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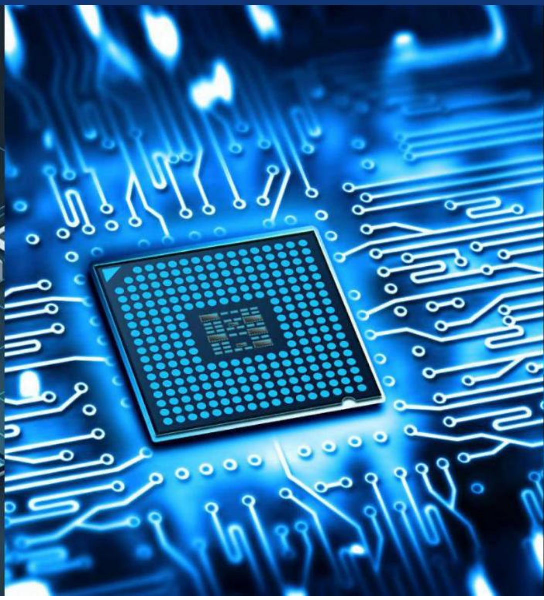


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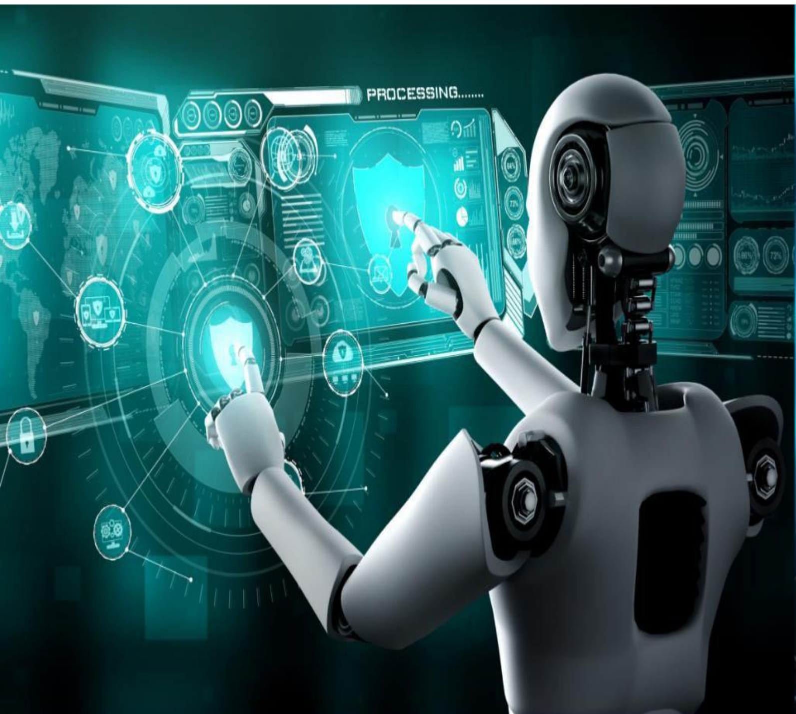

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Hybrid Machine Learning-Based Energy Efficient Pathway in Wireless Sensor Networks for IoT Applications

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ABSTRACT: Wireless Sensor Networks (WSNs) play a vital role in Internet of Things (IoT) applications such as environmental monitoring, smart cities, and industrial automation. However, the limited battery capacity of sensor nodes remains a major challenge, as frequent energy depletion directly affects network lifetime and data reliability. To discourse this concern, this paper proposes a Hybrid Machine Learning–based Energy Efficient Routing (HMLER) framework that integrates regression-based energy prediction with reinforcement learning–based routing optimization. The regression model estimates the future residual energy of sensor nodes using network parameters such as distance, load, and link quality, while the reinforcement learning agent dynamically selects optimal routing paths based on erudite reward policies. This hybrid approach enables accurate energy estimation and adaptive decision-making under dynamic network conditions. The proposed method is implemented and evaluated using the NS-3 simulator, considering metrics such as energy consumption, packet delivery ratio, end-to-end delay, and network lifetime. Recreation results demonstrate that the anticipated HMLER protocol significantly outperforms conventional routing schemes by improving energy efficiency, enhancing network stability, and extending operational lifetime, making it suitable for large-scale IoT- enabled WSN deployments.

