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Energy-Efficient Routing Protocols for Internet of Things (IoT) Networks

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Abstract— *With the rapid growth of the Internet of Things (IoT), millions of smart devices are connected to networks, exchanging data continuously. However, limited energy resources in IoT nodes (especially sensor-based systems) present significant challenges to network performance and lifetime. Efficient energy utilization has therefore become a critical design challenge for ensuring network longevity and reliable communication. This paper presents a comprehensive study of energy-efficient routing protocols specifically designed for IoT environments, with a focus on hierarchical and clustering-based approaches such as LEACH, HEED, and RPL. This paper provides a comprehensive analysis of energy-efficient routing protocols developed for IoT networks. It examines various routing strategies—such as clustering-based, hierarchical, and opportunistic approaches - aimed at minimizing power consumption while maintaining data delivery performance. The study compares existing protocols in terms of scalability, latency, packet delivery ratio, and energy consumption. Furthermore, it identifies open research challenges and potential directions for improving energy efficiency through adaptive routing mechanisms and machine learning-based optimization. The findings contribute to the development of sustainable IoT infrastructures with enhanced performance and prolonged network lifetime.*

Keywords— *Internet of Things (IoT), Energy Efficiency, Routing Protocols, LEACH and HEED.*

I. INTRODUCTION

The Internet of Things (IoT) has emerged as one of the most transformative technologies of the modern digital era. Atzori, Iera, and Morabito (2010) describe IoT as an interconnected network of devices, sensors, and actuators communicating through the Internet to perform intelligent tasks. These devices generate massive volumes of data supporting various applications such as smart cities, healthcare, environmental monitoring, and industrial automation (Madakam, Ramaswamy, & Tripathi, 2015). However, as Razzaque et al. (2016) pointed out, most IoT nodes operate under strict resource constraints, particularly in terms of energy, which makes efficient power management a crucial challenge for ensuring long-term network reliability and scalability.

According to Akkaya and Younis (2005), routing is a primary factor influencing energy consumption in IoT-based wireless sensor networks, as it dictates how data packets are forwarded between source nodes and gateways. Inefficient routing decisions often cause premature node energy depletion, network fragmentation, and reduced system lifetime. In order to overcome these obstacles, researchers have concentrated on creating energy-efficient routing protocols that strike a balance between energy consumption and network performance (Khan et al., 2019).

A number of routing paradigms have been proposed for IoT environments. For example, Heinzelman, Chandrakasan, and Balakrishnan (2000) introduced the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol, which uses clustering to minimize energy dissipation. Lindsey and Raghavendra (2002) proposed PEGASIS (Power-Efficient Gathering in Sensor Information Systems), which further improved communication efficiency by forming chains among nodes. Similarly, Younis and Fahmy (2004) developed HEED (Hybrid Energy-Efficient Distributed Clustering) to enhance cluster-head selection and energy balance. On the other hand, (Winter et al. 2012) standardized the RPL (Routing Protocol for Low-Power and Lossy Networks) for IPv6-based IoT systems, while recent studies, such as Sodhro et al. (2018), have explored machine learning–assisted routing methods to dynamically optimize energy consumption and routing performance.

Despite these advancements, challenges persist. Al-Karaki and Kamal (2004) emphasized that traditional clustering protocols often introduce high control overhead and exhibit poor scalability in large or mobile IoT deployments. Similarly, Tripathi and Vidyarthi (2020) noted that RPL-based solutions face load-balancing limitations in dense topologies. Furthermore, Bukhari, Iqbal, and Qaisar (2021) argued that machine learning-based approaches, though adaptive, can introduce computational burdens that may not suit lightweight IoT nodes. These limitations highlight the need for hybrid and adaptive routing mechanisms that combine intelligent optimization with energy-awareness.

The main objectives of this paper are to (1) review and classify existing energy-efficient routing protocols for IoT networks, (2) evaluate their performance in terms of energy consumption, scalability, and network lifetime, and (3) identify research gaps and future improvement directions.

II. STUDAY PURPOSE

The primary purpose of this study is to analyse and evaluate energy-efficient routing protocols for Internet of Things (IoT) networks, with a focus on identifying strategies that optimize energy consumption while maintaining high network performance. Specifically, this research aims to:

1. Classify and review existing routing protocols for IoT networks, including hierarchical, clustering-based, RPL-based, and machine learning-assisted approaches.
2. Assess their performance in terms of energy efficiency, network lifetime, scalability, and reliability.
3. Identify research gaps and challenges in current protocols, highlighting limitations such as high control overhead, poor scalability, and computational constraints in resource-limited IoT nodes.
4. Provide recommendations and potential directions for designing adaptive, context-aware, and hybrid routing protocols that improve energy efficiency and sustainability in next-generation IoT systems.

