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| RESEARCH ARTICLE

Sustainable IoT Networks: Designing Energy-Efficient Protocols for Smart Cities and Industries

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| ABSTRACT
The necessity for energy-efficient and sustainable communication protocols has been highlighted by the growth of Internet of Things (IoT) devices in smart cities and industrial environments. The design and implementation of energy-efficient Internet of Things protocols in these settings are examined in this research, emphasizing how they can lower energy usage without compromising network dependability. Along with cutting-edge routing protocols designed for IoT contexts, we go over important tactics like adaptive power control, duty cycling, data aggregation, and network topology optimization. Examined is how these protocols are incorporated into smart cities and sectors, with a focus on how they improve resource efficiency and sustainability.

| KEYWORDS
Internet of things, Sustainable IoT, Energy Efficient Communication Protocol, Energy efficient Routing protocol, Machine Learning based routing protocol.

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1. Introduction
The Internet of Things' (IoT) explosive growth has transformed several industries, including industrial automation and smart cities (Al Mahmud et al., 2025). IoT makes it possible for smooth data sharing, real-time monitoring, and sophisticated analytics by linking billions of devices, which makes operations more intelligent and efficient (Chowdhury et al., 2023; Mishra & Singh, 2023). But as IoT acceptance grows, so do worries about its environmental impact, network sustainability, and energy consumption (Mia Md Tofayel Gonee et al., 2020). To maintain the longevity and efficacy of these networks while reducing their environmental impact, energy-efficient IoT communication methods are now essential. Building on previous research, such as "Energy-Efficient Communication Protocols for Massive IoT Deployments," this study intends to investigate the development and implementation of sustainable IoT protocols suited for smart cities and industrial environments (Ferdousmou et al., 2025; Li, 2022; Taneja et al., 2024).

By facilitating real-time data collection, automation, and intelligent decision-making across a range of urban services, such as waste management, energy distribution, healthcare, and transportation, IoT networks are essential to the creation of smart cities (Kamruzzaman et al., 2025; Sinha et al., 2021). Nonetheless, these networks are frequently distinguished by a vast number of interconnected devices functioning in confined spaces with finite power and battery life (Mia Md Tofayel Gonee et al., 2022). Ineffective communication protocols can ultimately impede the scalability and sustainability of smart city programs by causing excessive energy consumption, network congestion, and higher operating expenses (Mao et al., 2021). To enable the smooth operation of smart city applications while lowering carbon emissions and increasing the lifespan of IoT devices, it is crucial to build energy-efficient IoT protocols (Prova, 2024a). Similarly, to improve safety standards, increase operational efficiency, and optimize production processes, industrial applications mostly rely on IoT-enabled automation and monitoring systems (Kumar et al., 2021; Md Alamgir Miah, 2025). Real-time asset tracking, predictive maintenance, and remote machinery monitoring are made possible by the integration of smart sensors, actuators, and communication technologies in the Industrial Internet of Things (IIoT) (Mia Md Tofayel Gonee et al., 2021). Energy limitations, however, continue to be a major problem in IIoT contexts, as devices are frequently placed in dangerous or isolated areas with little access to power supplies (Miah, 2025). By streamlining data transfer, lowering energy usage, and guaranteeing dependable connectivity in industrial settings, the use of sustainable communication protocols can lessen these difficulties (Prabha et al., 2024; Taneja et al., 2024).