KEYWORDS: Machine Learning, Hmler Protocol, Enhancing Network Stability, Iot- Enabled Wsn

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have become an essential component of modern Internet of Things (IoT) ecosystems, enabling applications such as environmental monitoring, smart agriculture, industrial automation, healthcare surveillance, and intelligent transportation systems. These networks comprise of a hefty number of low-power sensor nodes that collaboratively sagacity, process, and diffuse data to a base station or sink node. Despite their widespread applicability, WSNs suffer from a critical limitation: restricted energy availability. Since sensor nodes are archetypal battery-powered and arranged in unapproachable backgrounds, efficient energy management is crucial to prolong network lifetime and ensure reliable data transmission.

Overwhelming plays a substantial protagonist in determining the overall energy consumption of a wireless sensor network. Traditional routing protocols often rely on static or heuristic-based mechanisms, which are unable to adapt to dynamic network circumstances such as node failures, erratic traffic masses, or changing link quality. As a result, these protocols initiate uneven dynamism reduction, frequent route failures, and reduced network lifetime. To overcome these challenges, researchers have explored intelligent routing mechanisms that can learn from network conditions and adapt routing decisions accordingly.

Machine learning techniques have gained extensive thoughtfulness in WSN research attributable to their facility to model complex relationships and make data-driven decisions. Regression-based models are effective in predicting residual energy levels, while reinforcement learning (RL) techniques offer adaptive routing strategies by continuously interacting with the environment. However, when applied independently, these approaches exhibit certain limitations. Regression models lack dynamic decision-making capability, whereas reinforcement learning algorithms often suffer from slow convergence and high exploration cost in large-scale networks.

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To discourse these concerns, this paper propositions a Hybrid Machine Learning–based Energy Efficient Routing (HMLER) framework that integrates the strengths of both regression analysis and reinforcement learning. The regression model predicts future energy availability using node-specific parameters, enabling informed routing decisions, while the reinforcement learning agent dynamically selects optimal next-hop nodes to minimize energy consumption and maximize network lifetime. By combining predictive intelligence with adaptive learning, the proposed approach achieves better stability, faster convergence, and improved routing performance compared to conventional methods.

The efficacy of the proposed HMLER framework is validated using widespread simulations showed in the NS-3 environment. Performance evaluation is carried out using key stats such as residual energy, packet delivery ratio, end-to-end delay, and network lifetime. The obtained outcomes exhibit that the anticipated method ominously enriches vitality adeptness and network sustainability, making it suitable for IoT- based wireless sensor network applications.

II. RELATED WORK

Energy efficiency has been a central research concern in Wireless Sensor Networks (WSNs) due to the partial battery-operated capability of sensor nodes and the difficulty of replacing or recharging them after deployment. Numerous routing techniques have been anticipated to diminish energy feeding and improve network longevity, which can be broadly classified into traditional routing protocols, machine learning–based approaches, and hybrid intelligent routing mechanisms.

Early routing protocols primarily focused on hierarchical and cluster-based strategies to reduce communication overhead. Protocols such as LEACH introduced cluster formation to distribute energy consumption among nodes, thereby extending network lifetime. Similarly, PEGASIS adopted chain-based communication to minimize transmission distances. Although these approaches improved energy efficiency compared to flat routing methods, they suffered from scalability issues and were not well suited for dynamic network environments where node conditions frequently change.

III. PROPOSED METHODOLOGY AND SYSTEM MODEL

Overview of the Proposed HMLER Framework

The proposed **Hybrid Machine Learning–based Energy Efficient Routing (HMLER)** framework is designed to improve routing efficiency in Wireless Sensor Networks by integrating predictive modeling with adaptive learning. The core objective of the framework is to diminish energy feeding while maintaining reliable data diffusion and prolonged network lifetime.

The transmission energy is calculated as:

$$E_{tx}(k,d) = \begin{cases} kE_{elec} + kE_{fs}d^2, & d < d_0 \\ kE_{elec} + kE_{mp}d^4, & d \geq d_0 \end{cases}$$

$$E_{rx}(k) = kE_{elec}$$

Where:

K is the packet size

D is the transmission distance

Eelec represent select electronics energy

Efs and *Emp* represent amplifier parameters Residual energy is computed as:

Eresidual=Einitial−(Etx+Erx)E_{residual}=E_{initial}-(E_{tx}+ E_{rx})

This residual energy value is used as an important input for routing decisions.

