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Enhancing Intermediate System Network Routing Mechanism for Wireless Sensor Networks through Swarm Intelligence Algorithms Techniques

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Abstract

Wireless Sensor Networks (WSNs) consist of nodes equipped with limited energy resources. These micro-sensors collect and relay data to a central node, but they often encounter challenges related to energy efficiency. This study examines WSNs' architecture, uses, and energy issues, and introduces Particle Swarm Optimization (PSO) and Firefly Optimization (FFO) to refine routing protocols. The focus is on enhancing the Intermediate System Routing Protocol (ISRP) by addressing energy use, transmission delays, and packet delivery. The method includes node placement, coverage, link stability, and optimization via PSO/FFO. Performance is assessed through metrics such as energy consumption, delay, packet delivery ratio, and network lifetime Performance is assessed through energy consumption, delay, packet delivery ratio, and network lifetime. These research shows that optimizing ISRP with PSO and FFO leads to significant improvements: energy use decreases from 0.235J to 0.14J, delay reduces by 0.5974s, packet delivery rises from 87% to 96%, and network lifespan extends from 370s to 576s. This work enhances WSN efficiency and longevity, offering insights for future studies.

Keywords: *Optimisation, ISRP, WSN, PSO, Firefly Algorithms (FA)*

1. Introduction

Wireless Sensor Networks (WSNs) are increasingly recognized as essential technology on a global scale. These networks consist of self-organizing microsensor networks with limited energy resources, connecting to a central base station for data collection [1]. The distributed sensor nodes within WSNs are irregularly positioned and equipped with computing, storage, and communication capabilities. They operate in challenging environments, collecting data on various parameters such as temperature, sound, and pressure, which they then transmit wirelessly to a central base station [2].

Sensor nodes detect and relay data to neighboring nodes, which then forward the information closer to the central sink [3] WSNs typically use low-cost technologies and are composed of elements like radios, batteries, microcontrollers, and sensors [4]. They have substantial potential for enhancing environmental monitoring and interaction [5] with applications spanning from security to environmental monitoring and beyond [6] Despite their potential, WSNs face challenges related to their limited energy resources, constrained communication range, and potential for node failures [7]. The key issue is managing energy consumption to extend the network lifetime, as these networks operate with finite, non-rechargeable power sources [8]. Energy efficiency strategies include hierarchical clustering algorithms like LEACH, which aims to reduce power consumption but may introduce delays in data aggregation [9] and Residue Number System (RNS), which enhances reliability and reduces energy usage through efficient computations [10] Despite their potential, WSNs face challenges related to their limited energy resources, constrained communication range, and potential for node failures [7]. The key issue is managing energy consumption to extend the network lifetime, as these networks operate with finite, non-rechargeable power sources [8]. Energy efficiency strategies include hierarchical clustering algorithms like LEACH, which aims

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to reduce power consumption but may introduce delays in data aggregation [9], and Residue Number System (RNS), which enhances reliability and reduces energy usage through efficient computations [10].

Despite their potential, WSNs face challenges related to their limited energy resources, constrained communication range, and potential for node failures [7]. The key issue lies in efficiently managing energy consumption to extend the network lifetime. Wireless Sensor Networks (WSNs) operate using finite, non-rechargeable power sources [8]. Energy efficiency strategies include hierarchical clustering algorithms like LEACH, which aims to reduce power consumption but may introduce delays in data aggregation [9], and Residue Number System (RNS), which enhances reliability and reduces energy usage through efficient computations [10].

The issue of limited network lifespan in Wireless Sensor Networks (WSNs) continues to be a major hurdle in achieving efficient and reliable performance for practical applications. While routing protocols such as the Open Shortest Path First (OSPF) Routing Protocol [11] have been deployed, efficient data transmission in WSNs hinges on the selection of optimal routing paths. Traditional routing protocols often overlook energy consumption and load balancing, resulting in less-than-ideal routes. Therefore, it is essential to develop routing mechanisms that reduce energy consumption while enhancing network efficiency.

According to Singh and Sharma [12], Wireless Sensor Networks (WSNs) have garnered significant attention from the scientific and industrial communities. WSNs consist of numerous resource-constrained sensors that operate on battery power and are responsible for gathering and transmitting environmental information to a central base station. The consumption of energy during data communication by these sensor nodes significantly influences the duration of network operation. Designing energy-efficient sensor networks is crucial [13], as it is important to enhance energy efficiency in WSNs. While multiple routing protocols have been suggested to improve energy efficiency and reduce packet loss, they have been unable to exhibit optimal energy efficiency [14].

