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Research Article

A Study on Energy-Efficient Routing Protocols in Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) consist of spatially distributed, resource-constrained sensor nodes that monitor environmental or physical conditions and transmit data to a central sink. Energy efficiency is a critical concern, as limited battery life directly impacts network longevity and performance. This study presents a comprehensive analysis of energy-efficient routing protocols, including flat, hierarchical, location-based, and multipath approaches, alongside optimization techniques such as metaheuristic algorithms, multi-threshold segmentation, and load balancing with data aggregation. Performance evaluation focuses on network lifetime, energy consumption, packet delivery ratio, and latency. Challenges such as scalability, node heterogeneity, mobility, security vulnerabilities, and resource constraints are discussed, with potential solutions explored. Future research directions emphasize hybrid and adaptive routing, AI/ML-based energy optimization, IoT and edge integration, and energy harvesting strategies to enhance the sustainability and efficiency of WSN deployments.

Keywords Wireless Sensor Networks (WSNs), Energy-Efficient Routing, Optimization Techniques, Network Lifetime, Hybrid and Adaptive Protocols

1. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of spatially distributed autonomous sensor nodes that monitor physical or environmental conditions such as temperature, humidity, or motion, and collaboratively transmit the collected data to a central sink or base station. These networks have gained significant attention due to their applications in environmental monitoring, healthcare, industrial automation, military surveillance, and smart cities (Ketshabetswe et al., 2019). WSNs are typically composed of battery-powered nodes with limited energy, processing capability, and communication bandwidth. Since deploying and replacing batteries in large-scale networks is often impractical, efficient network protocols, particularly routing protocols, are essential to ensure reliable communication and extend the operational lifetime of the network (Heinzelman, Chandrakasan, & Balakrishnan, 2000).

Energy efficiency is a critical concern in WSNs because the lifetime of the network depends directly on the energy consumed by individual nodes during sensing, processing, and communication. In particular, data transmission consumes a significant portion of node energy. According to the first-order radio model proposed by Heinzelman et al. (2000), the energy required to transmit a k-bit message over a distance d is given by:

$Etx(k,d) = Eelec \cdot k + Eamp \cdot k \cdot dn$ (1)

where Eelec represents the energy dissipated per bit by the transmitter or receiver circuitry, Eamp is the energy consumed by the transmitter amplifier, and n is the path-loss exponent, typically 2 for free-space and 4 for multipath environments. The energy required to receive the same k-bit message is:

$Erx(k) = Eelec \cdot k$ (2)

Routing protocols that minimize Etx and Erx play a central role in prolonging network lifetime by reducing unnecessary transmissions, balancing energy consumption among nodes, and maintaining reliable communication. Techniques such as clustering, multi-hop routing, and power-aware routing have been widely explored in the literature to achieve energy efficiency (Chen & Weng, 2012; Devika, Santhi, & Sivasubramanian, 2013).

Designing energy-efficient routing protocols, however, is not without challenges. Sensor nodes possess limited computational and memory resources, which restrict the complexity of algorithms that can be implemented.

Large-scale networks, often composed of hundreds or thousands of nodes, require routing protocols capable of scaling efficiently without generating excessive communication overhead (Raja, Rajakumar, & Dhavachelvan, 2016; Sobti, 2015). Additionally, WSN topologies can change dynamically due to node failures, mobility, or environmental factors, complicating route selection and maintenance (Kharrufa, Al-Nidawi, & Kemp, 2015). Certain applications, such as real-time monitoring or industrial automation, demand low latency and high reliability, creating trade-offs between minimizing energy consumption and ensuring timely data delivery (Marhoon, Alubady, & Abdulhameed, 2020). Uneven energy consumption, especially among cluster heads or nodes near the sink, can also lead to premature network partitioning and reduce overall network performance (Ketshabetswe et al., 2019).

