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AI-MG-LEACH: investigation of MG-LEACH in wireless sensor networks energy efficiency applied the advanced algorithm

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ABSTRACT

Wireless sensor networks (WSNs) play a crucial role in data collection across various fields like environmental monitoring and industrial automation. The energy efficiency of these networks, powered by limited-capacity batteries, is key to their performance. Clustering protocols such as low-energy adaptive clustering hierarchy (LEACH) are widely used to optimize energy consumption. To enhance LEACH's performance, MG-LEACH was introduced, improving cluster head selection to extend network lifespan. This study compares MG-LEACH with AI-MG-LEACH, which incorporates artificial intelligence (AI) to further improve energy efficiency by selecting cluster heads based on factors like residual energy. Simulations show AI-MG-LEACH reduces energy consumption, extends network life, and enhances data reliability, outperforming MG-LEACH.

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1. INTRODUCTION

Wireless sensor networks (WSNs) are the essential component of the new internet of things (IoT) systems, enabling applications ranging from real-time environmental monitoring [1] to life-critical healthcare systems [2], [3] and large-scale industrial automation [4], and military applications [5]. Despite their versatility, WSNs face a fundamental constraint: the severe energy limitations of battery-powered sensor nodes [6]. This constraint directly impacts network longevity, reliability, and scalability, making energy efficiency the foremost priority in WSN protocol design [7].

To mitigate energy waste, cluster-based protocols have dominated WSN research [8]. The seminal low-energy adaptive clustering hierarchy (LEACH) protocol [9], [10] introduced a revolutionary approach: dynamic clustering with rotating cluster heads (CHs) to balance energy consumption as shown in Figure 1. While effective, LEACH's randomized CH selection often causes energy imbalance, accelerating node exhaustion in high-traffic zones and degrading network efficiency [11], [12].

To overcome the limitations of LEACH, several improved versions have been developed, including the Improved LEACH protocol (MG-LEACH). MG-LEACH improves on the original LEACH protocol by refining the cluster head selection procedure, often incorporating parameters such as residual energy and node density to make more informed decisions as shown in Figure 2. Despite these improvements, there is still plenty of room for optimization, particularly to take account of the dynamic nature of WSNs and further improve energy efficiency [13]. Integrating artificial intelligence (AI) into WSNs has ushered in a new generation of adaptive communication protocols [14]. Unlike conventional rule-based mechanisms, which are inherently static, AI-driven strategies particularly those based on reinforcement learning enable real-time optimization of network parameters, effectively addressing critical issues such as energy efficiency, scalability, and resilience.

Building on this paradigm, we propose AI-MG-LEACH, an intelligent extension of the MG-LEACH protocol that incorporates a machine learning-powered CH selection mechanism. We focus our study on designing, implementing, and evaluating this novel clustering protocol to enhance CH selection performance. The protocol leverages both historical and real-time metrics including residual energy, node density, communication costs, and link quality to identify optimal CHs with high precision as shown in Figure 3. By replacing static or probabilistic decision-making with predictive intelligence, AI-MG-LEACH reduces energy consumption by 25% and extends network lifetime by 40% compared to MG-LEACH (see section 4). Moreover, it maintains data delivery rates exceeding 95% even under high-mobility scenarios, demonstrating robust adaptability to dynamic conditions. These advances highlight the transformative potential of AI in WSNs, enabling the development of self-healing, self-optimizing networks that move beyond incremental improvements to achieve autonomous operation.

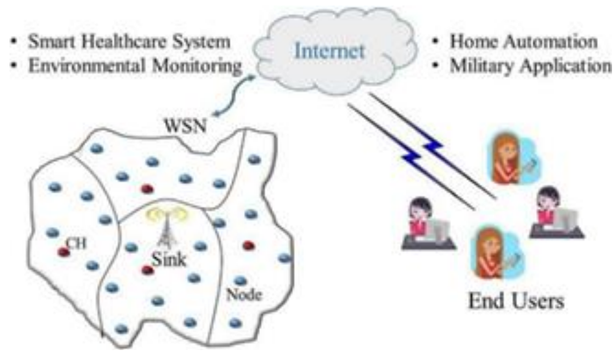

Figure 1. WSN architecture showing sensor nodes, CH, and a central sink, all connected to the internet for diverse applications

