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An Energy-Efficient IoT Sensor Network Framework Using Intelligent Energy Harvesting and Adaptive Routing

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ABSTRACT

The rapid growth of Internet of Things (IoT) applications has led to the deployment of large-scale sensor networks in smart cities, healthcare, agriculture, industrial automation, and environmental monitoring systems. However, the limited battery capacity of sensor nodes remains a major challenge affecting network lifetime and reliability. Frequent battery replacement increases maintenance costs and limits scalability, particularly in remote and inaccessible locations. This paper proposes an Energy-Efficient IoT Sensor Network Framework that integrates intelligent energy harvesting techniques, adaptive sleep scheduling, edge computing, and Artificial Intelligence (AI)-based routing algorithms to optimize power consumption and extend network longevity. The proposed system continuously monitors residual node energy, communication quality, and environmental conditions to dynamically select optimal routing paths and operational states. Machine learning algorithms predict energy consumption patterns and network traffic conditions, enabling proactive resource management. Experimental analysis demonstrates significant improvements in network lifetime, packet delivery ratio, energy utilization efficiency, and communication reliability compared to conventional routing approaches. The proposed framework offers a sustainable and scalable solution for next-generation IoT sensor networks operating in energy-constrained environments.

Keywords: *Internet of Things, Energy Efficiency, Wireless Sensor Networks, Energy Harvesting, AI-Based Routing, Edge Computing, Smart Environment, Sustainable IoT.*

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1. INTRODUCTION

The Internet of Things has emerged as a transformative technology that enables billions of interconnected devices to collect, exchange, and process information in real time. IoT sensor networks form the foundation of numerous applications including smart agriculture, environmental monitoring, healthcare systems, industrial automation, transportation, and smart cities. These applications rely heavily on wireless sensor nodes that continuously monitor physical parameters and transmit data to centralized systems for analysis and decision-making.

Despite their widespread adoption, IoT sensor networks face significant challenges related to limited energy resources. Sensor nodes are typically powered by batteries with finite lifetimes, making energy consumption a critical factor affecting network performance and sustainability. Excessive energy usage can lead to premature node failures, reduced network coverage, communication interruptions, and increased maintenance requirements.

Traditional routing protocols often focus primarily on communication efficiency without considering energy-aware decision-making. As a result, certain nodes experience rapid battery depletion due to uneven workload distribution. Recent advancements in artificial intelligence, energy harvesting technologies, and edge computing provide new opportunities for improving energy management in IoT environments.

This paper proposes an intelligent energy-efficient IoT sensor network framework that combines AI-driven routing algorithms, renewable energy harvesting mechanisms, adaptive sleep scheduling, and edge computing techniques to maximize network lifetime while maintaining reliable communication performance.

2. SURVEY OF RESEARCH

Energy conservation has been a primary research focus in wireless sensor networks for many years. Early studies introduced clustering-based protocols such as LEACH and PEGASIS to reduce communication overhead and distribute energy consumption among network nodes. These protocols improved network longevity but often suffered from scalability and adaptability limitations.

Researchers later explored energy-aware routing techniques that selected communication paths based on residual node energy and transmission costs. Such methods improved load balancing but lacked predictive capabilities for future energy requirements.

The integration of energy harvesting technologies has further enhanced network sustainability. Solar, wind, thermal, and vibration-based harvesting systems allow sensor nodes to replenish energy from surrounding environments. Studies have shown that harvested energy can significantly extend network operational lifetimes.

Machine learning algorithms have recently been employed to predict network traffic patterns, energy consumption behavior, and node failures. Artificial intelligence enables dynamic optimization of routing decisions and resource allocation strategies based on real-time network conditions.

Edge computing has also gained popularity in IoT architectures by reducing communication overhead and processing data near the source. This approach minimizes transmission energy consumption and improves response times.

Although significant progress has been achieved, challenges remain in integrating AI-driven routing, energy harvesting, and edge intelligence within a unified framework. The proposed system addresses these limitations through an adaptive and intelligent energy management architecture.

3. PROPOSED SYSTEM

The proposed Energy-Efficient IoT Sensor Network consists of five major layers: Sensor Layer, Energy Harvesting Layer, Edge Processing Layer, AI Routing Layer, and Cloud Monitoring Layer.

