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A Review on IOT Wireless Network Optimization Models and Techniques

Roshni Thakre[1], Prof. Rahul Patidar[2], Jayshree Boaddh[3]
[1]MTech Scholar, [2]Asst.Prof., [3]Prof. HOD
Department of Computer Science and Engineering
Vaishnavi Institutes of Technology and Science, Bhopal, MP, India

Abstract- Wireless Sensor Networks (WSNs) and Internet of Things (IoT) systems play a crucial role in modern smart applications such as smart cities, healthcare, industrial automation, and precision agriculture. Despite rapid advances in communication, cloud, and edge computing technologies, energy efficiency remains a fundamental challenge due to the limited power resources of sensor nodes. This survey presents a comprehensive review of energy losses in WSN-based IoT networks and systematically analyzes state-of-the-art optimization techniques aimed at prolonging network operation. The paper discusses architectural aspects of WSNs, sources of energy waste, and major optimization strategies, including radio optimization, data reduction, sleep/wakeup scheduling, and energy-aware routing. Furthermore, recent approaches based on metaheuristic optimization, swarm intelligence, and machine learning are reviewed and compared. By organizing existing methods into a unified taxonomy, this survey highlights current research trends, practical design trade-offs, and open challenges, thereby providing useful guidelines for developing scalable, energy-efficient, and reliable WSN-IoT systems.

Keywords: Adhoc Network, Wireless Sensor Network, Communication Attacks, Virtual machines.

I. INTRODUCTION

The Internet of Things (IoT) represents a vast network of interconnected smart devices embedded with sensors, processing units, and communication interfaces that enable them to sense, analyze, and exchange data over communication networks. These devices are often deployed over wide geographic regions to monitor environmental conditions, industrial processes, and societal activities in real time. By integrating key technologies such as wireless networking, embedded systems, and sensor technologies, IoT frameworks support the development of intelligent and adaptive environments. Owing to their scalability, affordability, and ability to operate autonomously, IoT devices have been widely adopted in diverse domains including healthcare, smart cities, agriculture, and defense.

IoT infrastructures facilitate large-scale data acquisition and analytics, frequently in combination with emerging technologies such as 5G/6G networks, cloud computing platforms, and edge computing paradigms [1].

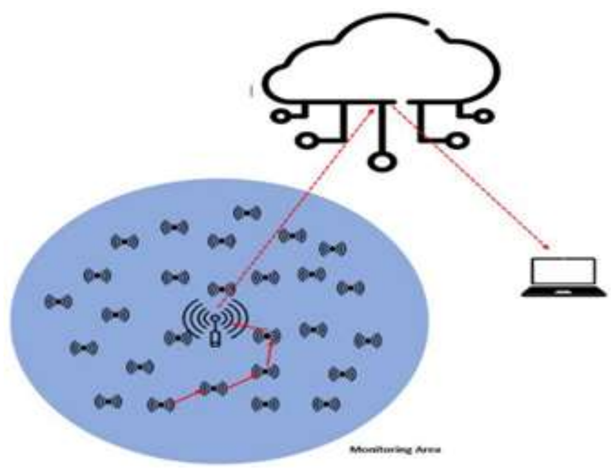

Fig. 1. IOT enabled wireless network.

Despite these advancements, energy consumption remains a critical challenge, especially for battery-operated devices. Many conventional communication and routing schemes are not optimized for long-term operation, leading to reduced network lifetime and premature node failures. To address this issue, energy-efficient clustering and routing strategies—particularly those leveraging metaheuristic optimization algorithms—are increasingly being investigated to improve the durability and overall efficiency of IoT systems [2].

Clustering is widely recognized as an efficient strategy for reducing energy consumption in IoT systems. By organizing devices into groups, it improves bandwidth utilization and supports better scalability in large IoT deployments. In this scheme, the network is partitioned into multiple logical clusters [3]. Each cluster is managed by a cluster head (CH), which gathers data from member devices, performs aggregation or preliminary processing, and forwards the refined information either directly or through other CHs to a central server or cloud gateway. These gateways are typically connected to broader public networks, such as the Internet, enabling real-time monitoring and timely event reporting.

In an IoT-based Wireless Sensor Network (WSN), every device is capable of sensing, storing, processing, and transmitting environmental data to neighboring nodes, thereby enabling distributed intelligence and rapid response to changes in the environment [4]. Such interconnected devices serve as the backbone of modern smart applications, including smart cities, industrial automation, and precision agriculture. Despite these advantages, a major and ongoing challenge is the limited energy availability of IoT nodes, which usually rely on batteries or energy-harvesting units with constrained capacity. If energy usage is not carefully controlled, prolonged operation and network reliability are compromised, particularly in large-scale or hard-to-reach deployments.

