# Energy-Efficient Routing Protocols in Wireless Sensor Networks a Comprehensive Survey and Future Directions

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**Abstract.** Wireless Sensor Networks (WSNs) play a crucial role in modern communication systems, enabling real-time data collection and transmission in various applications, including environmental monitoring, healthcare, and smart cities. However, energy efficiency remains a significant challenge due to the limited power resources of sensor nodes. While numerous studies have explored energy-efficient routing protocols, they often rely on theoretical models and simulations, neglecting real-world deployment constraints. This research presents a comprehensive survey and future directions for energy-efficient routing in WSNs, addressing key limitations found in existing studies. Unlike previous works, this study integrates real-time implementation, security-aware routing mechanisms, AI-driven optimization techniques, and cross-layer energy management strategies to enhance efficiency and scalability. Furthermore, it evaluates the adaptability of routing protocols in dynamic, large-scale, and mobile WSN environments, ensuring fault tolerance and sustainability. By incorporating emerging technologies such as 5G, IoT, and blockchain-based solutions, this study provides a future-proof, practical framework for next-generation WSNs. The findings and recommendations in this research contribute to the development of robust, energy-efficient, and intelligent WSN routing protocols for diverse real-world applications.

**Keywords:** Wireless Sensor Networks, Energy-Efficient Routing, AI-Driven Optimization, Real-Time Implementation, Security-Aware Routing, Cross-Layer Optimization, Scalability, Fault-Tolerant Mechanisms, IoT Integration, Blockchain in WSN, Sustainable Computing, Dynamic WSNs, Mobile Sensor Networks, Green Computing, Energy Harvesting, Clustering-Based Routing, Future-Proof WSNs, Hybrid Routing Protocols, Smart Cities, Adaptive Routing

## 1 Introduction

Wireless Sensor Networks (WSNs) have been widely applied as a key topic of modern applications ranging from environmental sciences, health care and industrial automation to smart cities. In fact, these are persistent networks of spatially distributed sensor nodes for collecting and transmitting the data to a central base station for further processing. The limited energy supply of sensor nodes is one of the most serious challenges, replacing or recharging sensor nodes' batteries is generally impractical, especially in inaccessible and harsh circumstances. Thus, designing routing protocols with energy efficiency in mind continues to be a pivotal research avenue with the goal of enhancing network lifetime and guaranteeing seamless data delivery.

There are many studies proposed different energy-efficient routing techniques; their focus on hierarchical, clustering and optimization-based strategies. Although these methods have shown significant energy savings in theory and simulations but they typically lack validation with real-time data. Most prior studies do not address the scalability and adaptability of protocols in real environments since the base conditions of sensor nodes such as static or mobility might change because of external factors and nodes may fail it should be understood that security vulnerabilities in the routing mechanisms have not received much attention, thus leaving the WSNs vulnerable to attacks which can lead to further energy resource depletion.

In order to bridge these gaps, In this paper, we provide a comprehensive survey on energy-efficient routing in WSNs, along with future directions focusing on practical deployment alongside cross-layer optimization and security-aware mechanisms. While existing studies concentrate only on heuristic optimization, this research focuses on dynamic, AI-based hybrid and adaptive routing algorithms to minimize energy consumption as per the dynamic network conditions. In addition, the report explores the integration of emerging technologies, including 5G, IoT, and blockchain, to improve network robustness, security, and scalability.

The framework of future next-generation WSNs proposed in this study focuses on not only bridging the gap between theoretical work and the actual implementation but also being future-proof. It reviews a range of energy-efficient routing protocols, assessing their potential advantages and disadvantages and offering new solutions that contribute to optimization, reliability, and sustainability. These findings will guide utility-based intelligent, secure, and energy-aware WSN architectures to satisfy applications with increasing demands.

## 2 Problem Statement

Wireless Sensor Networks (WSNs) are widely used in different sectors of applications, namely, healthcare, environment monitoring, industries, smart cities, etc. However, this class of resource-constrained nodes and limited energy resources on the part of sensor nodes is the main factor that limits its widespread deployment. Just like these nodes run on limited battery power, they are also deployed in remote or inaccessible locations, so energy-efficient data transmission and routing becomes important to prolong the lifetime of the network and make sure it keeps on running. Although there have been a number of energy-efficient routing protocols proposed, the majority of existing studies assume theoretical models/simulations, which do not consider real-world deployment scenarios.

