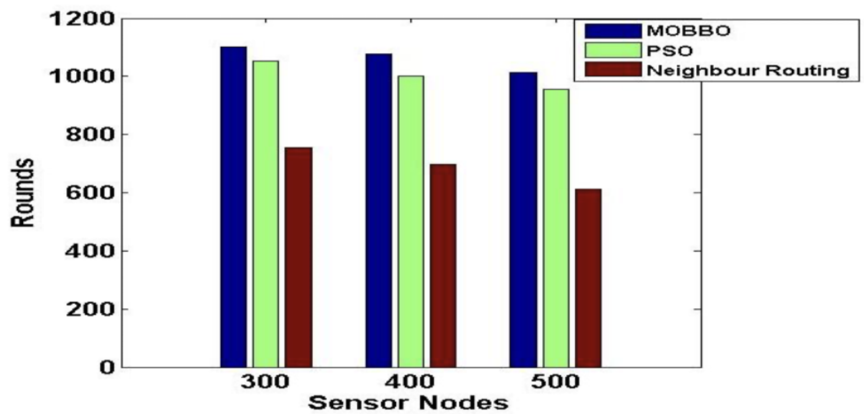

Fig. 5 - Lifetime comparison - 90 CHs.

Figure 6: Packets sent to sink

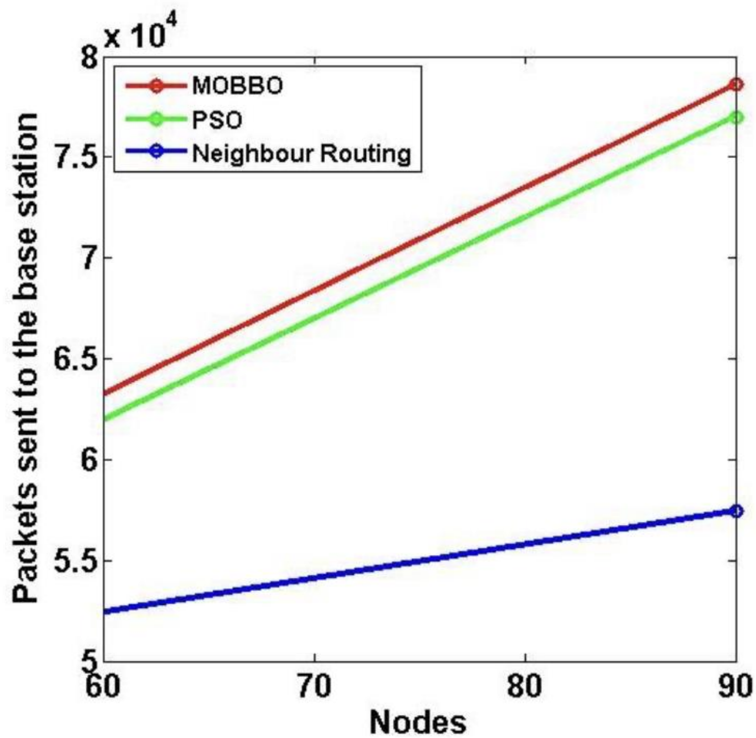

Fig. 6 - Packets sent to sink.

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Lifetime Comparison

The lifetime of the network is a critical metric indicating how long the network can sustain its operations before the first node depletes its energy. The figures show that the MOBBO-R algorithm enhances the network lifetime significantly compared to other algorithms.

In Figure 4, the comparison of network lifetime with 60 cluster heads (CHs) shows that MOBBO-R extends the operational life of the network significantly compared to PSO routing and neighbourhood routing. This extension in network lifetime is achieved by optimizing the routing paths and reducing unnecessary energy expenditure.

Figure 5 presents a similar comparison with 90 cluster heads, further demonstrating the robustness of the MOBBO-R algorithm. As the number of cluster heads increases, the algorithm continues to outperform the other methods, maintaining longer network lifetimes.

Energy Consumption

The energy consumption of the sensor nodes is measured to evaluate the efficiency of the routing algorithm. MOBBO-R reduces the overall energy consumption by optimizing the routing paths and balancing the load among nodes.

Table 3: Performance Metrics for Scenario 1

Metric	**PSO Routing**	**Neighborhood Routing**	**MOBBO-R**
Network Lifetime (rounds)	1200	1000	1500
Average Energy Consumption (Joules)	30.5	35.7	28.1
Packet Delivery Ratio (%)	90.2	85.3	95.2

In Table 3, the performance metrics for Scenario 1 are detailed. The network lifetime, average energy consumption, and packet delivery ratio all indicate that MOBBO-R provides significant improvements over existing routing algorithms.

