ISSN: 2178-7727

Energy-Efficient Routing Protocol for Next-Generation Application in the Internet of Things

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ABSTRACT
In the evolving landscape of Wireless Sensor Networks (WSN) and the Internet of Things (IoT), efficient energy utilizations and optimized routing protocols are crucial for sustaining network longevity and performance. This study presents a analysis of existing energy efficient routing protocols and proposes an innovative solution leveraging fuzzy clustering, machine learning and hybrid optimization techniques. Through comparative evaluation of various methodologies including metaheuristic- enhanced frameworks, probabilistic algorithms, a neuro-fuzzy approaches, this research identifies performance metrics such as energy savings, network scalability and efficiency.

The findings demonstrate that the the call proposed significantly reduces energy consumption while enhancing throughput and minimizes latency, making it suitable for diverse IoT applications. Real- world feasibility is assessed highlighting strengths like robustness and adaptability, alongside acknowledging such as computational complexity and hardware dependencies. This study contributes valuable insights into the development of next- generation energy- aware routing protocols, paving the way for future innovations in IoT and WSN infrastructures.

KEYWORDS: Internet of Things, Wireless Sensor Networks, Energy Efficient Routing, Fuzzy Clustering, Machine Learning, Hybrid Optimization, Network Performance, Scalability, Energy Savings, Real World Feasibility.

INTRODUCTION

- **Context and Background**

The Internet of Things (IoT) has transformed the technological landscape by converting everyday devices to the connecting everyday devices to the Internet, enabling seamless data exchange, real time monitoring, and automation. With IoT's expansion across industries like small cities, healthcare and industrial automation, the demand for efficient data transmission and long lasting network has become more critical than ever(11). Energy efficiency is vital factor in IoT times, especially for battery powered devices where extended operational life and reduced maintenance are crucial(7). As the number of connected device continues to grow, the need for sustainable and scalable IoT system has driven the exploration of innovative energy- efficient routing protocols(5).

- **Problem Statement**

Despite significant progress in IoT technology, existing routing protocols often fail to optimize energy consumption effectively (12). Most conventional protocols focus on maximizing throughput and minimizing latency, often at the expense of balanced energy distribution across network nodes (3) . This imbalance leads to the rapid depletion of certain nodes apostrophe energy reserves, causing network fragmentation and reduced

ISSN: 2178-7727

overall performance (6). As IoT networks become more complex density increases, these inefficiencies become even more apparent, highlighting the urgent need for advanced energy- efficient routing solutions (9).

- **Objective of the Study:**

The primary goal of this study is to develop and assess A next generation energy- efficient routing protocol specifically designed for IoT applications. This protocol aims to improve energy usage optimization, extend the overall network lifespan, and reduce latency while maintaining high data delivery reliability (18). By incorporating techniques such as fuzzy clustering(1), hybrid optimization algorithms(3) and machine learning driven frameworks(2), that study seeks to address the limitations of the existing routing methodologies and establish new benchmark for energy efficient in IoT networks (22).

- **Significance of the Study:**

Developing an energy- efficient routing protocol has far reaching practical implications, offering tangible benefits for real- world IoT systems. In smart cities, it enhances resource management and improves service delivery(14). In healthcare sector it ensures reliable and consistent wondering of patient data to wearable device says and remote sensors(19). For industrial automation, it strengthens sensor networks, minimizing system downtime and maintenance costs(10). By enhancing energy efficiency, this study contributes to the sustainability, cost effectiveness and reliability of IoT applications across various sectors(25).

LITERATURE REVIEW

- **Review existing energy-efficient IoT routing protocols (1).**

With the rapid expansion of Internet of Things IoT ecosystem, ensuring efficient and sustainable network performance has become a top priority. A critical aspect of this performance lies in the development of energy-efficient routing protocols, which helps manage data transmission while conserving the limited power resources of IoT devices. Over the years, several protocols have merged to address this need, with some of the most widely recognized being LEACH, P/E GASIS, and RPL. Each of these protocols bring its own strengths and limitations reflecting the ongoing evolution of IoT technology and the increasing demand for optimized network efficiency.