The issues of power consumption and network sustainability have been addressed by a number of energy-efficient Internet of Things communication protocols (Miah et al., 2025). To improve the effectiveness of IoT networks, these protocols make use of strategies like energy-aware routing, data aggregation, adaptive duty cycling, and compression (Metwally et al., 2022; Prova, 2024b; Siddiqa et al., 2025). For example, Low-Power Wide-Area Networks (LPWANs), such as NB-IoT and LoRaWAN, have shown promise in facilitating low-power, long-range communication in industrial and smart city applications (Mohammad Abdul et al., 2024). Furthermore, intelligent energy management techniques that dynamically optimize resource allocation and network operation depending on current conditions have been made possible by developments in machine learning and artificial intelligence (AI) (Alghamdi & Khan, 2021; Sobuz et al., 2025). Expanding on the results of "Energy-Efficient Communication Protocols for Massive IoT Deployments," this study investigates how sustainable IoT protocols can be used in actual smart city and industrial settings (Niropam Das 2025). This study intends to offer useful insights for policymakers, industry stakeholders, and researchers looking to create greener IoT solutions by examining the energy efficiency of various communication protocols, assessing their performance in large-scale deployments, and identifying important design principles (Chen et al., 2022; Tiwari et al., 2025).

For smart city and industrial applications to be sustainable and scalable, energy-efficient IoT protocols must be integrated (Yeasmin et al., 2025). The creation of creative and astute communication techniques will be essential to cutting down on energy use, lessening the impact on the environment, and improving the general functionality of IoT networks as the Internet of Things develops (Saimon et al., 2023). This study adds to the ongoing efforts to create a more sustainable digital ecosystem for coming generations by thoroughly analyzing current protocols and cutting-edge technologies (Siddiqa et al., 2024).

2. Literature review

The integration of IoT technology in smart cities has revolutionized our lives, but it also presents challenges like increased energy consumption and toxic pollution (Syed Nazmul Hasan, 2025). To ensure sustainability, green IoT is needed, leading to an eco-friendly environment (Chowdhury et al., 2023). Strategies for reducing pollution, traffic waste, resource usage, energy consumption, public safety, and cost management are crucial. A survey reviews techniques and strategies for making cities smarter, sustainable, and eco-friendly, focusing on IoT's potential to address smart city needs. It also discusses challenges and opportunities for future research in smart city applications (Almalki et al., 2023; Das et al., 2023). Wireless Sensor Networks (WSNs) have revolutionized information collection and processing in smart cities, but battery depletion is a concern due to extensive computational tasks and communication operations. This paper proposes a new variant of the LEACH protocol, LEACH enhanced with probabilistic cluster head selection (LEACH-PRO), to extend the sensors' lifetime. LEACH-PRO uses a probabilistic function to select cluster head nodes based on residual energy and distance to the sink. Simulation results show LEACH-PRO outperforms LEACH and direct transmission in network lifetime and traffic overhead (M. R. Sadik et al., 2024). This significantly extends sensor lifetime, making deployment more viable in smart city scenarios (Goffer et al., 2025; Yousif et al., 2021).

The Internet of Things (IoT) is a growing field that uses wireless sensor networks (WSNs) to gather and forward data intelligently (Mahmud et al., 2025). Green IoT applications are being developed in various sectors, including healthcare, engineering, industry, and smart cities (Kanellopoulos et al., 2023). To improve energy efficiency, autonomous interconnected nodes are interconnected to observe the environment. Edge computing improves network performance through distributed servers, but low-powered sensors have limitations in battery power, transmission range, and security (Mahmud et al.; Mehra, 2023). A paper presents an intelligent and secure edge-enabled computing (ISEC) model for sustainable cities using Green IoT, aiming to reduce energy management and data security (Yeasmin et al., 2025). The model uses deep learning for data routing and integrates distributed hashing with a chaining strategy for security (Tiwari et al., 2024). Experimental results show improved performance in energy consumption, network throughput, end-to-end delay, route interruption, and network overhead (Haseeb et al., 2021). The Internet of Things (IoT) is revolutionizing various industries, including smart industry and smart grids, by providing real-time data insights (Tiwari et al., 2025). Artificial Intelligence (AI) is crucial for big data analysis, but challenges like centralized approaches, security, privacy, resource limitations, and lack of training data exist. Blockchain promotes decentralized architecture for IoT applications, allowing secure data exchange and resource sharing (Al-Obaidi et al., 2022; Md Habibullah Faisal 1, 2022). A proposed approach combines Blockchain and AI for big data analysis, using an improved Delegated Proof of Stake (DPoS) algorithm for real-time data transmission (Tasnim et al., 2025). This approach accelerates IoT block generation and reduces energy consumption and transaction efficiency compared to the existing consensus mechanism. The proposed consensus algorithm addresses security issues and improves overall IoT performance (Mia Md Tofayel Gonee et al., 2022; Miah, 2025; Mohammad Abdul et al., 2024; Sasikumar et al., 2022; Siddiqa et al., 2024).

