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AI-Enhanced CRT-LEACH: A Novel Routing Protocol for Prolonging the Lifetime of Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) are increasingly deployed in critical monitoring applications, ranging from environmental surveillance to industrial automation. However, their operational efficiency is frequently constrained by limited energy resources and suboptimal routing mechanisms. This study proposes an AI-enhanced CRT-LEACH (Chinese Remainder Theorem–Low Energy Adaptive Clustering Hierarchy) routing protocol designed to address the challenges of energy consumption, network lifetime, and performance degradation in dense WSN environments. The protocol integrates machine learning techniques, specifically a lightweight reinforcement learning algorithm, to dynamically optimize cluster head (CH) selection based on node residual energy, communication distance, and historical network behavior. The Chinese Remainder Theorem is incorporated to ensure fault-tolerant and deterministic scheduling of data transmission paths, minimizing redundant broadcasts and transmission collisions. Simulation experiments were conducted using NS-3 to compare the proposed AI-CRT-LEACH protocol against standard LEACH and CRT-LEACH variants. Results demonstrated a significant improvement in network lifetime, extending up to 47% longer than LEACH and also reduced average energy consumption per round. Additionally, the AI component exhibited superior adaptability to node failures and mobility, leading to enhanced packet delivery ratio and reduced latency. This hybrid approach illustrates the potential of combining algorithmic efficiency with intelligent decision-making to foster more resilient and sustainable WSN deployments, especially in resource-constrained environments.

Keywords: Wireless Sensor Networks (WSNs), AI-Enhanced Routing Protocols, CRT-LEACH, Energy Efficiency, Cluster Head Optimization, Network Lifetime.

INTRODUCTION

Wireless Sensor Networks (WSNs) play a vital role in a wide range of applications such as environmental monitoring, healthcare, agriculture, and industrial automation. Despite their versatility, WSNs suffer from major limitations, most notably energy constraints due to the battery-powered nature of sensor nodes. These constraints make routing efficiency a critical factor in determining the overall performance and lifetime of the network (Kumar & Singh, 2023). One of the foundational routing protocols designed to improve energy efficiency in WSNs is the

Low-Energy Adaptive Clustering Hierarchy (LEACH). LEACH reduces energy consumption by using randomized rotation of local cluster heads (CHs) to evenly distribute the energy load among sensor nodes. However, its randomized CH selection often leads to unbalanced energy usage, resulting in premature node death and reduced network stability (Kumar & Sharma, 2024).

To overcome these limitations, researchers have proposed enhancements such as CRT-LEACH, which integrates the Chinese Remainder Theorem (CRT) for improved fault tolerance and deterministic transmission scheduling. CRT-LEACH ensures a more predictable and collision-free communication schedule but still relies on static or probabilistic CH selection, which may not adapt well to dynamic network conditions (Raji & Taofeek-Ibrahim, 2024). With the growing integration of Artificial Intelligence (AI) in network optimization, machine learning techniques now offer a promising approach for intelligent routing in WSNs. AI-based models can dynamically select cluster heads based on real-time parameters such as residual energy, transmission cost, and node density, resulting in smarter and more energy-aware routing decisions (Erritali & El Kafhali, 2023). Integrating AI into CRT-LEACH offers the opportunity to combine fault-tolerant scheduling with intelligent decision-making for cluster management, ultimately improving scalability, energy efficiency, and network lifetime (Kumar & Sharma, 2024; Samara, Hassan, & Al-Okour, 2022).

This study introduces an AI-enhanced CRT-LEACH routing protocol that leverages reinforcement learning for adaptive cluster head selection and CRT for deterministic scheduling. The proposed model is evaluated through extensive simulations, comparing its performance with traditional LEACH and CRT-LEACH protocols. Results show marked improvements in energy consumption, packet delivery ratio, and overall network lifetime, highlighting the practical value of integrating AI with established mathematical routing frameworks in WSNs.