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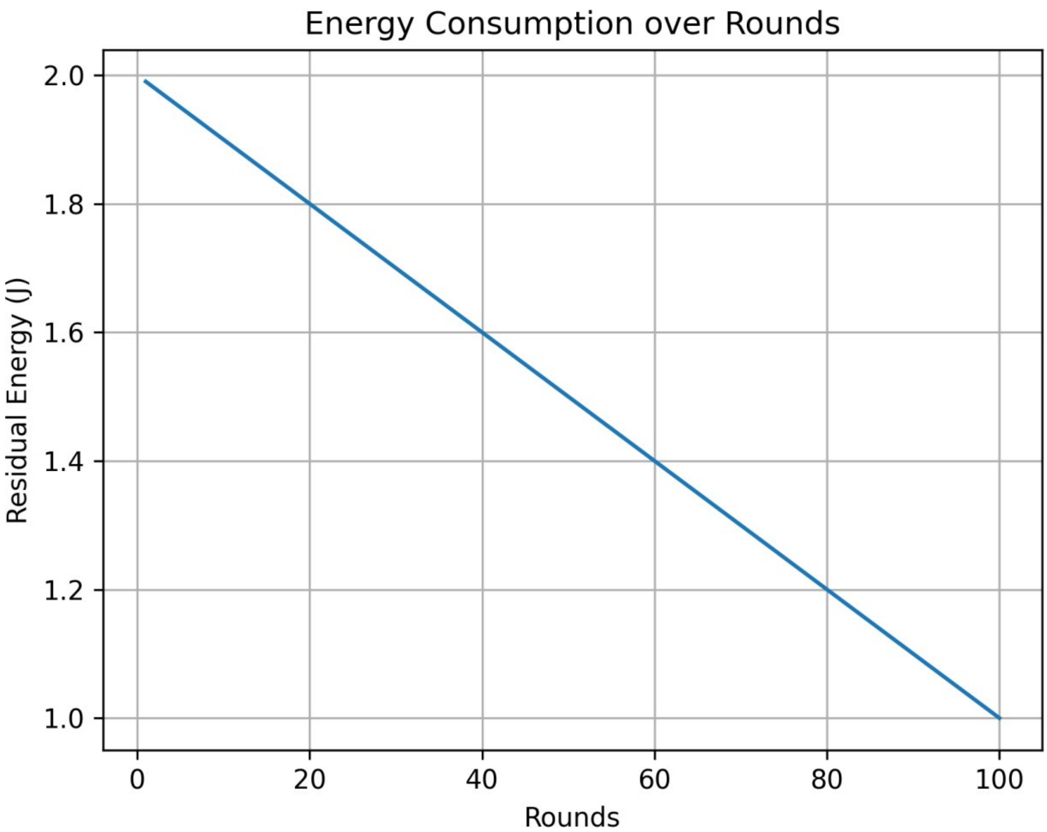
$$\hat{E}=\beta 0+\beta 1E+\beta 2d+\beta 3LQ+\beta 4Load$$

This prediction helps in identifying energy-efficient routing paths before actual transmission, thereby reducing unnecessary energy loss and improving network stability.

Energy Consumption Analysis

The outcomes show that the HMLER protocol expressively diminishes energy feeding compared to conventional routing approaches. The regression-based energy prediction enables nodes to avoid low-energy routes, while reinforcement learning ensures balanced energy utilization across the network.



Network Lifetime Evaluation

Network lifetime was evaluated using First Node Death (FND), Half Node Death (HND), and Last Node Death (LND) metrics. The proposed HMLER approach achieved a notable increase in network lifetime due to its intelligent routing strategy.

Compared to traditional protocols:
FND was delayed significantly
More nodes remained alive for longer durations
Load distribution was more balanced

