

# Energy Conservation Strategies in Wireless Sensor Networks: Surveying Routing, Clustering, and Cross-Layer Optimization Approaches

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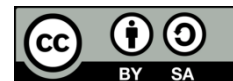
Energy-Aware Routing

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## ABSTRACT

Wireless Sensor Networks (WSNs) are a key part of the modern Internet of Things (IoT), facilitating real time sensing, monitoring, and data transfer in a variety of applications including environmental monitoring, healthcare, industrial automation, smart agriculture and smart cities. The battery capacity constraints of sensor nodes, however, are a major limitation and energy efficiency is an important factor in the design of sensor networks to ensure their operation and reliability over extended periods. A large number of solutions have been proposed to improve the energy consumption and the network lifetime over the years, such as energy-aware routing protocols, clustering, sleep scheduling, data aggregation, and transmission power optimization. Recent developments have also brought in the concept of intelligent solutions such as artificial intelligence, machine learning, game theory, and optimization algorithms to enhance routing decisions and resource utilization. Furthermore, energy harvesting approaches and self-powered sensor networks are becoming attractive approaches for sustainable and long-term deployment. This survey aims to provide an in-depth overview of the recent advances of energy-efficient wireless sensor networks (WSN) during the years 2020-2026. The study includes routing protocols, clustering and deployment strategies, techniques of optimization, energy harvesting techniques, solutions based on artificial intelligence and cross-layer optimization techniques. Additionally, a comparative study of the current methods is given, so as to show their advantages, disadvantages and suitability of their use. The survey highlights the challenges in the current research and talks about the future directions in the development of intelligent, sustainable and energy aware wireless sensor network architectures.

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## 1. INTRODUCTION

Wireless Sensor Networks (WSNs) are one of the key enabling technologies for the current Internet of Things (IoT) applications, which are used for real-time monitoring, data collection and communication in different fields like Environmental monitoring, Healthcare, Industrial automation, Smart agriculture, Military surveillance, Smart cities etc. A typical WSN is a collection of large number of sensor nodes with sensing, processing and wireless communication capabilities. The information is gathered by these nodes cooperatively and passed to a base station or sink node for further analysis. Although many applications can benefit from these networks, energy constraints are one of the most important challenges for sensor networks that impact the network's performance, reliability, and operational lifespan [1], [2].

The major energy consumption in WSNs is in the sensing, processing, and wireless communication operations. Of these, data transmission and reception make up the largest amount of energy use. Thus, there has been a significant research effort to develop energy-efficient communication schemes to achieve sustainable WSN architectures [1]. Several methods exist to lower energy usage such as energy-aware routing protocols, clustering techniques, sleep scheduling, data aggregation and transmission power control [2], [4]. These methods try to reduce the number of unnecessary communications, to ensure even distribution of energy use across the network and to maximize overall network lifetime.

The energy efficiency of WSNs can be greatly affected by routing protocols. Many routing methods in traditional routing systems face the problems of communication overhead and unequal energy consumption of the sensor nodes. Adaptive routing mechanisms, which dynamically find optimal communication paths with respect to the residual energy, network conditions, and traffic requirements, have been studied recently [5]. Moreover, game-theoretic routing models have been proposed to optimize the allocation of resources and manage congestion, enhance communication efficiency while saving energy consumption [3] and [10].