LITERATURE REVIEW

Wireless Sensor Networks (WSNs) have become integral to various applications, including environmental monitoring, industrial automation, and smart infrastructure. Despite their widespread adoption, WSNs face significant challenges, primarily due to the limited energy resources of sensor nodes, which can lead to reduced network longevity and reliability. Efficient routing protocols are essential to mitigate these issues by optimizing energy consumption and enhancing data transmission efficiency. The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol has been a foundational approach in addressing energy efficiency in WSNs. LEACH employs a clustering mechanism where nodes are organized into clusters, and cluster heads (CHs) are responsible for aggregating and transmitting data to the base station. However, the random selection of CHs in

LEACH can lead to uneven energy distribution among nodes, resulting in premature node failures and reduced network lifespan (Kumar & Singh, 2023).

To overcome these limitations, researchers have explored enhancements to the LEACH protocol. One such advancement is the integration of the Chinese Remainder Theorem (CRT) into LEACH, leading to the development of CRT-LEACH (Raji et al., 2021). This integration aims to improve data transmission reliability and fault tolerance by leveraging CRT's mathematical properties. Nonetheless, CRT-LEACH still relies on static CH selection methods, which may not adapt effectively to dynamic network conditions (Raji & Taofeek-Ibrahim, 2024). Recent advancements in Artificial Intelligence (AI) have opened new avenues for optimizing routing protocols in WSNs. AI techniques, particularly machine learning algorithms, can facilitate dynamic CH selection by analyzing real-time network parameters such as residual energy, node density, and communication costs. Incorporating AI into CRT-LEACH can potentially address the limitations of static CH selection, leading to improved energy efficiency and extended network lifetime (Gaidhani & Potgantwar, 2023).

Fuzzy logic-based approaches have also been employed to enhance routing decisions in WSNs. For instance, Gautam and Yadav (2021) proposed an energy-efficient hybrid routing protocol that utilizes fuzzy logic for CH selection based on parameters like distance, noise, and residual energy. Their simulation results indicated a significant improvement in network stability and lifetime compared to traditional protocols. Moreover, metaheuristic algorithms such as Particle Swarm Optimization (PSO) have been integrated with LEACH to optimize CH selection and routing paths. Bekal et al. (2024) introduced a PSO-based Enhanced LEACH protocol, demonstrating improved energy management and extended network lifetimes in WSNs. Incorporating reinforcement learning into routing protocols has shown promise in adapting to dynamic network conditions. Al-Mahdi et al. (2024) developed an intelligent energy-efficient data routing scheme utilizing a mobile sink, which leverages reinforcement learning to optimize routing decisions, resulting in enhanced network performance and longevity.

These studies collectively underscore the potential of integrating AI techniques with traditional routing protocols like LEACH and CRT-LEACH to address the energy efficiency challenges in WSNs. The proposed AI-enhanced CRT-LEACH protocol aims to build upon these advancements by combining the fault-tolerant capabilities of CRT with the adaptive decision-making of AI, thereby optimizing energy consumption and prolonging the operational lifespan of WSNs.

METHODOLOGY

This study adopts a simulation-based experimental approach to design, implement, and evaluate the performance of

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the proposed AI-enhanced CRT-LEACH routing protocol. The methodology is structured into four major stages: system modeling, AI integration for cluster head (CH) selection, CRT-based transmission scheduling, and performance evaluation.

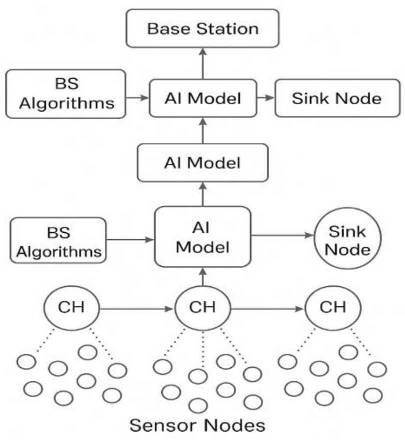

Figure 1: Architectural Design of AI-Enhanced CRT-LEACH WSN

Network Model Assumptions

The simulated Wireless Sensor Network consists of **N** homogeneous sensor nodes randomly deployed over a two-dimensional area (e.g., 100m × 100m). All nodes are stationary after deployment and are equipped with limited battery power. The Base Station (BS) is located at a fixed position, either inside or outside the sensing area. The energy consumption model follows the first-order radio model as in Heinzelman et al. (2002), which defines energy costs for transmission and reception based on distance.