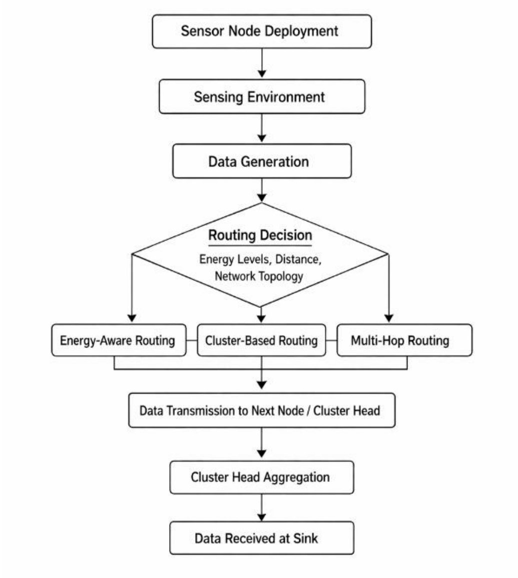

Figure 1: Energy-efficient routing flowchart in WSNs

Figure 1 shows the process of energy-efficient routing in Wireless Sensor Networks (WSNs). The flow begins with sensor node deployment, followed by sensing the environment and data generation. Next, a routing decision is made based on energy levels, distance, and network topology. Depending on this decision, the network uses energy-aware routing, cluster-based routing, or multi-hop routing to forward the data. Data is then transmitted to the next node or cluster head, aggregated at the cluster head, and finally delivered to the sink or base station for processing. This flowchart visually summarizes how routing decisions and strategies help conserve energy while ensuring reliable data delivery in WSNs.

Overall, the development of energy-efficient routing protocols in WSNs requires a careful balance between conserving energy, maintaining reliability, and ensuring scalability. By integrating analytical models of energy consumption, such as the first-order radio model, with intelligent routing strategies, researchers aim to maximize network lifetime while meeting the performance demands of diverse applications (Devika et al., 2013; Chen & Weng, 2012). Energy-aware routing remains a dynamic and critical research area, as improvements in protocol design directly impact the sustainability and practicality of WSN deployments in real-world scenarios.

2. BACKGROUND AND FUNDAMENTALS

Wireless Sensor Networks (WSNs) consist of numerous spatially distributed sensor nodes that monitor and report environmental or physical conditions such as temperature, humidity, or motion. The architecture of a typical WSN includes sensor nodes that sense and gather data, communication modules that transmit data to neighboring nodes or the sink, and a sink or base station that collects, processes, and forwards the data to external networks or users (Yadav, Sharma, & Yadav, 2021). Sensor nodes can be organized in flat or hierarchical network topologies. In hierarchical or cluster-based architectures, nodes are grouped into clusters, with a designated cluster head (CH) responsible for aggregating data from member nodes and communicating with the sink. This clustering approach reduces energy consumption and communication overhead, improving network scalability and efficiency (Toor & Jain, 2016; Singh & Sharma, 2015).

Energy consumption is a fundamental concern in WSNs because sensor nodes are typically battery-operated and often deployed in inaccessible areas. The main sources of energy consumption include sensing, data processing, and communication. For nodes performing data aggregation, typically cluster heads, the energy per round is:

$$ECH = Erx\_member + Eagg + Etx\_sink \quad (3)$$

where Erx_member is energy for receiving data from member nodes, Eagg is energy for aggregating data, and Etx_sink is energy to transmit aggregated data to the sink (Arjunan & Pothula, 2017). In multi-hop routing, where data is forwarded through intermediate nodes rather than sent directly to the sink, the total energy to transmit k-bits over h hops is:

$$\mathrm{Emulti-hop} = \sum_{i=1}^{h} \mathrm{Etx(k, di) + Erx(k} \qquad (4)$$

To balance energy consumption across nodes, many energy-aware routing protocols consider the residual energy ratio of nodes:

$$\mathrm{RER} = \frac{\mathrm{Eresidual}}{\mathrm{Einitial}} \qquad (5)$$

and a weighted cost function for routing decisions can be expressed as:

$$\mathrm{Cost} = \alpha \cdot \frac{d}{\mathrm{dmax}}\ \beta \cdot \left(1 - \frac{\mathrm{Eresidual}}{\mathrm{Einitial}}\right) \qquad (6)$$

where α and β are weighting factors, d is the distance to the next node, and Eresidual/Einitial is the normalized residual energy (Yadav et al., 2021; Singh, Sagar, & Kathuria, 2019).