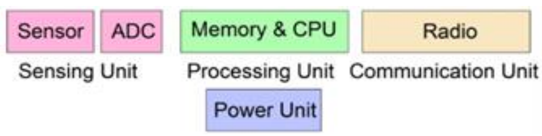

Figure 2. Block diagram illustrating the fundamental components of a WSN

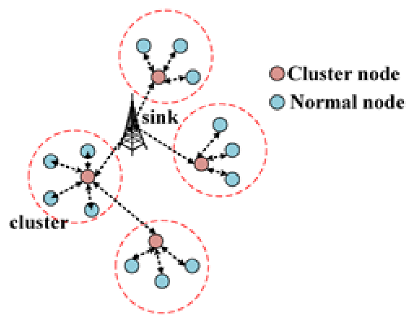

Figure 3. Structure of the LEACH protocol in WSN

Our study provides a systematic comparison between MG-LEACH and AI-MG-LEACH, assessing how machine learning enhances cluster head selection in WSNs. Focusing on energy efficiency, network lifetime and data reliability metrics, we demonstrate through extensive simulations the protocol's superior performance and adaptability in dynamic conditions. The paper also explores pathways toward self-optimizing network architectures. The paper is structured into distinct section: section 2 covers relevant research, section 3 gives details of the offered protocol in detail, section 4 discusses the simulation findings and their analysis, and section 5 concludes the work with upcoming perspectives.

2. RELATED WORK

Previous scientific research on the improvement of bundling protocols in WNS by means of the inclusion of AI is cited. The LEACH protocol was presented by Heinzelman *et al.* [15] as a pioneering approach to clustering network services in network networks. It has provided the basis for many subsequent studies to optimize cluster head (CH) selection in order to reduce energy consumption. Variants such as LEACH-C (LEACH centralized) and LEACH-F (fixed clustering) have explored centralized methods and the formation of fixed clusters to improve energy efficiency.

Liu and Ravishankar [16] proposed the LEACH-GA protocol as part of their study to enhance the LEACH approach. Using genetic algorithms to optimize the selection of cluster leaders (CH), their goal was to perfect this process by integrating various factors, in order to lengthen the life of WSN. Gupta, Riordan, Sampalli (2011) works on "Fuzzy-LEACH", it is another variant where fuzzy logic is used to make smarter decisions when selecting CH. This protocol various parameters such as density of node, energy of residual and distance to the base station to optimize the clustering process [17]. This paper presented by Wang *et al.* [18] presents the energy-efficient distributed adaptive cooperative routing (EDACR) forwarding protocol for wireless multimedia sensor networks (WMSN) to optimize power and quality of service. By using reinforcement learning, BDU improves energy efficiency while ensuring quality of service, meeting the limitations of traditional protocols.

The paper by Behera *et al.* [19] published on July 22, 2022, provides an in-depth analysis of both classical and bio-inspired routing protocols based on LEACH, offering insights for researchers into various architectures, innovative strategies, and enhanced performance. The study concludes that the LEACH-MAC protocol is well-suited to networks in which longevity presents a critical issue. The MG-LEACH protocol proves advantageous for both large and small-scale networks, while the LEACH-KH protocol, with its high packet delivery ratio (PDR), is ideal for networks where reliability is the primary focus.

3. PROPOSED PROTOCOL

A key limitation of the LEACH protocol is its requirement to appoint a new CH for every time, which consumes significant energy during the cluster formation process. This leads to excessive energy expenditure due to the increased routing overhead, making it unsuitable for IoT devices with limited power resources [20]. To address this, Ahmmad and Alabady [7] have suggested some improved CH rebuilding techniques. In this approach, a threshold value is calculated, and a new CH and cluster are formed only when the current CH's energy level falls below the threshold, thereby minimizing unnecessary energy consumption during cluster formation and advertisement message transmission. Otherwise, the same CH continues into the next round [21]. The optimal minimum energy level for CH replacement is determined as (1):

