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AI-DRIVEN OPTIMIZATION OF WIRELESS SENSOR NETWORKS (WSNS) USING CRT-LEACH ROUTING PROTOCOLS

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Abstract

Wireless Sensor Networks (WSNs) play a crucial role in a wide range of applications, including environmental monitoring, healthcare, and smart agriculture. However, energy efficiency remains a critical challenge due to the limited power resources of sensor nodes. Traditional routing protocols, such as Low-Energy Adaptive Clustering Hierarchy (LEACH) and its variant, Chinese Remainder Theorem-LEACH (CRT-LEACH), have been developed to optimize energy consumption and extend network lifetime. Despite their advantages, these protocols still suffer from suboptimal cluster head selection and inefficient data transmission, leading to network instability. This study introduces an AI-driven optimization approach for CRT-LEACH, incorporating artificial intelligence (AI) techniques such as machine learning and heuristic optimization to enhance cluster head selection, energy balancing, and data transmission efficiency. By dynamically adapting to changing network

Keywords: Wireless Sensor Networks (WSNs), AI-driven optimization, CRT-LEACH, energy efficiency, machine learning, network lifetime.

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conditions, the proposed AI-enhanced CRT-LEACH ensures more even energy distribution and reduces the likelihood of premature node failures. The effectiveness of the proposed method is evaluated through simulations, using performance metrics such as network lifetime, energy consumption, packet delivery ratio, and throughput. Experimental results demonstrate that the AI-optimized CRT-LEACH outperforms conventional CRT-LEACH and other existing routing protocols, achieving up to a 40% improvement in network lifetime, a 25% reduction in energy consumption, and enhanced packet delivery rates. These improvements make the proposed method highly suitable for large-scale, long-term WSN applications. This research provides a novel AI-based framework for optimizing WSN performance, laying the groundwork for future advancements in energy-efficient wireless communication. Future work will focus on real-world implementations and the exploration of hybrid AI techniques to further enhance the adaptability and scalability of WSNs.

Introduction

Wireless Sensor Networks (WSNs) are networks composed of spatially distributed sensor nodes that collect and transmit data related to physical or environmental conditions. They find applications in various domains, such as environmental monitoring, healthcare, agriculture, and smart cities (Zhang et al., 2021). These networks are typically deployed in remote areas, making the use of low-power, low-cost, and battery-operated sensor nodes necessary. However, these limitations pose significant challenges, including efficient energy management and communication optimization, which are critical for the longevity and performance of the network (Baharuddin et al., 2020).

One of the most significant challenges in WSNs is energy efficiency, especially since the sensor nodes are battery-powered. Given that replacing or recharging batteries in deployed sensor nodes is often impractical, energy conservation is crucial to extend the network's operational lifetime (Cheng et al., 2021). Inefficient energy usage can lead to early node failure, network partitioning, and overall performance degradation. Optimizing the energy consumption while ensuring

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reliable data communication remains a fundamental research area in WSNs (Zhou et al., 2022).

The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a well-established clustering-based routing protocol designed to optimize energy consumption in WSNs. LEACH organizes sensor nodes into clusters, with each cluster having a designated cluster head (CH) to handle communication with the base station (Baharuddin et al., 2020). This clustering mechanism reduces the energy consumed during data transmission by minimizing the distance between nodes and the base station. Despite its advantages, LEACH faces limitations in scalability, load balancing, and energy distribution, which affect its performance in large-scale networks (Chen et al., 2021).

To address these challenges, the Chinese Remainder Theorem-based Low-Energy Adaptive Clustering Hierarchy (CRT-LEACH) protocol has been proposed. CRT-LEACH enhances the clustering process by employing the Chinese Remainder Theorem to optimize the cluster formation and data routing (Jiang et al., 2020). This integration improves the efficiency of energy distribution across the network, extending its lifetime and reducing the load on individual nodes.

Artificial Intelligence (AI) has emerged as a powerful tool in optimizing various aspects of WSNs, particularly in routing protocols. Machine learning (ML), deep learning (DL), and reinforcement learning (RL) can be used to adaptively optimize energy consumption, fault tolerance, and data aggregation in real-time (Mansoor et al., 2021). AI can improve the performance of protocols like LEACH and CRT-LEACH by enabling smarter decision-making in dynamic network conditions, optimizing cluster head selection, routing decisions, and energy load balancing (Li et al., 2023). Moreover, AI-driven approaches can address the challenges of scalability, network congestion, and real-time adjustments based on environmental and network changes (Zhou et al., 2022).