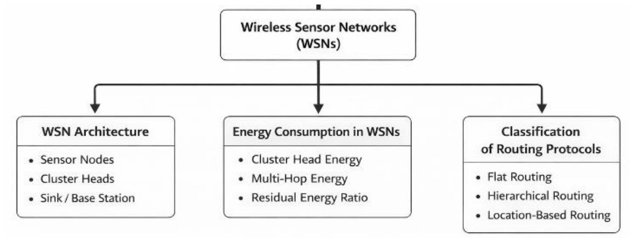

Figure 2: Wireless sensor networks overview flowchart

Figure 2 shows a simple black-and-white flowchart representing the background and fundamentals of Wireless Sensor Networks (WSNs). The figure illustrates the central concept of WSNs and its division into three major components: WSN architecture, energy consumption in WSNs, and classification of routing protocols. The WSN architecture block highlights the key elements such as sensor nodes, cluster heads, and the sink or base station. The energy consumption block emphasizes critical energy factors including cluster head energy, multi-hop energy, and residual energy ratio. The classification block presents the major routing protocol categories, namely flat routing, hierarchical routing, and location-based routing. Overall, Figure 2 provides a concise structural overview of WSN fundamentals relevant to energy-efficient routing protocol design.

Routing protocols in WSNs can be broadly classified into three main types: flat (or data-centric) routing, hierarchical (or cluster-based) routing, and location-based (or geographic) routing. In flat routing, all nodes perform similar functions and collaborate to forward data to the sink, which can result in high energy consumption due to redundant transmissions. Hierarchical routing divides the network into clusters, with cluster heads managing data aggregation and communication with the sink, improving energy efficiency and scalability (Singh & Sharma, 2015; Toor & Jain, 2016). Location-based routing leverages the geographic positions of nodes to select energy-efficient routes. Modern approaches increasingly incorporate intelligent routing mechanisms, such as reinforcement learning, to dynamically select paths based on energy levels, node density, and network topology (Yadav et al., 2021). Unequal clustering protocols are another variant, designed to distribute energy load more evenly among cluster heads and prevent early depletion of nodes near the sink (Arjunan & Pothula, 2017).

In summary, understanding WSN architecture, energy consumption patterns, and routing protocol classifications is essential for designing efficient, reliable, and sustainable networks. Advances in hierarchical clustering, energy-aware routing, and intelligent algorithms continue to improve network lifetime and performance while addressing the challenges posed by resource-constrained sensor nodes and dynamic network topologies (Mundada, 2012; Sivaram et al., 2018; Singh, Sagar, & Kathuria, 2019).

3. ENERGY-EFFICIENT ROUTING PROTOCOLS

Although a wide range of routing protocols have been proposed for Wireless Sensor Networks (WSNs), existing studies consistently indicate that no single routing strategy can efficiently address all energy-related challenges across diverse deployment environments. Energy constraints, dynamic topology changes, node heterogeneity, and application-specific traffic patterns significantly affect routing performance. Large-scale and dense WSN deployments often experience rapid energy depletion when routing decisions are not optimized. Consequently, energy-efficient routing protocols have been developed to minimize communication overhead, balance energy consumption, and prolong network lifetime (Tanwar, Kumar, & Rodrigues, 2015; Kumbhare & Wahane, 2013).

Energy-efficient routing protocols in WSNs are generally classified into flat routing protocols, hierarchical (cluster-based) routing protocols, location-based routing protocols, and multipath routing protocols (Bhushan & Sahoo, 2019; Devika, Santhi, & Sivasubramanian, 2013).