The Sensor Layer comprises distributed IoT nodes equipped with environmental sensors such as temperature, humidity, pressure, motion, gas, and light sensors. These nodes continuously collect data from the surrounding environment.

The Energy Harvesting Layer utilizes renewable energy sources including solar panels, piezoelectric harvesters, and thermoelectric generators to supplement battery power and enhance node sustainability.

The Edge Processing Layer performs local data filtering, aggregation, and anomaly detection before forwarding information to higher-level systems. This reduces unnecessary communication and conserves energy.

The AI Routing Layer employs machine learning algorithms to analyze node energy levels, communication quality, network congestion, and traffic patterns. Based on these factors, the system dynamically selects optimal routes that minimize overall energy consumption.

The Cloud Monitoring Layer provides centralized visualization, network analytics, performance monitoring, and long-term data storage. Administrators can monitor network health and optimize deployment strategies through an interactive dashboard.

4. WORKING METHODOLOGY

The operation of the proposed system as shown in the fig 1 begins with distributed sensor nodes continuously monitoring environmental conditions and generating data packets. Each node periodically measures its residual battery energy, harvested energy availability, and communication quality indicators.

Energy harvesting modules collect renewable energy from environmental sources and recharge onboard storage units. The harvested energy information is integrated into the node's energy management system.

Sensor data is initially processed at edge devices where redundant information is filtered and aggregated. Local processing reduces communication overhead and minimizes energy-intensive transmissions.

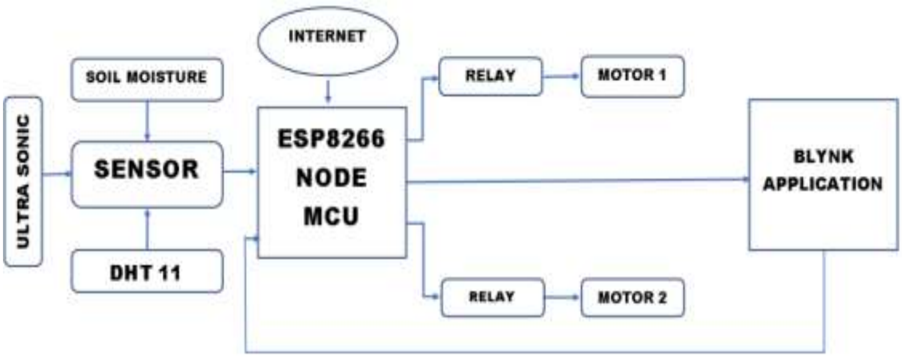

Fig 1: System Architecture

The AI-based routing engine analyzes network conditions including residual energy levels, link quality, node density, traffic load, and historical energy consumption patterns. Machine learning models predict future energy requirements and identify optimal routing paths.

Adaptive sleep scheduling mechanisms place inactive nodes into low-power states during periods of reduced activity. Nodes automatically transition between active and sleep modes based on sensing requirements and communication demands.

Data packets are forwarded through dynamically selected energy-efficient routes toward gateway nodes and cloud servers. Continuous feedback from network operations enables the AI engine to update routing policies and improve future decision-making.

This intelligent combination of energy harvesting, AI routing, and adaptive power management significantly extends network lifetime while maintaining communication reliability and sensing accuracy.

5. RESULTS AND DISCUSSION

The proposed system was evaluated using simulation models representing large-scale IoT sensor deployments under varying environmental and traffic conditions. Performance metrics included network lifetime, energy consumption, packet delivery ratio, throughput, and latency.

Simulation results demonstrated that AI-based routing effectively balanced energy consumption among sensor nodes, preventing premature battery depletion of heavily utilized devices. The energy harvesting subsystem provided continuous supplemental power, significantly extending operational lifetimes.