To mitigate this problem, scalable optimization techniques can be integrated with mobile IoT nodes to adaptively manage energy distribution and task assignment across the network [5]. These methods dynamically schedule sensing, data collection, and communication activities based on current energy levels and network conditions, thereby extending the operational lifetime of devices. In addition, dividing the monitored area into smaller logical regions allows finer-grained supervision of energy consumption throughout the network. This regional partitioning supports more accurate estimation of energy usage patterns and enables targeted optimization strategies, which collectively improve overall network efficiency while maintaining the required quality of service (QoS) [6].

II. ENERGY LOSSES AND TECHNIQUES FOR MANAGEMENT

In Wireless Sensor Networks (WSNs), sensor nodes consume energy while performing sensing, processing, transmitting, and receiving operations to accomplish their assigned tasks. The sensing module is primarily responsible for collecting data from the environment, and it is well established that reducing unnecessary data acquisition from transducers can significantly conserve the limited energy resources of constrained sensor nodes. Due to the inherent redundancy in WSN deployments, multiple nodes often report similar or correlated data, which increases the amount of traffic that must be forwarded toward the sink. Experimental studies confirm that the communication module is the most energy-intensive component of a sensor node.

Beyond useful data transmission, a substantial amount of energy is also wasted in operational states that provide little benefit from the application’s perspective. These sources of inefficiency include the following:

Overhearing: When a node transmits a packet, all nodes within its radio range receive it, even if they are not the intended recipients. As a result, nodes waste energy processing packets that are not meant for them.

Idle listening: One of the major contributors to energy consumption occurs when a node keeps its radioactive while waiting for potential traffic, even when no data are being transmitted.

Control packet overhead: A certain amount of control traffic is required to coordinate data transmission; however, excessive control packets increase energy usage without directly contributing to useful data delivery.

Collisions: If a node receives multiple packets at the same time, packet collisions occur, causing the corrupted data to be discarded and retransmitted, which leads to additional and unnecessary energy expenditure.

Interference: Nodes located within the interference range of a transmission may receive signals that they cannot correctly decode, resulting in wasted energy for reception without successful data recovery.

As network lifetime has become a primary performance metric for WSNs, a wide range of techniques have been proposed to reduce energy consumption and extend operational duration. These approaches aim to address energy losses at different layers of the protocol stack and through various architectural and algorithmic optimizations. This work therefore presents a systematic classification of such energy-saving methods.

III. ARCHITECTURE OF WIRELESS SENSOR NETWORKS

The architecture of a Wireless Sensor Network (WSN) describes the structural arrangement of its components and has a significant influence on network performance, scalability, and energy efficiency. A typical WSN consists of a large number of sensor nodes deployed over a target area, one or more sinks or base stations responsible for collecting data, and a communication model that defines how information is exchanged within the network. The design choices associated with each of these architectural elements directly affect energy consumption patterns and, consequently, the overall lifetime of the network.

Sensor Nodes Sensor nodes form the core components of a Wireless Sensor Network (WSN). Each node is a small, low-cost, and resource-limited device designed to carry out sensing, computation, and wireless communication. A standard sensor node is composed of four main functional modules. The sensing module measures physical or environmental variables such as temperature, humidity, pressure, light, or motion. It typically includes sensors along with analog-to-digital converters that convert real-world signals into digital data for further processing. The processing module, usually implemented using a low-power microcontroller or microprocessor, is responsible for data handling, storage management, and execution of networking protocols. Tasks such as data filtering, aggregation, encryption, and routing control are performed within this unit, making energy-efficient processing essential to reduce power consumption. The communication module consists of a radio transceiver that enables wireless data exchange between sensor nodes and the sink. Since wireless transmission and reception account for the largest share of energy usage, designing energy-aware communication protocols is crucial for prolonging node lifetime. Finally, the power module, commonly powered by a rechargeable or non-rechargeable battery, supplies energy to all other components. Because battery replacement is often impractical in real deployments, conserving energy is a key requirement for long-term network operation.

Sink / Base Station The sink, also known as the base station, acts as the central point for data collection and control in a WSN. It gathers sensed information from sensor nodes either through direct communication or via multi-hop routes. Compared to ordinary sensor nodes, the sink typically has higher computational capability, larger storage capacity, and a stable power supply. Once data are collected, the sink forwards them to external servers or networks for further processing, analysis, and decision-making. In many applications, the sink also performs network management functions, including coordinating data aggregation, scheduling tasks, and distributing control messages. The location and number of sink nodes play a critical role in determining network efficiency, communication delay, and overall energy consumption.