A. FLAT ROUTING PROTOCOLS

Flat routing protocols, also referred to as data-centric routing protocols, treat all sensor nodes as functionally equivalent. Nodes cooperate to forward data toward the sink without forming any hierarchical structure. Communication is usually query-driven, where the sink requests information and sensor nodes respond with relevant data. While this approach reduces protocol complexity and control overhead, it often leads to redundant transmissions and increased energy consumption in large networks due to repeated packet forwarding (Kumbhare & Wahane, 2013; Devika et al., 2013). As a result, flat routing protocols are more suitable for small-scale WSN deployments.

B. HIERARCHICAL (CLUSTER-BASED) ROUTING PROTOCOLS

Hierarchical or cluster-based routing protocols divide the network into clusters, each managed by a cluster head (CH). Member nodes transmit their sensed data to the CH, which aggregates the data and forwards it to the sink. This hierarchical organization significantly reduces long-distance transmissions and improves energy efficiency. Cluster-based routing protocols also enhance scalability and network lifetime by periodically rotating the CH role among nodes to balance energy consumption (Tanwar et al., 2015; Bhushan & Sahoo, 2019).

The energy consumption of a cluster head during a single communication round can be expressed as:

$$ECH = Erx + Eagg + Etx \qquad (7)$$

where Erx represents the energy consumed in receiving data from member nodes, Eagg denotes the energy required for data aggregation, and Etx is the energy used to transmit aggregated data to the sink.

C. LOCATION-BASED ROUTING PROTOCOLS

Location-based routing protocols utilize geographic information of sensor nodes to make routing decisions. Nodes estimate their positions using GPS or localization techniques and forward data based on distance or proximity to the sink. By selecting shorter transmission paths, these protocols reduce energy consumption associated with long-range communication. However, the requirement for location information introduces additional hardware and computational overhead, which may affect deployment feasibility in certain applications (Devika et al., 2013; Bhushan & Sahoo, 2019).

Routing decisions in location-based protocols often consider residual energy along with distance, using a cost function such as:

$$\text{Cost} = \frac{\text{dEresidual}}{\text{Cost}} \qquad (8)$$

where d is the distance to the next hop and Eresidual is the remaining energy of the node.

D. MULTIPATH ROUTING PROTOCOLS

Multipath routing protocols establish multiple alternative paths between sensor nodes and the sink to improve reliability, fault tolerance, and load balancing. Data packets are distributed across several routes to avoid congestion and prevent early energy depletion of frequently used nodes. Multipath routing is particularly effective in dynamic or failure-prone environments; however, maintaining multiple routes increases control overhead and computational complexity. Recent studies have incorporated heuristic and bio-inspired optimization techniques, such as ant-based routing, to improve energy efficiency while preserving robustness (Voruganti & Joshi, 2022; Taruna, Tiwari, & Shringi, 2013).

In summary, energy-efficient routing protocols adopt diverse strategies to address the inherent limitations of resource-constrained sensor nodes. Flat routing emphasizes simplicity, hierarchical routing enhances scalability and energy balance, location-based routing optimizes distance-aware communication, and multipath routing improves robustness and fault tolerance. The choice of routing protocol depends on network size, node density, application requirements, and energy constraints, making energy-efficient routing a critical research area in Wireless Sensor Networks (Tanwar et al., 2015; Bhushan & Sahoo, 2019).

4. OPTIMIZATION TECHNIQUES FOR ENERGY EFFICIENCY

Energy efficiency remains a critical design objective in Wireless Sensor Networks (WSNs) due to the limited battery capacity of sensor nodes and the impracticality of battery replacement in most deployment scenarios. Beyond conventional routing strategies, optimization techniques have been extensively explored to further reduce energy consumption, balance network load, and extend overall network lifetime. These techniques focus on intelligent decision-making in routing, clustering, data transmission, and aggregation processes. Prominent optimization approaches for energy efficiency in WSNs include metaheuristic algorithms, multi-threshold segmentation techniques, and load balancing with data aggregation mechanisms (Heinzelman, Chandrakasan, & Balakrishnan, 2000; Gupta, Jain, & Sinha, 2013).