3. Energy Efficient Communication Protocols for IoT

Reducing the environmental impact of IoT networks requires energy-efficient communication protocols. Several tactics have been created to maximize energy use:

3.1 Adaptive Power Control:

This modifies the transmission power according to the communication channel's quality and the distance between devices (Sobuz et al., 2025). By reducing superfluous power use, devices can preserve data integrity while saving energy. Advanced techniques, particularly machine learning-based predictive analytics, can further increase adaptive power control by dynamically altering real-time transmission parameters (Syed Nazmul Hasan, 2025).

3.2 Duty cycling:

This method lowers idle time energy usage by alternating devices between active and sleep modes regularly (Siddiqa et al., 2025). In situations when gadgets do not need to be continuously active, it works very well. Low-power listening (LPL) and wake-up radio techniques, which enable devices to engage only when necessary and drastically reduce power waste, can be used to further optimize duty cycling (Md Rezwane Sadik et al., 2024).

3.3 Data Aggregation:

Data aggregation minimizes the amount of transmissions needed, which lowers overall energy usage, by gathering and processing data at intermediate nodes prior to transmitting it to the central server (Prabha et al., 2024). By eliminating redundant data and increasing overall network efficiency, clustering techniques like compressed sensing and hierarchical data aggregation improve this strategy (Prabha et al., 2024).

3.4 Network Topology Optimization:

This process entails setting up the network such that there are as few hops and as little distance between devices as possible, resulting in more economical communication routes. By constantly modifying network topologies in response to current traffic conditions, techniques like software-defined networking (SDN), multi-hop routing, and hierarchical clustering can greatly increase energy efficiency (Noor et al., 2024).

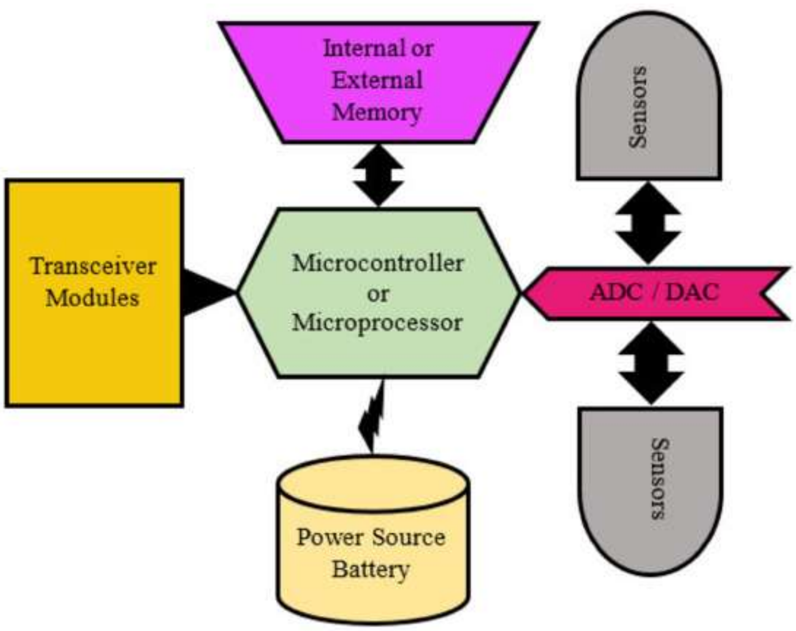

Fig. 1. Energy efficient communication protocol (Dhabliya et al., 2022).