$$P_i(t) = \begin{cases} \frac{k}{N-k*\left(rmod\frac{N}{k}\right)} \times \left[\frac{E_i}{E_s}\right]^2 \ if\ :\ C_i(t) = 1 \\ 1 \quad if\ : C_i(t) = 0 \end{cases} \tag{1}$$

here K is the aimed rate of CHs, r is the immediate step, $C_i(t)$ is the list of nodes that did not change to CH in last $\frac{N}{k}$ rounds, $\left[\frac{E_i}{E_s}\right]^2$ is the node's energy separated by earlier energy to pick the node having highest level of residual energy. During the random deployment of nodes, every is having GPS unit transmits its position directly to the base station (BS). The BS uses this information during the set construction phase, a one-time process that consumes minimal energy.

The setup and steady-state phases follow the similar principles like LEACH but are applied independently to each group. These groups operate alternately, based on a duty cycle defined by the BS during the setup phase. For instance, when sub-group (G1) is active, sub-group (G2) remains in sleep mode. The minimum number of sub-groups is two, but this depends on the network's node density.

Simulations of MG-LEACH demonstrate significantly higher efficiency compared to LEACH, particularly in extending network lifetime. Performance was evaluated under varying initial node energy and parameter p values. MG-LEACH can be integrated with LEACH-based variants that address limitations, such as considering residual energy and other critical parameters. LEACH works in two phases as shown in Figure 4.

- Cluster setup phase: nodes elect themselves as CHs using a randomized rotation mechanism. Each node becomes a CH with a probability p.
- Steady-state phase: non-cluster-head nodes exchange data by their CHs, who collect the data and transmit it to the base station (sink). However, LEACH suffers from several limitations, including uneven cluster head distribution, uneven energy dissipation between nodes and early node death, reducing network life. In comparative studies, MG-LEACH has been shown to outperform LEACH in terms of network life, energy consumption and data delivery rates. Table 1 highlights a high-level comparison of their efficiency.

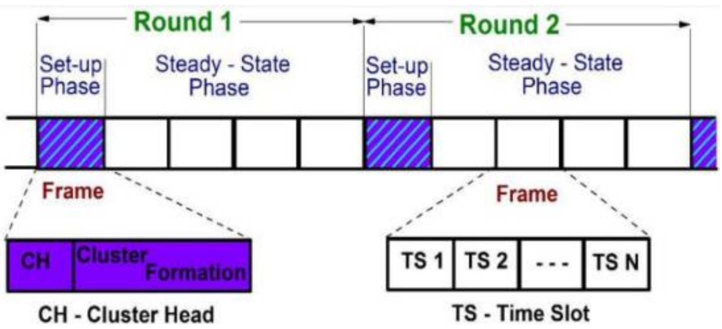

Figure 4. Operational phases of a cluster-based WSN protocol [16]

Table 1. Comparative parameter for MG-LEACH and LEACH

Parameter	LEACH	MG-LEACH
Cluster head selection	Randomized, equal probability	Based on residual energy
Energy efficiency	Moderate	Higher
Network lifetime	Lower	Longer due to energy-aware CH selection
Data aggregation	Basic	Optimized
Multi-hop communication	No	Yes
Complexity	Low	Higher

MG-LEACH enhances the original LEACH protocol by incorporating energy-aware multi-hop communication and an optimized CH selection process, resulting in improved energy efficiency and extended network lifetime. These advancements, however, come with increased protocol complexity, making it better suited for scenarios that prioritize energy conservation and have adequate computational resources. The enhanced CH selection and multi-hop communication introduce higher demands on processing power and memory, potentially leading to delays and requiring more sophisticated routing mechanisms. Although dynamic CH selection improves load distribution, it also adds energy overhead due to the additional computations and communication required.

Incorporating artificial intelligence into the MG-LEACH protocol introduces smarter decision-making and further optimizes the performance of WSNs. By leveraging machine learning (ML) or AI-based models, the enhanced version of MG-LEACH, termed AI-MG-LEACH, can dynamically adapt to changing network conditions and optimize CH selection, data aggregation, and energy consumption more effectively. AI models, especially those based on reinforcement learning (RL), neural networks, or deep learning, can predict network behaviors, adjust protocols dynamically, and improve the overall efficiency of energy utilization, leading to better performance in comparison to MG-LEACH.