A. METAHEURISTIC ALGORITHMS FOR ENERGY OPTIMIZATION

Metaheuristic algorithms have gained significant attention in WSN research due to their ability to solve complex, nonlinear, and multi-objective optimization problems. Algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO) are widely employed to optimize routing paths, cluster head selection, and energy distribution across sensor nodes. These algorithms mimic natural evolutionary or social behaviors to iteratively search for near-optimal solutions with reduced computational complexity.

Table 1: Metaheuristic Algorithms for Energy Optimization in WSNs

Algorithm	Optimization Objective	Key Advantage
Genetic Algorithm (GA)	Cluster head selection, routing optimization	Global search capability
Particle Swarm Optimization (PSO)	Energy-efficient path selection	Fast convergence
Grey Wolf Optimization (GWO)	Load-balanced clustering	Simple implementation and robustness

In energy-efficient routing and clustering, metaheuristic algorithms are commonly used to select cluster heads based on parameters such as residual energy, node distance, and network density. By selecting energy-rich and well-positioned nodes as cluster heads, these algorithms help balance energy consumption and prevent early node failures. Studies have demonstrated that metaheuristic-based optimization significantly improves network lifetime compared to traditional deterministic approaches (Balakrishnan, 2018; Choudhary, 2012).

B. Multi-Threshold Segmentation Approaches

Multi-threshold segmentation approaches focus on classifying sensor nodes or data transmission conditions based on multiple threshold values, such as residual energy, communication distance, and traffic load. Instead of using a single fixed threshold, these approaches dynamically adjust routing and clustering decisions according to varying network conditions. For example, nodes with higher residual energy may be assigned additional forwarding or aggregation responsibilities, while low-energy nodes are protected from excessive communication.

Table 2: Multi-Threshold Segmentation Approaches

Threshold Parameter	Purpose	Energy Benefit
Residual Energy	Node role assignment	Prevents early node failure
Distance to Sink	Routing decision	Reduces transmission energy
Traffic Load	Forwarding control	Avoids congestion and overload

Such segmentation techniques are particularly effective in heterogeneous WSNs, where nodes may have different initial energy levels or sensing roles. By adapting routing behavior based on multiple thresholds, energy consumption is distributed more evenly across the network, thereby reducing node failures and enhancing network stability (Gupta et al., 2013; Heinzelman et al., 2000).

C. LOAD BALANCING AND DATA AGGREGATION

Load balancing and data aggregation are fundamental optimization strategies aimed at reducing redundant transmissions and preventing energy hotspots within the network. Data aggregation techniques combine data from multiple sensor nodes at intermediate nodes or cluster heads, thereby reducing the number of transmissions to the sink. Load balancing mechanisms ensure that communication and processing responsibilities are evenly distributed among nodes, preventing excessive energy depletion of specific nodes.

Table 3: Load Balancing and Data Aggregation Techniques

Technique	Description	Impact on Energy Efficiency
Data Aggregation	Combines data at intermediate nodes	Reduces redundant transmissions
Load Balancing	Distributes communication tasks	Prevents energy hotspots
Mobile Sink Support	Moves sink to reduce distance	Extends network lifetime

The effectiveness of load balancing and aggregation can be expressed through an average energy consumption model:

$$\mathrm{Eavg} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{Ei} \qquad (9)$$

where N represents the total number of sensor nodes and Ei denotes the energy consumed by the ith node. Optimization techniques aim to minimize Eavg while maintaining reliable data delivery.
Routing protocols that integrate mobile sinks, ring-based routing, or line-based data dissemination further enhance load balancing by reducing communication distance and avoiding congestion near static sinks (Tunca et al., 2014; Ben Hamida & Chelius, 2008). These approaches significantly improve energy efficiency and extend network lifetime, especially in large-scale WSN deployments.
In summary, optimization techniques play a vital role in enhancing energy efficiency in Wireless Sensor Networks. Metaheuristic algorithms provide intelligent optimization for routing and clustering, multi-threshold segmentation enables adaptive energy-aware decisions, and load balancing with data aggregation reduces redundant communication. The integration of these optimization strategies with energy-efficient routing protocols has proven effective in extending network lifetime and improving overall network performance (Heinzelman et al., 2000; Gupta et al., 2013).