The fact is that most of these protocols are static and can only work in environments that do not have dynamic characteristics such as node failure, mobility, and network density changes. Further, routing mechanism security vulnerabilities deplete this energy; thus, WSN becomes more prone to other attacks (e.g., data interception, spoofing or denial of service). The lack of cross-layer optimization strategies among routing layer, MAC layer, and physical layer, which can substantially improve energy efficiency, is another limitation in the current research.

The development of new intelligent, adaptive and secure energy-efficient routing protocols is possible with the help of emerging technologies like artificial intelligence (AI), machine learns myer, 5 generation (5G), blockchain and Internet of things (IoT) advancements. Hence, a holistic approach for addressing the significant challenges posed by routing methods of energy-efficient routing has to be proposed (e.g., AI-based optimization, routing with security in mind, and adaptability in real-time).

## 3 Literature Review

Energy-efficient routing in Wireless Sensor Networks (WSNs) is a subject widely studied and many approaches have been proposed to accomplish this with the aim of minimizing energy use and prolonging the life of the network. Some research efforts based on hierarchy and clustering routing protocols in which data is drawn at the cluster head and routed outward to minimize energy dissipation. According to Guleria and Verma, 2019 it was a detailed survey that explained how hierarchical routing protocols are capable to balance the energy utilization of the network and total efficiency of the network [20]. However, their study focused on the models without validating the models in the real deployment.

Another important perspective of WSN routing research includes game theory and metaheuristic-based optimization approaches. They recommended that routing protocols based on game theory concept are promising in both resource allocations and energy savings (Habib and Moh 2019). However, their method does not adapt to real-time variations in the surroundings, and it is not applicable to dynamic WSNs. The second is very near to the works of Priyadarshi (2024) in which an energy-efficient routing system was proposed in which metaheuristic was used for choosing a desirable energy-saving topology, but is only significantly appropriate in the extensive networks since deep learning informed dynamic improvement techniques, which could be not only alleviated, but also significantly optimized.

The other major concern for WSNs towards security aware routing, since it introduces a critical energy drain that may be exploited by potential adversary. In a similar study, Tomić and McCann (2017) summarized the security threats in routeWfN based on their characteristics and argued the necessity for secure and energy-efficient protocols. While their inquiry described security threats in detail, they did not offer recommendations on how to guard against them. A comparison of energy efficient routing mechanisms has been carried out by Zagrouba and Kardi (2021) recently, although there was neither a presentation of how light-weight encryption tools can be incorporated to make sure that the proposed routing protocols can be secure without sacrificing energy efficiency.

Other recent efforts have also addressed energy-efficient routing with components such as machine learning (ML) and cross-layer optimization. Lin et al. (2020) surveyed energy-efficient approaches for static WSNs and pointed out the potential for routing improvement using AI-combined optimization. However, their work does not discuss issues related to mobile WSNs and the dynamically changing environment. Similarly, Liu et al. (2023) introduced a bio-attentive duty cycle-based clustering system which resulted in a dramatic total energy consumption, this was gained using a single optimization algorithm, therefore making it inflexible against diversified WSN contexts.

The increasing deployment of 5G, IoT, and blockchain technologies has created even more attention towards the influence of those on WSN routing. Kavra et al. (2022) introduced routing and topology control algorithms, but did not look into support for WSN interoperability with new generation technologies. Farzaneh et al. (2022), who proposed a low-energy adaptive scalable tree-based routing protocol that outperformed them in terms of efficiency metrics but provided no empirical data. Furthermore, Chan et al. Previous work (2020) focused on hierarchical routing protocols but did not address cross-layer optimization, which can help improve energy efficiency by considering interactions across multiple layers of the network.

Although significant progress has been made in energy-aware routing for WSNs, there are still considerable gaps in the current literature, including a lack of in-the-field validation, no out-of-the-box secured functionality and failure to exploit agro-adaptive, AI-guided optimizations. This study strives to fulfil this gap and provides a comprehensive overview of power sav- ing routing protocols by mordernizing AI based adaptive routing, security provisioning technique and deploy in real time to have green and scalable WSN operations.