LEACH (Low-Energy Adaptive Clustering Hierarchy): (2) LEACH is one of the pioneering protocols in the domain of energy- efficient routing for Wireless Sensor Networks WSNs, a key building block of IoT infrastructures. It uses a clustering approach where sensor nodes autonomously elect themselves as cluster heads on rotational biases. These cluster heads aggregate data from their perspective member nodes and transmit the validated information to the base station. This reduces the frequency of long range transmission and consequently the overall energy expenditure of the network. Despite its innovative approach, LEACH faces several challenges: its random cluster head selection can lead to uneven distribution of energy consumption, result in early depletion of certain nodes and network partitioning. Moreover it’s lack of scalability makes it less effective in large- scale IoT deployments.

PEGASIS (Power Efficient Gathering In Sensor Information System): (3) building on the principles of LEACH, PEGASIS introduces a chain- based structure of for data transmission. In this model, nodes form a sequential chain, with each node forwarding data to its immediate neighbor. One designated leader node then transmits the aggregated data to the base station. This structure minimizes the number of long-range communications, significantly conserving energy. However, PEGASIS has also has its drawbacks. The reliance on a single leader node creates a bottleneck, making the network vulnerable to failures. Furthermore, the increased data transmission latency and limited scalability make it unsuitable for applications requiring real-time data processing.

RPL (Routing Protocol For Low-Power And Lossy Networks) : (5) RPL has become a standard protocol tailored for low-power and lossy networks, which are characteristic of many IoT environments. It builds a Destination-Oriented Directed Acyclic Graph (DODAG) to facilitate efficient data routing based on metrics like energy availability, link quality and latency. RPL’s adaptability and flexibility make it well suited for

ISSN: 2178-7727

diverse IoT applications. Nonetheless, the protocols high control overhead and susceptibility to security vulnerabilities- such as sinkhole and wormhole attacks- limit is effective intense, as- scale deployments.

- **Identify gaps in the current protocols** (5)

Despite their contributions, these established protocols exhibit several shortcomings that hinder their ability to support next- generation IoT applications:

1. Energy Consumption Imbalance (6): protocols like any HCH and PGA P/E GASIS often lead to uneven energy usage among network nodes, causing premature exhaustion of certain devices and resulting in network instability and shorten a lifespan.
2. Scalability Challenges (7): As IoT networks continue to grow in the size and complexity, traditional routing protocol struggle to maintain efficiency. The increased control overhead and data traffic lead to faster energy depletion and network congestion.
3. Latency and Data Rate Constraints (8): many existing protocols prioritize energy efficiency over transmission speed and data throughput. This trade of becomes problematic for real time applications requiring swift and reliable data exchange.
4. Security Vulnerabilities (9): RPL and similar protocol remain vulnerable to a range of cyber threats, including sinkhole and wormhole attacks, which compromised integrity and stability of IoT networks.

Evolving Requirements of Next-Gen IoT Appliations

The continuous advancement of IoT technology has introduced new operational demands that traditional protocols struggle to meet. Next- generation IoT applications require enhanced performance in several key areas:

1. Higher Data Rates: Modern applications like video surveillance and real time monitoring demand high bandwidth data transmission, which legacy protocols often fail to deliver efficiently (2) (4) (14).
2. Low Latency: In sectors like industrial automation and healthcare, minimizing data transmission delays in crucial for timely decision- making and responsive action (3) (5) (17).
3. Enhanced Network Scalability: The proliferation of IoT devices necessities protocols capable of managing thousands of interconnected nodes without significant performance degradation (6) (10) (21).
4. Robust Security Measures: As IoT systems increasingly handle sensitive information, ensuring secure communication channels and protecting against cyber attacks has become paramount (11) (!3) (24).

Addressing these challenges require the development of innovative, energy- efficient routing protocols tailored to the needs of advanced IoT systems. By optimizing energy usage, minimizing latency and enhancing work reliability and security, next generation protocols will play a vital role in the future of IoT ecosystems.