V. PERFORMANCE EVALUATION OF ROUTING PROTOCOLS

Performance evaluation plays a vital role in determining the effectiveness of routing protocols in Wireless Sensor Networks (WSNs). Due to limited battery power, processing capability, and bandwidth, routing strategies must be assessed using well-established performance metrics. These evaluations help identify protocols that can ensure energy efficiency, reliability, and scalability under diverse deployment conditions (Behera et al., 2022; Liu, 2012).
Common evaluation parameters include network lifetime, energy consumption, packet delivery performance, and delay characteristics. A systematic analysis of these metrics enables researchers to compare routing protocols and select appropriate solutions for application-specific requirements such as environmental monitoring, healthcare, and smart agriculture (Sabor et al., 2017).

A. NETWORK LIFETIME

Network lifetime is one of the most significant performance metrics in WSNs, as it directly reflects the sustainability of the network. It generally refers to the time duration during which sensor nodes remain operational before their energy resources are depleted. Many studies define network lifetime using criteria such as the time until the first node dies, half of the nodes die, or the last node becomes inactive (Behera et al., 2022).
Routing protocols that distribute communication loads evenly among sensor nodes tend to prolong network lifetime. Hierarchical and cluster-based routing protocols are particularly effective in this regard, as they reduce redundant transmissions and balance energy usage across the network (Liu, 2012).
Furthermore, optimization-based routing techniques, including metaheuristic approaches, enhance network lifetime by dynamically selecting energy-efficient routes and cluster heads. Such methods have demonstrated significant improvements over traditional routing protocols in large-scale WSN deployments (Zhao et al., 2018).

B. ENERGY CONSUMPTION METRICS

Energy consumption metrics evaluate how efficiently routing protocols utilize the limited energy of sensor nodes during data sensing, processing, and transmission. Since communication operations consume the majority of node energy, routing strategies must minimize transmission distances and control overhead to improve overall efficiency (Yao et al., 2022).

Table 4: Energy Consumption Metrics in WSNs

Metric	Description	Energy Insight
Average Energy Consumption	Mean energy used per node	Overall efficiency
Residual Energy	Remaining energy after rounds	Network sustainability
Energy Variance	Difference in node energy levels	Load balancing effectiveness

Average energy consumption and residual energy levels are commonly used indicators to assess routing performance. Protocols that maintain uniform residual energy distribution among nodes are considered more efficient, as they prevent early node failures and extend network stability (Behera et al., 2022).
Recent research emphasizes energy-aware and adaptive routing mechanisms that adjust routing decisions based on real-time energy conditions. These approaches significantly reduce unnecessary energy expenditure and enhance the robustness of the network under dynamic conditions (Sabor et al., 2017).

C. PACKET DELIVERY RATIO AND LATENCY

Packet Delivery Ratio (PDR) is a critical Quality of Service (QoS) metric that measures the reliability of data transmission in WSNs. It represents the ratio of successfully received packets at the sink node to the total number of packets generated by sensor nodes. A high PDR indicates efficient routing and minimal packet loss (Sinche et al., 2019).

Table 5: QoS Metrics for Routing Performance

Metric	Definition	Desired Outcome
Packet Delivery Ratio	Successfully received packets / sent packets	High
End-to-End Latency	Total transmission delay	Low
Packet Loss Rate	Dropped packets during transmission	Minimal

Latency refers to the time delay between data generation at the sensor node and its successful reception at the sink. Low latency is particularly important in time-sensitive applications such as healthcare monitoring and disaster detection. Routing protocols must therefore ensure timely data delivery while maintaining energy efficiency (Behera et al., 2022).
Energy-efficient routing protocols often face a trade-off between minimizing delay and conserving energy. Advanced routing techniques aim to balance this trade-off by optimizing path selection and reducing retransmissions, thereby achieving both high PDR and acceptable latency levels (Yao et al., 2022).