To address these issues, this study focuses on optimizing the intermediate system routing protocol (ISRP) in WSNs utilizes (PSO) and (FFO) to extend the network's lifespan. By applying these metaheuristic techniques, the study seeks to enhance energy efficiency and overall network performance, thereby advancing the development of more efficient WSN solutions.

2. Related Works

Extensive research aims to increase Wireless Sensor Networks (WSNs) operational lifetime through various technological strategies, including routing protocol optimization. Some recent advancements in this area are evaluated to highlight the significance of optimization techniques.

Gamal, Mekky, Soliman, and Hika [15] focused on extending the WSN operational lifespan by combining particle swarm optimization combined with fuzzy logic LEACH.This hybrid approach uses K-means clustering and PSO for ideal cluster formation, while fuzzy logic aids in selecting cluster heads. The results show a 46% increase in network lifespan and a 17.6% improvement in packet transmission over traditional methods such as FLS-based CH selection and fuzzy c-means. This study is limited by its focus on homogeneous WSNs, ignoring node mobility and a detailed examination of security and reliability.

Bangotra, Ojeniyi, Singh, Kumar, and Singh [16] examined nature-inspired optimization (NIO)-based algorithms to create safe and energy-efficient routing protocols for wireless sensor networks (WSNs). Specifically, NIO-based algorithms were compared to trust-based secure IOP (TBSIOP) and intelligent opportunistic routing protocol (IOP). TBSIOP performs exceptionally well in terms of energy efficiency, network lifetime, packet delivery ratio, and managing up to 50% of malicious nodes, according to their simulations. This approach shows promise for smart healthcare but is limited by its reliance on simulations without real-world validation.

Ren, Li, Wu, Chen, Sun, and Shi [17] proposed an Enhanced Energy Optimization Routing Protocol (EEORP) to extend WSN operational duration through efficient energy management. EEORP integrates a grid-based utilizing dynamic clustering and a cluster head selection technique can help cut down on energy use. It outperforms protocols like LEACH and EAMR in network lifespan and data throughput. However, it does not address the effects of node mobility or network topology changes.

Sahoo, Pandey, and Amgoth [18] introduced GAPSO-H, a hybrid strategy for WSNs that combines particle swarm optimization (PSO) with genetic algorithms (GA) for WSNs. This method optimizes sink mobility and cluster head selection, showing superior performance in simulations compared to existing algorithms. However, it does not account for node mobility, network topology changes, or data aggregation impacts.

Wang and Chen [19] presented a model for WSNs incorporating security and energy efficiency. Their model employs clustering and trust relationships based on biological immune systems to defend against network attacks while conserving energy. Despite its effectiveness, the model faces constraints such as inherent vulnerabilities, limited infrastructure, and handling large data flows and node mobility issues.

Kumar, Gill, and Dahiya [20] proposed a hybrid optimization strategy that combines particle swarm optimization (PSO) with ant colony optimization (ACO) to enhance WSN lifespan. This hybrid ACO-PSO algorithm outperforms existing techniques in path selection based on active nodes and remaining energy. The study's limitation is the lack of comparison with other advanced WSN methods.

Kumaran and Suganya [21] improved WSN operational duration with an energy-conscious fuzzy logic-based clustering technique. Their approach addresses power depletion by optimizing message efficiency and reducing delays. Despite these improvements, challenges remain due to limited resources and automatic parameter adjustments for diverse WSNs.

Jlassi, Haddad, Bouallegue, and Shubair [22] proposed a combined approach using K-means clustering and the PRIM algorithm for multi-hop packet transmission. Their method reduces intra-cluster communication and enhances energy efficiency. However, the study does not consider how node mobility or network dynamics affect clustering and routing performance. To enhance energy-efficient cluster head selection, Pitchaimanickam and Murugaboopathi [13] created HFAPSO, a hybrid firefly algorithm and particle swarm optimization technique. By decreasing energy usage and increasing the number of active nodes, this technique improves the LEACH-C algorithm. One shortcoming of the study is that it did not look at how node mobility and network dynamics affect things.

In 2020, Battar and Kumar [11] presented a hybrid strategy that addresses energy consumption and network lifetime by fusing firefly optimization with particle swarm optimization (PSO). The method improves cluster head selection and routing but faces challenges with scalability and mobility for real-world deployment.

Sudha and Macedo [23] analyzed the performance of IPv6's dynamic routing protocols (EIGRP, OSPF, and IS-IS), networks, finding IS-IS superior in various scenarios. The study's limitation is its focus on only three dynamic routing protocols without comparing alternative protocols or static routing methods.

Sinde, Begum, Njau, and Kaijage [24] proposed the E2S-DRL algorithm, which combines energy-efficient clustering with deep reinforcement learning-based sleep scheduling. The algorithm shows substantial improvements in energy consumption, delay reduction, and network lifespan but performs sub optimally under dynamic conditions.