3.5 Energy-Aware Routing Protocols:

Because of duplicated data transmissions, traditional routing techniques frequently result in inefficient energy use. Routes that maximize power usage while preserving network dependability are given priority by energy-conscious routing protocols like RPL (Routing Protocol for Low-Power and Lossy Networks) and LEACH (Low-Energy Adaptive Clustering Hierarchy). To make well-informed routing decisions, these protocols make use of variables such as residual energy, link quality, and data transfer priority (Nilima et al., 2024) (Akter et al., 2024).

3.6 Low-Power Wide-Area Networks (LPWANs):
Technologies like Sigfox, NB-IoT, and LoRaWAN were created especially to enable long-distance communication while using the least amount of power possible. These protocols are especially helpful for industrial and smart city applications where energy efficiency and wide coverage are essential (Md Alamgir Miah, 2025).

3.7 Machine Learning for Energy Management:
By combining machine learning and artificial intelligence (AI), IoT networks may become even more energy efficient. Predictive models powered by AI can reduce wasteful energy use by anticipating network congestion, optimizing power allocation, and dynamically modifying transmission schedules (Manik et al., 2025).

4. Energy efficient Routing protocols for IoT
Routing protocols are essential to IoT networks because they control the flow of data between devices (Khair et al., 2025). The lifespan of battery-powered Internet of Things devices depends on energy-efficient routing protocols, which are developed to reduce energy usage while preserving network performance (Kaur et al., 2023). Numerous techniques have been created to maximize routing choices according to communication needs, device capabilities, and network architecture. Some of the most important energy-efficient routing strategies for Internet of Things networks are listed below (Dewan Arpita et al., 2025):

4.1 Flat Routing:
There is no established hierarchy among network nodes because all of them are treated equally by flat routing protocols (Kamruzzaman et al., 2025). By forwarding packets according to shared information, every node takes part in the routing process. Despite being straightforward and appropriate for small networks, this method could not function well in bigger deployments because of redundant transmissions and higher communication overhead (Kamruzzaman et al., 2024).

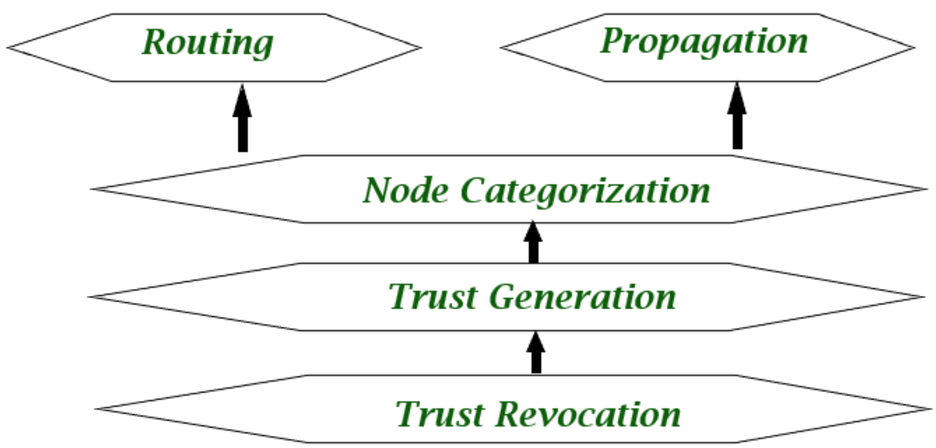

Fig. 2. Trust-Based Energy-Efficient and Secure Routing Protocols for IoT.

The following are some instances of flat routing protocols:

- Flooding: This might result in excessive energy usage since each node transmits received packets to all of its neighbors.
- Sensor Protocols for Information via Negotiation (SPIN): This energy-saving technique reduces unnecessary transmissions by utilizing data negotiation.
- Directed Diffusion: Uses data-centric routing, effectively managing data queries and responses to cut down on pointless transmissions (Johora et al., 2024).