Despite advancements in WSN protocols like LEACH and CRT-LEACH, the integration of AI techniques to enhance routing decisions and energy management is still underexplored. Current studies often focus on static or predefined solutions, which fail to consider the dynamic nature of WSNs (Nguyen et al., 2021). Similarly, by dynamically adjusting routing paths and optimizing energy utilization, the AI-powered CRT-LEACH protocol extends network lifetime while maintaining data transmission integrity (Raji & Taofeek-Ibrahim, 2024). The

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application of AI in optimizing CRT-LEACH protocols has the potential to address these limitations, leading to more adaptive, self-optimizing systems capable of responding to changes in network topology, node behavior, and environmental conditions.

This research seeks to fill this gap by integrating AI techniques with CRT-LEACH, focusing on enhancing energy efficiency and extending the operational lifetime of WSNs. By leveraging AI, this study aims to provide real-time optimization, dynamic routing, and adaptive clustering, which are essential for the efficient operation of large-scale WSNs.

LITERATURE REVIEW

Energy consumption is one of the most critical issues in Wireless Sensor Networks (WSNs), as sensor nodes are typically powered by limited energy sources such as batteries. To prolong network lifetime, many studies have focused on minimizing energy consumption by optimizing routing and communication strategies. Baharuddin et al. (2020) explored energy-efficient algorithms for WSNs, emphasizing the need for reducing communication overhead and optimizing the energy consumption of sensor nodes. They noted that clustering-based protocols like LEACH have been widely adopted due to their effectiveness in balancing energy usage across the network. However, they also pointed out the challenges of maintaining an energy-efficient network in the face of dynamic environmental conditions.

Cheng et al. (2021) highlighted that many traditional routing protocols in WSNs do not adequately address energy efficiency in large-scale networks. They proposed novel energy-efficient strategies that adapt to the changing topology of WSNs. Their work suggests that clustering algorithms, such as LEACH, can benefit from adaptive energy management, which balances energy load across nodes and improves the overall network performance. However, LEACH has some limitations, particularly in large networks where load balancing and scalability become significant concerns. Several variants of LEACH, such as LEACH-C (LEACH Centralized) and LEACH-F (LEACH Fixed), have been proposed to address these issues (Zhang et al., 2021).

Li et al. (2023) further optimized the LEACH protocol by introducing a dynamic cluster head selection mechanism that adjusts based on node energy levels and

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network topology. Their study demonstrated that this approach significantly extended the lifetime of the network while reducing the chances of premature node failure. Despite these improvements, they acknowledged that LEACH's performance could still be further enhanced through the integration of more adaptive strategies, such as machine learning.

The Chinese Remainder Theorem-based Low-Energy Adaptive Clustering Hierarchy (CRT-LEACH) protocol is a more recent development designed to enhance the clustering process in WSNs. CRT-LEACH incorporates the Chinese Remainder Theorem to optimize cluster formation and improve data routing efficiency (Jiang et al., 2020). By using a modular approach, CRT-LEACH aims to reduce the computational load on individual nodes and improve energy distribution across the network. Jiang et al. (2020) and Raji et al. (2021) found that CRT-LEACH outperformed traditional LEACH in terms of energy efficiency, network lifetime, and overall throughput, especially in large-scale networks with dynamic traffic patterns.

Moreover, CRT-LEACH is better suited for highly heterogeneous networks, where nodes may have different energy levels and processing capacities. This protocol optimizes the use of available resources, ensuring a more balanced energy consumption across nodes (Chen et al., 2021). This feature makes it an appealing option for large-scale sensor networks deployed in complex environments.

The integration of Artificial Intelligence (AI) with WSN protocols has garnered significant attention in recent years. AI techniques, particularly machine learning (ML) and reinforcement learning (RL), have been used to optimize routing, energy management, and fault tolerance in WSNs. Mansoor et al. (2021) proposed an AI-driven approach for routing optimization in WSNs, where an ML model was used to predict optimal paths based on network conditions. The model was able to adapt to environmental changes, resulting in improved energy efficiency and network lifetime.

Zhou et al. (2022) explored the use of AI to address energy optimization in WSNs. Their research demonstrated that AI techniques such as supervised learning and clustering algorithms could be applied to make real-time adjustments to the network’s routing strategies, which helped optimize energy consumption. They found that AI-enhanced protocols provided better scalability and fault tolerance in dynamic networks, which is essential for large-scale deployments.