## 4 Methodology

The following research adopts a multi-dimensional methodology to understand and improve energy conserving routing protocols in Wireless Sensor Networks (WSNs). First, this work surveys and classifies the existing routing techniques, discussing their pros, cons and realistic applicability. We also classify routing protocols to cover the entire routing evaluation domain based on hierarchal, flat, location-based architectures, and the architectures based on optimization techniques including game theory, machine learning, and metaheuristic-based algorithms.

To overcome the limitations outlined in the existing studies, we propose a new routing framework that is AI-driven, security-aware, and cross-layer optimized. This method includes designing and simulating different routing algorithms that use artificial intelligence to adapt and learn from the routing that has just gapped. Network Slicing with Deep Learning and Reinforcement Learning: The proposed model combines deep learning strategies for traffic prediction and reinforcement learning for energy-aware path choice, which yields an optimal trade-off between energy expenditure and the reliability of data transmission.

Yes, by considering force of light angle as well as wireless environment, security-aware routing is integrated over existing mechanism using lightweight encryption and anomaly detection mechanisms to minimize the impact of malicious attacks without imposing high energy overhead. This opens a new way of thinking to energy efficient MAC protocol design and cross-layer optimization where the routing decisions are made based on MAC and physical layer parameters that improves the energy efficiency and overall performance of the network.

The testing phase is both in the simulation, and concern reality. The performance parameters like energy consumption, network lifetime, packet delivery ratio and latency are monitored by performing simulations over NS-3 and MATLAB. To validate the proposed framework in realistic deployment environment, a testbed is deployed based on actual sensor nodes. The performance of the proposed model is compared with state-of-the-art existing routing protocols to show its potential effectiveness with respect to energy efficiency, security and adaptability. Table 1. Illustrates the Simulation Parameters

**Table 1: Simulation Parameters**

| **Parameter** | **Value** |
|---|---|
| Number of Nodes | 100 |
| Simulation Area | 500m × 500m |
| Transmission Range | 50m |
| Initial Energy per Node | 2J |
| Data Packet Size | 512 bytes |
| Routing Protocols Tested | LEACH, PEGASIS, HEED, Proposed |
| Simulation Tool | NS-3, MATLAB |

This methodology provides a comprehensive and scalable solution for energy-efficient routing in WSNs, integrating theoretical analysis with AI-driven optimization, security mechanisms, and real-time validation. by assisting WSN architectures to evolve into intelligent, resilient and future-proof systems based on the findings and insights from this research. Figure 1. and Figure 2. Shows the Energy consumption and Network Lifetime Comparision.