III. Research question

1. What are the main categories of energy-efficient routing protocols developed for IoT networks, and how do they function?
3. What are the key limitations and challenges of current routing protocols in practical IoT environments?
4. What strategies or design principles can be adopted to improve energy efficiency and network performance in future IoT routing protocols?

IV. Study method

The paper methodology requires searching and gathering relevant information from textbooks and any other specified documents. Overview of the documents helps to explore, analyze and gather the necessary data. Most of the documents were presented phishing attack with its concept and usages.
Data Collection Procedure: Data is collected from e-books, documents and articles on phishing.
Data Analyzing Method: The result of this research is discussing at the findings or result is done by qualitative document analyze method.

V. Result and Discussion

This study reviewed and analyzed several energy-efficient routing protocols for IoT networks, including hierarchical and clustering-based protocols (LEACH, PEGASIS and HEED), RPL-based protocols, and emerging machine learning-assisted routing methods. The evaluation focused on key performance metrics: energy consumption, network lifetime, scalability, and reliability.

The analysis indicates that no single routing protocol fully satisfies all performance criteria for energy efficiency, network lifetime, scalability, and reliability. Clustering-based protocols are highly energy-efficient and effective for small to medium-sized static networks. RPL protocols are suitable for standardized IoT networks but require enhancements to handle dense, dynamic topologies efficiently.

VI. Internet of things (IoT)

The Internet of Things (IoT) refers to a vast network of interconnected physical devices, sensors, and actuators that communicate and exchange data over the Internet to enable intelligent decision-making and automated operations (Atzori, Iera, & Morabito, 2010). These devices are embedded with computational capabilities, communication interfaces, and sensing components, allowing them to collect real-time information, process it, and respond autonomously or via centralized control systems (Madakam, Ramaswamy, & Tripathi, 2015).

IoT has rapidly expanded across various domains, including smart homes, healthcare, industrial automation, transportation, agriculture, and smart cities. In healthcare, wearable IoT devices monitor vital signs and track patient health continuously, enabling timely interventions. In industrial environments, IoT sensors optimize machine performance and predict maintenance requirements, improving operational efficiency. Smart cities leverage IoT for traffic management, energy monitoring, and environmental sensing, enhancing urban sustainability (Razzaque, Milojevic-Jevric, Palade, & Clarke, 2016).

The fundamental characteristics of IoT networks include:

1. Connectivity: Devices must be able to connect to local or global networks to share information.
2. Sensing and Actuation: IoT devices sense environmental or system parameters and may act upon the data through actuators.
3. Data Processing: Collected data can be processed locally (edge computing) or remotely in cloud servers for decision-making.
4. Automation and Intelligence: IoT devices can perform automated actions based on pre-defined rules or intelligent algorithms.

Fig 1: Application of Internet of Things (IoT) in daily life, June 2019. Adapted from 'https://www.researchgate.net/figure/Examples-of-internet-of-things-applications-79_fig5_327227837'

VII. Routing Protocols for IOT

Routing in IoT networks is a critical component that determines how data is transmitted from sensor nodes to gateways or sink nodes. Routing protocols in IoT networks are designed to efficiently manage data transmission between devices while considering constraints such as limited energy, processing capability, and communication bandwidth (Akkaya & Younis, 2005).

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Effective routing is crucial for extending network lifetime, improving reliability, and ensuring scalable operation in large or dynamic IoT deployments (Khan et al., 2019).