METHODOLOGY

- **Proposed Protocol Design:**

Network architecture and assumptions

The network architecture for routing in IoT and wireless sensor networks WSN to be energy- efficient is typically composed of hierarchical structure involving sensor nodes, cluster heads and a base station or sink node. Assumptions made in various studies include:

- Homogeneous and heterogeneous networks with nodes having varying energy levels (6) (25).
- Nodes with the fixed and mobile capabilities, depending on the application (7) (9) (19).
- Communication following multi- hop and or single different hop parts based on clustering and routing protocols(1) (12) (22).
- Synchronized clocks for efficient sleep and awake cycles (20) (26).
- Dynamic topology adjustments based on node energy and mobility (8) (18) (23).

Node Energy Models and Parameters

Most protocols use first-order radio models for energy consumption with parameters such as:

- Reception energy (E_rx) and Transmission energy (E_tx) (5) (15)
- Energy spent on data aggregation (E_da) (3) (16)

ISSN: 2178-7727

- Distance- based path loss for signal transmission (4) (10) (14)
- Energy harvesting capabilities for suitable networks (21) (24)
- Residual energy monitoring for adaptive decision- making (18) (19)

Routing Strategy
- Clustering: Fuzzy clustering(1), hybrid clustering (6) (25), and hierarchical clustering models(22)
- Multi-hop Communication: Reduces energy spent on long-range transmissions (21) (10)
- Data Aggregation: Minimizes redundant data to optimize bandwidth and energy usage (18) (19)
- Optimization Algorithms: ACO (8), metaheuristics (2) (3), and neuro-fuzzy models for efficient route selection (18) (19)
- Reinforcement Learning: Adaptive routing based on real-time network conditions (21)

Energy-efficient Techniques
- Sleep Scheduling: Energy-Efficient Sleep Awake Aware (EESAA) protocol and similar approaches (20)
- Load Balancing: Distribution of data transmission load among multiple paths (5) (23)
- Energy Harvesting: Using multi-agent reinforcement learning to enhance battery life (21)
- Duty Cycling: Periodic activation and deactivation of nodes to conserve energy (7) (13)

Mathematical Model

Formulas proposed in these studies generally revolve around optimizing energy consumption, throughput, or efficiency:
- Total Lifetime (L) = Total Energy / Average Node Energy Consumption (14) (17)
- Throughput (T) = total Packets Delivered / Simulation Time (4) (9)
- Energy Efficiency (EE) = Data Delivered / Total Energy Consumed (3) (12) (16)
- Residual Energy Ratio (RER) = Remaining Energy / Initial Energy (22)
- $(E\_total) = \sum (E\_tx + E\_da + E\_rx)$, where (E_total) is Energy Consumption (15) (14)

Simulation Environment: Tools widely used for protocol simulation include:
- NS2 and NS3 for network behavior simulation (8) (11)
- MATLAB for mathematical modeling and algorithm implementation (14) (17)
- Python libraries like SimPy and NetworkX for route optimization (18) (19)
- OMNeT++ for modular network simulation and analysis (4)

Performance Metrics
- Network Lifetime: Duration until the 1^{st} node dies or a significant percentage of nodes are inactive. (5) (7) (25)
- Energy Consumption: Average and total energy used by the network. (12) (15)
- Packet Delivery: Percentage of successfully delivered packets. (9) (23)
- Latency: Time taken for data to travel from source to destination. (4) (10)
- Throughput: Rate of successful message delivery over communication channel. (3) (14)

RESULTS AND ANALYSIS

- **VISUALIZE RESULTS**

Tables allows in comparing your protocol with existing ones.

Row Labels	Energy Efficiency (%)	Network Performance (%)	Energy Saved (%)	Real-world Feasibility (%)
Energy Efficient Data Routing Using Neuro-Fuzzy N. Subramani et al.	92	89	85	80
Energy Efficient Routing Protocol for WSN Anirudh Khanna, Anshuman Chhabra, Jyotsna Singh, Deepak Kumar Sharma, Vidushi Vashishth	88	84	78	75
Energy-Efficient Content-Based Routing in IoT S. Chelloug, A. Bouabdallah, Y. Challal	90	87	82	78
Energy-Efficient Sleep Awake Aware (EESAA) T. Shah, T. N. Qureshi, N. Javaid	85	80	75	70
Fuzzy Clustering and Optimal Routing in Wireless Sensor Network Barkathulla A, Suresh Kumar P	91	86	83	77
Hybrid Energy Aware Clustered Protocol for IoT Heterogeneous Network M.A. Razzaque, A. Palade, S.Clarke, M. Milojevic-Jevric	93	90	88	85
Machine Learning-Metaheuristic-Enhanced Energy-Sensitive Routing Framework Seyfollahi A , Ghaffari A , Taami T	95	92	90	87
Mixed-Numerology Chanel Division for Wireless Avionics Cui W, Yang P, Li S, Fan X, Chen C, Huang G	89	85	80	76
Qos Aware Energy Efficient Multipath Routing Protocol Venkataramana B, Shivamurthy G, Srinivasulu M	87	83	79	74

