A Review of Sink Relocation Strategies for Energy Efficiency, Load Balancing, and Lifetime Enhancement in Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) have become essential for modern monitoring and automation systems, but their performance is often limited by energy constraints, uneven communication load, and the formation of energy holes around static sinks. Sink relocation emerges as a powerful strategy to address these challenges by dynamically repositioning the sink to balance energy consumption, reduce communication distances, and enhance overall network stability. This study presents a comprehensive analysis of sink relocation strategies including random, controlled, and intelligent mobility models and evaluates their impact on key performance metrics such as energy efficiency, packet delivery ratio, throughput, and network lifetime. Optimization-based and AI-driven mobility approaches further strengthen network resilience by adapting to residual energy, node density, and traffic variations. The findings demonstrate that effective sink relocation significantly improves WSN performance, minimizes hotspot formation, and enables sustainable long-term operation in diverse real-world applications.

Keywords - *Wireless Sensor Networks, Sink Relocation, Energy Efficiency, Network Lifetime*.

1. Introduction

Load balancing in Wireless Sensor Networks (WSNs) is a crucial performance objective that focuses on distributing communication and computation workload evenly among all sensor nodes to prevent premature energy depletion of specific nodes. In typical WSN deployments with a static sink, nodes located close to the sink often handle a disproportionate amount of traffic because they must forward data from distant nodes as well as transmit their own sensed information. This creates “hotspot” regions where nodes exhaust their battery rapidly, leading to energy holes, network partitioning, reduced coverage, and a sharp decline in overall network lifetime [1-4]. Effective load balancing strategies aim to avoid such concentration of traffic by intelligently managing routing paths, clustering structures, and sink positions. Techniques such as hierarchical or cluster-based routing (e.g., LEACH-like protocols), multi-path routing, and dynamic role rotation ensure that forwarding tasks are shared among different nodes over time. Sink relocation or mobile sink strategies further enhance load balancing by periodically moving the sink to different regions of the sensing field, thereby shifting the relay burden to new sets of nodes and allowing previously stressed nodes to conserve energy. Optimization-based and AI-driven methods can also be employed to select routes and sink positions based on residual energy, node density, and traffic patterns. Through achieving better load balancing, WSNs maintain higher packet delivery ratio, improved throughput, more uniform energy consumption, and longer stable operation periods (time before the first and half of the nodes die). Thus, load balancing is fundamental for designing scalable, energy-efficient, and reliable WSN architectures capable of supporting long-term monitoring in diverse real-world applications [5-8].

1.1 Importance of Energy Efficiency in WSN Architecture

Energy efficiency is a central design concern in Wireless Sensor Networks because sensor nodes operate on limited battery power and are often deployed in locations where maintenance or battery replacement is impractical. Every operation—whether sensing, processing, or communication consumes energy, with wireless transmission being the most power-intensive. As a result, network protocols, routing decisions, and data handling techniques must be optimized to minimize unnecessary energy expenditure. Ensuring energy-efficient operation directly influences network durability, data reliability, and the feasibility of long-term monitoring applications. This makes energy management strategies such as clustering, duty-cycling, and sink relocation essential components of modern WSN design [9].

1.2 Challenges in Maintaining Reliable Network Performance

Maintaining reliable performance in a WSN is challenging due to environmental uncertainty, node failures, dynamic traffic load, and communication constraints such as interference and limited bandwidth. External factors like terrain, weather, obstacles, or mobility can further degrade link quality and lead to packet loss or increased delay. Additionally, uneven data generation or hotspot formation can overload certain nodes and reduce the effectiveness of multi-hop communication. As a result, WSN protocols must be robust, adaptive, and capable of maintaining connectivity under fluctuating conditions. Techniques like mobile sink strategies, fault-tolerant routing, and adaptive topology control help ensure consistent performance despite these inherent challenges [10-12].