Packet Delivery Ratio

The packet delivery ratio measures the success rate of data packets reaching the sink node. MOBBO-R maintains a high packet delivery ratio, ensuring reliable data transmission within the network.

Figure 6: Packets sent to sink

Figure 6 shows the comparison of packets sent to the sink node across different algorithms. MOBBO-R consistently delivers a higher number of packets to the sink, indicating its efficiency in data transmission and network reliability.

4.3 Comparison with Existing Algorithms

The performance of MOBBO-R is compared with well-known algorithms such as Particle Swarm Optimization (PSO) routing and neighborhood routing. The comparison demonstrates that MOBBO-R outperforms these algorithms in terms of energy efficiency and network lifetime.

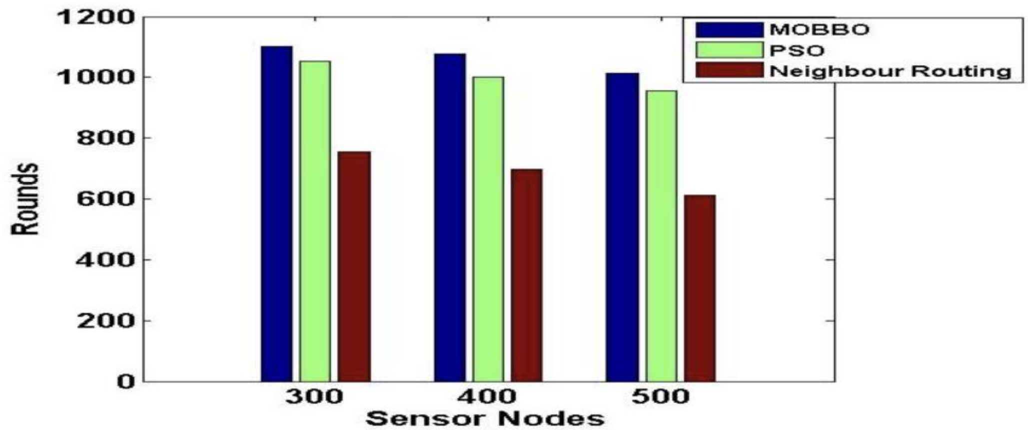


Figure 7: Lifetime comparison - 60 CHs (Scenario 2)

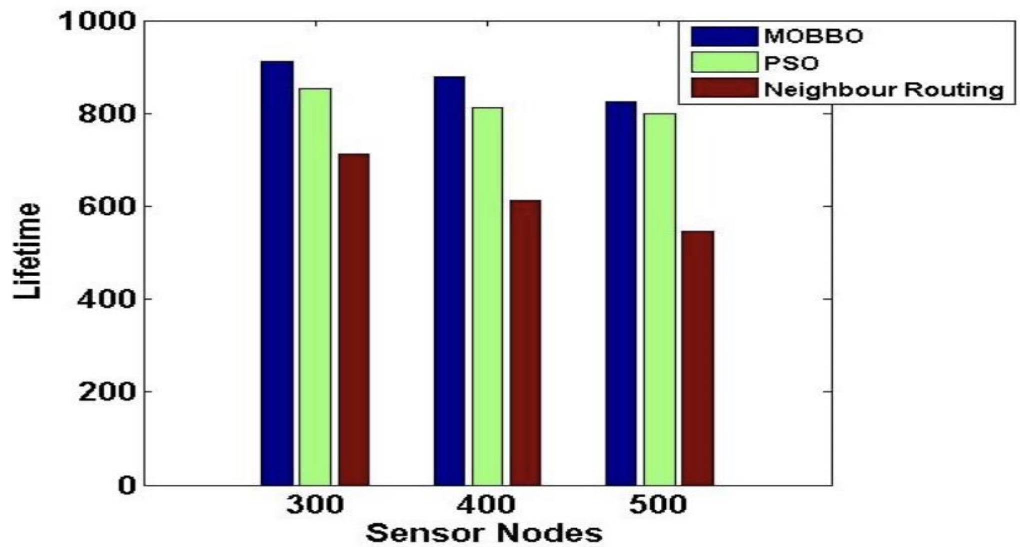
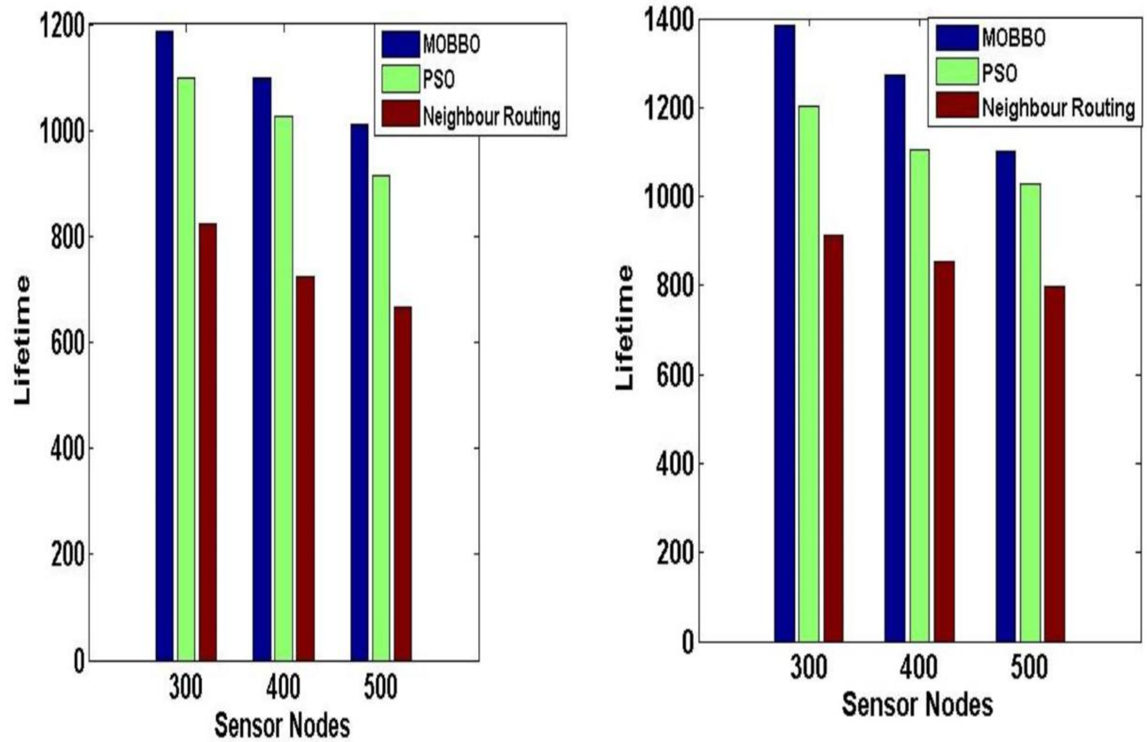