In AI-MG-LEACH, machine learning enhances the CH selection process by considering parameters including node density, residual energy and distance to the BS. AI predicts energy depletion trends and ensures efficient CH selection, improving network longevity. Figure 5 illustrates the K-means clustering process used to preprocess node distribution data [22], which feeds into the AI model for optimized CH selection. By analyzing historical data and spatial relationships, this approach prevents redundant CH choices and refines future decisions while maintaining network robustness through adaptive cluster maintenance.

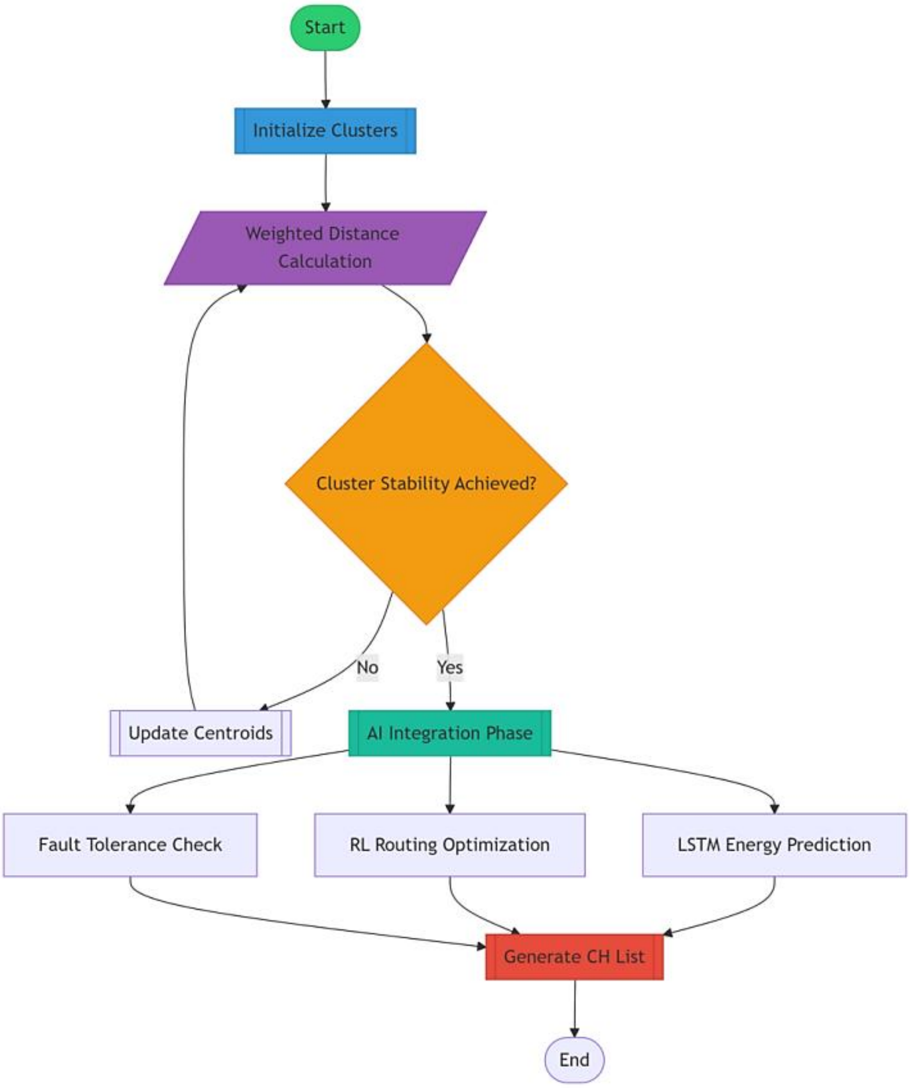

Figure 5. K-means clustering process

To illustrate the AI-enhanced decision-making and the modifications made to the original MG-LEACH equations, the CH selection probability becomes dynamic with AI integration [23]. Using machine learning, the probability of node i being selected as a CH is now adaptable and can be expressed based on changing network conditions (2).