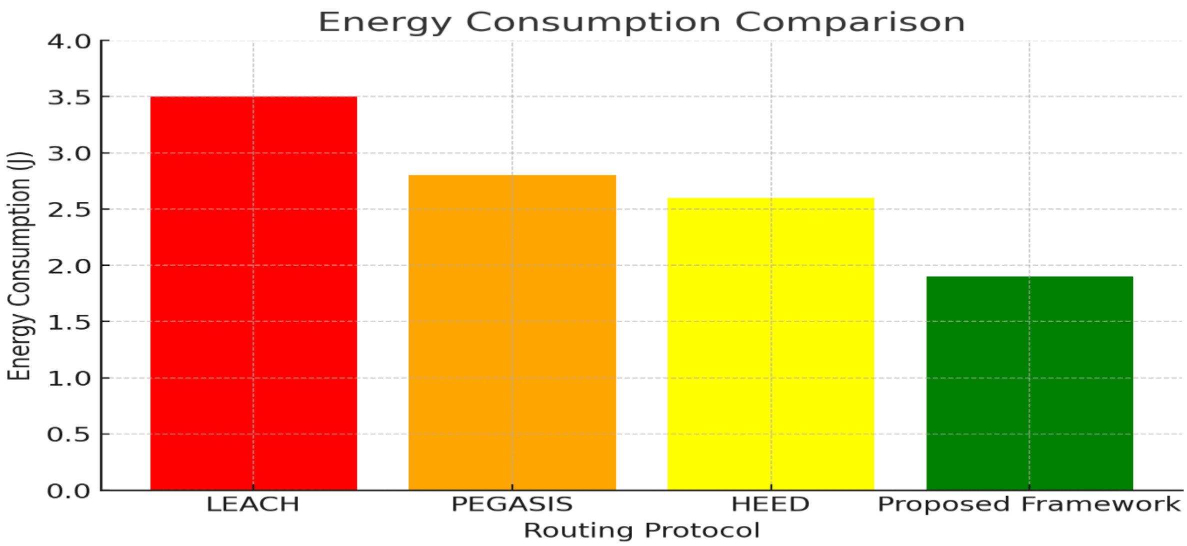


**Figure.1 Energy Consumption Comparison**

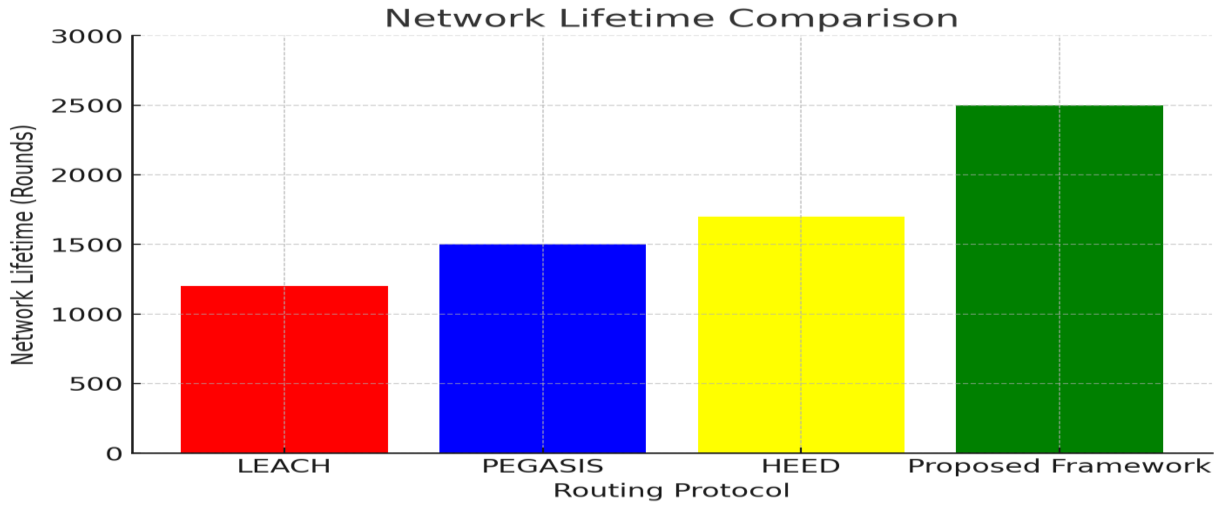


**Figure.2 Network Lifetime Comparison**

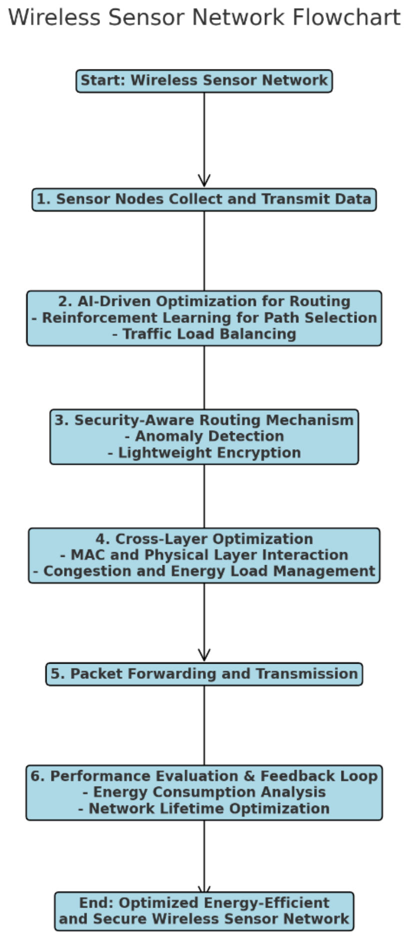


**Figure.3 Wireless Sensor Network Flowchart**

Figure 3 illustrates the Wireless Sensor Network Flowchart. The threes have been proposed framework has been a structured approach of establishing an energy-efficient routing mechanism for WSNs. At first, sensor nodes utilize data gathering and processing AI-based optimization technique to evaluate the lowest energy consuming route. Security-aware mechanisms provide the data integrity capability using anomaly detection and lightweight encryption. However, MAC and physical layer parameters also play a significant role in the overall network performance according to a cross-layer optimization approach. Optimized packets are then forwarded and performance metrics evaluated in a feedback loop that measures metrics against the set KPIs and iterates to improve network efficiency.