D. COMPARATIVE ANALYSIS OF ROUTING PROTOCOLS

Comparative analysis provides a comprehensive understanding of the strengths and limitations of different routing protocols by evaluating them across multiple performance metrics. Flat routing protocols are simple and suitable for small networks but often suffer from poor scalability and high energy consumption in dense deployments (Liu, 2012).
Hierarchical routing protocols outperform flat approaches by organizing nodes into clusters, which reduces communication overhead and improves energy efficiency. These protocols are particularly effective in extending network lifetime and enhancing scalability (Sabor et al., 2017).
More recently, optimization-based and intelligent routing protocols have demonstrated superior performance by integrating energy awareness, adaptive decision-making, and optimization algorithms. Such protocols consistently achieve better results in terms of energy efficiency, network lifetime, and QoS, making them suitable for modern WSN applications (Zhao et al., 2018; Behera et al., 2022).

6. CHALLENGES AND OPEN ISSUES

Despite extensive research on energy-efficient routing protocols in Wireless Sensor Networks (WSNs), several challenges and open issues continue to limit their practical applicability. Surveys and comparative studies on WSN communication and routing protocols emphasize that real-world deployments introduce complexities that are often not fully addressed in simulation-based evaluations (Ketshabetswe et al., 2019; Sobti, 2015). These challenges are primarily related to scalability, dynamic network behavior, security vulnerabilities, and severe resource constraints.
As WSN applications expand to smart cities, industrial monitoring, healthcare, and mobile sensing environments, routing protocols must evolve beyond static and homogeneous assumptions. The following subsections discuss the major unresolved issues that influence the effectiveness and sustainability of energy-efficient routing mechanisms.

A. SCALABILITY AND NODE HETEROGENEITY

Scalability remains a fundamental challenge in the design of routing protocols for large-scale WSNs. As network size increases, routing overhead, control packet exchanges, and cluster maintenance costs grow significantly, leading to higher energy consumption and reduced network lifetime. Comparative surveys highlight that many routing protocols perform well only under limited network sizes and fail to maintain efficiency in dense or large-scale deployments (Ketshabetswe et al., 2019; Raja et al., 2016).
Node heterogeneity further complicates routing decisions, as modern WSNs increasingly employ nodes with different energy capacities, sensing roles, and computational capabilities. Traditional homogeneous routing protocols do not effectively exploit such diversity, resulting in uneven energy depletion and premature failure of critical nodes. Studies on network-structure-based routing protocols indicate that ignoring heterogeneity often leads to inefficient load distribution and reduced reliability (Sobti, 2015).
Future routing protocols must incorporate adaptive and role-aware mechanisms that dynamically account for node heterogeneity. Energy-aware cluster head selection, differentiated routing responsibilities, and hybrid architectures are promising directions for achieving scalability while maintaining balanced energy consumption.

B. NETWORK DYNAMICS AND MOBILITY

Many energy-efficient routing protocols assume static network topologies; however, real-world WSN deployments frequently involve node mobility, mobile sinks, and dynamic link conditions. Mobility introduces frequent topology changes, route breakages, and increased control overhead, which directly affect energy efficiency and data delivery performance. Research on mobile WSNs demonstrates that static routing strategies are often inadequate in such environments (Kharrufa et al., 2015).

Dynamic network conditions also impact delay-sensitive applications, where frequent route recalculations can increase latency and packet loss. Protocols designed to minimize energy consumption may inadvertently increase delay due to longer routing paths or delayed route recovery. Techniques such as direct-line routing and mobility-aware clustering have been proposed to mitigate these effects, but their effectiveness is often scenario-dependent (Marhoon et al., 2020).

To address these challenges, routing protocols must integrate lightweight mobility management and predictive routing strategies. Adaptive clustering, localized route repair, and sink mobility support are essential to maintaining energy efficiency and network stability in dynamic WSN environments.