4.2 Hierarchical Routing:
Using clusters with assigned cluster leaders to oversee communication, hierarchical routing divides a network into several tiers. This method is appropriate for large-scale IoT networks since it balances device energy usage and drastically lowers communication overhead (Islam et al., 2025). The main advantages consist of:

- Energy conservation: By combining data from member nodes before sending it, cluster heads cut down on unnecessary transfers (Khan et al., 2024; Prova, 2024c).
- Load balancing: Cluster heads rotate to prolong network life by preventing energy depletion in a single node.
- Scalability: Hierarchical routing effectively manages larger networks by segmenting them into smaller clusters (Imran et al., 2024).

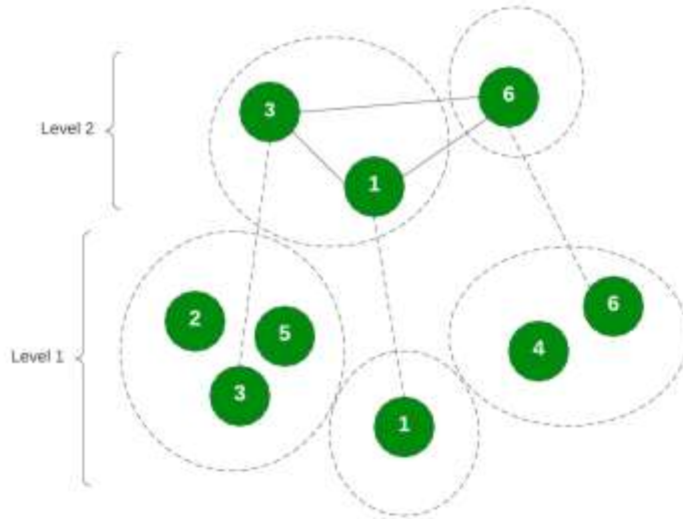

Fig. 3. Multi cluster Hierarchical routing protocol.

Hierarchical routing protocols include, for example:

- Low-Energy Adaptive Clustering Hierarchy (LEACH): This method divides energy usage by randomly rotating cluster heads.
- Power-Efficient Gathering in Sensor Information Systems (PEGASIS): Reduces transmission costs by forming a chain of nodes and permitting only one node to communicate with the base station per round.
- Threshold-sensitive Energy Efficient sensor Network protocol (TEEN): Designed to minimize needless communication in time-sensitive applications, TEEN uses threshold-based data transfer (Hossain et al., 2025).

4.3 Cluster-Based Routing:

A subset of hierarchical routing, cluster-based routing groups network nodes into clusters to maximize energy efficiency. The leader or gateway node in each cluster is in charge of sending the base station aggregated data. This method is especially helpful for sensor networks with nodes that have limited energy resources since it reduces long-distance broadcasts. Among the essential features of cluster-based routing are:

- Localized communication: Restricting transmissions to inside a cluster lowers energy consumption.
- Periodic Cluster Reformation: Assists in allocating the energy load to every node.
- Hybrid Approaches: To increase energy efficiency, a lot of cluster-based routing algorithms incorporate adaptive or machine learning approaches.

Many cluster-based routing methods are in use, such as Hybrid Energy-Efficient Distributed Clustering (HEED), which chooses cluster heads according to node degree and residual energy. Reducing the quantity of direct transmissions to the sink node is the main goal of Energy-Efficient Hierarchical Clustering (EEHC).

4.4 Machine Learning-Based Routing:

Intelligent algorithms are used by machine learning-based routing protocols to optimize routing choices in response to current network conditions. Through the use of methods like fuzzy logic, deep learning, and reinforcement learning, these protocols are able to dynamically modify routes in order to improve energy efficiency.