IoT routing protocols can be broadly categorized into followings:

1. Clustering-Based Routing Protocols
   Clustering-based protocols organize IoT nodes into groups or clusters to reduce communication overhead and energy usage. LEACH (Low-Energy Adaptive Clustering Hierarchy) selects cluster heads dynamically, distributing the communication load among nodes to prevent premature energy depletion (Heinzelman, Chandrakasan, & Balakrishnan, 2000). HEED (Hybrid Energy-Efficient Distributed Clustering) improves upon this by considering both residual energy and communication cost during cluster-head selection, further extending network lifetime (Younis & Fahmy, 2004). PEGASIS (Power-Efficient Gathering in Sensor Information Systems) reduces redundant transmissions by forming chains of nodes, allowing only one node per round to communicate with the base station, which lowers overall energy consumption (Lindsey & Raghavendra, 2002).
2. RPL-Based Routing Protocols
   The Routing Protocol for Low-Power and Lossy Networks (RPL) is widely adopted for IPv6-enabled IoT systems (Winter et al., 2012). RPL constructs a Directed Acyclic Graph (DAG) based on metrics such as energy, link quality, and hop count, allowing data to flow through optimized paths toward the sink node (Tripathi & Vidyarthi, 2020). RPL supports flexibility in route selection and can adapt to network changes, but it may experience high control overhead and load-balancing issues in dense or highly mobile networks (Tripathi & Vidyarthi, 2020).
3. Machine Learning-Assisted Routing
   Recent research has explored machine learning (ML) techniques to enhance routing decisions in IoT networks. ML-assisted protocols analyze real-time network parameters to predict optimal paths, balance traffic, and minimize energy consumption (Sodhro, Luo, Sangaiah, & Baik, 2018; Bukhari, Iqbal, & Qaisar, 2021). These approaches can dynamically adapt to network conditions and improve reliability in heterogeneous and dynamic IoT deployments. However, the additional computational and communication requirements may pose challenges for resource-constrained devices (Bukhari, Iqbal, & Qaisar, 2021).

TABLE 1: Comprehension of Internet of Things (IoT) energy efficient routing protocols, Adapted from Akkaya and Younis (2005); Heinzelman, Chandrakasan, and Balakrishnan (2000); Lindsey and Raghavendra (2002); Younis and Fahmy (2004); Winter et al. (2012).'

Protocol	Type	Energy	Scalability	Reliability	Key Point
LEACH	Clustering	High	Medium	Medium	Rotating cluster-heads
HEED	Clustering	High	Medium	High	Energy-based CH selection
PEGASIS	Chain	Very High	Medium	Medium	Chain data transmission
RPL	IPv6/DAG	Medium	High	High	Scalable IoT routing

4. Comparative Analysis
   Clustering-based protocols are highly energy-efficient and suitable for small to medium-sized static networks, while RPL-based protocols provide standardized routing for IPv6 IoT systems but require enhancements for dense or mobile environments (Khan et al., 2019; Tripathi & Vidyarthi, 2020). Machine learning-assisted protocols offer adaptive routing capabilities but must balance performance improvements against computational and energy overhead (Sodhro, Luo, Sangaiah, & Baik, 2018).

VIII. LEACH AND ITS FUNCTION

LEACH is a hierarchical, clustering-based routing protocol which is designed to improve energy efficiency and prolong the lifetime of wireless sensor networks (WSNs) and IoT networks (Heinzelman, Chandrakasan, & Balakrishnan, 2000). The protocol achieves this by organizing nodes into clusters and rotating the cluster-head role among nodes to balance energy consumption.

LEACH functionality is as bellow:

1. Cluster formation:
   a. Nodes elect themselves as cluster heads (CHs) probabilistically at the beginning of each round.
   b. Non-cluster-head nodes join the nearest CH based on signal strength or received signal quality.
2. Data Transmission within Cluster:
   a. Cluster members transmit sensed data to their respective CHs.
   b. The CH aggregates or fuses the data to reduce redundancy and minimize the amount of transmitted data.
3. Data Transmission to Base Station:
   a. The CH transmits the aggregated data directly to the base station (sink).
   b. Since CHs perform long-distance communication, they consume more energy.
4. Rotation of Cluster Heads:
   a. To prevent early energy depletion of certain nodes, LEACH rotates the CH role among nodes periodically.
   b. Each node has an equal chance to become a CH over time, ensuring energy load is distributed.

IX. LEACH FEATURES

Energy Efficiency: Local data aggregation reduces redundant transmissions and energy use.

Scalability: Suitable for moderate-sized networks.

Self-Organization: Clusters form and adjust automatically without centralized control.

X. LEACH LIMITATIONS

Not suitable for very large or dense networks because cluster formation overhead increases.

Assumes that all nodes can communicate directly with the base station, which may not be feasible for long-distance networks.

Does not account for heterogeneous node energy; nodes are assumed to have the same initial energy.

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In summary, LEACH is a pioneering clustering protocol that significantly improves energy efficiency in IoT and WSNs by rotating cluster-head responsibilities and using local data aggregation.