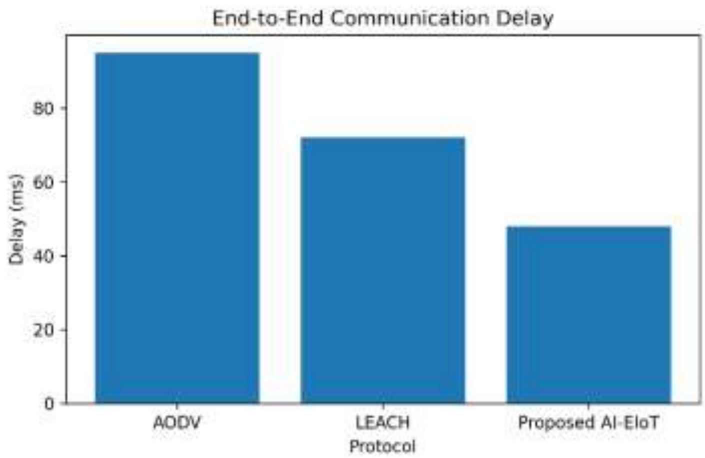

Fig 2: End-to-End Communication Delay Comparison of IoT Routing Protocols

The fig 2 illustrates the average end-to-end communication delay for AODV, LEACH, and the proposed AI-EIoT framework. The proposed AI-EIoT protocol achieves the lowest delay of 48 ms, compared to 72 ms for LEACH and 95 ms for AODV. This reduction in latency is attributed to intelligent AI-based routing, edge computing, and adaptive network management, which enable faster and more efficient data transmission across the IoT sensor network.

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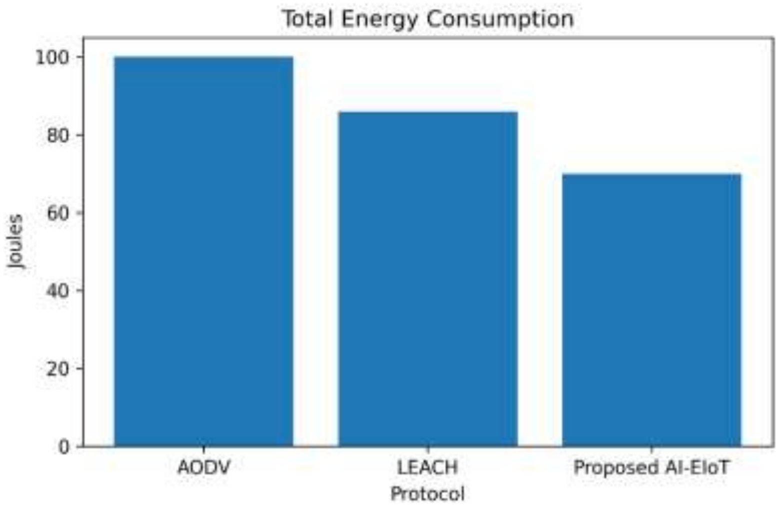

Fig 3: Total Energy Consumption Comparison of IoT Routing Protocols

As shown in the fig 3 the total energy consumption of AODV, LEACH, and the proposed AI-EIoT framework. The proposed AI-EIoT protocol consumes the least energy (70 J), compared to LEACH (86 J) and AODV (100 J), demonstrating a significant reduction in power usage. This improvement is achieved through AI-based routing, energy harvesting mechanisms, edge processing, and adaptive sleep scheduling, which collectively enhance energy efficiency and prolong network lifetime.

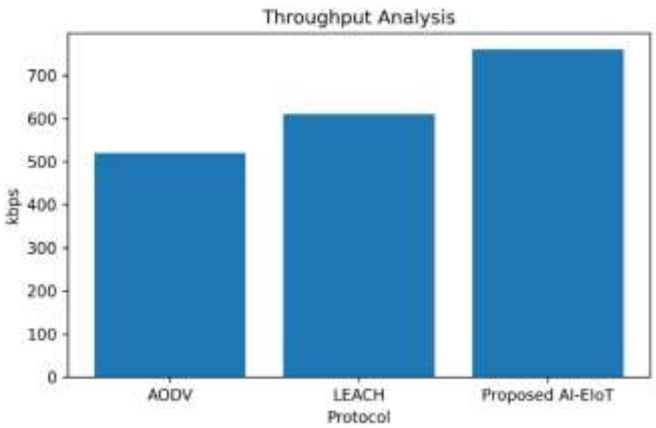

Fig 4: Throughput Comparison of IoT Routing Protocols

The fig 4 presents the throughput performance of AODV, LEACH, and the proposed AI-EIoT framework. The proposed AI-EIoT protocol achieves the highest throughput of 760 kbps, surpassing LEACH (610 kbps) and AODV (520 kbps). The improved throughput is attributed to AI-driven routing optimization, edge-based data processing, and efficient resource management, which enhance data transmission efficiency and overall network performance in IoT sensor environments.