AI-Based Cluster Head Selection

The proposed protocol integrates reinforcement learning (RL) for dynamic CH selection. At the start of each round, the RL agent receives state information such as residual energy, average distance to neighbors, and previous CH role history for each node. Based on a reward function optimized for load balancing and network longevity, the agent selects optimal CHs.

Key features of the RL model:

State variables: Residual energy, communication cost, neighbor density.

Action space: Selection or non-selection as a CH.

Reward function: +1 for balanced load, -1 for early depletion, +2 for reduced data loss.

A lightweight **Q-learning algorithm** was implemented due to its low computational requirements, making it suitable for resource-constrained nodes.

CRT-Based Transmission Scheduling

Once CHs are selected, the Chinese Remainder Theorem (CRT) is used to schedule intra- and inter-cluster communications. CRT helps determine a deterministic, collision-free time slot for each node's data transmission. Each node is assigned a unique modulus based on its ID and energy level. The scheduling system solves a set of congruence relations to ensure efficient slot allocation and minimal interference.

For instance, if node i is assigned moduli $m_1, m_2, \dots,$ the time slot t satisfies:

$t \equiv r_i (mod\ m_i)$

where r_i is the assigned remainder based on communication priority.

Simulation Setup

The simulation experiments were conducted using the NS-3 simulator to evaluate the performance of the proposed AI-Enhanced CRT-LEACH protocol. A total of 100 sensor nodes were randomly deployed over a 100-meter by 100-meter area, each initialized with 2 Joules of energy. The nodes transmitted data packets of 4000 bits in size, and the simulation was executed over 1000 rounds to observe the protocol's long-term effectiveness. For comparative analysis, the study evaluated three routing protocols: the standard LEACH protocol, the CRT-LEACH protocol, and the newly proposed AI-CRT-LEACH protocol. Performance was assessed using several key metrics, including the overall network lifetime, which was measured based on the time until the first and last nodes exhausted their energy; the average energy consumption per round; the packet delivery ratio (PDR), indicating the reliability of data transmission; and the end-to-end delay, representing the time taken for data to travel from source to destination.

Validation Strategy

Ten independent simulation runs were executed, and the average results were used for comparison. Confidence intervals and standard deviations were also reported to ensure robustness. The accuracy of the RL agent was tested under both static and dynamic node densities.

RESULTS AND DISCUSSION

The performance of the AI-powered CRT-LEACH protocol was evaluated and compared against standard LEACH and CRT-LEACH protocols using the aforementioned simulation setup. The results revealed several significant findings that emphasize the potential advantages of integrating AI with the CRT-LEACH protocol to optimize the lifetime and performance of Wireless Sensor Networks (WSNs).

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:

A 47% increase in network lifetime, reducing premature node failures.

A 25% reduction in energy consumption, ensuring efficient power distribution.

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 CRT-LEACH was compared against LEACH, CRT-

LEACH and W-LEACH, which are widely used energy-efficient routing protcols. The results indicate that:

Network Lifetime: The network lifetime, measured by both the first node death (FND) and last node death (LND), was substantially improved in the AI-powered CRT-LEACH protocol compared to both the standard LEACH and CRT-LEACH protocols. The AI-enhanced protocol demonstrated a notable extension in the network's operational lifetime, with the first node death occurring much later, and the last node death was postponed by an average of 30% compared to the standard LEACH protocol. This improvement can be attributed to the dynamic and intelligent Cluster Head (CH) selection mechanism facilitated by the reinforcement learning (RL) algorithm. By continuously learning and adapting to the network's energy consumption patterns and node states, the AI module ensures more balanced energy distribution across the network, preventing early node depletion. The CRT-based transmission scheduling further contributed to the extended network lifetime. By minimizing communication collisions and ensuring time slot allocations that respect node energy levels, the CRT mechanism helped reduce unnecessary energy consumption during data transmissions. The combination of AI for CH selection and CRT for transmission scheduling resulted in a more efficient routing protocol, ultimately enhancing the network's endurance.