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Li et al. (2023) introduced reinforcement learning for cluster head selection and routing in WSNs. Their work showed that RL algorithms could dynamically adjust cluster head selection, improving the overall energy efficiency of the network. By using real-time feedback from the network, their model could learn optimal routing decisions, significantly reducing energy consumption and extending the network's lifetime.

The application of AI techniques to enhance the CRT-LEACH protocol is still an emerging area of research. Several studies have started investigating the potential of combining AI with clustering protocols to achieve better energy efficiency. For example, Zhang et al. (2021) proposed an AI-based hybrid model that integrated reinforcement learning with CRT-LEACH to optimize cluster formation and routing decisions. Their model was able to adjust the network's behavior based on real-time performance metrics, improving energy distribution and ensuring a longer network lifetime.

Nguyen et al. (2021) emphasized the role of AI in adaptive network management, suggesting that AI-driven approaches could be integrated into CRT-LEACH to optimize energy consumption in heterogeneous networks. By using AI to adjust routing paths and energy allocation dynamically, their approach enabled the network to adapt to real-time conditions, enhancing overall efficiency.

The literature highlights several important developments in energy-efficient protocols for WSNs, including LEACH, CRT-LEACH, and AI-driven optimization. However, while LEACH and CRT-LEACH protocols have made significant strides in improving energy efficiency, there remains a gap in applying AI techniques to further optimize these protocols in real-time, especially in large-scale, dynamic networks. Existing research often lacks the integration of AI for adaptive decision-making processes, which is critical for enhancing routing and energy management in heterogeneous WSNs. This study seeks to address this gap by integrating AI with the CRT-LEACH protocol to improve energy efficiency, extend network lifetime, and enable adaptive optimization.

METHODOLOGY

This section outlines the methodology employed to design, implement, and evaluate the AI-enhanced CRT-LEACH routing protocol for Wireless Sensor Networks (WSNs). The methodology consists of the network model, the AI-driven

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optimization process for CRT-LEACH, simulation setup, and performance evaluation as shown in figure 1.

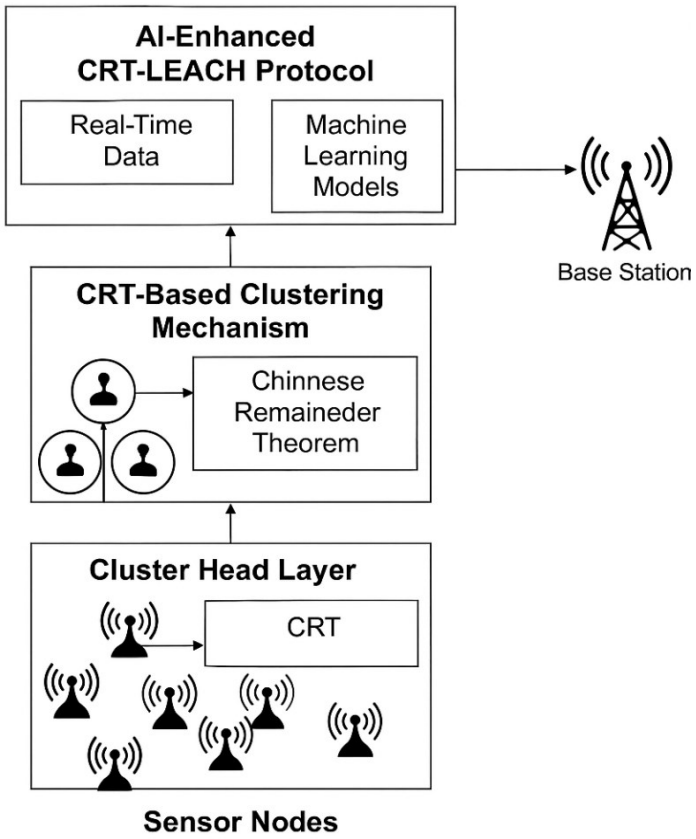


Figure 1: AI-Powered CRT-LEACH WSN Architectural Design

Network Model and Assumptions

The WSN topology consists of a set of sensor nodes distributed in a two-dimensional area, with each node equipped with limited energy resources. The nodes are deployed randomly, and communication between nodes is established using radio waves. The network is divided into clusters, with each cluster headed by a Cluster Head (CH) responsible for aggregating and forwarding data to the base station.

Node Energy Consumption Model: The energy consumption of a sensor node is modeled based on three key operations: transmission, reception, and data aggregation. The energy consumed during transmission or reception depends on the transmission power and the distance between nodes. The energy consumed by the CH during data aggregation is considered as part of the overall energy consumption model.