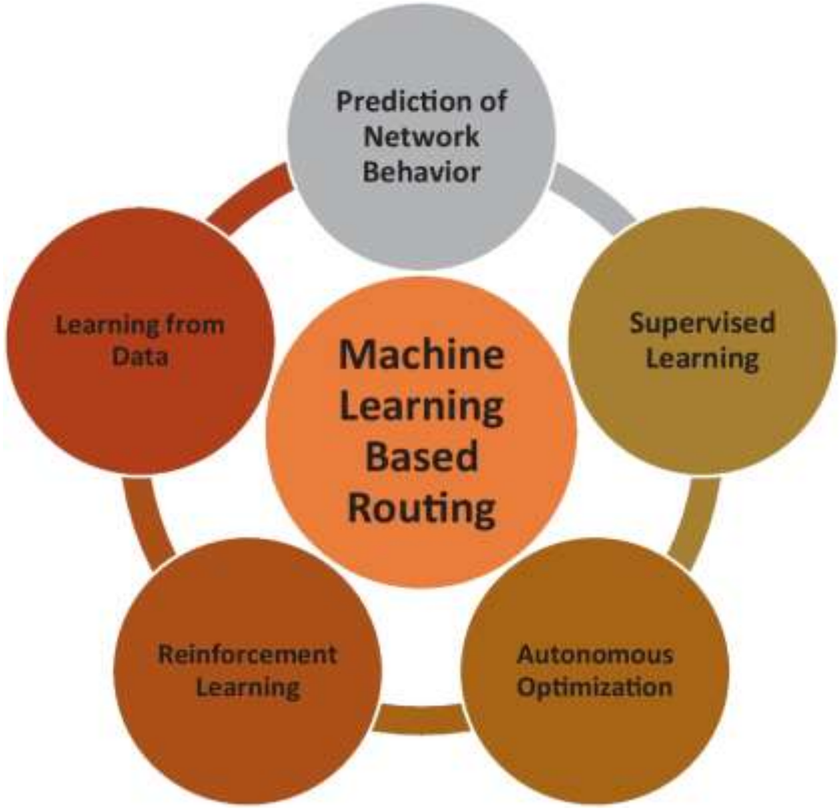

Fig. 4. ML based routing protocol.

Machine learning-based routing has the following benefits:

- Adaptive Decision-Making: Modifies routes according to traffic congestion, energy levels, and network quality.
- Predictive analysis: Predicts network circumstances to optimize routing in advance.
- Autonomous Operation: This minimizes the requirement for intervention and manual configuration.

Among the noteworthy methods are:

- Reinforcement Learning-Based Routing: This method uses reward-based processes to teach nodes the best routes.
- Neural network-based routing: This method optimizes routing patterns and forecasts network circumstances using deep learning models.
- Fuzzy Logic-Based Routing: This method manages network parameter uncertainty to produce more effective routing choices.

5. Conclusion

An essential component of Internet of Things (IoT) networks is energy-efficient routing, particularly for battery-operated devices with constrained processing power. The significance of managing energy consumption in routing protocols becomes even more evident as IoT continues to grow and extend across a variety of industries, including healthcare, smart cities, industrial automation, and environmental monitoring. In addition to increasing the operational lifespan of IoT devices, efficient routing also improves network performance and dependability, which eventually results in a more economical and sustainable system. One of the most basic routing techniques used in Internet of Things networks is flat routing. With this method, there is no hierarchical structure and all network nodes participate in routing decisions with equal responsibility. Because of its ease of use and simplicity, flat routing works especially well for small-scale IoT networks. Flat routing protocols are simpler to administer and maintain since they do not require clustering or hierarchical organization. However, the absence of a structured method results in scalability problems, higher energy consumption, and inefficiencies as the network size grows. Flat routing's primary disadvantage in big IoT networks is that it can cause premature failures and network disconnections due to its excessive energy consumption on some nodes.