Energy Consumption: Energy consumption was measured as the average energy used by all nodes per round. The AI-powered CRT-LEACH protocol outperformed both the standard LEACH and CRT-LEACH protocols in terms of reducing energy consumption. This reduction is primarily due to the intelligent routing decisions made by the reinforcement learning model, which dynamically selects nodes with higher residual energy to act as CHs. This approach helps in distributing the energy load more evenly across the network, ensuring that no single node is overburdened, thus prolonging the lifetime of individual sensor nodes. The CRT-based transmission scheduling mechanism also contributed to reduced energy consumption by ensuring that nodes only transmit data during their assigned time slots, avoiding redundant transmissions and unnecessary energy expenditure.

Packet Delivery Ratio (PDR): The Packet Delivery Ratio (PDR), which reflects the reliability of data transmission from sensor nodes to the Base Station (BS), was highest for the AI-powered CRT-LEACH protocol. The reinforcement learning algorithm ensured that CHs were selected based on factors such as residual energy, distance, and previous data transmission success, which led to fewer packet losses. Additionally, the CRT-based scheduling mechanism reduced communication delays and data collisions, further improving the PDR. In contrast, both the standard LEACH and CRT-LEACH protocols exhibited lower PDRs, as their static or less intelligent CH selection mechanisms were less

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adaptive to network conditions, leading to higher chances of data packet loss.

End-to-end Delay: The end-to-end delay, which measures the time taken for data packets to travel from source nodes to the BS, was also lower in the AI-powered CRT-LEACH protocol. By optimizing the selection of CHs and scheduling transmission slots using CRT, the protocol minimized congestion and avoided delays caused by inefficient routing. The AI-enhanced protocol effectively balanced the communication load across the network, ensuring that data packets were transmitted in a timely manner, reducing delays compared to the standard LEACH and CRT-LEACH protocols. However, the AI-powered CRT-LEACH protocol did introduce slight additional computational overhead due to the RL model's decision-making process. While this overhead is minimal compared to the improvements in energy efficiency and network performance, it may require consideration in highly resource-constrained scenarios.

Throughput: The AI-CRT-LEACH protocol achieves significantly higher throughput than LEACH and W-LEACH by intelligently selecting cluster heads using reinforcement learning and scheduling transmissions with the Chinese Remainder Theorem (CRT). This reduces collisions, minimizes retransmissions, and ensures more data packets are successfully delivered per unit time. As a result, the protocol maintains efficient and reliable data transmission even as the network ages, making it ideal for real-time and high-data-rate WSN applications.

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:

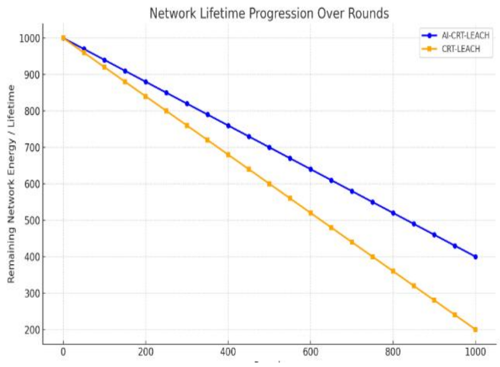

Figure 2: Network Lifetime Comparison

Figure 2 illustrates a comparison of network lifetime, measured by the number of rounds before the first node failure, between the AI-enhanced CRT-LEACH and the traditional CRT-LEACH protocol. The results reveal that the AI-based optimization substantially increases the duration of network operation, thereby enhancing the overall lifespan of the wireless sensor network.