2. Related Reviews

Ahmed and Quaisar (2025) were reported to have proposed a novel framework that integrated sink relocation, joint clustering, and compressed sensing (CS) to achieve energy-efficient data collection in Wireless Sensor Networks (WSNs). The suggested work lead to an uneven area in energy depleting and hence a network failure which required the repositioning of mobile sink and clustering based route optimization from the mobile sink. They characterize their system as using compressed sensing to eliminate redundancy in the transmissions, while ensuring data fidelity, and perform simulations based on mathematically modelled and real-world inspired scenarios to evaluate energy consumption, throughput, packet delivery ratio, and node survivability. The authors also claimed to have improved their framework with Transformer-based CS, trust-aware clustering, and Generalized TSP-based path planning, all of which contributed to better accuracy and performance. In conclusion, the results showed that dynamic sink relocation along with smart routing can significantly improve the energy consumption, latency, and packet delivery in a way that makes long-term WSN deployment in environmental monitoring; agricultural and disaster management possible.

Singh and Vir (2025) had examined wireless sensor networks (WSNs) as a key emerging IoT technology with widespread applications in healthcare, environmental biology, and facility monitoring, emphasizing how these systems depended on small, resource-constrained sensors for data collection, processing, and transmission. In their study they had pointed out that one of the key operational challenges in WSNs is how often the mobile sinks changes its route — because, even if the mobility of the sinks is a beneficial feature for gathering data, it incurs problems including heterogeneous energy consumption and service quality degradation of WSNs. They built upon the historical weaknesses of previous methods to argue that sink mobility aggravated issues with poor routing control and decreased network fidelity. In order to mitigate these issues, the authors proposed an improved Intelligent Routing Protocol based on Intelligent Monitoring for Mobile Sinks in Mobile WSNs. Simulation results had shown significant performance improvements (38% network throughput gains, 42% end-to-end latency reduction, improved energy efficiency, lower control overhead, all of which improved network lifetime) when compared with existing protocols.

Guo (2025) was reported to have examined Wireless Sensor Networks (WSNs) as essential IoT components used in environmental monitoring, healthcare, and facility management, emphasizing their constraint-driven architecture and the challenges posed by mobile sinks. They described these mobile sink, energy constrained WSNs and mentioned that the paper proposed, "an intelligent routing protocol designed for mobile-sink, energy-aware WSNs to optimize data routing, prolonging the network lifetime, and to minimizing the delay." The protocol was then described as using smart monitoring and adaptive clustering which provided the advantages of energy efficiency, reduced control overhead and better data delivery. It was highlighted that simulation results show a 42% decrease in end-to-end latency and a 38% increase in throughput relative to previous schemes, highlighting the great ability of the protocol in the implementation of smart monitoring and the sustainability of performance in an unequal network.

Lateef and Al-Qurabat (2024) had described how Wireless Sensor Networks (WSNs) were challenged by hot-spot or sink-hole problems arising from multi-hop routing to a static sink, and they noted that mobile sinks (MS) had been proposed to improve data collection efficiency. They showed that while MS-based approaches consistently outperformed static sink (SS) approaches, designing a near-optimal MS trajectory is NP-hard, making practical deployment infeasible. The survey had previously discussed available path-optimization methods and provided a framework for several data-collection approaches–SS vs. MS–highlighting their advantages and limitations. They also wrote about various MS-based data-collection models and practical implementation challenges observed in real-case-settings. Last, they suggested a level-based classification (static versus dynamic) of trajectory-design schemes to provide a clearer analytical basis among them.

Gupta and Singh (2022) had examined how wireless sensor networks were increasingly used for data collection and monitoring critical parameters, noting that energy efficiency and latency remained major challenges, especially with dynamic sink locations. They did a comparative study on some of the well-known routing schemes for centralized data collection in WSN, with the purpose to assess the routing performance with grid-based dynamic sink placement. In the work, first, they detailed about some of the shortcomings of the current WSN communication technologies and then provided a case study on how dynamic sink routing can benefit the energy limitation and increase the lifetime of the network. The authors compared the LEACH and its variants with various clustering-based algorithms like PEGASIS, SEP, DEC and many more and evaluated it based on network delay, throughput, latency, energy consumption and lifetime. They tested the protocol on the longest span of a network when subjected to a grid-based dynamic sink scenario, and they evaluated the EDEEC. To summarize, the article discussed WiSNs essential duties of design elements, and then focused out the importance of clustering-based and dynamic-sink methods to level up the life-cycle of the network.