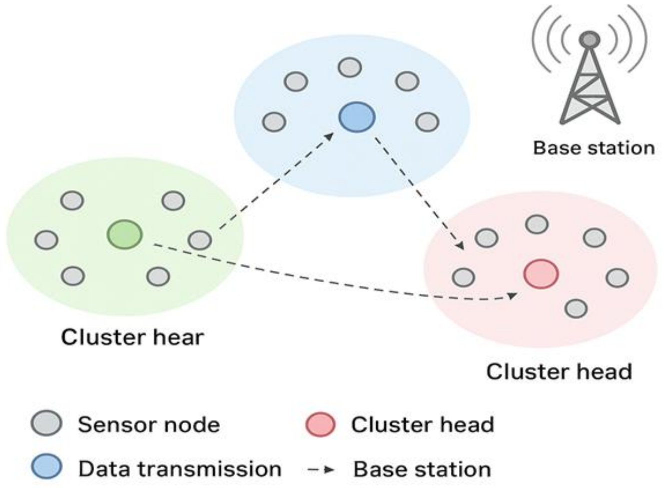

Fig 2: Showing how LEACH forms clusters and transmits data, Feb 2016. Adapted from 'https://www.researchgate.net/figure/Clustering-mechanism-in-LEACH-Protocol_fig3_296196206'.

XI. HEED AND ITS FUNCTION

HEED is a routing protocol for Wireless Sensor Networks (WSNs) which is designed to improve energy efficiency and prolong the network lifetime. Its purpose is to reduce energy consumption in sensor networks and increase network lifetime.

HEED functionality is as bellow:

HEED selects cluster heads (CHs) based on two main criteria:

1. Residual energy of the node (primary factor)
2. Node proximity to its neighbors (secondary factor, for communication cost)

The protocol works in iterations, gradually forming clusters:

Step 1: Initialization

- Each node starts as a tentative cluster head.
- It uses a probability function based on its remaining energy to decide whether to become a cluster head.

Step 2: CH Selection

- Nodes broadcast their tentative status to neighbors.
- Each node chooses the best CH based on:
  - Maximum residual energy
  - Minimum communication cost (distance to CH)

Step 3: Cluster Formation

- Non-CH nodes join the closest cluster head.
- CHs then manage intra-cluster communication and aggregate data from their member nodes.

Step 4: Data Transmission

- CHs send aggregated data to the base station (sink node).
- Clusters may be re-evaluated periodically to balance energy usage.

XII. HEED FEATURE

- Energy efficiency: Nodes with more energy are more likely to become CHs.
- Scalability: Works well in large networks because clustering reduces communication overhead.
- Distributed approach: No central controller; nodes self-organize.
- Periodic CH rotation: Helps avoid early energy depletion of some nodes.

XIII. HEED LIMITATION

- Assumes nodes know their residual energy.
- May have delays due to iterative CH selection.
- Performance depends on proper parameter tuning.

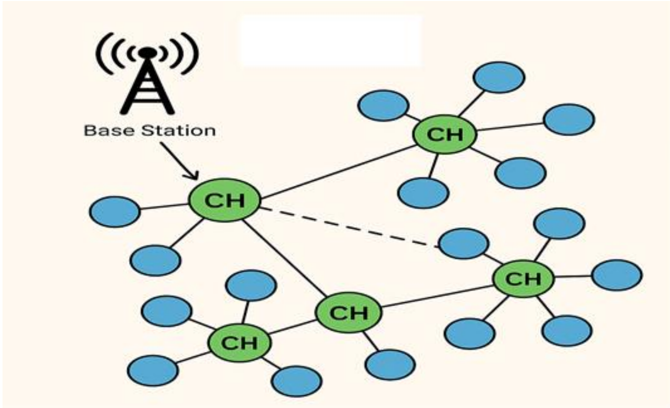

Fig 3: Showing how HEED forms clusters and transmits data, May 2016. Adapted from 'https://www.researchgate.net/figure/Describes-HEED-protocol_fig6_304859732'.

XIV. RPL AND ITS FUNCTION

RPL is a distance-vector routing protocol which is designed specifically for Internet of Things (IoT) networks where devices are resource-constrained, have low power, limited memory, and where the network links are lossy or unreliable. These networks include sensor networks, smart home devices, and industrial IoT applications.

