Abhishek Saini, 2024, 12:3
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology

An Open Access Journal

Comprehensive Review of Energy-Efficient Region-Based WSN Protocols

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Abstract- Owing to its many uses in manufacturing automation, healthcare, military inspection, and ecological monitoring, wireless sensor networks (WSNs) have become increasingly popular. To extend network lifetime, energy-efficient procedures must be developed because sensor nodes have limited resources for energy. This is a significant issue. A possible alternative has emerged: region-based protocols, which divide the network into discrete sections to optimize energy use. The present cutting-edge energy-efficient region-based procedures for WSNs are thoroughly examined in this paper. We examine different designs of region-based protocols and highlight how they use data aggregation, hierarchical organizing, and clustering to save energy. The review assesses the energy efficiency, scalability, and resilience of various protocols by classifying them according to their operating approaches. The assessment also discusses the drawbacks and restrictions of current protocols, including their inability to adjust to changing network circumstances, their unequal distribution of energy, and their overhead expenses. Additionally covered are current developments and new directions in region-based WSN protocols, such as cross-layer optimization tactics, adaptive clustering methods, and machine learning algorithms.

Keywords- WSN, Clustering, Node Distribution, Region Division

I. INTRODUCTION

Wireless Sensor Networks (WSNs) represent a transformative technology in the realm of distributed sensing and data collection. These networks consist of spatially distributed autonomous sensors that monitor physical or environmental conditions, such as temperature, humidity, pressure, motion, or pollutants, and cooperatively pass their data through the network to a central location or sink [1]. Sensor Nodes: The fundamental units of a WSN, each sensor node typically comprises a sensing unit, a processing unit, a communication unit, and a power unit. These nodes are responsible for sensing data, processing it locally, and transmitting it to other nodes or a base station[2]. Base Station (Sink): This is the central node in the network where data from various sensor nodes is aggregated, processed, and possibly forwarded to external systems for further analysis. Communication Protocols: These protocols define how sensor nodes communicate with each other and with the base station. They are crucial for managing data transmission, energy consumption, and network scalability[3]. WSNs have a broad spectrum of applications across various domains: Used for tracking environmental conditions such as temperature, humidity, and air quality, WSNs can monitor ecosystems, agricultural fields, and weather patterns, in medical applications, WSNs enable remote monitoring of patient vital signs, chronic disease management, and assisted living., WSNs enhance automation and monitoring of industrial processes, machinery health, and supply chain management.

Deployed in defense applications, WSNs are used for battlefield surveillance, target tracking, and intrusion detection. WSNs contribute to urban management by monitoring traffic, pollution levels, energy usage, and infrastructure health. Despite their versatility, WSNs face several challenges that need to be addressed to optimize their performance and sustainability: Sensor nodes typically rely on battery power, making energy consumption a critical issue. Efficient power management strategies are essential to prolong the network’s operational lifetime.

WSNs must support the addition of numerous sensor nodes without significant degradation in performance. Ensuring consistent and accurate data transmission in the presence of environmental interferences, node failures, and varying network conditions is vital. Protecting the network from malicious attacks, ensuring data integrity, and maintaining user privacy are significant concerns.

Minimizing the cost of deployment and maintenance while maximizing the network’s utility is an ongoing challenge. To address some of these challenges, particularly energy efficiency, region-based protocols have been developed. These protocols optimize energy consumption by organizing the network into distinct regions or clusters, each managed independently. By doing so, they reduce redundant data transmissions and balance the energy load among sensor nodes, thus extending the overall network lifetime.

II. RESEARCH BACKGROUND

A variety of projects have been finished recently. The SSE route routing system was developed by authors in [4] as a flexible, dependable, and sustainable routing strategy for WSN-IoT. To transfer the data packets from the sender to the recipient, it takes the least traveled path. The Advanced Zone-Stable Election Protocol (AZ-SEP), proposed by Rana et al.[5], considers the features of different WSNs in IoT contexts. The authors created AZ-SEP and compared it to the industry-standard LEACH routing protocol. The (OSR), which offers WSNs a dependable and adaptable downward routing mechanism, was first presented by[6]. The authors presented an analytical model and evaluated OSR's effectiveness using real-world testbed tests and simulations. The CH, which employs the LTE-M protocol, and the intra cluster, which implements the low power wide area network (LPWAN) self-networking algorithm in the WSN, were covered by Zhao et al. [7].

The traditional K-mean approach is used to study the number of cluster heads and the optimal scale within each cluster. Furthermore, an asynchronous dynamic cluster head selection and clustering technique are shown, based on an improved K-means technique. In the framework of 5G, C. Jothikumar et al. [8] proposed a system that maximizes energy efficiency and network longevity through improved cluster-based routing while employing a hierarchical routing technique for IoT applications. Unless three-fourths of the nodes are dead, the clustering phase begins before the chaining phase for the remainder sending data begins.