Bagais et al. (2022) were reported to have examined the challenges of integrating Wireless Sensor Networks (WSNs) with the Internet of Things (IoT), particularly focusing on energy constraints and delays in transmitting urgent data. The authors noted that Mobile Sinks (MSs) had been widely explored to enhance network efficiency, but large-scale MS-based data collection still caused intolerable delays for sensitive, high-priority messages. To address this gap, they were said to have proposed an *energy-efficient path planning of MS-based area priority* (EEPP-BAP) model, which incorporated both urgent and non-urgent messages. Their framework involved dividing the monitoring field into priority-based zones, selecting cluster heads using Particle Swarm Optimization (PSO), directing the MS first toward high-priority and shorter-distance zones using Brain Storm Optimization, and establishing a PSO-based multi-hop routing strategy for urgent messages. Simulation findings were reported to demonstrate significant improvements, including a 206.6% increase in sensor-node lifetime, a 7.1% reduction in end-to-end delay, and a 36.9% rise in packet delivery ratio compared to existing models.

Rady et al. (2021) were reported to have examined the growing interest in mobile wireless sensor networks and proposed the Joint Nodes and Sink Mobility–based Immune Routing-Clustering Protocol (JNSMIC) to address mobility challenges of both sensor nodes and the mobile sink. The situation was addressed by Satyanarayana et al. (2012) where mobile sink was used both to mitigate the hotspot effect and a Multi-Objective Immune AlgorithMOIA) was utilized to cluster the network and discover optimal sink visiting locations. In addition, to decrease the complexity, the objective functions (energy consumption, network coverage, link connection time, residual energy, and mobility) are divided into two phases for CH clustering; first, JNSMIC selects candidate CHs based on the three parameters (energy, mobility, and LCT), then it utilizes multi-objective imperialist competitive algorithm (MOIA) to choose the final CHs with three objectives (minimize communication cost, enhance deliverability, and maximize stability of networks) [23]. He pointed out that, while residual energy was above a threshold, JNSMIC only set clustering to minimize overhead, and incorporated a deputy CH for fault tolerance and frame-based link-stability checks. The protocol was observed from simulation results to have improved throughput, lowered energy consumption, and shortened end-to-end delay.

Ashween et al. (2020) had examined the challenges introduced by using a mobile sink in Wireless Sensor Networks (WSNs), noting that although mobility offered advantages, it also created complications related to continuous sink-position updates. It is when the mobile sink has to broadcast its location throughout the network several (re-transmission) times, which consumes a lot of energy and raises collision rate (due to rebroadcasting). As a solution to this, the authors previously suggested only updating whether a position needs to be updated if the routing structures are different. The purpose of their work was to come up with a design of energy embedded routing protocol, which updates position of mobile sink optimally so as sensor nodes can store only the newly updated sink entry with implicit environment. When nodes determine each other sink position with embedded routing, they propagated its position information only to nodes within certain discs, meanwhile others could get the up-to-date information by querying its nearest disc [6]. The authors also explained that the identification of message receivers is performed with the aid of a fuzzy-based clustering method and its optimization is done through the Oppositional Grey Wolf Optimization (OGWO) algorithm. The study had compared existing routing approaches and had shown that the proposed protocol improves efficiency in terms of extended network lifetime and reduced delays.

Sui et al. (2019) were reported to have proposed a movement-control strategy for a robot-assisted mobile sink node in wireless sensor networks. They assumed that the mobile sink knows the coordinates, residual energy, and degree of each static sensor node. For every node, we calculated a weighted value is defined based on its transmission power, remaining energy, and connectivity degree. With the acquired information, the mobile sink was steered to move to the target weight centre (TWC) of nodes in its communication locality. In the study, the overall average power savings achieved using the TWC method with respect to the sink node position, were also compared with the average savings for the Markov chain–based robot-assisted weighted relocation algorithm (MRWR), which showed that for static nodes that remained connected to the sink both before and after relocation, the TWC strategy achieved over 30% total transmission-power savings.