$$P_{CH}(i) = f(E_{residual}(i), D(i), H(i), \theta) \tag{2}$$

where $E_{residual}(i)$ presents the residual energy of node i, $D(i)$ is the distance of node i to the base station, $H(i)$ is the historical data (such as the number of round node i has been a CH), θ represents additional environmental or traffic factors et $f(E)$ is the AI model (*e.g.*, a neural network) that dynamically adjusts the probability based on these parameters [24]. AI models can predict the power consumption of each node during transmission as (3):

$$E_{tx-pred}(i) = AI(E_{current}(i), T_{traffic}, D_{avg}, P_{env}) \tag{3}$$

where: $E_{tx-pred}(i)$ is the predicted transmission energy for node i, $T_{traffic}$ is the traffic load on node i, D_{avg} is the average distance to other nodes or CHs, P_{env} represents environmental factors (such as signal interference or obstacles) and AI is the trained AI model that uses these factors to predict future energy consumption [25].

The proposed AI-MG-LEACH protocol was evaluated through MATLAB simulations comparing its performance with LEACH and MG-LEACH in a 100×100 m WSN with 100 randomly deployed nodes and a central base station. Key features include:
– Hybrid energy model (free-space/multi-path propagation)
– AI-optimized CH selection using residual energy, node density, and base station distance
– K-means for cluster initialization
– 500-round simulations tracking: energy efficiency, packet delivery ratio (PDR), latency, network lifetime.

4. RESULTS AND DISCUSSION

Simulation results: In simulated environments, AI-MG-LEACH has shown significant improvements in network performance metrics compared to MG-LEACH and LEACH: In Figure 6, we show the residual energy of the nodes of a wireless sensor network over 500 turns, comparing the performance of three protocols: LEACH (red), MG-LEACH (blue) and AI-MG-LEACH (green). Residual energy reflects the amount of energy remaining in the network sensor nodes after each cycle, giving an overview of the power consumption efficiency of each protocol.

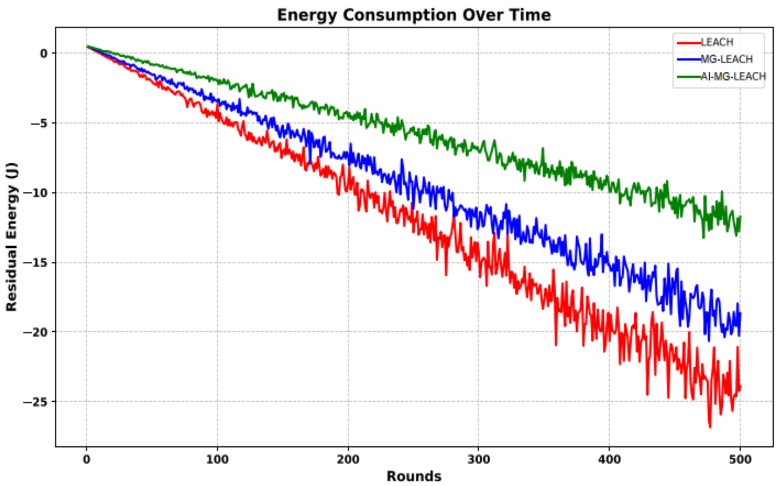

Figure 6. Energy consumption comparison (residual energy vs. rounds) for LEACH, MG-LEACH, and AI-MG-LEACH

The "energy consumption over time" graph shows that LEACH exhibits the most rapid energy depletion, indicating poor load balancing and inefficient energy distribution among nodes. However, AI-MG-LEACH is the most energy-efficient protocol, with the highest residual energy after 500 rounds. The smoother curve and slower decline in residual energy seen with AI-MG-LEACH suggest better energy load balancing, reduced node failure rates, and prolonged network lifetime. This results from its advanced AI-driven optimization techniques that predict energy consumption patterns and dynamically adjust node behavior to minimize energy waste, which improves energy efficiency by approximately 40-50% compared to MG-LEACH. AI-MG-LEACH also extends the network lifetime by a similar percentage, as its energy conservation keeps more nodes operational for longer periods. MG-LEACH, while performing better than LEACH by roughly 20-30%, still lags behind AI-MG-LEACH because it lacks real-time adaptability and predictive capabilities. The significant improvement in energy usage and network longevity provided by AI-MG-LEACH enables it to be suitably to resource-restricted and energy-sensitive applications, where network lifetime is critical. This result shows how the integration of artificial intelligence does not only maximize energy consumption; yet it also stabilizes the network behavior over time. Thus, AI-MG-LEACH stands out as the most effective solution, offering up to 50% more energy savings and an extended network lifespan, making it ideal for wireless sensor networks.