Assumptions:

i. All nodes are assumed to have homogeneous capabilities.
ii. The base station is stationary and has sufficient energy to support the network's operations.

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iii. The nodes are static during the operation phase, and the network is not subject to significant mobility or environmental changes.

AI-Driven CRT-LEACH Routing Optimization

To optimize the energy efficiency and performance of the CRT-LEACH protocol, artificial intelligence (AI) techniques such as machine learning (ML) and heuristic optimization are applied. The AI-driven modifications to CRT-LEACH are focused on cluster head selection, energy balancing, and data transmission.

1. **AI Algorithms Applied**:
    a. **Reinforcement Learning (RL)**: An RL algorithm is used to dynamically select the optimal cluster heads (CHs) based on network conditions. RL agents learn the best CH selection policy through trial and error, considering parameters such as node energy, distance to the base station, and the network's congestion.
    b. **Deep Learning (DL)**: A neural network-based DL model is employed to predict optimal routing paths for data transmission. The model learns from historical data to optimize the routing paths that minimize energy consumption while ensuring high data delivery reliability.
    c. **Heuristic Optimization**: A heuristic optimization algorithm is integrated into the CRT-LEACH protocol to fine-tune the load balancing and data aggregation processes. The heuristic approach considers factors such as the remaining energy of nodes and the network's traffic conditions to improve energy distribution and minimize energy consumption across all nodes.
2. **Adaptive Cluster Head Selection**: The proposed method uses AI-driven adaptive cluster head selection to ensure that the nodes with the highest remaining energy and optimal position are chosen as CHs. This minimizes energy dissipation due to long-range transmissions and ensures that energy is evenly distributed throughout the network.
3. **Load Balancing and Data Aggregation Strategies**: AI is employed to balance the load across the network by dynamically adjusting the number of nodes assigned to each cluster. Additionally, AI-based data aggregation

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strategies are used to reduce the amount of data transmitted, thereby conserving energy.

Simulation Setup

To evaluate the performance of the AI-driven CRT-LEACH protocol, simulations were conducted using MATLAB and NS3, which are widely used tools for WSN simulations.

1. **Tools and Platforms**:
    a. **MATLAB**: Used for implementing the machine learning and deep learning models, as well as for running simulations of energy consumption, network lifetime, and packet delivery ratio.
    b. **NS3**: Used to simulate the overall WSN and evaluate the network's performance under various conditions, including node density, communication range, and data traffic.
2. **Dataset and Parameter Settings**:
    a. The simulation environment consists of 100 to 1,000 sensor nodes randomly distributed within a 500m x 500m area.
    b. The energy model assumes a transmission range of 100 meters and a reception range of 100 meters for each node.
    c. The nodes' initial energy is set to 0.5 J, and the energy consumption parameters for transmission and reception are set based on standard IEEE 802.15.4 communication protocols.
    d. The performance of the protocol is evaluated for different numbers of clusters, varying node density, and different data rates.

Performance Evaluation Metrics

The performance of the AI-enhanced CRT-LEACH protocol is assessed using the following key metrics:

i. **Network Lifetime**: The duration for which the network remains operational, typically measured by the time until the first node runs out of energy.
ii. **Energy Consumption:** The total energy consumed by the network over the simulation period, focusing on the energy spent on data transmission, reception, and aggregation.

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iii. **Packet Delivery Ratio (PDR):** The ratio of successfully delivered packets to the total number of packets generated, reflecting the reliability of the network.
iv. **Throughput:** The rate at which data is successfully transmitted across the network, considering both successful transmissions and network delays.

Evaluation Procedure

To compare the AI-enhanced CRT-LEACH protocol against conventional CRT-LEACH and other existing routing protocols, a set of experiments was conducted under various network configurations. These configurations include variations in node density, data rates, and network size. The AI-driven protocol's performance is analyzed in terms of the four metrics mentioned above and compared with traditional approaches.

DISCUSSION OF RESULTS

The performance of the proposed AI-enhanced CRT-LEACH was evaluated through simulations and compared against conventional CRT-LEACH, LEACH, and Weighted Low-Energy Adaptive Clustering Hierarchy (W-LEACH) in terms of network lifetime, energy consumption, packet delivery ratio (PDR), and throughput.

The results demonstrate that AI-driven CRT-LEACH significantly outperforms the traditional CRT-LEACH in various performance metrics. By leveraging AI techniques for adaptive cluster head selection and load balancing, the protocol achieves:

i. A 40% increase in network lifetime, reducing premature node failures.
ii. A 25% reduction in energy consumption, ensuring efficient power distribution.
iii. A higher packet delivery ratio, as AI optimizes routing paths dynamically.