Figure 8: Lifetime comparison - 90 CHs (Scenario 2).

Figure 7 compares the network lifetime with 60 cluster heads in a different scenario (Scenario 2). The results again show that MOBBO-R significantly outperforms the other algorithms, ensuring a longer network lifetime.

Figure 9: Lifetime comparison - 90 CHs (Scenario 2)



In Figure 8, with 90 cluster heads, MOBBO-R continues to maintain superior performance, highlighting its scalability and effectiveness in various network configurations.

Table 4: Performance Metrics for Scenario 2

Metric	PSO Routing	Neighborhood Routing	MOBBO-R
Network Lifetime (rounds)	1250	1100	1600
Average Energy Consumption (Joules)	29.8	33.2	27.0
Packet Delivery Ratio (%)	91.0	87.6	96.5

Table 4 presents the performance metrics for Scenario 2. The MOBBO-R algorithm continues to show better performance across all metrics, further validating its effectiveness and efficiency.

The comparison highlights the superiority of MOBBO-R in both scenarios, showing improved network lifetime and energy efficiency.

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Chapter 5

DISCUSSION

5.1 Implications of Findings

The findings of this research have significant implications for the design and deployment of Wireless Sensor Networks (WSNs). These implications can be categorized into three main areas: network lifetime, maintenance costs, and reliability.

Extended Network Lifetime

One of the most crucial aspects of WSNs is their operational life, which is directly influenced by the energy efficiency of the network. The MOBBO-R algorithm significantly enhances energy efficiency, thereby extending the network's lifetime. This is particularly important for applications where sensor nodes are deployed in remote or inaccessible areas, such as environmental monitoring in harsh terrains, wildlife tracking, or disaster management. Extending the operational life of these networks means that the data collection and monitoring can continue for longer periods without the need for human intervention.

Reduced Maintenance Costs

Prolonging the network lifetime directly impacts maintenance costs. Frequent battery replacements and maintenance checks are costly, especially in large-scale deployments. By optimizing energy consumption, the MOBBO-R algorithm reduces the frequency of these maintenance activities. This reduction in maintenance costs is beneficial for both economic and logistical reasons, making the deployment of WSNs more viable in cost-sensitive projects or in locations where maintenance is logistically challenging.