III. ENERGY EFFICIENT ROUTING PROTOCOLS IN WSN

Energy-efficient routing protocols in Wireless Sensor Networks (WSNs) are strategies designed to optimize the way data is transmitted between sensor nodes and the central base station or sink.

The main goal of these protocols is to prolong the network's operational lifetime by minimizing the energy consumption of each sensor node.

These reduce the power required for data transmission and reception, ensure that the network can function as long as possible before the energy resources of the nodes are depleted, prevent certain nodes from depleting their energy resources faster than others to avoid network partitioning.

Table 1: A comparison of energy efficient routing protocols in WSN

Network Type	Key Metrics	Main Focus	Optimization Technique	Protocol References	Criterion	Limitations	Advantages
Wireless Sensor Networks	Network Lifetime, Coverage, Connectivity	Coverage-Connectivity and Lifespan Maximization	Intelligent Water Drop Algorithm	[1]	Sharma & Lobiyal (2019)	May necessitate intricate calculations and parameter adjustment	increases coverage and connection while extending the life of the network
Sensor Networks	Network Lifetime	Lifespan Maximization	Dual Transmission Power and Ant Colony Optimization	[2]	Sharma & Lobiyal (2015)	Complicated by two different optimization strategies	effectively extends the life of a network with a hybrid optimization strategy
Wireless Sensor Networks for IoT	Energy Consumption, Collision Rate	Energy Efficiency and Collision Avoidance	Energy-aware and Collision-aware Techniques	[8]	Patel et al. (2021)	needs precise energy and collision simulations; implementation may be challenging	minimizes collisions and balances energy use, making it appropriate for intelligent Internet of Things applications.
Wireless Sensor Networks for IoT	Network Lifetime, Energy Consumption	Cluster-Head Selection based on Residual Energy	Residual Energy-based Selection	[9]	Behera et al. (2019)	The decision-making process depends on precise residual energy data and may cause delays.	Network lifespan and energy consumption are increased by effective cluster-head selection.
Multi-hop Clustered WSN	Energy Efficiency, Network Lifetime	Multi-hop Clustered WSN for 5G System	Simultaneous Wireless Information and Power Transfer (SWIPT)	[10]	Han et al. (2021)	presumes SWIPT capability, which not all WSNs have.	Appropriate for 5G systems, improves energy efficiency and network performance

IV. REGION-BASED CLUSTERING ROUTING PROTOCOLS FOR WSN

Region-based or zone-based routing protocols for Wireless Sensor Networks (WSNs) are designed to divide the sensor network into distinct regions or zones. Each region typically has a central node, known as a cluster head, that coordinates data collection and communication within the region.

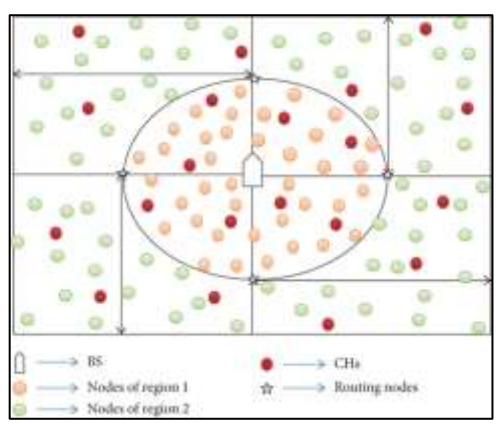

Figure 1: Region Based Routing in WSN[12]

This approach can significantly improve energy efficiency, scalability, and network management[11].

Table 2: A comparison of Region Based Clustered routing protocols in WSN

Protocol	Network Structure	Cluster Formation	Cluster Head Selection	Data	Main Focus	Advantages	Limitations
LEACH [13]	Hierarchical	Random	Random rotation	Yes	Energy Efficiency,	Decreases data transmission overhead - Balances energy load across the	- Cluster heads can become a bottleneck - Frequent re-clustering
HEED [14]	Hierarchical	Residual Energy & Proximity	Periodic based on residual energy	Yes	Energy Efficiency,	Improves network lifetime - Balances energy consumption	- Periodic selection overhead
TEEN [15]	Hierarchical	Threshold-based	Based on thresholds	Yes	Time-critical	- Lessens data transmissions - Suitable for event-driven applications	- May not suit continuous monitoring applications
APTEEN [16]	Hierarchical	Threshold-based + Periodic updates	Based on thresholds + Periodic	Yes	Combination of	- Flexible reporting - Combines periodic and event-driven mechanisms	- Higher complexity - Requires more sophisticated algorithms
PEGASIS [17]	Chain-based	Chain formation among nodes	Sequential nodes in a chain	Yes	Reducing	- Reduces number of transmissions - Balances energy consumption	- Chain formation complexity - Not suitable for dynamic networks
ZRP [18]	Hybrid Proactive & Reactive	Zones with intra/inter-zone routing	Proactive within zone, reactive outside	Yes	Scalability, Efficiency	- Efficient intra/inter-zone routing	- Complexity in zone management
CCL [19]	Hierarchical	Collaborative learning	Based on collaboration algorithms	Yes	Energy Efficiency, Data	- Collaborative data processing - Improved energy efficiency	- Complex algorithms - Higher computational requirements