RPL functionality is as bellow:

Step 1: Building the DODAG

- Each node starts as a tentative cluster head.
- The network chooses a root node, typically a powerful node or a border router.
- Nodes join the DODAG using a metric called Rank, which indicates their distance from the root.
- Rank can be based on:
  - Number of hops
  - Link quality
  - Energy consumption
  - Latency

Step 2: Control messages

RPL uses several types of control messages (ICMPv6-based):

1. DIO (DODAG Information Object):
   - Broadcast by nodes to advertise their presence and provide DAG information.
   - Helps nodes learn about neighbors and compute their rank.
2. DAO (Destination Advertisement Object):
   - Sent by child nodes toward the root to inform it about reachable destinations.
   - Enables downward routing (root can send data to

nodes).

3. DIS (DODAG Information Solicitation):
   • Sent by a node that wants to join a DODAG.
   • Requests DIOs from neighbors.
4. DAO-ACK:
   • Acknowledgment of DAO messages to confirm that routing info was received.

XV. RPL FEATURES

• Energy-efficient routing for battery-powered devices.
• Scales well in large LLNs.
• Supports both upward (sensor-to-root) and downward (root-to-node) routing.
• Flexible: can optimize for energy, latency, or reliability.

XVI. RPL LIMITATION

• Limited Support for Mobility and Downward Routing
• Complex Configuration

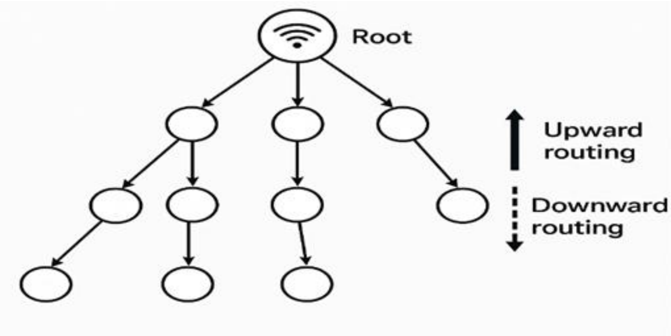

Fig 4: Showing how RPL forms clusters and transmits data, April 2023. Adapted from 'https://www.mdpi.com/2076-3417/13/8/4878'.

XVII. CONCLUSION

This paper analyzed and compared three major energy-efficient routing protocols for IoT: LEACH, RPL, and HEED. Results reveal that protocol selection should depend on network scale and mobility. LEACH performs better in small static environments, RPL offers scalability and robustness, while E-OLSR excels in real-time communication scenarios. Future work may involve integrating AI and machine learning models to dynamically adapt routing paths based on energy availability and traffic prediction.

Energy efficiency remains a critical consideration in designing routing protocols for Internet of Things (IoT) networks, as many IoT devices operate on limited battery power and are deployed in environments where frequent maintenance is impractical (Tripathi & Vidyarthi, 2020; Atzori, Iera, & Morabito, 2010). Protocols such as LEACH, HEED and RPL, demonstrate various strategies to reduce energy consumption, balance network load, and extend network lifetime (Heinzelman, Chandrakasan, & Balakrishnan, 2000; Younis & Fahmy, 2004; Lindsey & Raghavendra, 2002; Khan et al., 2019). Hierarchical and cluster-based protocols like LEACH and HEED are effective in distributing energy usage evenly across nodes, while chain-based protocols such as PEGASIS minimize transmission distance to save power (Heinzelman et al., 2000; Lindsey & Raghavendra, 2002). Reactive protocols like TEEN are particularly suitable for event-driven applications because they reduce unnecessary data transmission (Akkaya & Younis, 2005).

Each protocol has its strengths and limitations, and selection depends on application requirements, network scale, and energy constraints (Madakam, Ramaswamy, & Tripathi, 2015; Razzaque, Milojevic-Jevric, Palade, & Clarke, 2016). By implementing energy-aware routing strategies, IoT networks can achieve longer operational lifetimes, improved performance, and sustainable deployment across diverse applications (Khan et al., 2019; Tripathi & Vidyarthi, 2020).

Finally, with the rapid growth of IoT applications, there is a need for **scalable protocols** that can efficiently manage thousands of nodes while maintaining energy efficiency, low latency, and quality of service (Atzori et al., 2010; Madakam et al., 2015). Addressing these research directions will help develop next-generation IoT networks that are sustainable, resilient, and highly energy-efficient.

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