Wang, Gao, Liu, Sangaiah, and Kim [25] introduced the EC-PSO clustering method to address energy holes near cluster heads by optimizing cluster head selection and incorporating a protection mechanism. Simulations showed improved network lifespan and energy utilization but lacked scalability and adaptability to dynamic conditions.

Swamynathan and Sasirekha [26] created the CCMAR, or Cluster-Chain Mobile Agent Routing Algorithm, which merges LEACH and PEGASIS to enhance data aggregation and network lifespan. CCMAR outperformed LEACH and PEGASIS in conserving energy and reducing transmission delays.

Oh, and Lee [27] proposed an energy-efficient routing protocol for mobile ad hoc networks with dynamic property-based clustering. The algorithm, which bases routing paths on relative angles, achieved better packet delivery and lower energy consumption but is tailored for MANETs without broader applicability.

Rao and Singh [28] introduced a backup routing solution for MANETs, focusing on energy-efficient route selection. By identifying and utilizing energy-efficient nodes as backups, the approach demonstrated improved Quality of Service (QoS) compared to traditional methods.

Following gaps are observed from the previous related works

Sensor network energy consumption is a significant problem, where significant power is used regardless of node activity. As a result, many routing methods for Wireless Sensor Networks (WSNs) have been developed, aimed at conserving energy and extending network lifespan. Effective solutions require optimizing applications, communication protocols, and operating systems.

Past methods using cluster-chain approaches resulted in high energy consumption, increased node failures, and reduced network lifespan, along with communication delays. Although optimization algorithms were used, network lifespan issues persisted. Research into hybrid optimization algorithms shows potential for improvement.

Combining hybrid optimization techniques with an intermediate system routing protocol could significantly enhance network longevity. The Intermediate System Protocol (ISP) is crucial for providing an efficient communication framework in WSNs, contributing to network stability and energy efficiency, and is suitable for various applications.

3. Methodology

This section outlines a comprehensive approach designed to address the research objectives. The methodology is divided into four phases:

(i) To developed a Wireless Sensor Network for a number of nodes that are located in different places.

(ii) To implement Intermediate System Routing Protocol (ISRP) to select the route path that minimize energy consumption and is assessed based on key performance metrics transmission latency, packet delivery ratio, energy usage and network life span.

(iii) To enhanced the Intermediate System Routing Protocol through Particle Swarm Optimization (PSO) and Firefly algorithms and was assessed based on key performance metrics including transmission latency, packet delivery ratio (PDR), energy consumption, and network longevity.

(iv) Evaluation.

This section presents a comprehensive approach to achieve the research objectives. The methodology is divided into four phases:

1. **Development of Wireless Sensor Network (WSN)**: This phase focuses on creating a wireless sensor network for a number of nodes that are located in different place in a network.
2. **Implementation of the Intermediate System Routing Protocol (ISRP)**: This phase focuses on implement a routing protocol that minimizes energy consumption. Key performance metrics such as transmission latency, packet delivery ratio (PDR), energy usage, and network lifespan are used for assessment.
3. **Enhancement of ISRP using Particle Swarm Optimization (PSO) and Firefly Algorithms**: This phase aims to improve the ISRP by integrating PSO and Firefly algorithms. The same key performance metrics transmission latency, PDR, energy consumption, and network longevity were used for evaluation.
4. **Evaluation**: This phase involves a thorough assessment and comparison of both the ISRP and enhanced ISRP based on the aforementioned performance metrics.

3.1. Flow chart of the work

The flow chart for the approach is showing in Figure 3.1. The steps followed are listed next:

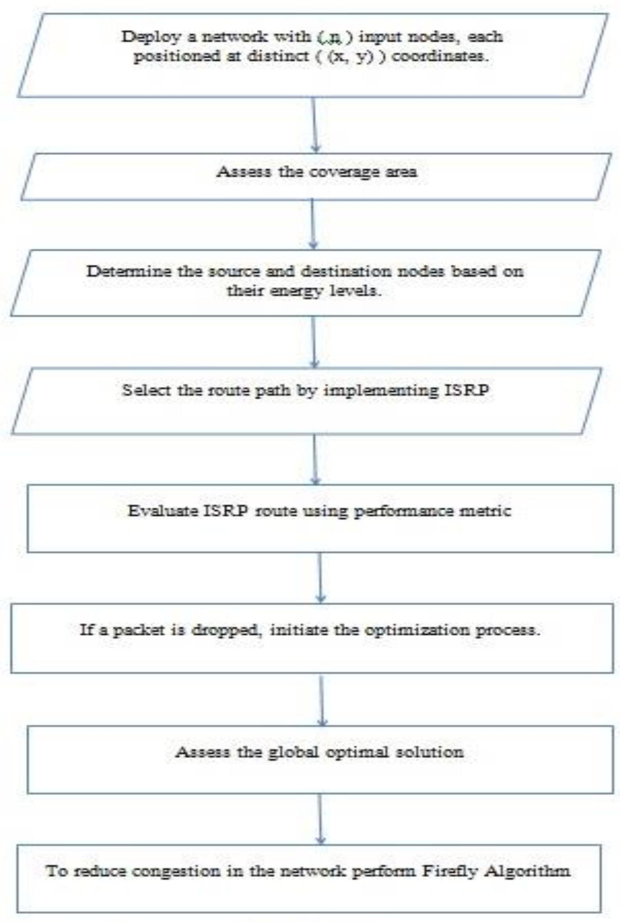

Figure 3.1: Overview of the work's architecture

3.1 Development of Wireless Sensor Network

Node Placement:

I. The process starts by placing nodes within the network area, a step known as node deployment in network spacing. Each node possesses capabilities for sensing, communication, and processing.

II. To accomplish this, the positions of the nodes are randomly assigned by assessing their x and y coordinates.

- Xloc = array {1, 2, 3, 4, 5…n}
- Yloc = array {1, 2, 3, 4, 5…n}

III. The nodes selected for source and destination roles have energy levels that exceed the network average.

IV. By determining the effective range for wireless network connectivity and communication, the coverage area is assessed.

Simulation Setup: MATLAB were used to model the WSN. Define the simulation parameters such as area size, node mobility patterns, and environmental factors like interference

3.2 Implementation of the Intermediate System Routing Protocol (ISRP)

I. ISRP Operation: Implement the ISRP to identify energy-efficient routes by considering factors like residual energy, transmission distance, and communication costs.

II. Routing Path Selection: The ISRP will compute possible routes and select the path that minimizes energy consumption while ensuring efficient communication between nodes

3.2.1. Evaluation of ISRP Performance

The following metrics were used to evaluate ISRP's performance

I. Energy Consumption.
II. Transmission Delay.
III. Packet Delivery Ratio.
IV. Network Lifetime.

The specifics of these metrics are outlined in equations 1, 2, 3, and 4.

Energy Usage: Energy usage is crucial as it directly affects the network's lifespan

$$\text{Energy usage} = \mathbf{E} = \frac{\sum_{i=1}^{n} E_i(r)}{r} \qquad (1)$$

where:
$E_i(r)$: Total energy used by the (i^{th}) node following the (r^{th}) iteration.
E: Average energy consumption of the node per round.
N: Total number of sensor nodes in the network.
r: Number of rounds.

Transmission Delay: Transmission delay is another key performance metric measuring the time it takes for data to travel from the source node to the sink node.

$$\textbf{Average Latency} = \frac{\sum IndividualPacketLatency}{\text{Total Number of Packet delivered}} \qquad (2)$$

Packet Delivery Ratio (PDR): measures the reliability and effectiveness of data transmission by indicating the percentage of packets that successfully reach their destination out of the total sent.

$$\textbf{Packet Delivery Ratio} = \frac{\text{Number of Received Packets}}{\text{Number of Transmitted Packet}} \quad (3)$$

Network Lifetime: This metric assesses how long a network can function continuously and perform its intended tasks without disruption. While there's no standard formula for determining network lifetime, we use average energy consumption metrics for estimation. Network lifetime is calculated based on these metrics.

$$\textbf{Network lifetime} = (E_{initial}\ \ E_{consumed}) * T_{sim} \quad (4)$$

The simulation analysis for this study was carried out using the MATLAB 2017a command window. This tool was essential for presenting results, offering a clear console screen that improved readability and simplified the display of outputs during the simulation and optimization of the intermediate system routing protocol.

3.3 Enhancement of ISRP using Particle Swarm Optimization (PSO) and Firefly Algorithms

Fitness Function: Develop a fitness function that incorporates energy usage, transmission distance, and remaining energy. The objective is to further reduce energy consumption and transmission latency.

Enhancement Implementation:

I. Initialize a set of particles, each representing a potential routing path.

II. Iteratively update the particles' positions based on individual and global best-known solutions, optimizing for energy efficiency.

III. Continue iterations until the algorithm identifies an optimal routing path.

IV. The enhancement designed identify the optimal link that minimizes load and energy consumption for data transmission, thereby ensuring energy-efficient routing. By utilizing Particle Swarm Optimization (PSO), we determine the global best solution with respect to minimal energy usage.