Energy Efficiency	Scalability	Suitable Applications
High	Moderate	Automation in factories and monitoring of the environment
High	High	Automation in factories and monitoring of the environment
High	Moderate	Time-sensitive and Health-related Monitoring
High	Moderate	Automation in factories and monitoring of the environment
High	High	Environmental Monitoring, Industrial Automation
Moderate	High	Large-scale WSNs, Mobile Networks
High	High	Automation in factories and monitoring of the environment

V. GATEWAY-BASED ROUTING PROTOCOLS IN (WSNS)

Gateway-based routing protocols in Wireless Sensor Networks (WSNs) use a centralized or semi-centralized approach where data from sensor nodes is routed through designated gateway nodes before reaching the base station.

This approach can enhance network scalability, reduce energy consumption, and simplify network management. The gateway is mainly used in Region based protocol for efficient relay of data from all nodes to BS node.

The GNER ((Gateway-Node-based Efficient Routing)) uses gateway nodes to collect data from sensor nodes and then transmit it to the base station. This reduces the number of direct transmissions to the base station, saving energy.

The Virtual Grid Architecture (VGA) divides the sensor network into virtual grids, with each grid managed by a gateway node.

The gateway nodes handle intra-grid communication and relay data to the base station.

The Cluster-Tree Protocol
This protocol organizes sensor nodes into clusters with a hierarchical tree structure. Gateway nodes (usually cluster heads) manage data aggregation and transmission to the base station.

The Two-Tier Data Dissemination (TTDD)
TTDD uses a two-tier architecture where sensor nodes send data to nearby gateway nodes, which then relay it to the base station. It supports both continuous and event-driven data reporting.

The Gateway-Based Energy-Aware Multi-hop Routing (GEM)
It elects energy-aware multi-hop paths through gateway nodes to route data to the base station. It considers both energy efficiency and network reliability.

The Hierarchical Power-efficient Adaptive Clustering (HPAC) uses a hierarchical structure with gateway nodes acting as intermediate aggregation points. It focuses on reducing power consumption and balancing the load.

The Distributed Gateway Discovery (DGD) allows sensor nodes to dynamically discover gateway nodes for data transmission. It adapts to network topology changes and optimizes communication paths.

Table 3: A comparison of Gateway Based routing protocols in WSN

Protocol	Main Focus	Cluster Formation	Data Aggregation	Advantages	Limitations	Suitable Applications	Scalability	Energy Efficiency
GNER	Energy Efficiency, Scalability	Gateway nodes collection	Yes	Decreases energy consumption - Extends network lifetime	Gateway nodes can become bottlenecks - Requires proper management	Environmental Monitoring, Industrial Automation	High	High
VGA	Efficient Data Management	Virtual grids	Yes	Effectual intra-grid communication - Balances energy consumption	Accurate grid formation needed - Gateway node placement complexity	Environmental Monitoring, Smart Agriculture	High	High
Cluster-Tree Protocol	Load Balancing, Scalability	Clusters with hierarchical tree structure	Yes	Lessens redundant transmissions - Supports large-scale networks	-Tree preservation complexity - Not suitable for dynamic environments	Environmental Monitoring, Industrial Automation	High	High
TTD	Large-Scale Networks, Energy Efficiency	Two-tier architecture	Yes	Effective for extensive networks - Lowers energy usage	Gateway node placement and mobility - Challenging	Large-scale WSNs, Smart Cities	High	High
GEM	Energy Efficiency, Reliability	Multi-hop paths through gateway nodes	Yes	- Balances energy consumption - Extends network lifetime	Needs complex path selection algorithms	Environmental Monitoring, Smart Grid	High	High
HPAC	Power Efficiency, Adaptive Clustering	Hierarchical clustering	Yes	- Extends network lifetime - Reduces energy consumption	Hardness of dynamic adaptation: May call for complicated algorithms	Environmental Monitoring, Industrial Automation	High	High
DGD	Dynamic Discovery, Flexibility	Dynamic discovery of gateway nodes	Yes	- Enhances network flexibility - Supports dynamic environments	Overhead from the discovery process could cause communication delays.	Environmental Monitoring, Dynamic Networks	High	High

VI. CONCLUSION

Both region-based and gateway-based routing protocols significantly contribute to enhancing the energy efficiency and scalability of WSNs. Region-based protocols excel in localized data management and load balancing, making them suitable for applications requiring fine-grained control over network segments. Gateway-based protocols, on the other hand, offer streamlined data flow and centralized management, ideal for large-scale and high-density networks. Selecting the appropriate protocol depends on the specific requirements of the application, including network size, deployment environment, and criticality of energy conservation. Continued advancements in these protocols will further improve the performance and longevity of WSNs, supporting a wide range of applications from environmental monitoring to industrial automation.

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