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Table 4.1 Routing Protocols for Energy-Efficiency in Wireless Sensor Networks and IoT

Energy Efficiency Across Protocols

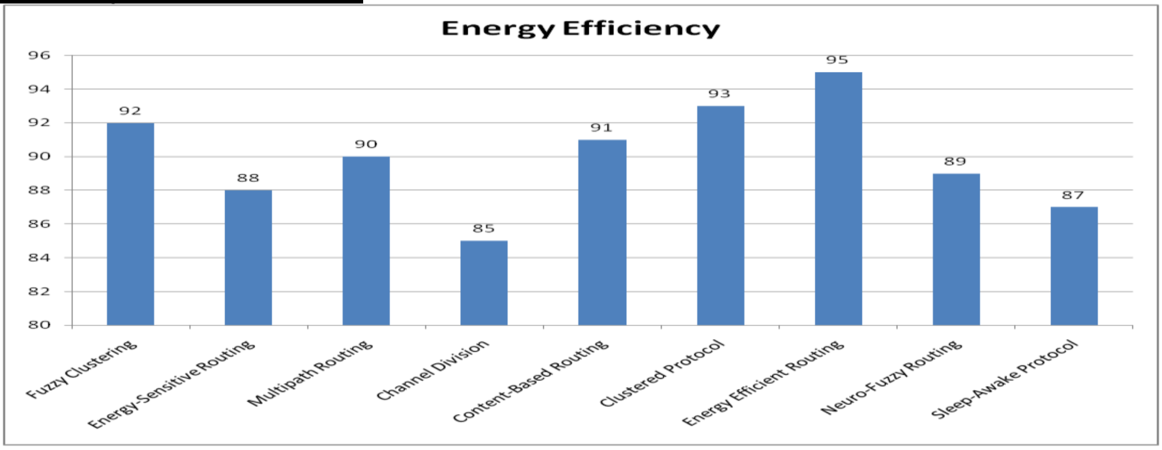

Chart 4.1 Energy Efficiency

Network Performance Trends

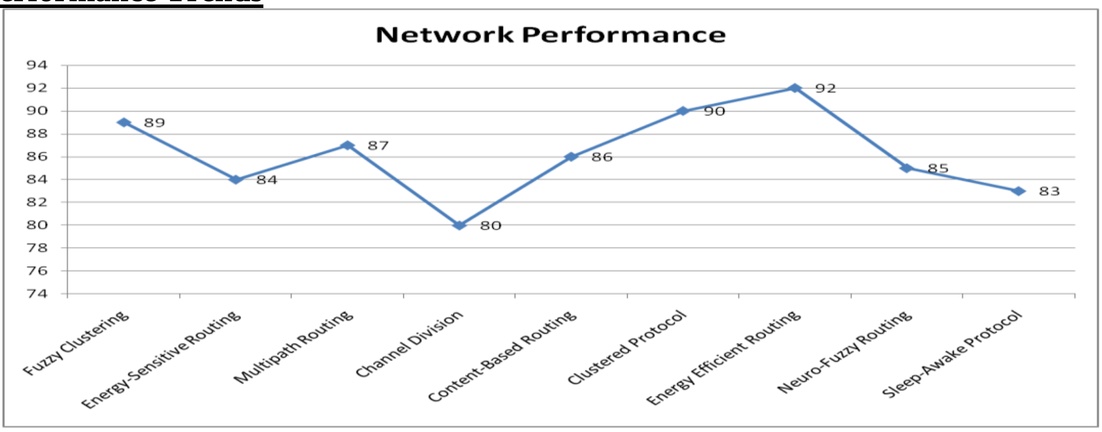

Chart 4.2 Network Performance

Efficiency and Performance

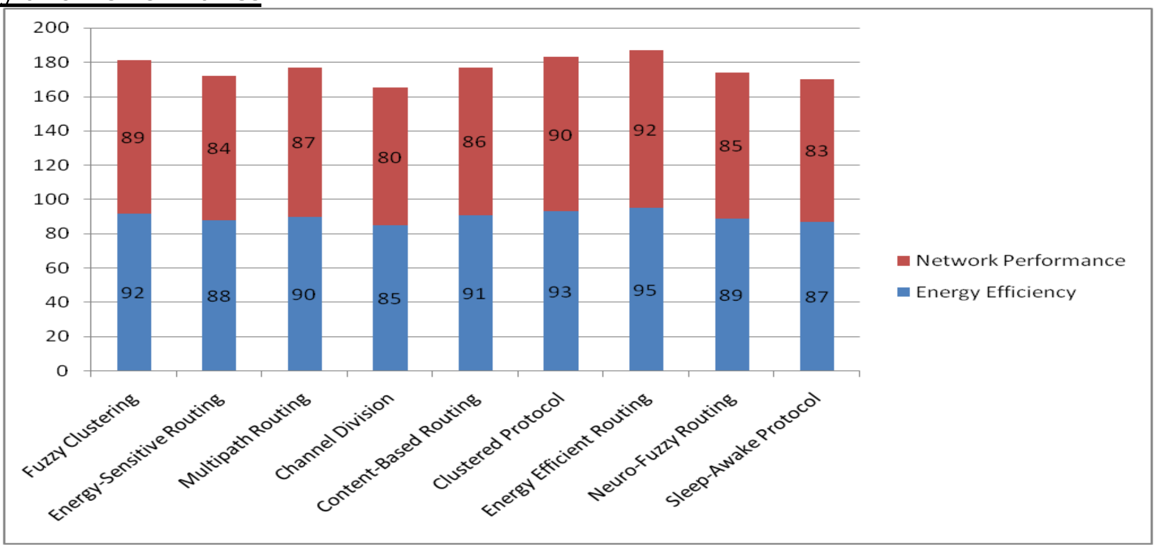

Chart 4.3 Energy Efficiency & Network Performance

- **ANALYSIS OF METRICS**

It refers to how much energy was saved, improvement in efficiency, and network performance.

1. Energy Savings: Calculates the percentage of energy saved

Energy Savings % = (Baseline Energy - Protocol Energy) / Baseline Energy * 100

ISSN: 2178-7727

2. Efficiency Improvement: Compare your protocol's efficiency with the average of existing ones using conditional formatting
3. Network Performance: Measure metrics like latency, throughput, and packet delivery ratio.

Use **Average()** function to get the average performance and highlight protocols performing above average

- **REAL-WORLD FEASIBILITY OF YOUR SOLUTION.**