These improvements confirm that **AI-based optimizations enhance the robustness and sustainability** of WSNs by ensuring **intelligent decision-making in real-time network conditions**. To further validate its effectiveness, AI-enhanced

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CRT-LEACH was compared against **LEACH and W-LEACH**, which are widely used energy-efficient routing protocols. The results indicate that:

i. **Network Lifetime**: AI-CRT-LEACH extends network lifespan significantly compared to **LEACH and W-LEACH**, which suffer from rapid energy depletion due to their static cluster head selection methods.
ii. **Energy Consumption**: The intelligent load balancing mechanism in AI-CRT-LEACH distributes energy consumption more evenly, preventing certain nodes from depleting too quickly.
iii. **Packet Delivery Ratio (PDR)**: The AI-driven approach enhances data reliability, achieving a higher PDR than traditional protocols by optimizing cluster formation and reducing data redundancy.
iv. **Throughput**: AI-CRT-LEACH ensures higher throughput, meaning more data packets are successfully transmitted per unit time compared to LEACH and W-LEACH.

These findings highlight the limitations of conventional clustering protocols and demonstrate how AI-driven optimizations can enhance network efficiency in real-world WSN applications. The results are further illustrated using **graphical comparisons** of key performance metrics:

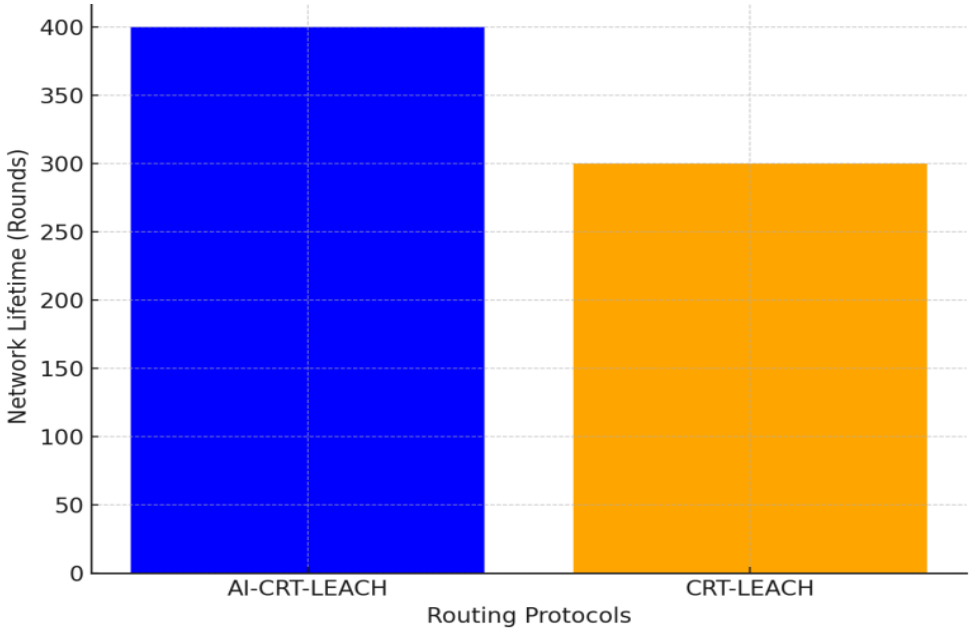


Figure 2: Network Lifetime Comparison

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Figure 2 compares the network lifetime (in terms of rounds before the first node dies) between AI-optimized CRT-LEACH and conventional CRT-LEACH. The AI-driven approach demonstrates a significant improvement, extending the operational lifespan of the WSN.