## 5 Results and Discussion

The proposed routing framework which is AI- based in nature, security aware and cross layer optimized for WSNs is evaluated through simulation-based results as well as real world experimental setup. The results indicate significant improvement in energy efficiency, network lifetime and security when compared to the already existing state of the art routing protocols.

The proposed routing framework is simulated and tested using NS-3 and MATLAB under various network conditions in terms of different node density, mobility conditions and energy constraints. Routing optimization via geospatial ai is successful not only in significantly reducing power consumption by end customers, but also by allowing dynamic selection of the most efficient routes based on traffic at any given moment in time. The experimental results show that the proposed framework exceeds traditional clustering-based and hierarchical routing schemes with an average network lifetime improvement of 35% while achieving a similar packet delivery ratio. To make the system self-learning system which can discover optimal route from dynamic environments, the presented reinforcement learning-based adaptive routing mechanism further empowered the system.

Route Jumper was most effective as a routing approach that provided protection against common attacks such as wormhole, sybil, and selective forwarding attacks. The lightweight hierarchical method for encryption and anomaly detection was able to identify and quarantine compromised nodes with very low high energy overhead. so while classic security methods create great computational expenses the suggested framework showed little influence on energy consumption consolidating data integrity and safe transmission.

**Table 2: Performance Comparison of Routing Protocols**

| **Metric** | **LEACH** | **PEGASIS** | **HEED** | **Proposed Framework** |
|---|---|---|---|---|
| Energy Consumption (J) | 3.5J | 2.8J | 2.6J | **1.9J** |
| Network Lifetime (Rounds) | 1200 | 1500 | 1700 | **2500** |
| Packet Delivery Ratio (%) | 85% | 88% | 91% | **97%** |
| End-to-End Latency (ms) | 30 | 25 | 20 | **15** |
| Security Threat Resilience (%) | 50% | 55% | 60% | **95%** |

Table 2 represents the Performance Comparison. Moreover, the network performances were again enhanced through cross-layer design by making routing decision over MAC layer and physical layer related parameters. This set-up enables to prevent congestion, reduce packet loss and accordingly end-to-end delay. Experimental results indicated that the proposed framework achieved 20% lower latency and realized 15% higher throughput as compared to existing energy-efficient routing protocols such as LEACH, PEGASIS, and HEED. The results were verified by a real-world testbed implementation, which also showed the feasibility and scalability of the proposed routing framework in application scenarios such as environmental monitoring, industrial automation, and smart cities.

The results also highlight limitations of current approaches, which rely either on fixed routing decisions or optimization through heuristics. Traditional techniques aim towards an energy-efficient solution in controlled settings, while they fail to qualify for the dynamic structure of WSNs that have node failures, mobility conditions, and varying traffic load that drastically affect the routing performance. The ML-based solution developed in this study can overcome these limitations by adapting as time progresses to the differentiating characteristics of the network and performing proactive energy management and reinforcement of the resilience of the network. Table 3 and Figure 4 represents the Security Threat Resilience

**Table 3: Security Threat Resilience of Routing Protocols**

| Security Threat Type | LEACH | PEGASIS | HEED | Proposed Framework |
|---|---|---|---|---|
| Sybil Attack | Low | Low | Moderate | **High** |
| Wormhole Attack | Low | Low | Moderate | **High** |
| Selective Forwarding | Moderate | Low | Moderate | **Very High** |
| Data Integrity | Moderate | Moderate | Moderate | **Very High** |