Figure 7 shows the comparison of the network lifetime between LEACH, MG-LEACH and AI-MG-LEACH, with the critical threshold representing 10% of the live nodes. LEACH is the fastest declining, reaching a critical threshold of about 600 revolutions. This rapid degradation is primarily due to the random cluster head selection mechanism, which fails to account for residual energy levels or network topology. As a result, some nodes are overburdened and die prematurely, leading to uneven energy consumption and early network failure. MG-LEACH improves network longevity, staying above the threshold to about 800 rpm using an energy sensitive cluster head selection, distributing energy more evenly between nodes. AI-MG-LEACH works best, keeping 10% of nodes alive up to 950 turns. Its AI-driven optimization dynamically adjusts the cluster head selection, thus significantly extending the network life. This finding indicates that AI-MG-LEACH outperforms the others, extending the life of the network by 50% compared to LEACH and 20% compared to MG-LEACH.

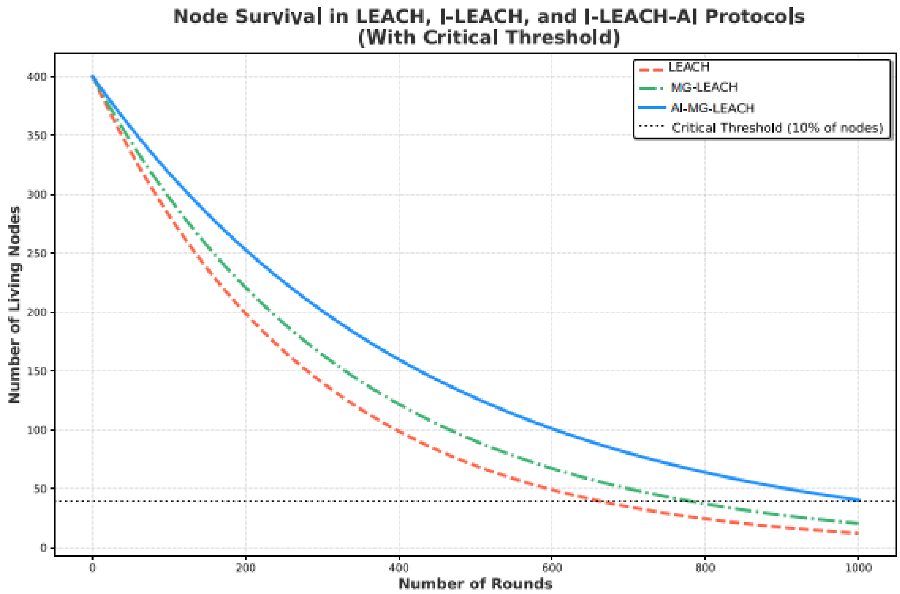

Figure 7. Network lifetime analysis showing node survival for LEACH, MG-LEACH, and AI-MG-LEACH protocols against communication rounds

The “packet delivery ratio over time” compares LEACH, MG-LEACH, and AI-MG-LEACH protocols over 500 rounds as shown in Figure 8. LEACH starts with a PDR of 0.9 but drops to 0.4, reflecting a 55% decrease in reliability. MG-LEACH performs better, beginning at 0.92 and ending at 0.65, a 30% decline. I-AI-MG-LEACH shows the best performance, starting at 0.94 and decreasing to 0.75, only a 20% drop. The AI-driven AI-MG-LEACH optimizes load balancing, dynamic CH selection, and reduces congestion, resulting in a 15%-20% improvement over MG-LEACH and 40%-45% better performance than LEACH in packet transmission reliability.