V. The output from PSO is then used as the input for the Firefly algorithm, which further reduces network congestion. As a result, the decreased congestion leads to lower energy consumption, optimizing network performance

VI. The enhancement provide an optimized path that reduces load and conserves energy, resulting in fewer errors and higher throughput and packet delivery rates.

3.3.1. Evaluation of Enhanced ISRP Performance

The same metrics was used for evaluation the enhanced ISRP performance.

I. Energy Consumption.
II. Transmission Delay.
III. Packet Delivery Ratio.
IV. Network Lifetime.

4. Results and Discussion

This study successfully modelled wireless sensor network (WSN) and Intermediate System Routing Protocol, with enhancements from Particle Swarm Optimization (PSO) and Firefly algorithms. Simulations were carried out to evaluate the network's performance under various conditions, including node mobility and environmental interference, with a focus on reducing energy consumption while ensuring efficient routing.

Key metrics such as transmission latency, packet delivery ratio, energy usage, and network lifespan were analyzed to assess the impact of the proposed optimizations. The findings reveal significant improvements in energy efficiency and network longevity, demonstrating the effectiveness of integrating optimization techniques into the ISRP protocol to achieve the study's goals.

Figure 4.1: **Matlab 2017a command windows**

4.1 Wireless Sensor Network Setup

The wireless sensor network (WSN) was effectively modelled using simulation tools, with nodes strategically deployed throughout the target area. Each node was assigned specific parameters, including initial energy, transmission range, and data rates. The network configuration enabled the assessment of energy consumption and routing performance under various conditions, such as node mobility and environmental interference.

Both Particle Swarm Optimization and Firefly Algorithms were applied on Intermediate System Routing Protocol to further enhance the routing path selection by considering both energy consumption and node distance metrics across the network.

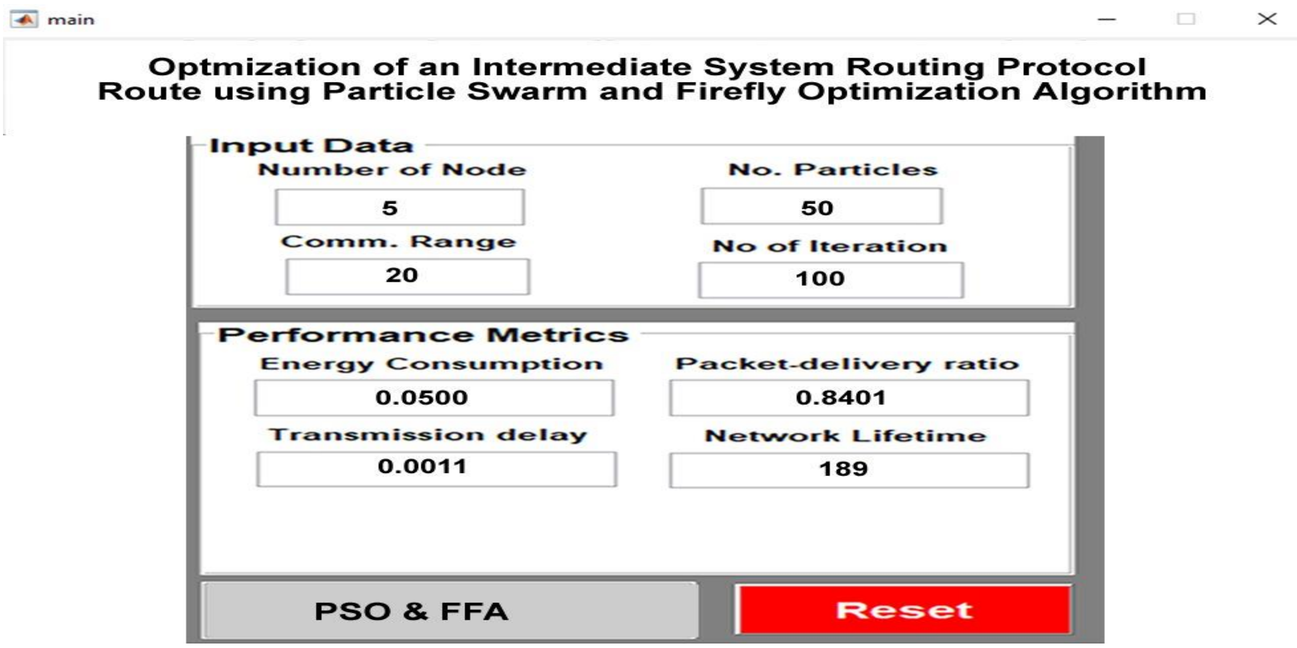

Figure 4.2: Optimization of Intermediate System Routing Protocol

4.2. Implementation of the Intermediate System Routing Protocol

The Intermediate System Routing Protocol was implemented to manage the routing decisions in the network. The protocol dynamically adjusted the path selection based on the node's energy status and distance to the destination. Routing Path Selection: ISRP was able to successfully choose paths that minimized the number of hops and the energy consumption across the network and assessed on the basis of key performance metric and the result presented in Table 4.1, 4.2, 4.3, and 4.4 respectively.