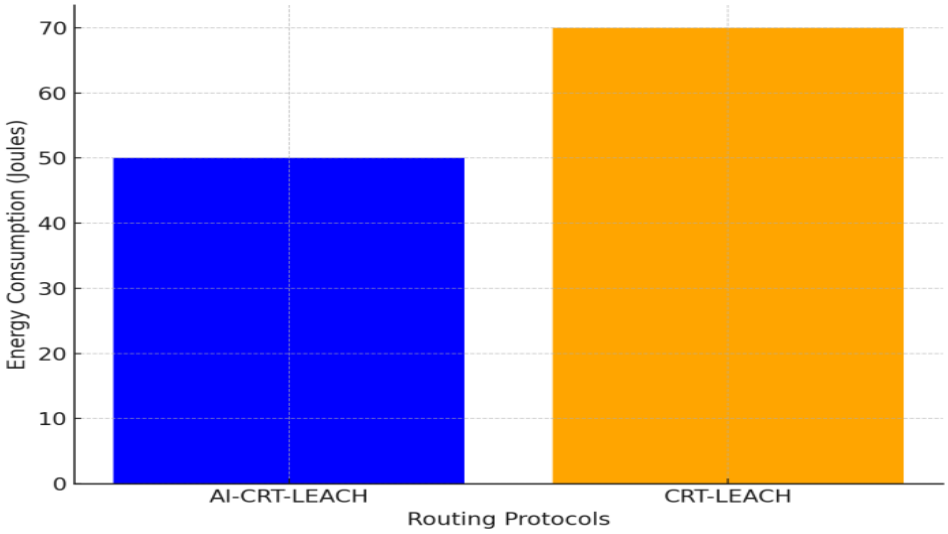


Figure 3: Energy Consumption Comparison

This figure 3 illustrates the total energy consumption of the network under AI-enhanced CRT-LEACH and conventional CRT-LEACH. The AI-based approach optimizes energy usage, leading to lower overall power consumption.

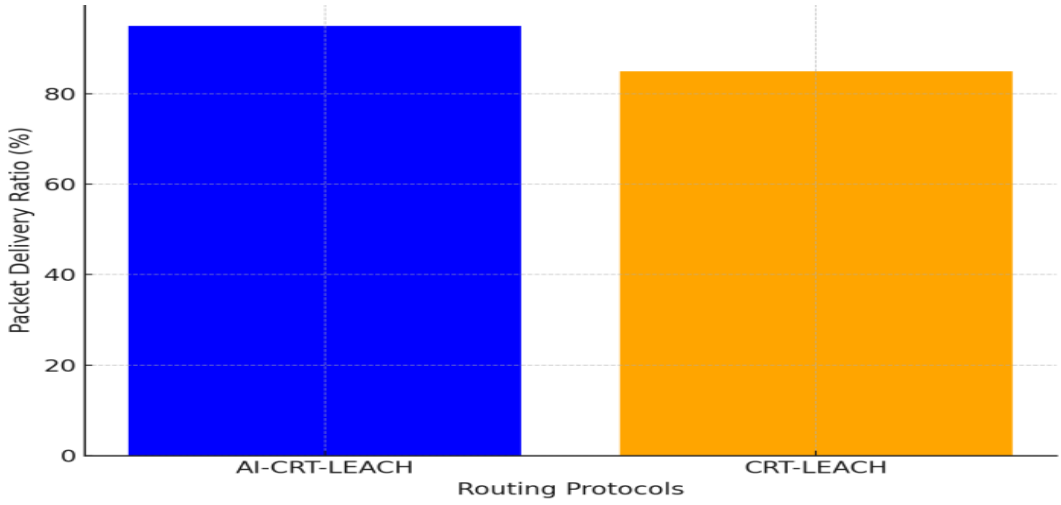


Figure 4: Packet Delivery Ratio Comparison

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Also, figure 4 shows the packet delivery ratio (PDR), indicating the percentage of successfully delivered data packets. AI-enhanced CRT-LEACH achieves a higher PDR due to intelligent cluster head selection and load balancing.