Communication Model The communication model describes how sensor nodes exchange information among themselves and with the sink. Two main communication strategies are commonly used in WSNs: single-hop and multi-hop communication. In single-hop communication, each sensor node sends its data directly to the sink, which simplifies routing but leads to high energy consumption for nodes that are far away, making this approach unsuitable for large-scale deployments. In multi-hop communication, data packets are relayed through intermediate nodes before reaching the sink. This method reduces the energy required for long-distance transmissions, distributes energy usage more evenly across the network, and significantly enhances scalability and network lifetime. As a result, multi-hop communication is widely preferred in large and energy-constrained WSN environments.

IV. RELATED WORK

Humayun et al. [8] highlighted energy optimization as a major challenge in smart city environments and addressed this issue by integrating emerging technologies such as IoT, 5G, and cloud computing. Their proposed framework targets energy-efficient operation in smart homes and urban infrastructures, including street lighting systems, buildings, display boards, and smart parking facilities. In this model, electrical devices in smart cities are equipped with IoT sensors to detect activity and execute control commands over the network. Data exchange between devices and cloud platforms is carried over 5G networks, while cloud services are used for efficient data storage and access. The authors employed mathematical modeling to evaluate the proposed system, and the results indicate that the framework has strong potential to improve energy utilization in smart city applications.

Nagaraju et al. [9] presented a secure and energy-aware routing approach for IoT applications deployed over integrated wireless sensor networks. Their scheme establishes protected communication paths for transmitting IoT data across sensor nodes using a multipath routing strategy. The approach incorporates TEEN-based variants within a hybrid ad hoc network framework, where a hybrid TEEN method enhances energy efficiency and network lifetime, and a ubiquitous data storage protocol improves storage performance. Simulation results, compared against two existing routing protocols, show improvements in key performance metrics such as throughput, energy efficiency, end-to-end delay, network lifetime, storage capability, and overall data capacity. The study also emphasizes that ensuring end-to-end security remains a critical design challenge in hybrid WSNs.

Amutha et al. [10] proposed a new cluster-based hybrid optimization technique, referred to as EE-CHOA, to improve energy efficiency in wireless sensor networks using both static and mobile sink nodes [17]. The primary goal of this approach is to extend network lifetime by dynamically selecting the most suitable sink and optimizing data transmission paths within a grouping-based communication model. Simulation results demonstrate that the proposed method achieves approximately a 20% improvement in energy efficiency and extends the network lifetime by about 35%.

Rawat et al. [11] presented a sleep scheduling and clustering scheme for wireless sensor networks based on Particle Swarm Optimization (PSO) [18]. Their method aims to improve energy efficiency by adaptively managing the sleep and active periods of sensor nodes and by forming efficient clusters. Simulation results demonstrate that the proposed approach can reduce overall energy consumption by nearly 50% while extending the network lifetime by about 60%.

M. Haris et al. [12] proposed a PSO-driven clustering technique that employs a double-exponential adaptive inertia weight strategy to dynamically balance global exploration and local exploitation. This adaptive mechanism helps avoid premature convergence, enhances the precision of cluster head (CH) selection, and improves the overall energy performance of the network. The method categorizes nodes into cluster members, CHs, and free nodes, and uses residual energy information to determine the optimal number of clusters during the clustering process. It then forms clusters of nearly uniform size and assigns high-energy nodes as CHs based on their spatial positions. The effectiveness of the approach is validated across different network scenarios and benchmarked against LEACH, LEACH-FL, LEACH-FC, and KM-PSO.

Soltani et al. [13] introduced a multi-agent reinforcement learning–based routing framework in which distributed agents collaboratively adapt their routing strategies according to changing network conditions. This cooperative learning process leads to more balanced energy usage and a noticeable extension of network lifetime.

Similarly, Godfrey et al. [14] integrated reinforcement learning into software-defined wireless sensor networks, allowing centralized controllers and edge devices to jointly optimize routing decisions in real time. This coordinated control improves energy distribution across the network and enhances overall robustness.

Li and Ai [15] proposed a hybrid clustering approach that combines Tabu Search with Ant Colony Optimization to achieve more effective cluster head selection and routing path optimization. By better balancing the communication workload among nodes, their method reduces the likelihood of early node failures and contributes to longer network operation.