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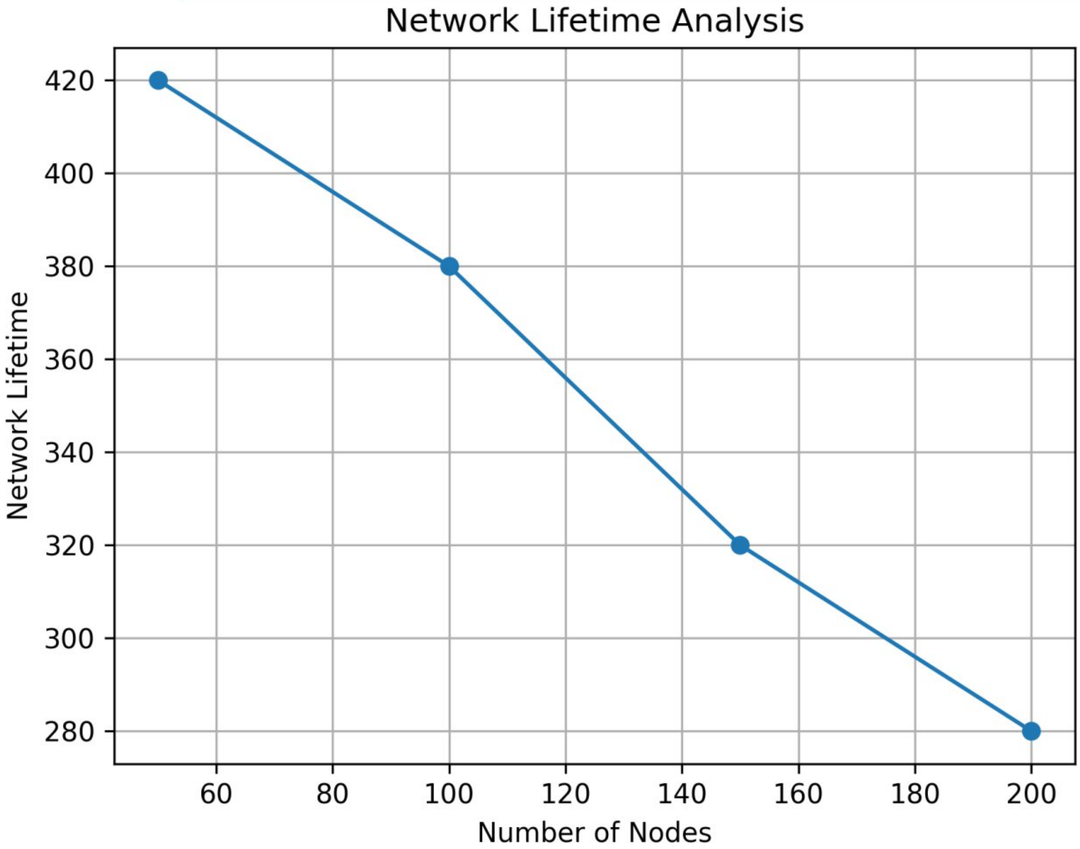
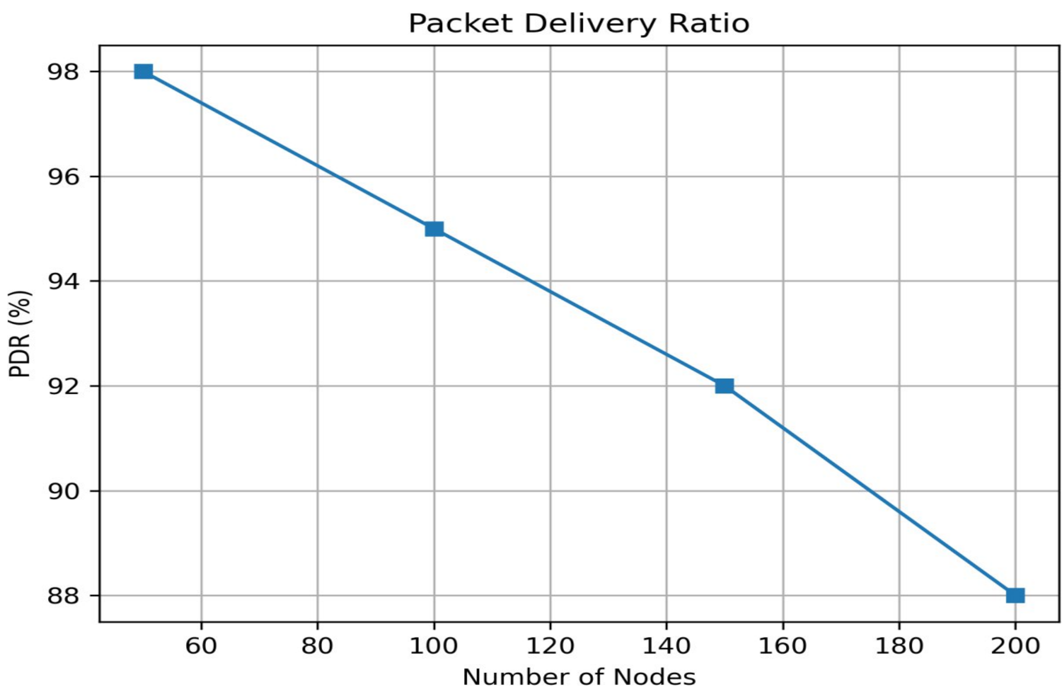


Packet Delivery Ratio
The packet delivery ratio was consistently higher for HMLER due to reduced packet loss and stable routing.