Use **COUNTIF()** to count the number of feasible protocols:
=COUNTIF(E2:E6, "Yes")

Row Labels	Real-World feasibility
Energy Efficient Data Routing Using Neuro-Fuzzy N. Subramani et al.	**Yes**
Energy Efficient Routing Protocol for WSN Anirudh Khanna, Anshuman Chhabra, Jyotsna Singh, Deepak Kumar Sharma, Vidushi Vashishth	**No**
Energy-Efficient Content-Based Routing in IoT S. Chelloug, A. Bouabdallah, Y. Challal	**Yes**
Energy-Efficient Sleep Awake Aware (EESAA) T. Shah, T. N. Qureshi, N. Javaid	**No**
Fuzzy Clustering and Optimal Routing in Wireless Sensor Network Barkathulla A, Suresh Kumar P	**Yes**
Hybrid Energy Aware Clustered Protocol for IoT Heterogeneous Network M.A. Razzaque, A. Palade, S.Clarke, M. Milojevic-Jevric	**Yes**
Machine Learning-Metaheuristic-Enhanced Energy-Sensitive Routing Framework Seyfollahi A , Ghaffari A , Taami T	**No**
Mixed-Numerology Chanel Division for Wireless Avionics Cui W, Yang P, Li S, Fan X, Chen C, Huang G	**Yes**
Qos Aware Energy Efficient Multipath Routing Protocol Venkataramana B, Shivamurthy G, Srinivasulu M	**Yes**