V. TECHNIQUES OF WSN OPTIMIZATION

Energy efficiency and network lifetime are central design goals for Wireless Sensor Networks (WSNs) and Internet of Things (IoT) systems because sensor nodes typically operate on limited battery power. Network lifetime is commonly defined by metrics such as the time until the first or last node dies, network coverage loss, or when the rate of data delivery to the sink falls below a threshold. Energy efficiency generally refers to achieving desired sensing and communication outcomes while consuming as little energy as possible, or delivering higher service quality (e.g., packet delivery ratio or detection accuracy) for the same energy budget.

Researchers have developed a variety of energy-saving mechanisms to extend network lifetime while meeting application requirements. These mechanisms can broadly be categorized into radio optimization, data reduction, sleep/wakeup schemes, and energy-efficient routing.

Radio Optimization Radio communication dominates energy consumption in WSNs; hence optimizing the physical and MAC layers is critical. Techniques such as modulation and coding optimization aim to balance transmission power, data rate, and bit error rate to minimize energy expenditure. Collaborative communication methods form virtual multiple-antenna systems to enhance signal quality while consuming less individual node energy through spatial diversity [16].

(Recent research has also explored correlated data-driven beam forming approaches to optimize uplink transmission energy in IoT networks, combining routing decisions with machine learning to mitigate energy hot spots and cut transmission costs.)

Directional antennas and dynamic transmission power control (TPC) adjust radio behavior based on network conditions to reduce unnecessary energy use. Furthermore, adaptive cognitive radio techniques that select communication channels based on spectrum availability are being investigated for their ability to reduce energy waste despite higher complexity.

Data Reduction Communication energy can be significantly reduced by transmitting only essential data. Data aggregation combines sensor readings to reduce the number of transmissions. Adaptive sampling adjusts sensing frequency based on the dynamics of the monitored phenomenon, avoiding redundant data collection [17].

Techniques like network coding mix multiple packets into coded transmissions, reducing channel usage and saving energy. Likewise, compressive sensing and lightweight data compression algorithms tailored to low-power sensor nodes reduce packet sizes and overall communication load.

Significant research has also highlighted AI-assisted data validation frameworks that enhance both reliability and energy efficiency by pre-filtering data at the node, reducing unnecessary transmission overhead.

Sleep/Wakeup Schemes Idle listening and unnecessary active time drain energy unnecessarily. Duty cycling protocols transition nodes between sleep and active states based on traffic patterns, significantly cutting idle power consumption. Passive wake-up radios use ultra-low-power circuits to activate main radios only when required, minimizing idle listening energy costs [18].

Topology control techniques exploit node redundancy by selectively deactivating nodes while preserving coverage and connectivity. This dynamic adaptation of active nodes helps sustain long-term operation in dense deployments.

Advanced research has also proposed transformer-based scheduling algorithms that dynamically optimize sleep patterns based on real-time data prediction, achieving >30% reductions in energy use for pipeline monitoring networks.

Energy-Efficient Routing Routing decisions heavily influence energy distribution across the network. Cluster-based architectures assign cluster heads to manage local data aggregation and forwarding, reducing overall communication distances and enabling load balancing through periodic rotation. Energy-aware routing metrics, such as residual energy-based cost functions, prioritize nodes with higher remaining power to prolong network lifetime [19].

Multipath routing protocols distribute traffic across multiple paths, improving reliability and balancing energy load. AI-driven clustering and routing protocols that use reinforcement learning have recently shown significant performance gains, reducing energy consumption by adapting routing decisions dynamically based on node energy states.

Additionally, hybrid swarm and optimization-based routing methods leverage heuristic algorithms to select energy-balanced routes in complex deployments, further enhancing network lifetime and data reliability.

VI. CONCLUSION

This survey reviewed the key challenges and solutions related to energy optimization in WSN-based IoT networks, where limited power resources remain the primary constraint on long-term operation and reliability. We discussed the fundamental architecture of WSNs, major sources of energy loss such as overhearing, idle listening, collisions, and control overhead, and examined how these factors impact overall network lifetime. A systematic classification of optimization techniques was presented, including radio optimization, data reduction, sleep/wakeup schemes, and energy-efficient routing strategies. In addition, recent advances using metaheuristic algorithms, swarm intelligence, and machine learning-based approaches were highlighted for their ability to adaptively balance energy consumption and improve network performance.

While significant progress has been achieved, challenges remain in terms of scalability, dynamic network conditions, and real-time adaptability in large-scale deployments. Future research should focus on lightweight, intelligent, and cross-layer optimization frameworks that integrate edge intelligence and learning-based control to further enhance energy efficiency, robustness, and quality of service in next-generation WSN-IoT systems.

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