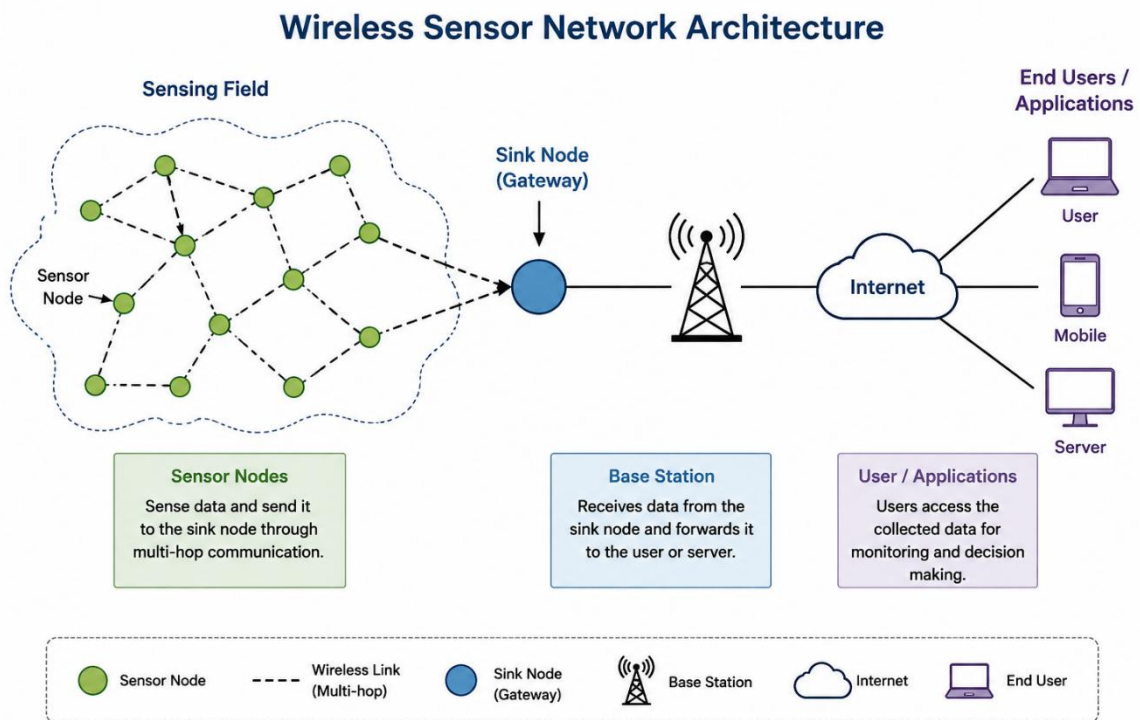


Fig. 1. General architecture of WSNs

Another aspect of research that is important is the concept of cluster and topology optimization. Clustering-based approaches divide the sensor nodes into clusters, and select cluster heads to execute data aggregation and communicate with a sink node. These methods can greatly decrease the overhead required for communication and optimize energy use. The most prominent methods for the optimization of cluster-head selection and routing are advanced optimization techniques such as fuzzy logic, quantum particle swarm optimization and bio-inspired algorithms, which have shown promising results in cluster-head selection and routing optimization [7] and [8]. Further, the optimal deployment of nodes also result in better coverage and shorter distances between the nodes which implies better efficiency of the network [9].

The recent developments in the field of Artificial Intelligence and Machine Learning have also revolutionized energy management in WSNs. AI-based routing protocols use a smart decision making process to dynamically adjust to varying network conditions and energy availability [13]. At the same time, the incorporation of the energy harvesting technologies allows energy to be harvested from the environmental sources like from the sun, from the temperature differences, from vibrations and from radio-frequency signals, which decreases the use of conventional battery system by the sensor nodes [12]. The idea of self-powered wireless sensor networks has attracted much interest for its ability to operate autonomously over extended periods of time without much maintenance [14].

Besides, some cross-layer optimization techniques, which consider the parameters of routing, medium access control (MAC), and physical layer together, have been explored in order to achieve global energy efficient gains [18]. Multi-channel MAC protocols, intelligent scheduling algorithms and communication-efficient learning frameworks have also helped to decrease communication overhead and enhance network sustainability [16, 17].

Energy efficiency is still a fundamental research problem in wireless sensor networks because of the vast application of IoT and the growing needs of sustainable sensing infrastructures. In this survey, recent advances in energy efficient WSN technologies are discussed, such as the routing protocols, clustering techniques, energy optimization methods, energy harvesting solutions, artificial intelligence related solutions and cross-layer optimization. The goal is to give a detailed overview of the state of the art, the existing problems and future perspectives on energy-efficient and sustainable design of WSNs.

## 2. LITERATURE REVIEW

Real-time sensing, monitoring, and communications feature of Wireless Sensor Networks (WSNs) has made them an integral part of modern Internet of Things (IoT) infrastructures. The small battery sizes of sensor nodes, however, are still one of the key challenges in the performance and longevity of networks. Thus, the energy efficient communication, routing, clustering and resource management techniques are receiving considerable research interest in the last few years.

Samara et al., [1] gave an extensive survey of energy efficient routing in WSNs. The study categorized the routing protocols into flat, hierarchical, location based, multipath and highlighted that the communication overhead must be minimized and the energy consumption must be balanced between the sensor nodes. The authors found that the biggest source of energy was routing and noted that adaptive routing strategies are good ways of prolonging network life.

In [2], Masood studied different energy saving approaches used for WSNs such as duty cycling, energy-aware routing, data aggregation, sleep scheduling, and transmission power control. The study showed that a hybrid of more than one energy-saving mechanism can increase the network lifetime while maintaining satisfactory Quality of Service (QoS) performance.