Dahiya and Singh (2018) were reported to have examined the role of a mobile sink (MS) in wireless sensor networks (WSN) for improving network lifetime by dynamically altering its position. Their study indicated that key quality-of-service parameters in WSN—such as coverage, energy consumption, and overall network longevity—had been central concerns in previous research. They described how several methods had been attempted to restore coverage holes and minimize energy usage. In response to these limitations, the authors were said to have proposed a novel protocol, MSCOLER (MS-based Coverage Optimization and Link-stability Estimation Routing), designed for optimal coverage restoration and link-stability estimation. The approach reportedly used an optimization algorithm to detect coverage holes and reposition redundant nodes around them. Furthermore, link-quality-based routing was employed to select relay nodes by estimating link stability, thereby enhancing network lifespan and maintaining ideal transmission distances for energy efficiency. Their experimental results were presented as showing that MSCOLER effectively addressed coverage restoration challenges, lowered energy consumption, and improved overall network lifetime, as measured through metrics such as Average Residual Energy, Receiving Packet Ratio, Moving Energy Consumption, Network Lifetime, Percentage of Coverage, and Average Energy Consumption.

Irish et al. (2018) had examined the fundamental task of wireless sensor networks as the monitoring of large areas through data gathered by sensor nodes and forwarded to a sink node. They had noted that multi-hop data dissemination from cluster heads to the sink caused uneven energy consumption and reduced network lifetime, which led to the introduction of sink mobility. To optimize this mobility, they had proposed a random-movement–based data collection approach called Dynamic Sink Mobility for Data Collection (DSMDC), where sink migration relied on Detected Event Frequency (DEF). In this technique, the mobile sink first moved to the grid with the highest DEF and then proceeded clockwise, using SDMA to collect data in parallel while returning to its original location. The authors had classified and analyzed existing sink-mobility-based data collection methods and demonstrated through NS2 simulations that DSMDC outperformed DEF-A and DEF-D strategies, where sink movement depended on ascending or descending DEF values.

Zhao et al. (2017) were reported to have examined the challenge of optimizing sink deployment and sensor-to-sink routing in large-scale wireless sensor networks, where hundreds of energy-constrained nodes typically transmit data through single- or multi-hop paths. The study was described as modeling the deployment challenge as a mixed-integer optimization problem and proposing a novel layer-based diffusion particle swarm optimization method to address it. The authors were said to have integrated two sensor-to-sink binding algorithms as an inner-layer evaluation mechanism to compute fitness values for potential solutions. Unlike earlier approaches that restricted sink placement to predefined candidate locations, their method allowed sinks to be positioned freely within a geometric plane, resulting in improved performance. Numerical experiments were noted to have validated the approach, showing that it outperformed existing techniques and demonstrated strong scalability for deploying large-scale sensor networks.

Shweta and Sharma (2016) had examined how sensor nodes in a Wireless Sensor Network (WSN) typically forwarded sensed data to the sink through multi-hop communication, which caused nodes closer to the sink to consume higher battery power and thus reduce overall network lifetime. They had described sink relocation as an effective method for extending network longevity by preventing excessive energy depletion in specific node groups. Their proposed Lower Energy Aware Sink Relocation (LEASR) mechanism used residual battery energy information to adaptively adjust node transmission ranges and guide sink movement. The NP-LEASR scheme had focused on identifying when the sink should relocate and determining the optimal direction and distance for repositioning. Routing decisions were based on remaining node energy, supported by the LEASR algorithm. The sink relocation mechanism, as they reported, consisted of two stages: triggering relocation based on predefined conditions and selecting the sink’s new position. They also noted that integrating clustering into the EASR topology helped reduce transmission delays and prevented continuous overloading of nodes near the sink, thereby further enhancing network lifetime.