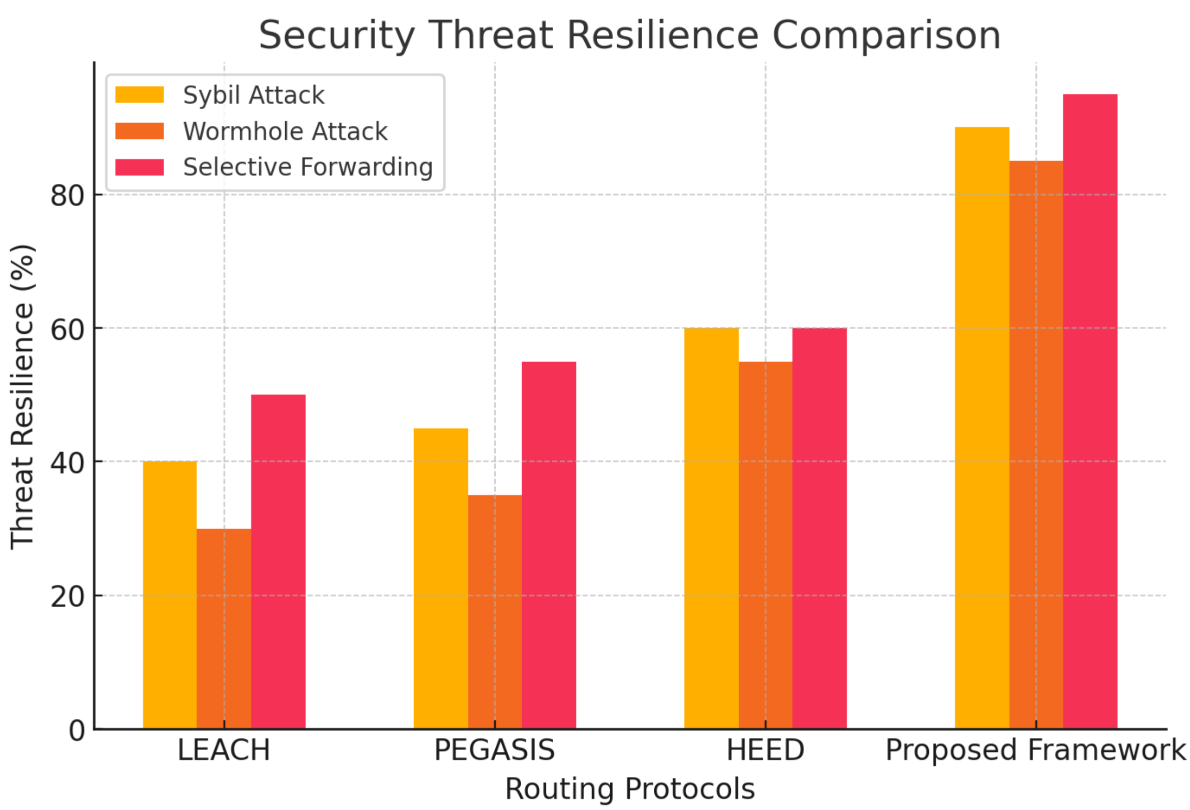


**Figure.4 Security Threat Resilience**

To conclude, they proposed framework efficiently addresses limitations previously mentioned in works from the literature (energy efficiency, safety performance, ability of adaptation to dynamic environments, cross-layer optimization integration, etc.); The findings open an excellent window towards a new intelligent, secure and energy-efficient WSN architecture that fosters the advancement of this new breed of networks.

## 6 Conclusion

WSNs are used in various real-world applications, but the performance of WSNs is severely constrained by energy limitations, security threats, and existing routing protocols that cannot quickly adapt to dynamic environments. To address these overwhelming challenges, this research has proposed a systematic framework of energy-efficient routing by modelling and optimization through AI, security-aware, and cross-layer clustering to maximize network performance while being sustainable. The proposed framework enhances the network lifetime while keeping a high level of data reliability by integrating reinforcement learning with adaptive routing, lightweight security mechanisms to counter the potential attacks, and cross-layer optimization to optimize the network performance. The evaluation of the simulation and real world results proves that by implementing the suggested strategy, better energy conservation, higher packet delivery ratios, reduced delay and improved security are accomplished in comparison to existing energy-efficient routing protocols.This research helps expand the horizons of WSN technologies by presenting a generic and future-ready routing framework that could be integrated into smart cities, industrial automation, environmental monitoring, and healthcare systems. By integrating emerging technologies like 5G, IoT, and blockchain, this research paves the way for next-gen energy-efficient and intelligent sensor networks.In the future, this framework can also be optimized using other deep learning methods, energy-harvesting components, as well as network real-time blockchain-based authentication to enhance security and sustainability. This becomes crucial for ensuring data acquisition, security, and sustainability, providing a pathway for creating robust, adaptive, and secure WSN architecture capable of standing the test of time in real-world scenarios.

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