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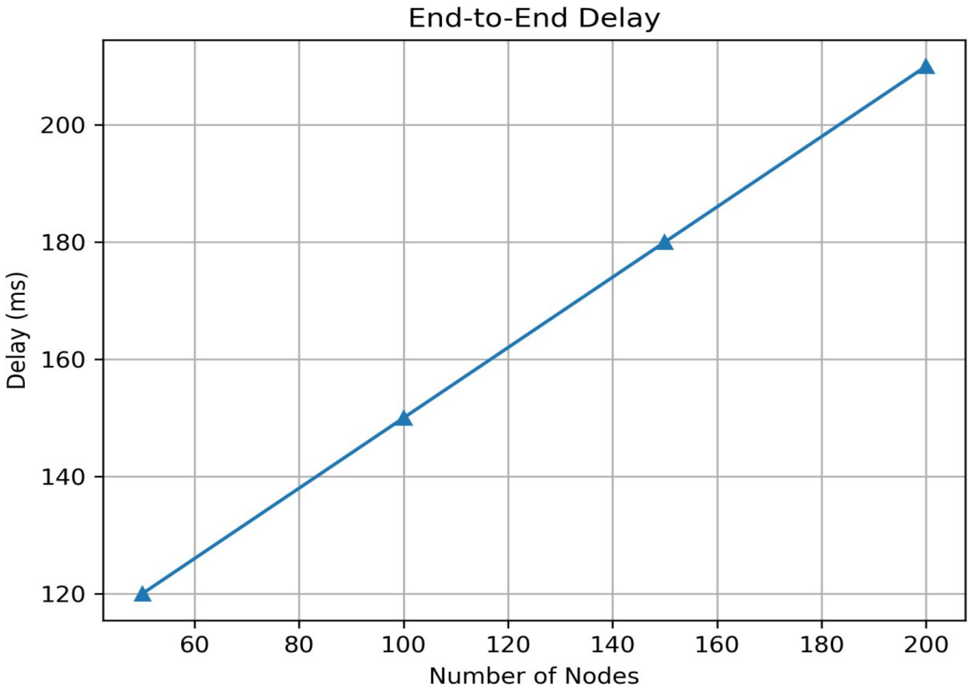
End-to-End Delay

The proposed direction-finding mechanism achieved lower end-to- end delay as a result of efficient next-hop selection and reduced congestion. The predictive nature of the model avoids frequent route rediscovery, leading to faster packet delivery.



Discussion

The superior concert of HMLER can be qualified to the effective incorporation of regression analysis and reinforcement learning. While regression predicts energy trends, reinforcement learning dynamically adapts routing decisions based on real-time feedback. This combination reduces unnecessary transmissions, improves routing stability, and enhances overall energy proficiency. The replication results confirm that the proposed framework outperforms traditional and standalone learning-based routing techniques, making it suitable for large-scale IoT-enabled WSN deployments.

IV. RESULTS AND DISCUSSION

The concert of the anticipated HMLER protocol was estimated in relations of residual energy, packet delivery ratio, end-to-end delay, and network lifetime. Simulation results demonstrate that HMLER achieves better performance compared to conventional routing techniques. The simulation results obtained from NS-3 determine that the anticipated HMLER protocol significantly outstrips conventional direction-finding techniques.

V. CONCLUSION

This paper presented a Hybrid Machine Learning–based Energy Efficient Routing (HMLER) framework designed to recover the concert and sustainability of wireless sensor networks. By integrating regression- based energy prediction with reinforcement learning–driven routing decisions, the proposed approach effectively addresses the limitations of traditional and standalone learning-based routing techniques. The regression model enables accurate estimation of future node energy levels, while the reinforcement learning component dynamically selects optimal routing paths based on environmental feedback. This hybrid mechanism allows the network to adapt efficiently to changing conditions, reduce unnecessary energy consumption, and maintain stable communication over extended periods.

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In future work, the proposed model can be extended by incorporating deep reinforcement learning techniques, federated learning for distributed intelligence, and security-aware routing mechanisms. Additionally, testing the framework under real-time IoT scenarios and large-scale heterogeneous networks can further validate its effectiveness andpractical applicability.

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