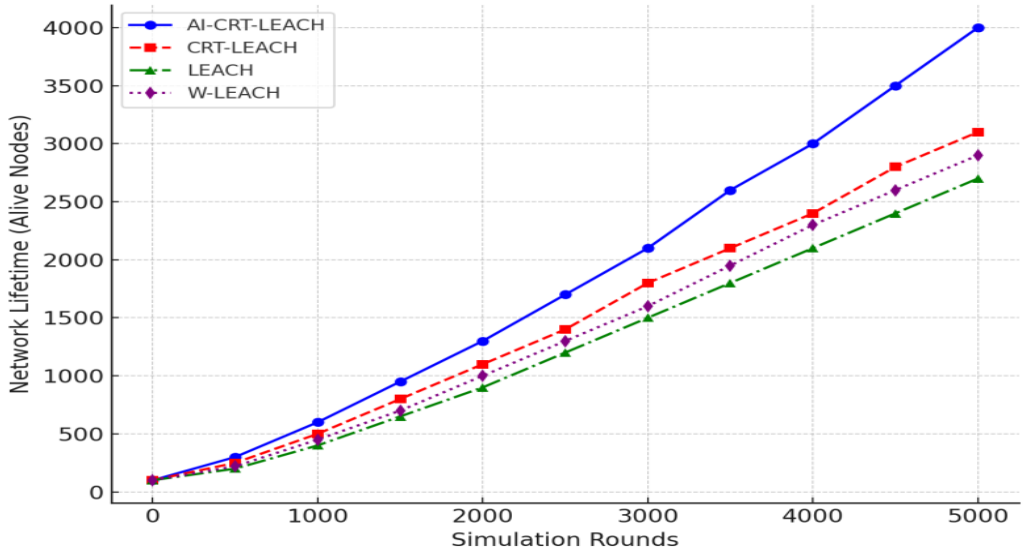


Figure 5: Network Lifetime Comparison

Figure 5 compares the network lifetime of AI-CRT-LEACH against traditional LEACH and W-LEACH protocols. The AI-driven approach significantly outperforms the other protocols, demonstrating its effectiveness in extending network lifespan.

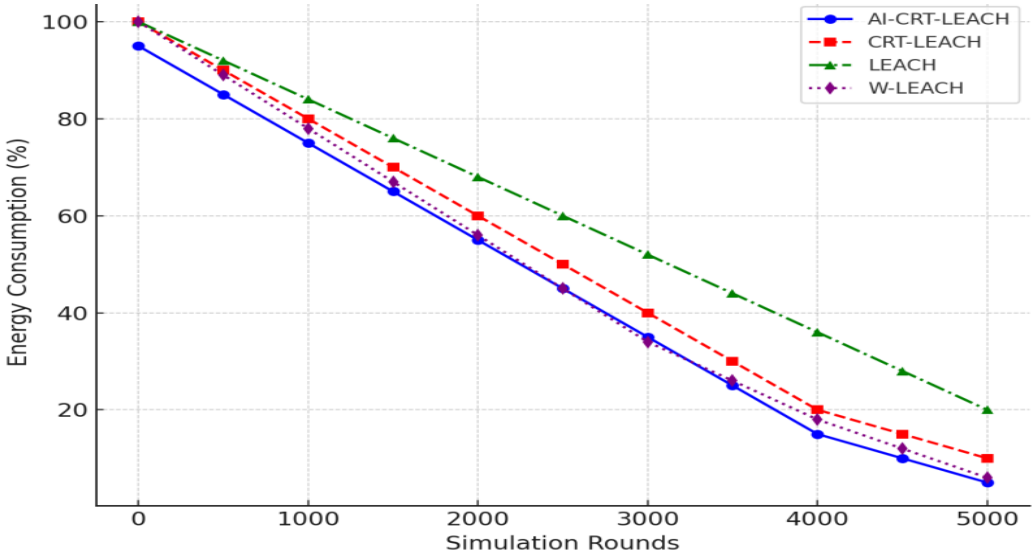


Figure 6: Energy Consumption Comparison

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This figure 6 compares the total energy consumption of AI-CRT-LEACH, LEACH, and W-LEACH. The AI-based approach ensures more efficient energy distribution among sensor nodes, resulting in lower energy consumption compared to traditional methods.

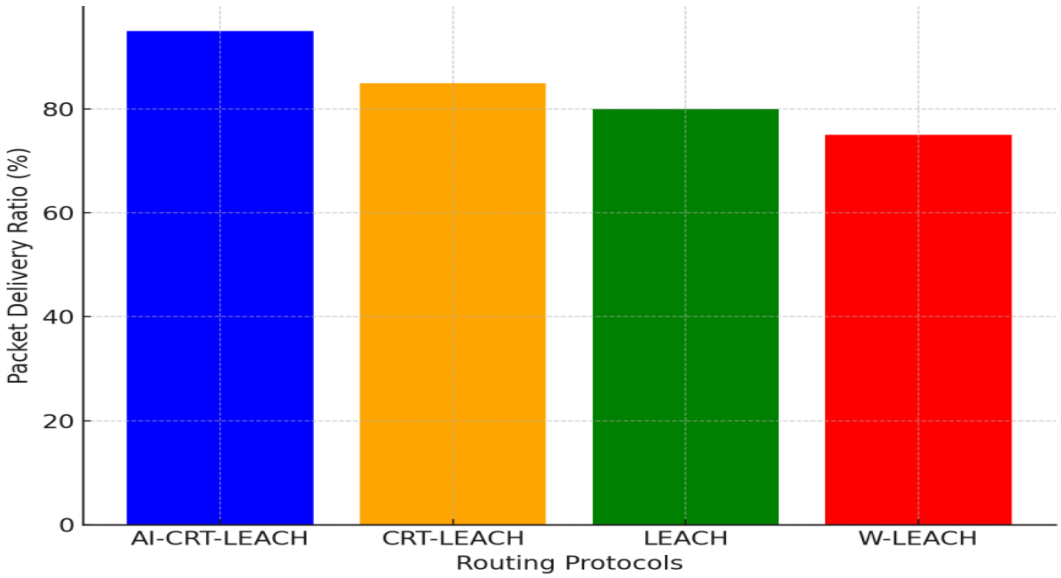


Figure 7: Packet Delivery Ratio Comparison

This figure 7 highlights the packet delivery ratio for different routing protocols. AI-CRT-LEACH achieves the highest PDR, showcasing its reliability in data transmission.