C. SECURITY CONCERNS IN ENERGY-EFFICIENT ROUTING

Security is a critical yet often underemphasized issue in energy-efficient routing protocols. Many routing mechanisms prioritize energy savings at the expense of robust security features, making them vulnerable to attacks such as sinkhole attacks, selective forwarding, spoofing, and denial-of-service attacks. Comprehensive surveys on WSN communication protocols highlight that routing layers are among the most targeted components in network attacks (Ketshabetswe et al., 2019).

Implementing security mechanisms in WSNs is challenging due to limited computational power, memory, and energy resources. Lightweight routing protocols may lack sufficient authentication and encryption mechanisms, while secure routing solutions often introduce additional overhead that reduces network lifetime. This trade-off between security and energy efficiency remains a major open research issue.

Future routing designs must focus on integrating lightweight, energy-aware security solutions. Trust-based routing, anomaly detection mechanisms, and adaptive security levels offer promising approaches to achieving secure communication without significantly compromising energy efficiency.

D. RESOURCE CONSTRAINTS

Resource constraints are inherent to WSNs and significantly influence routing protocol performance. Sensor nodes operate with limited battery power, processing capability, memory, and communication bandwidth. Routing protocols that require frequent control messages, global network knowledge, or complex computations are often unsuitable for such constrained environments (Raja et al., 2016).

Energy-efficient routing must therefore minimize communication overhead and computational complexity while ensuring reliable data transmission. Surveys on routing protocol classifications emphasize that overly complex routing strategies can lead to rapid energy depletion and reduced network lifetime, particularly in dense or long-term deployments (Sobti, 2015). Designing lightweight, distributed, and adaptive routing protocols remains an open challenge. Future research should emphasize simplicity, localized decision-making, and cross-layer optimization to ensure that routing mechanisms operate effectively within the strict resource limitations of WSN nodes.

7. FUTURE DIRECTIONS

Future research on energy-efficient routing in Wireless Sensor Networks (WSNs) must address the increasing complexity of modern deployment environments. As WSNs evolve toward large-scale, heterogeneous, and dynamic applications, routing protocols must become more adaptive, intelligent, and sustainable. Hybrid and adaptive routing protocols represent a key research direction, as they combine the advantages of flat, hierarchical, and location-based routing strategies. By dynamically adjusting routing behavior based on network conditions such as residual energy, node density, and traffic load, these protocols can improve energy balance and network lifetime.

Artificial Intelligence and Machine Learning–based routing approaches are also gaining prominence. Techniques such as reinforcement learning enable sensor nodes to learn optimal routing decisions from network behavior, improving energy efficiency and adaptability in dynamic environments. However, future work must focus on reducing computational overhead to ensure suitability for resource-constrained sensor nodes. The integration of WSNs with IoT and edge computing platforms offers new opportunities for energy optimization. Edge-assisted data processing can reduce communication overhead and latency, while energy-aware routing can support scalable IoT-enabled sensing applications.

Finally, energy harvesting technologies provide a promising solution to the limited battery capacity of sensor nodes. Routing protocols that incorporate energy harvesting awareness can significantly extend network lifetime and enhance long-term sustainability.

8. CONCLUSION

This study highlights the critical role of energy-efficient routing protocols in extending the operational lifetime and reliability of Wireless Sensor Networks (WSNs). Key findings indicate that hierarchical and cluster-based routing strategies, combined with optimization techniques such as metaheuristic algorithms and load balancing, significantly reduce energy consumption while maintaining network performance. Multipath and location-based routing further enhance robustness and adaptability, particularly in dynamic or large-scale deployments.

The implications for WSN design are clear: protocols must balance energy efficiency, scalability, and reliability while considering resource constraints, network dynamics, and security vulnerabilities. Intelligent, adaptive routing strategies that integrate real-time network conditions and predictive decision-making are increasingly necessary for sustainable WSN operation.

For future research, the integration of hybrid routing, AI/ML-based optimization, IoT and edge-assisted processing, and energy harvesting techniques presents promising directions. Continued innovation in these areas will enable WSNs to support complex, large-scale, and long-term applications with improved energy sustainability and operational effectiveness.

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