New developments have been made with the use of intelligent routing mechanisms based on game theory and cooperative decision making. Shyamala et al. [3] introduced a game theory-based coalition routing approach that uses the concept of congestion, communication cost and resource utilization to optimize the routing decisions. The proposed framework is applicable to Delay Tolerant Networks (DTNs) but can provide useful insights to future energy-aware WSN routing protocols where dynamic path selection can help to minimize wasted energy.

Ramaiah et al. [4] addressed the problem in heterogeneous WSNs, where the energy level and computation power of sensor nodes are different. The survey covered different energy efficient control techniques, like clustering, load balancing, and adaptive scheduling techniques. They also found that heterogeneous architectures can greatly enhance network lifetime with energy management policies that are fairly efficient.

Table 1. Comparison of Routing Approaches

Ref.	Technique	Main Objective	Advantages	Limitations
[1]	Energy-Efficient Routing Survey	Routing optimization	Comprehensive classification	Survey only
[3]	Coalition Game-Theoretic Routing	Cost and congestion reduction	Adaptive decision-making	Higher complexity
[5]	Query-Driven Routing	Reduce redundant transmissions	Lower communication overhead	Application-specific
[13]	AI-Driven Routing	Dynamic route optimization	Intelligent adaptation	Computational cost
[18]	Cross-Layer Routing	Joint optimization	Improved energy efficiency	Design complexity

Bekal et al. [5] summarized the routing protocols used to reduce redundant transmissions, which are query-driven protocols. They found that the schemes of Directed Diffusion, TEEN and APTEEN reduce the communication overhead by only sending sensed information that is relevant to the communication. These techniques are

especially useful in event-driven monitoring situations where the data does not need to be transmitted continuously.

Another research direction that has come to the fore is optimization-based energy management. Machiwa et al. [6] looked at the linear programming and mathematical optimization approaches to maximize network lifetime. The study showed that optimization methods can effectively allocate energy resources, while maintaining coverage and connectivity constraints. These techniques are well founded and can be used as a basis for designing energy efficient routing and scheduling algorithms.

The underwater wireless sensor network (UWSN) environment is even harder to consider energy efficiency, as the communication environment is harsh and there are high communication costs. The localization methods and bio-inspired optimization methods for UWSN were discussed by Murali and Shankar [7]. They emphasized the importance of intelligent localization algorithms in minimizing the communication overhead and maximizing energy savings.

Table 2. Comparison of Clustering and Deployment Techniques

Ref.	Method	Key Feature	Energy Impact
[4]	Heterogeneous WSN Control	Load balancing	High
[8]	QPSO + Fuzzy Clustering	Optimized cluster-head selection	Very High
[9]	Deployment Optimization	Coverage-aware placement	High
[15]	Universal Coverage Strategy	Reduced redundancy	High
[16]	MAC + Clustering Integration	Efficient communication	Very High

Clustering is still one of the most successful approaches to minimize communications costs in WSNs. Hu et al. [8] introduced a quantum particle swarm optimization (QPSO) based clustering and routing protocol by fusing the fuzzy logic. The proposed approach was able to optimize the routing decisions using the residual energy and node distribution to achieve balanced cluster-head selection, reduce energy consumption and extend network lifetime.

The positioning of sensors is also very important when considering energy conservation. Anusuya et al., [9] discussed the different deployment strategies that are used to achieve maximum coverage with minimum energy consumption. The research highlighted the benefits of placing nodes optimally and decreasing the distance in transmission, which enhance the network's efficiency.

Recently, there are a number of research works which have employed game theory for intelligent resource allocation. Chaurasia et al. [10] proposed a game-theory based smart routing framework incorporating with capacity model, congestion model and cost model. The proposed methodology showed an enhanced utilization of the resources and routing efficiency, which gives useful ideas for future energy-aware WSN routing mechanisms.

Environmental monitoring is one of the most crucial applications of WSNs. Rana et al. [11] polled energy efficient protocols specially engineered for environmental sensing applications. They found that adaptive routing, clustering, and sleep scheduling mechanisms have a significant effect on the longevity of a network in large-scale monitoring systems.

The energy harvesting technologies have provided new opportunities for the deployment of WSNs sustainably. Mushtaq et al. [12] discussed the various methods of energy harvesting from solar, thermal, vibration and radio frequency. The authors' findings suggest that hybrid systems of energy harvesting can provide the highest possibility for near-permanent network operation.