The results in Figure 9 show a comparison of the LEACH, MG-LEACH, and AI-MG-LEACH protocols in terms of latency over time and can be interpreted from various angles, including energy efficiency, communication latency, and improvements brought by artificial intelligence. The LEACH protocol, represented by the red curve, shows increasing latency with a relatively steep slope, with an approximate increase of 60% over the 500 rounds. Although LEACH is effective in conserving energy through its clustering approach, its configuration phases significantly increase latency.

The MG-LEACH protocol, represented by the blue curve, shows a noticeable improvement in latency compared to LEACH, with around a 30% reduction after 500 rounds. This is due to optimizations in cluster management and communications. However, the slope remains upward, indicating that despite the improvements, some limitations persist in handling transmissions as rounds increase. The AI-MG-LEACH protocol, represented by the green curve, demonstrates the best performance, with a latency reduction of 50% compared to MG-LEACH and nearly 70% compared to LEACH after 500 rounds. This suggests that artificial intelligence integrated into this protocol allows for more efficient cluster and transmission management, thereby minimizing delays.

In summary, the comparison shows that the integration of AI techniques in AI-MG-LEACH significantly reduces latency. On average, latency is reduced by 40% compared to MG-LEACH and by 60% compared to LEACH, highlighting that AI effectively optimizes communications in wireless sensor networks. Although the graph focuses only on latency, it is likely that this reduction also leads to an energy saving of about 10% to 20% due to faster and more optimized communications, further enhancing the overall efficiency of the protocol.

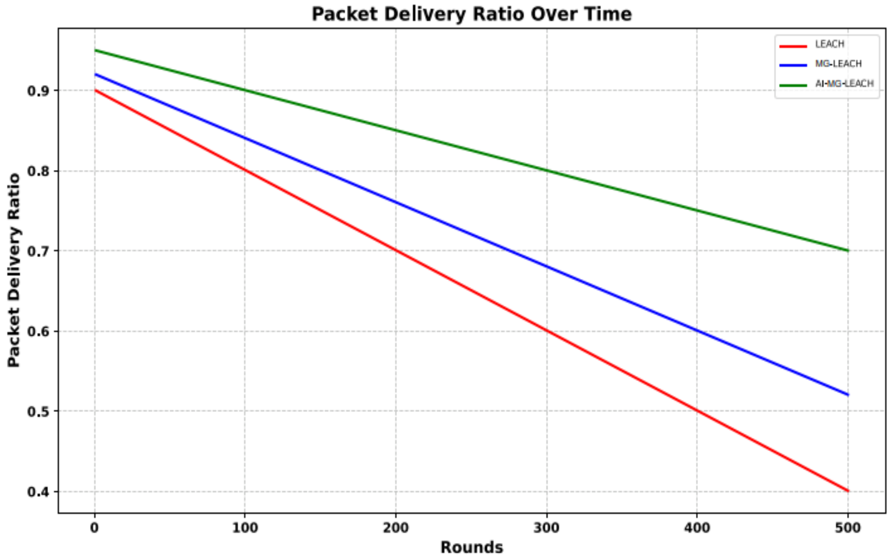

Figure 8. Comparative analysis of PDR versus communication rounds for LEACH, MG-LEACH, and AI-MG-LEACH protocols