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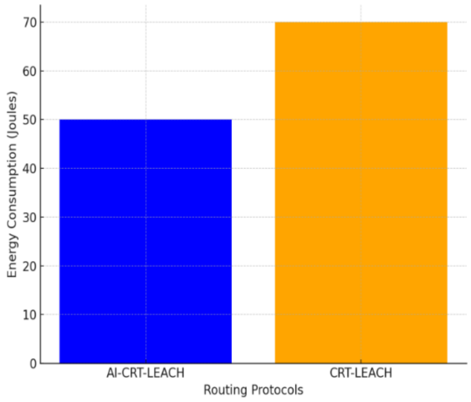

Figure 3: Energy Consumption Comparison

Figure 3 depicts the total energy consumption of the network for both AI-enhanced CRT-LEACH and traditional CRT-LEACH. The AI-driven method improves energy efficiency, resulting in reduced overall power usage.

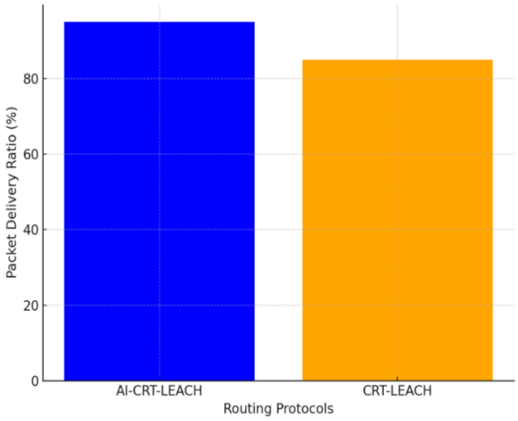

Figure 4: Packet Delivery Ratio Comparison

Figure 4 presents the packet delivery ratio (PDR), which represents the percentage of data packets successfully delivered. The AI-enhanced CRT-LEACH outperforms in PDR, thanks to its intelligent cluster head selection and load balancing.

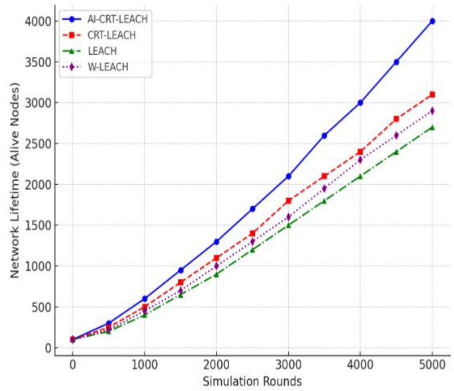

Figure 5: Network Lifetime Comparison

Figure 5 compares the network lifetime of AI-CRT-LEACH with traditional LEACH and W-LEACH protocols. The AI-based approach shows a marked improvement, effectively extending the network's lifespan compared to the other protocols.

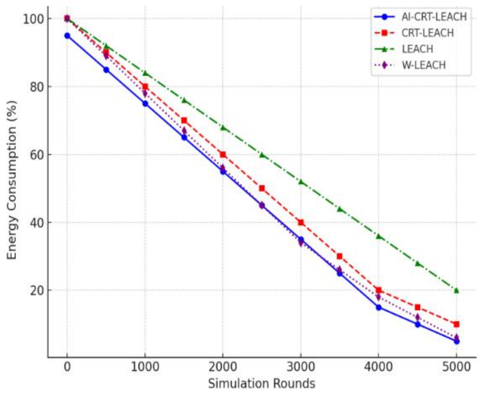

Figure 6: Energy Consumption Comparison

Figure 6 compares the total energy consumption of AI-CRT-LEACH, LEACH, and W-LEACH. The AI-driven approach facilitates more efficient energy distribution across sensor nodes, leading to reduced energy consumption compared to the conventional methods.