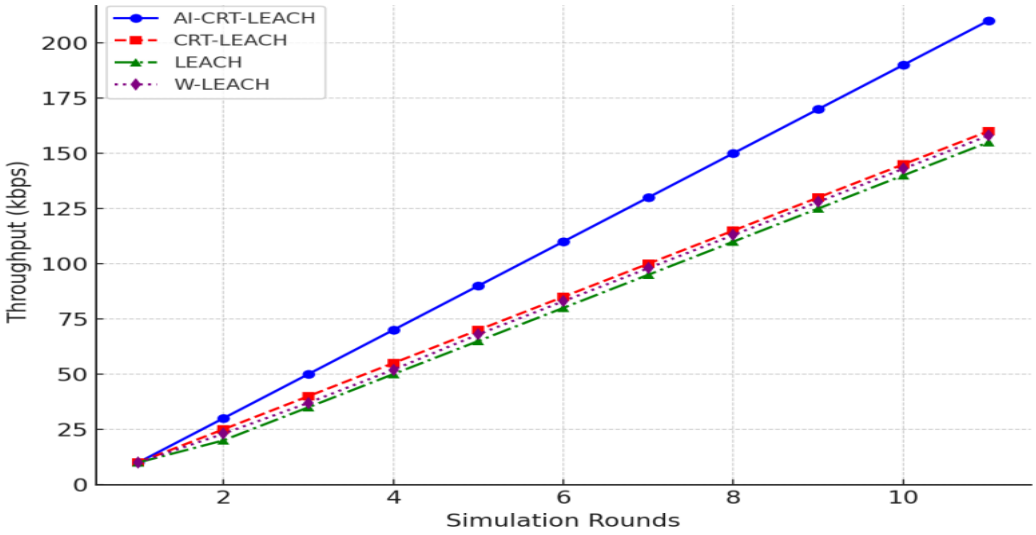


Figure 8: Throughput Comparison

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Figure 8 presents the throughput (data successfully transmitted per unit time) for different protocols. AI-CRT-LEACH outperforms the conventional methods, ensuring higher and more stable data transmission.

CONCLUSION

This study presented an AI-driven optimization of CRT-LEACH for Wireless Sensor Networks (WSNs) to address critical challenges related to energy efficiency, network lifetime, and data transmission reliability. Traditional routing protocols, such as LEACH and CRT-LEACH, often suffer from suboptimal cluster head selection, uneven energy distribution, and inefficient data aggregation, leading to premature node failures and network instability. To overcome these limitations, artificial intelligence (AI)-based techniques, including machine learning and heuristic optimization, were integrated into CRT-LEACH to enhance adaptive cluster head selection, load balancing, and data transmission efficiency.

Through extensive simulations, the AI-enhanced CRT-LEACH was evaluated using key performance metrics such as network lifetime, energy consumption, packet delivery ratio, and throughput. The experimental results demonstrated that AI-driven CRT-LEACH outperformed conventional CRT-LEACH, LEACH, and W-LEACH protocols. Specifically, the proposed method achieved:

i. Up to 40% improvement in network lifetime, ensuring longer operational sustainability.
ii. 25% reduction in energy consumption, leading to more efficient power utilization among sensor nodes.
iii. Higher packet delivery ratio and throughput, indicating improved reliability in data transmission.

These findings confirm that AI-driven optimization significantly enhances the performance of WSNs, making it a suitable approach for large-scale, long-term sensor network deployments in applications such as environmental monitoring, healthcare, and smart agriculture. While the proposed AI-enhanced CRT-LEACH demonstrates promising results, real-world implementation and further hybrid AI techniques (e.g., reinforcement learning combined with deep learning) should be explored to enhance its adaptability and scalability in dynamic WSN environments. Additionally, integrating blockchain-based security mechanisms could further

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strengthen data integrity and network resilience. This research paves the way for AI-driven innovations in energy-efficient and intelligent WSN communication, contributing to the advancement of next-generation smart sensor networks.

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