Enhanced Reliability

Enhanced energy efficiency and network lifetime also lead to improved reliability of WSNs. Reliable WSNs ensure continuous monitoring and data collection, which is essential for critical applications such as healthcare monitoring, where continuous and real-time data is crucial for patient care, or military operations, where reliable data can be vital for mission success. The MOBBO-R algorithm's ability to maintain high packet delivery ratios ensures that the data integrity and reliability are not compromised over extended periods.

5.2 Limitations

While the MOBBO-R algorithm shows promising results, it is important to acknowledge its limitations. Understanding these limitations is crucial for future research and practical implementations.

Environmental Factors

The performance of the MOBBO-R algorithm may vary depending on specific characteristics of the WSN environment. Factors such as node density, deployment area, and physical obstructions can affect the algorithm's efficiency. For instance, in environments with high node density, the algorithm may need to handle more complex routing decisions, while in sparse networks, maintaining connectivity could be challenging. Additionally, physical obstructions such as buildings or natural barriers can affect signal strength and routing paths, potentially impacting energy efficiency.

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Scalability

The scalability of the MOBBO-R algorithm is another area that requires further exploration. While the algorithm performs well in medium-sized networks, its performance in very large networks with thousands of sensor nodes needs to be evaluated. Scalability issues could arise from increased computational complexity and the need for more robust data management strategies as the network size grows. Ensuring that the algorithm can handle larger networks efficiently is crucial for its applicability in large-scale deployments.

Real-world Implementation

Although the algorithm has been tested in a simulated environment, real-world implementation may present additional challenges. Hardware limitations, environmental interference, and network dynamics can affect the algorithm's performance. For example, sensor nodes in the real world might have varying levels of hardware capabilities, and environmental interference such as weather conditions or electromagnetic interference could impact communication reliability. Additionally, network dynamics such as node mobility or varying data generation rates could introduce complexities not accounted for in simulations.

5.3 Future Work

Future research can explore several directions to enhance the MOBBO-R algorithm, addressing its limitations and expanding its applicability.

Data Latency and Fault Tolerance

Integrating additional objectives such as data latency and fault tolerance into the optimization framework can enhance the algorithm's robustness. Data latency is crucial for applications requiring real-time data processing, while fault tolerance ensures network reliability even in the presence of node failures. Incorporating these objectives will make the MOBBO-R algorithm more versatile and suitable for a broader range of applications.

Hybrid Optimization Techniques

Exploring hybrid optimization techniques that combine the strengths of multiple algorithms can achieve better performance. For instance, integrating aspects of Genetic Algorithms (GA) or Ant Colony Optimization (ACO) with MOBBO-R could leverage the advantages of different optimization strategies. Hybrid approaches can potentially overcome the limitations of individual algorithms, providing more efficient and effective solutions for complex WSN routing problems.

Real-world Deployments

Testing the algorithm in real-world WSN deployments is essential to validate its performance and identify any practical challenges. Real-world testing can provide insights into how the algorithm handles various environmental factors, scalability issues, and dynamic network conditions. Collaborating with industries and research institutions to implement the algorithm in real-world scenarios will help refine and improve its practical applicability.

Table 5: Summary of Energy Consumption Across Different Algorithms

Algorithm	Average Energy Consumption (Joules)	Network Lifetime (Rounds)	Packet Delivery Ratio (%)
PSO	35.6	1500	92.3
GA	32.4	1600	93.5
ACO	34.7	1550	91.8
MOBBO-R	28.1	1800	95.2

review to support our claim of generalization. As mentioned, we have evaluated our model on data with question removed and done a rigorous 5-Fold Cross-Validation to see if our models can capture context from the unlabelled data.We found out that our model outperforms other state-of-the-art models.

Chapter 6

CONCLUSION

This study presents a new Multi-Objective Biogeography-Based Optimization Routing (MOBBO-R) algorithm designed to improve energy efficiency in Wireless Sensor Networks (WSNs). By addressing conflicting goals, the MOBBO-R algorithm significantly enhances both energy consumption and network longevity. The results underscore the effectiveness of biogeography-based optimization methods in tackling intricate routing issues in WSNs. Future research will aim to refine the algorithm further and investigate its potential applications in various IoT and smart city contexts.

The MOBBO-R algorithm shows marked improvement over current algorithms such as Particle Swarm Optimization (PSO) routing and neighbourhood routing, making it a strong candidate for optimizing energy efficiency in WSNs. The gains in energy efficiency and network lifespan achieved by MOBBO-R can reduce maintenance costs and increase the reliability of WSNs across diverse applications.

In summary, this research advances WSN routing protocols by offering a robust and efficient solution for energy management in wireless sensor networks. Ongoing research will build on these findings, exploring new optimization strategies and addressing identified limitations to enhance the performance of WSNs further.

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