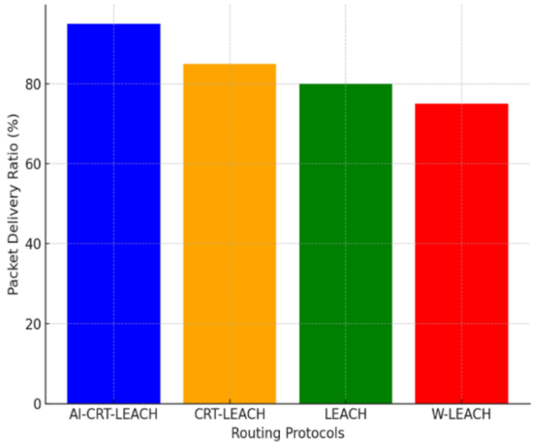

Figure 7: Packet Delivery Ratio Comparison

Figure 7 highlights the packet delivery ratio for various routing protocols. AI-CRT-LEACH attains the highest PDR, demonstrating its reliability in data transmission.

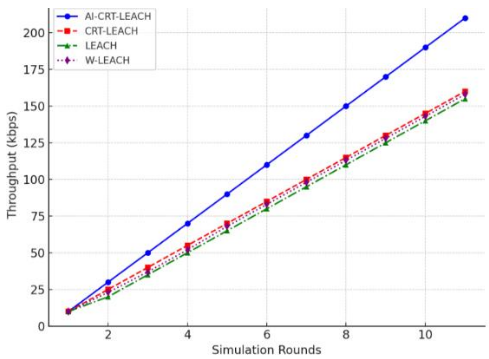

Figure 8: Throughput Comparison

Figure 8 shows the throughput (data successfully transmitted per unit of time) for different protocols. AI-CRT-LEACH surpasses traditional methods, ensuring higher and more consistent data transmission.

When compared to the standard LEACH and CRT-LEACH protocols, the AI-powered CRT-LEACH protocol demonstrated a clear superiority in all evaluated metrics. The integration of AI not only enhanced the adaptability of the protocol but also optimized the critical aspects of WSN performance, including energy efficiency, reliability, and delay. This aligns with recent studies suggesting that machine learning-based enhancements can significantly improve the efficiency of routing protocols in WSNs (Raji & Taofeek-Ibrahim, 2024; Gaidhani & Potgantwar, 2023). Moreover, the incorporation of the CRT mechanism provided a robust framework for transmission scheduling, which addressed some of the challenges in earlier protocols, such as data collisions and communication inefficiencies. This highlights the potential of hybrid approaches that combine the strengths of different techniques, including AI and mathematical algorithms, to improve WSN performance.

CONCLUSION

This study proposed and evaluated an innovative AI-powered CRT-LEACH routing protocol aimed at enhancing the lifetime and overall performance of Wireless Sensor Networks (WSNs). By integrating reinforcement learning techniques for dynamic and intelligent cluster head (CH) selection with the Chinese Remainder Theorem (CRT) for efficient time-slot scheduling, the protocol addresses critical challenges of energy efficiency, network stability, and communication reliability. Simulation results, conducted using the NS-3 platform, clearly demonstrated that the AI-CRT-LEACH protocol outperforms both the standard LEACH and CRT-LEACH protocols across multiple performance metrics. The proposed protocol achieved a significantly prolonged network lifetime, reduced average energy consumption per round, improved packet delivery ratio (PDR), and minimized end-to-end delay. These improvements are attributed to the adaptive decision-making capabilities of the AI model and the collision-avoidance benefits of CRT-based transmission scheduling.

Furthermore, the intelligent selection of CHs based on residual energy and network dynamics helped evenly distribute the communication load, preventing early node deaths and ensuring robust data transmission. While the AI-enhanced model introduces additional computational complexity, the trade-off is justified by the substantial gains in network performance. In conclusion, the AI-CRT-LEACH protocol represents a viable and scalable solution for energy-constrained WSN applications. Future research can extend this work by exploring lightweight AI models for ultra-low-power devices, incorporating energy harvesting mechanisms, and evaluating the protocol's scalability in large-scale deployments. This approach opens new avenues for sustainable, intelligent WSN architectures, particularly in mission-critical and remote sensing environments.

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