Table 3. Comparison of Energy Optimization Techniques

Ref.	Optimization Method	Application	Benefit
[2]	Duty Cycling	General WSNs	Reduced idle energy
[6]	Linear Programming	Resource allocation	Maximized lifetime
[10]	Game Theory	Smart routing	Better resource utilization
[13]	Machine Learning	Adaptive routing	Dynamic optimization
[18]	Cross-Layer Optimization	Protocol integration	Enhanced efficiency

Artificial Intelligence (AI) is a game-changer technology in energy-efficient networking. Thakur et al. [13] discussed the routing approaches based on artificial intelligence that make use of machine learning, deep learning

and reinforcement learning to dynamically optimize the route selection and energy consumption. These smart systems automatically adjust to fluctuations in network conditions and optimize routing.

Likewise, Zhang et al. [14] studied self-powered wireless sensor networks, and offered a co-design framework where they optimize the energy harvesting and signal processing simultaneously. The results suggest that even with the use of battery energy, self-powered WSNs can be successfully used for long term autonomous operation.

Optimization of coverage is another problem of significant importance in designing an energy efficient WSN. Tian [15] introduced the consensus estimation and universal coverage mechanisms that enhance the sensing effectiveness with a minimal amount of redundant communication. The study proved that intelligent coverage planning can play an important role in energy saving.

Pawale and Patil [16] studied multi-channel MAC and clustering protocols for the energy-efficient communication at the MAC layer. The study showed that the communication overhead and network lifetime can be significantly improved by collision avoidance, channel allocation and adaptive duty cycling.

Table 4. Comparison of Sustainable Energy Solutions

Ref.	Technique	Energy Source	Expected Lifetime Improvement
[11]	Environmental Monitoring Protocols	Battery-powered	Moderate
[12]	Energy Harvesting	Solar, RF, Thermal, Vibration	High
[14]	Self-Powered WSNs	Hybrid Harvesting	Very High
[17]	Communication-Efficient Learning	Bandwidth reduction	Moderate
[18]	Cross-Layer Energy Management	Integrated optimization	High

Wireless health care systems have made the development of communication-efficient learning frameworks possible recently. In healthcare networks where bandwidth is limited, Radhika et al. [17] designed a model called Communication-Efficient Federated Learning (CEFL). While it's mostly targeted to healthcare applications, the framework illustrates the potential of communication reduction techniques to indirectly help in energy savings in wireless applications.

Finally, Alatabani et al. [18] studied cross-layer optimization approaches which take into account both routing and MAC layer operations as well as the physical layer characteristics. According to their results, approaches for cross-layer optimization offers better energy efficiency than those which involve isolated protocol optimization.

### 3. CONCLUSION

Wireless Sensor Networks (WSNs) are still crucial for various modern applications of the Internet of Things (IoT) such as environmental monitoring, healthcare, industrial automation, smart agriculture and smart city infrastructures. But, the lack of energy resources in sensor nodes is one of the most important issues directly impacting the network lifetime, reliability and performance. This survey covered the recent advances in energy efficient WSNs for routing protocols, clustering, deployment strategies, optimization techniques, energy harvesting systems and AI based solutions, and cross layer optimization approaches from 2020 to 2026. The literature provides ample evidence that considerable gains in energy saving can be obtained by adopting intelligent routing, optimal cluster-head selection, adaptive duty-cycling, efficient resource allocation mechanisms etc. In addition, new technologies like machine learning, game theoretic decision making, energy harvesting have made WSNs more efficient to work in dynamic and resource-limited environments. However, there are still many issues that have yet to be solved. For future work, lightweight Artificial Intelligence algorithms that could run on resource-constrained sensor nodes with minimal computation and memory costs should be developed. Self-powered and maintenance-free sensor networks can be further realized by combining energy harvesting technologies with intelligent energy management systems. The energy-saving solutions will be more complete if they take into account routing, MAC, and physical layer parameters through a cross-layer optimization framework. Furthermore, with the integration of WSNs with large-scale IoT systems, secure and energy-efficient communication protocols will gain significant importance. Future research will also focus on federated learning, edge intelligence, digital twins and sensing environments enabled by 6G to further enhance adaptability and sustainability of networks. These research directions show the potential for creating more autonomous, intelligent and energy efficient WSNs that can be used to support next generation smart applications.

## CONFLICT OF INTEREST STATEMENT

No conflict of interest.

## DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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