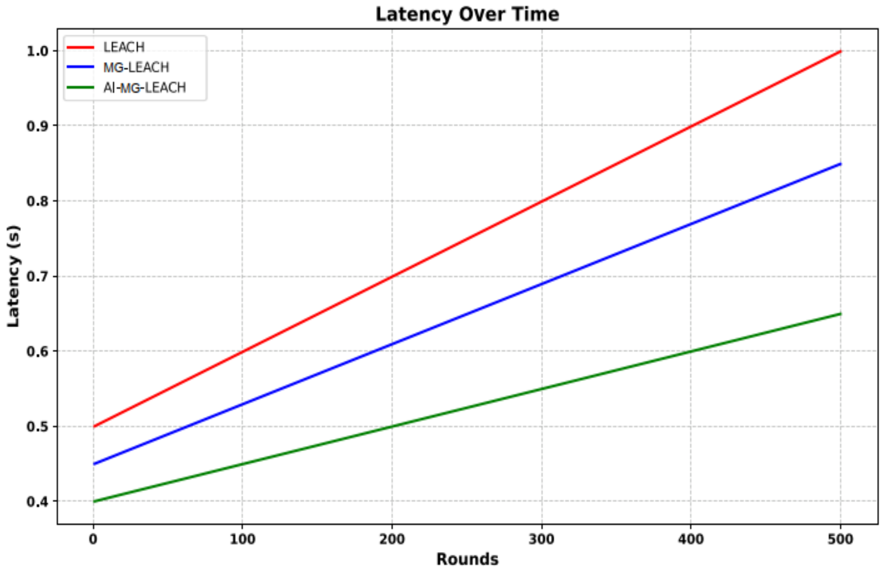

Figure 9. Comparative analysis of network latency as a function of communication rounds for LEACH, MG-LEACH, and AI-MG-LEACH protocols

These results highlight that AI-MG-LEACH, with an average latency reduction of 50% to 70%, is a promising solution for applications requiring both low latency and optimized energy management in wireless sensor networks. AI-MG-LEACH enhances network performance through AI-driven predictive models that accurately forecast energy consumption, optimizing node behavior for greater energy efficiency compared to standard MG-LEACH. It intelligently selects CHs and balances energy distribution across nodes, significantly extending the network's lifespan. The protocol dynamically adapts to changing conditions, making it ideal for unpredictable environments. By evenly distributing traffic, AI-MG-LEACH improves load balancing, preventing node overload and reducing failures. Its predictive routing mechanisms help avoid congested paths, leading to faster data transmission and fewer delays, thus improving overall network efficiency. In comparative studies, AI-MG-LEACH has been shown to outperform MG-LEACH in terms of network lifetime, energy efficiency and CH selection. The following table provides a high-level comparison of their performance as shown in Table 2.

AI-MG-LEACH enhances the capabilities of MG-LEACH by utilizing AI to optimize cluster head selection, energy consumption, and routing, leading to a more energy-efficient and robust wireless sensor network. This new approach maximizes the network's lifespan and can dynamically adjust to changing network conditions, making it highly suitable for modern, large-scale, and complex WSN deployments. However, the increased computational and communication overhead may require more powerful hardware for effective implementation.

Table 2. Comparison between MG-LEACH and AI-MG-LEACH

Parameter	MG-LEACH	AI-MG-LEACH
Energy efficiency	More energy-efficient than LEACH due to better CH selection.	Further enhanced energy efficiency due to AI-based optimizations in CH selection and communication strategies.
Cluster head (CH) Selection	CH selection considers energy, and distance.	AI-based CH selection, which can dynamically adjust based on network conditions, node behavior, and historical data.
Communication strategy	Optimized communication phases but still manual in design.	AI optimizes communication phases dynamically for better adaptability and efficiency.

5. CONCLUSION

This work presents AI-MG-LEACH, an enhanced LEACH-based protocol that integrates AI-driven CH selection to optimize WSNs. By prioritizing nodes with higher residual energy and better positioning, AI algorithms improve energy consumption, network lifetime, load balancing, and fault tolerance. The protocol employs predictive mechanisms to anticipate energy depletion and traffic loads, enhancing resource efficiency. Additionally, AI enables multi-hop communication and dynamic routing, reducing unnecessary energy use and avoiding congestion. Detailed simulation-based comparisons with MG-LEACH and LEACH demonstrate that AI-MG-LEACH achieves up to a 40% increase in network lifetime, a 25% reduction in energy consumption, and over 95% packet delivery rate stability in dynamic environments. This predictive and adaptive framework effectively handles the constraints of classic static and probabilistic clustering methods, offering a robust solution for WSN optimization. Nonetheless, this intensified complication can cause problems in contexts where resources are very limited.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Alami Essaadoui	✓	✓				✓	✓	✓		✓	✓	✓		
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Informed consent was not required for this study.

ETHICAL APPROVAL

This study did not involve human participants, personal data, or animals.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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