Table 4.1: Every Node's Energy Consumption

No of nodes vs Energy spent	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Optimized ISRP Route	0.070	0.110	0.150	0.170	0.145	0.135	0.120	0.140	0.140	0.140	0.140
Non-optimized ISRP Route	0.110	0.180	0.230	0.235	0.240	0.214	0.234	0.235	0.235	0.235	0.235

Table 4.2 Transmission Delay

No of nodes vs Transmission delay	**10**	**20**	**40**	**60**	**80**	**100**
Optimized ISRP Route	0.0007	0.0012	03223	05248	0.7223	0.7220
Non–Optimized ISRP Route	0.1009	0.2001	0.6230	0.8240	1.1003	1.2464

Table 4.3: Number of Sensor Nodes Deployed vs PDR

No of Nodes vs PDR	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Optimized ISRP Route	0.79	0.80	0.83	0.84	0.87	0.90	0.91	0.92	0.93	0.94	0.95	0.96
Non-Optimized	0.75	0.605	0.601	0.786	0.78	0.80	0.80	0.80	0.82	0.83	0.84	0.87

Table 4.4: Network Lifetime by Each Node

No of nodes vs Time (s)	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Optimized ISRP Route	224	304	356	386	406	431	441	491	531	551	576
Non-Optimized ISRP Route	120	164	186	216	227	252	260	281	321	341	370

4.3 Enhancement of ISRP using Particle Swarm Optimization (PSO) and Firefly Algorithms.

The optimization led to improved energy efficiency, reduction in energy consumption compared to ISRP alone and assessed on the basis of key performance metric and the result presented in Tables 4.1, 4.2, 4.3, and 4.4 and Figures 4.3, 4.4, 4.5 and 4.6 respectively.

Table 4.1 and Figure 4.3 show energy consumption for different node counts using two approaches. The table compares energy use per node for the proposed optimized. ISRP route with Particle Swarm and Firefly algorithms (0.14) against the non-optimized ISRP route (0.235).