The use of hierarchical and cluster-based routing approaches helps to solve the scalability and energy issues associated with flat routing. The network is separated into several layers in hierarchical routing, and nodes are given distinct responsibilities according to their location and capabilities. As a subset of hierarchical routing, cluster-based routing groups nodes into clusters and chooses a cluster head to oversee communication inside and between clusters. By reducing redundant data transmissions, this structure saves energy and drastically lowers routing overhead. LEACH (Low-Energy Adaptive Clustering Hierarchy) is one of the most used cluster-based routing methods in Internet of Things networks. To divide the energy load across nodes fairly, LEACH chooses cluster chiefs regularly. Cluster heads reduce the amount of direct transmissions and save energy by combining data from member nodes and sending it to the base station. PEGASIS (Power-Efficient GAthering in Sensor Information Systems) is another sophisticated hierarchical routing technique that creates a network of nodes and sends data to each node's closest neighbor. By reducing the number of long-distance transfers, this method optimizes network energy use.

IoT network management is being revolutionized by the incorporation of machine learning (ML) into routing protocols, which goes beyond conventional routing strategies. Algorithms like fuzzy logic, deep learning, and reinforcement learning are used by machine learning-based routing protocols to facilitate flexible and intelligent decision-making. These protocols can dynamically modify routes in response to traffic patterns, node energy levels, and network conditions. ML-based routing improves energy conservation, lowers latency, and increases efficiency by learning from past data and forecasting future network behavior. Reinforcement learning-based routing, for example, allows nodes to choose the best routes by rewarding energy-efficient pathways. The most effective routing techniques can be found by using deep learning models to examine intricate network topologies and traffic patterns. In contrast, fuzzy logic-based routing ensures higher adaptability in dynamic IoT contexts by enabling nodes to make decisions based on approximations rather than rigid rules.

Flat routing's simplicity and ease of use make it a viable option for small-scale networks. However, because they offer superior scalability and energy optimization, hierarchical and cluster-based routing algorithms are better suited for medium- to large-scale deployments. Machine learning-based routing protocols have the benefit of intelligent decision-making and adaptation in extremely dynamic or uncertain contexts. Furthermore, choosing the best routing protocol depends heavily on the needs of the particular application. For instance, low-latency and energy-efficient routing protocols are required to guarantee continuous connection in healthcare IoT applications, where reliability and real-time data transmission are crucial. Hierarchical routing with machine learning advancements can maximize data transfer while reducing energy usage in industrial IoT (IIoT) contexts, where extensive sensor networks monitor machinery and processes. The function of energy harvesting is a crucial factor in energy-efficient routing for Internet of Things networks. Energy-harvesting features enable certain Internet of Things devices to gather energy from external sources, including solar, thermal, or radio frequency energy. Routing protocols must dynamically modify routing decisions based on available power sources and accommodate the fluctuating energy levels of nodes in energy-harvesting Internet of Things networks. In these kinds of situations, machine learning-based routing can be especially helpful since it can forecast energy availability and adjust data transport accordingly.

Another factor that needs to be taken into account while creating energy-efficient routing protocols is security. Since many IoT networks function in untrusted contexts, they are susceptible to threats like node compromise, data tampering, and eavesdropping. Energy-efficient encryption, authentication, and intrusion detection systems must all be included in secure routing protocols. Trust-based routing strategies and lightweight cryptography techniques contribute to increased security without placing an undue computational burden on IoT devices with limited resources. Finally, for IoT networks, energy-efficient routing is essential, especially for devices with limited resources and battery life. For small-scale networks, flat routing is a straightforward and efficient solution; however, hierarchical and cluster-based routing approaches offer superior scalability and energy optimization. Energy efficiency has been further improved with the introduction of machine learning-based routing protocols, which allow for intelligent and adaptive routing choices. Numerous factors, including as network size, application needs, energy limits, security considerations, and possible energy-harvesting capabilities, influence the choice of routing protocol. Future developments in routing protocols will concentrate on enhancing effectiveness, security, and adaptability as IoT develops further, guaranteeing smooth and long-lasting IoT network operations.

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