Kostin et al. (2016) had proposed and examined a routing scheme for wireless sensor networks that incorporated mobile sensors and multiple mobile sinks. Their method had relied on expanding ring search, anycast messaging, and a reactive routing mode in which sensors maintained route-state information. After a successful routing request, a sensor was said to join a routing tree rooted at a particular sink, while anycast was used only during initial path establishment and all sink replies were forwarded via unicast to reduce traffic and energy use. The authors had further assumed each node's receiving area to be divided into independent directional sectors with randomly changing link states. Using a detailed simulation model built on extended Petri nets, they had evaluated performance metrics such as response ratio, relative traffic, and energy consumption across varying time-to-live values and different combinations of sinks, sensor availability, and link availability. Their findings had indicated that the proposed scheme outperformed earlier models in which sensors maintained no routing state information.

Gu et al. (2015) had examined sink mobility as an important technique for enhancing wireless sensor network performance by reducing traffic loads on specific nodes. They noted that, although extensive research had been conducted over previous decades, systematic summarization and guidance were largely missing. Their survey was presented as an effort to address this gap by reviewing mobility-management schemes from an evolutionary perspective. The authors had categorized existing approaches into four types—uncontrollable mobility, path-restricted mobility, location-restricted mobility, and unrestricted mobility—and described representative solutions within each category. They had also outlined relationships among these solutions to clarify developmental patterns and provided detailed analyses. Through this synthesis, the study had highlighted potential extensions and identified several underexplored issues requiring further research.

Perumal and Dhandapani (2015) were reported to have examined the limitations of existing data-gathering and path-selection protocols in wireless sensor networks, noting that conventional approaches often resulted in collisions that increased packet drops and reduced overall efficiency. Their study was said to have proposed a relay-node-based secure routing protocol for multiple mobile sinks (RSRPMS) to address these issues by minimizing collisions, enhancing security, and reducing delay. The authors were described as having used a splitting-tree technique to identify rendezvous points within a tree-shaped topology and a Biased Random Walk model to determine subsequent sink positions. During event occurrences, the sink was indicated to gather data directly when within range, or otherwise rely on a selected relay node for packet forwarding. The protocol reportedly incorporated symmetric key cryptography for secure data transmission. Through simulations, RSRPMS was shown to have improved network lifetime when compared with the Intelligent Agent-Based Routing (IAR) protocol.

Wang et al. (2014) were reported to have examined recent advancements in micromanufacturing that enabled the creation of low-cost, low-power, multifunctional sensor nodes for wireless communication, thereby supporting applications such as environmental monitoring, intrusion detection, and battlefield surveillance. Their study was described as emphasizing that conserving limited sensor power to maximize wireless sensor network (WSN) lifetime remained a central design challenge, especially because nodes near the sink consumed energy more quickly due to multihop transmission. To address premature battery depletion around the sink, the authors were said to have proposed an energy-aware sink relocation (EASR) strategy for mobile sinks, which used residual energy information to adaptively adjust node transmission ranges and determine optimal sink movement. Theoretical and numerical analyses were reported to demonstrate that EASR significantly extended overall WSN lifetime.

3. Conclusion

Sink relocation has emerged as an effective solution for addressing the fundamental limitations of Wireless Sensor Networks, particularly the energy hole problem and uneven workload distribution near static sinks [13-16]. Through dynamically repositioning the sink, communication distances are reduced, relaying responsibilities are distributed more evenly, and energy consumption becomes more balanced across all nodes. The analysis of various strategies including random mobility, controlled trajectories, and intelligent optimization techniques demonstrates that mobile sinks significantly enhance network lifetime, packet delivery ratio, throughput, and overall reliability [17]. Intelligent strategies such as PSO, GA, and reinforcement learning [18] further optimize movement decisions by adapting to network conditions in real time. Although sink mobility introduces overhead and requires careful scheduling, its benefits in sustaining stable, long-term network performance are substantial. Overall, sink relocation represents a robust and scalable approach for improving efficiency and extending the operational lifespan of WSNs in diverse environmental, industrial, and smart applications.

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