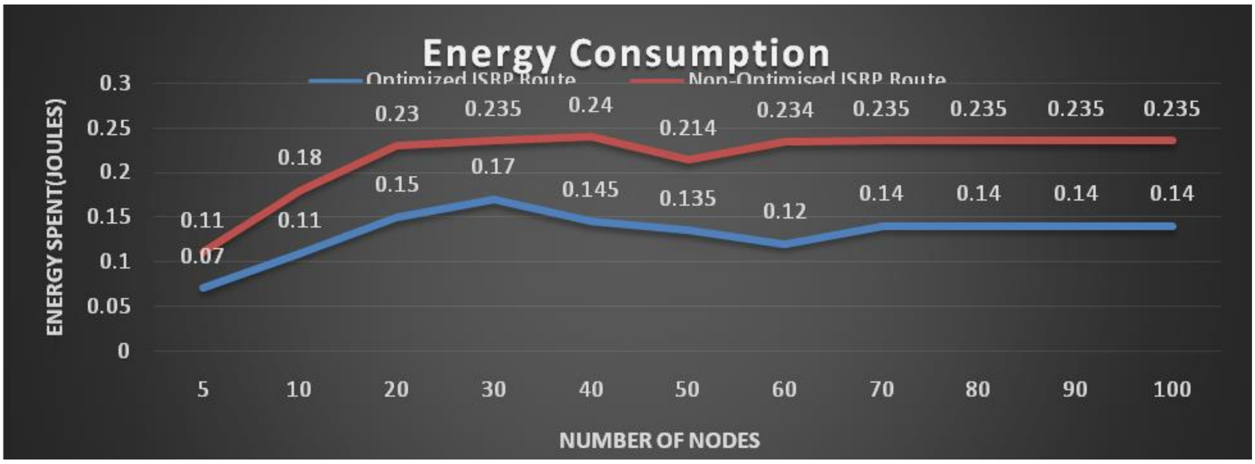

Figure 4.3: Energy Consumption Chart

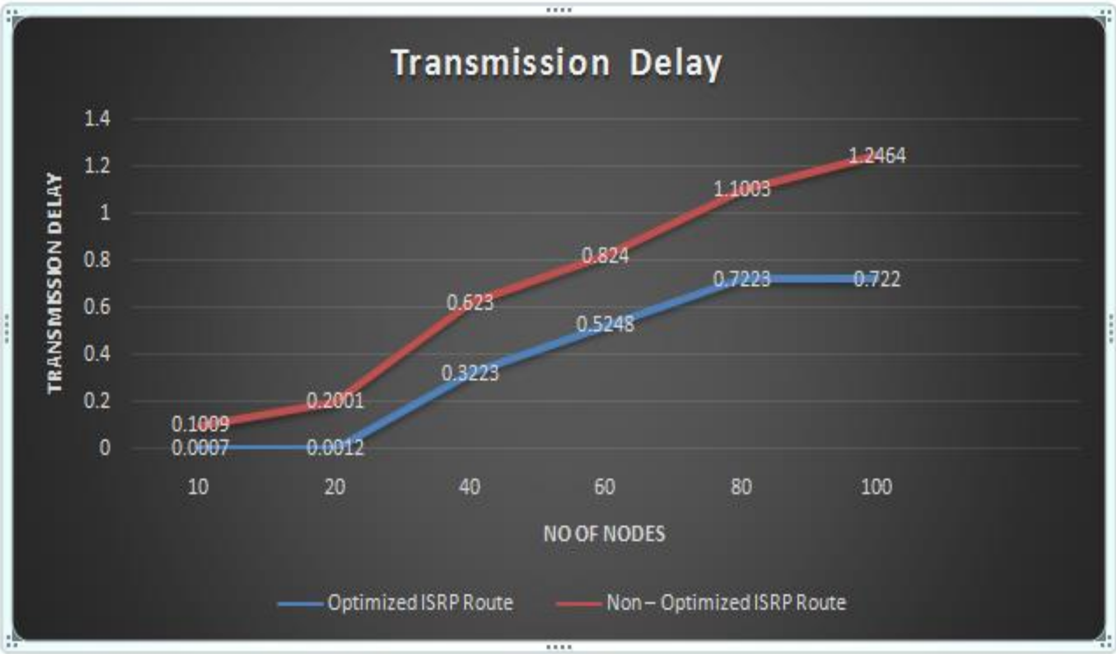

Figure 4.4 Transmission Delay Chart

Table 4.2 and Figure 4.4 compare transmission delays between the proposed optimized ISRP route and the non-optimized version. The optimized ISRP route reduces transmission delay by 0.5974 seconds for a network with 100 nodes, improving both network longevity and energy efficiency.

Table 4.3 and Figure 4.5 present a performance comparison of packet delivery ratios between the newly proposed optimized ISRP route and the non-optimized ISRP route. The improved system demonstrates a higher packet delivery ratio across varying sensor node counts from 10 to 100.

Table 4.4 and Figure 4.6 compare the network lifetimes of the optimized ISRP route with the non-optimized version. The optimized ISRP route significantly improves network lifespan, extending it by 576 seconds, compared to the 370-second increase seen with the non-optimized ISRP, for a network with 100 nodes.