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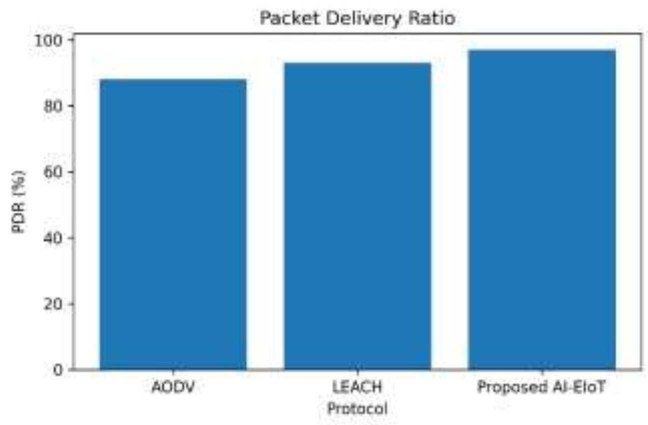

Fig 5: Packet Delivery Ratio (PDR) Comparison of IoT Routing Protocols

The fig 5 shows the Packet Delivery Ratio (PDR) achieved by AODV, LEACH, and the proposed AI-EIoT framework. The proposed AI-EIoT protocol attains the highest PDR of 97%, outperforming LEACH (93%) and AODV (88%). This improvement demonstrates the effectiveness of AI-based routing, adaptive energy management, and edge-assisted communication in ensuring reliable packet transmission and minimizing data loss within IoT sensor networks.

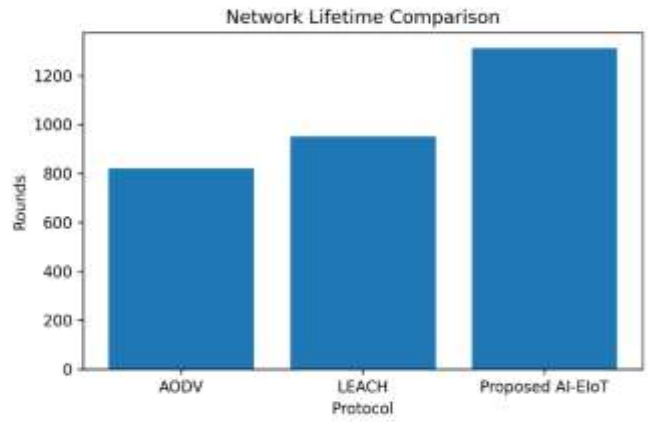

Fig 6: Network Lifetime Comparison of IoT Routing Protocols

The fig 6 shows the network lifetime achieved by AODV, LEACH, and the proposed AI-EIoT routing framework. The proposed AI-EIoT protocol attains the highest network lifetime of 1310 rounds, significantly outperforming AODV (820 rounds) and LEACH (950 rounds). This improvement is achieved through AI-based routing, adaptive sleep scheduling, and energy harvesting mechanisms that efficiently balance energy consumption and extend sensor network operation.

The results confirm that integrating artificial intelligence with energy harvesting and edge computing provides substantial benefits for sustainable IoT sensor network operations.

6. CONCLUSION

This paper presented an Energy-Efficient IoT Sensor Network Framework that integrates AI-based routing, renewable energy harvesting, adaptive sleep scheduling, and edge computing technologies. The proposed architecture addresses critical energy constraints associated with large-scale IoT deployments and improves network sustainability.

Experimental evaluation demonstrated significant enhancements in network lifetime, communication reliability, energy utilization efficiency, and operational scalability. The intelligent routing mechanism successfully balanced energy consumption while maintaining high-quality communication performance.

Future research may explore deep reinforcement learning for autonomous routing optimization, blockchain-based energy trading among sensor nodes, federated learning for distributed intelligence, and 6G-enabled ultra-low-power IoT communication systems.

The proposed framework provides a promising foundation for sustainable and intelligent IoT infrastructures capable of supporting future smart environments and Industry 5.0 applications.

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