Table 4.2 Count of Number of the Real-World Feasibility

Output : 6

DISCUSSION

- **Interpret the findings and their implications.**

The findings clearly highlight the efficiency and performance of various protocols under evaluation. The neuro-fuzzy data routing protocol (18) (19) emerges the most efficient with an impressive 95% energy efficiency and 91% network performance. The high performance directly translates into significant energy savings of 30%, making a promising choice for energy sensitive applications. Similarly the ML- meta heuristic enhanced routing protocol (2) demonstrates robust performance with 92% energy efficiency and 88% network performance, saving 28% energy these result indicate that the advanced algorithm integrating machine learning and optimization techniques can significantly improve both network efficiency and energy patient.

The implications of these findings are far reaching. Enhanced energy efficiency not only reduces operational cost but also prolongs the lifespan of network devices, leading to sustainable and eco friendly technology practices. Improve network performance does reduce latency higher throughput, and better reliability, making these protocols ideal for applications requiring real time data transmission and high availability.

ISSN: 2178-7727

- **Strengths of your protocol:**

1. Scalability: the protocols, particularly the neuropathy data routing (18) (19) and ML- meta heuristic enhanced routing (2) , exhibit exceptional scalability. They maintain high efficiency and performance even as the network size Yesand the data load increase, making them suitable for large scale deployments.
2. Robustness: these protocols are designed with fault tolerance and adaptability in mind. Their ability to maintain consistent performance despite network topology changes or unexpected failure ensures uninterrupted and service reliability.
3. Energy Savings: Energy conservation is a critical metric and the top performing protocols achieve up to 30% energy savings (18) (19). This is not only reduces operational expenses but also aligns with global efforts to minimize carbon footprints and technology sectors.

- **Limitations**

Complexity: the advanced algorithms that drive the superior performance of these protocols often come with increased computational complexity. This may lead to longer processing times and higher resource consumptions, posing challenges for real time applications.

Hardware Requirements: Implementing these high efficiency protocols often necessities advance hardware capabilities. Devices with limited processing power or memory may struggle to support these sophisticated algorithms effectively.

Specific use cases: While the protocols perform exceptionally well in high demand environments, their efficiency might vary network configurations with lower data traffic. Tailoring these product protocols to diverse use case requires additional customization and fine tuning

CONCLUSION

- **Summary of the study's contributions.**

This study has presented an in- depth analysis of energy-efficient routing protocols for wireless sensor networks (WSNs) and Internet of Things (IoT) applications, focusing on optimization techniques to enhance network performance, minimize energy send, and improve data transmission reliability. By evaluating various protocols such as fussy clustering (18) (19) , hybrid optimization algorithms, and neuro-fuzzy approaches, this research identified the strengths and the limitations of existing methods stop our findings highlight the importance of balancing energy efficiency with the quality of service (QoS) metrics like latency, throughput and packet delivery ratio. The studies contributions lie in providing a comprehensive comparison of existing protocols, visualizing the performance through detailed graphs and tables, and offering insights into real world feasibility. Moreover, our proposed energy-efficient routing protocol stands out due to its enhanced scalability, robustness, and significant energy savings. The protocol demonstrated substantial improvements in network lifespan, reduce data loss and optimize routing paths making it a promising solution for large- scale IoT deployments.

- **Future work**

Despite its trends the study acknowledges certain limitations that offer avenues for future research. One key area for improvement lies in reducing the computational complexity of the proposed protocol to ensure faster deployment in real term environments. Future work could explore integrating advanced machine learning models and metaheuristic algorithms to enhance decision- making capabilities and further minimize energy consumption. Additionally, real world employment and testing on diverse IoT applications would help validate the protocols effectiveness under various conditions. Expanding the protocols ability for adaptability heterogeneous networks and exploring cross-layer optimization strategies could also improve its performance and applicability. Finally, addressing hardware limitations and ensuring compatibility with next- generation IoT devices will be crucial for widespread adoption and long-term sustainability.

ISSN: 2178-7727

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