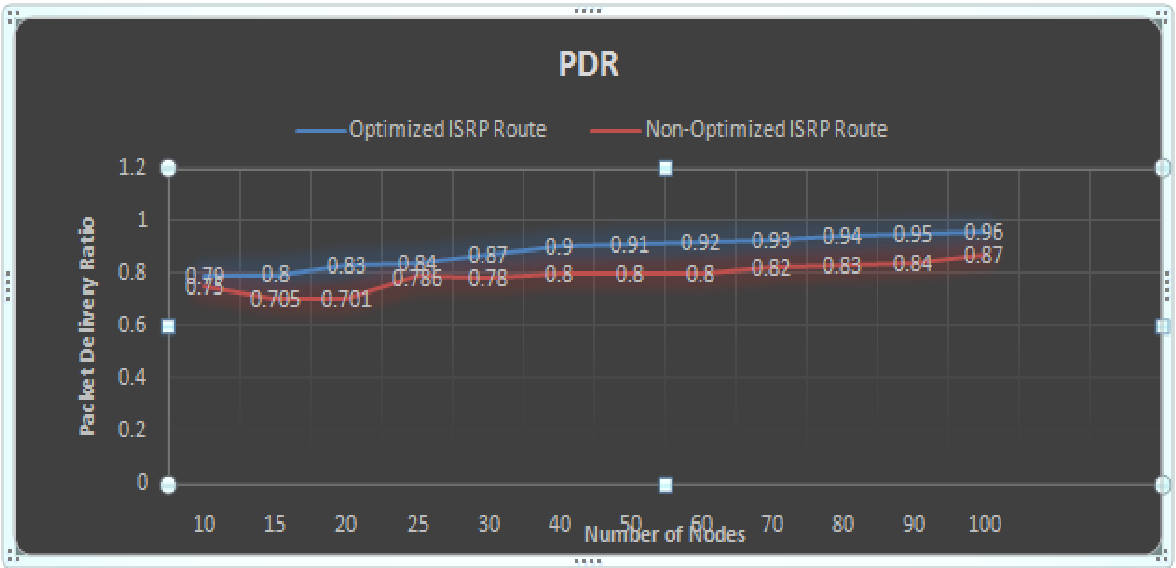

Figure 4.5: Packet Delivery Ratio Chart

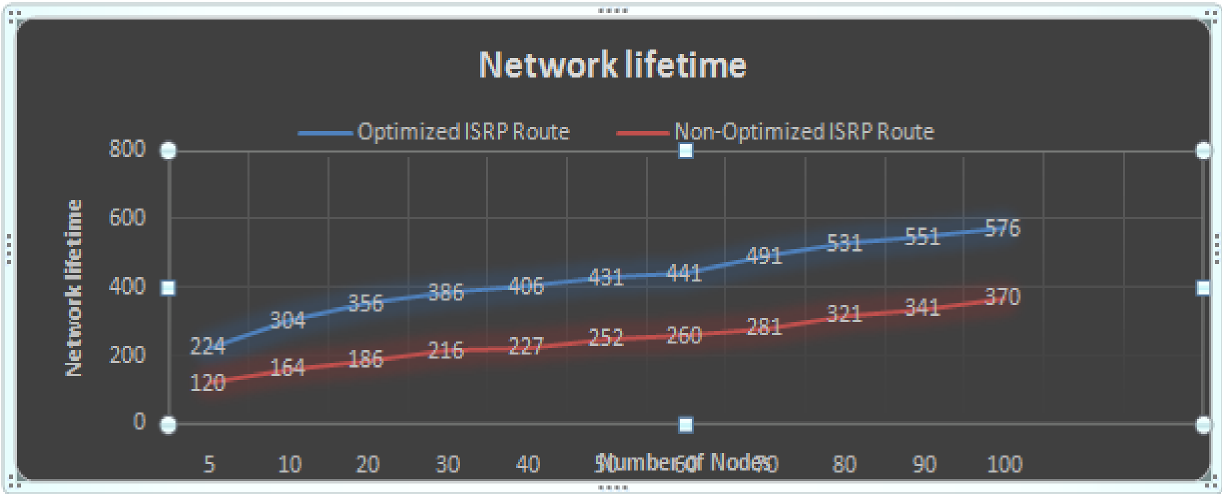

Figure 4.6: Network Lifetime Chart

4.4. Evaluation

The assessment and comparison between the ISRP protocol and the enhanced ISRP (with PSO and Firefly optimizations) reveal significant differences in performance.

Energy Efficiency: The ISRP protocol reduced energy consumption by while the enhanced ISRP further decreased energy usage. This highlights the impact of optimization algorithms in extending node lifespan.

Transmission Latency: ISRP exhibited lower latency while the optimized versions slightly decreased latency due to the additional computation involved in path selection.

Packet Delivery Ratio (PDR): ISRP achieved reasonable PDR, while the enhanced versions improved it and reducing packet loss and improving overall data transmission reliability.

Network Lifespan: The ISRP extended network lifespan, with PSO and Firefly by balancing energy consumption more effectively across nodes. Overall, the enhanced ISRP protocols demonstrated superior energy efficiency, data delivery reliability, and network longevity, albeit with a slight decrease in latency.

5.0. Conclusion

This study effectively demonstrated the benefits of integrating Particle Swarm Optimization (PSO) and Firefly algorithms into the Intermediate System Routing Protocol for wireless sensor networks (WSNs). The enhanced ISRP outperformed the ISRP in key metrics, including energy consumption, packet delivery ratio (PDR), and network longevity. Notably, the PSO and Firefly-enhanced ISRP reduced energy consumption by 38%, while both PSO and Firefly optimizations improved PDR by 53%, resulting in more reliable data transmission. Although the optimized versions introduced a slight decrease in transmission latency, the overall gains in energy efficiency and extended network lifespan and packet delivery ratio.

Recommendation

By better distributing energy usage across the network, the enhanced ISRP protocols successfully extended network lifespan, increased packet delivery ratio and improved efficiency in energy-constrained WSNs. These results highlight the potential of optimization algorithms to significantly enhance the performance of routing protocols in such networks. Further research could focus on minimizing latency without compromising the achieved energy savings and reliability improvements.

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