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Review of Energy Management in Wireless Sensor Networks for Disaster Applications

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A B S T R A C T

Wireless Sensor Networks (WSNs) provides a dynamic technology for real time tracing of disasters like floods, earthquakes, wildfires, and industrial mishaps. WSN able to function independently in challenging and isolated environment and makes them perfect for collecting data in real time which are essential for emergency decision-making. Energy resources are very limited in WSN and that is one of the most crucial issues during the deployment of WSNs for disaster applications. predominantly when there is no practical or less way to replace or recharge batteries. A comprehensive review of energy management strategies in WSNs for disaster application is discussed in this paper. Various energy-efficient routing protocols, adaptive sleep scheduling mechanisms, energy harvesting technologies, and data aggregation methods for efficient energy management techniques were discussed in this paper.

Keywords: Wireless Sensor Networks, Energy Management, Disaster Monitoring, Energy Harvesting, Sleep Scheduling, Routing Protocols

1. Introduction

In the recent years natural and man-made disasters like earth quakes, landslide, flood, wildfires and accidents are often. This emphasizes the critical need for real-time monitoring and predicting systems. WSNs are capable of sense, process, and send environmental information autonomously about risky or hard-to-reach areas, they have emerged as a possible solution for such scenarios.

WSNs are made up of numerous low-power sensor nodes that work together to monitor several physical parameters, including motion, temperature, humidity, gas levels, and vibrations in structures. WSNs are essential for delivering early alerts, assisting with search and rescue efforts, and evaluating environmental damage during disaster occurrences. They can, for example, detect ground motion during earthquakes, identify harmful gas leaks in industrial zones, or detect rising water levels in flood-prone locations. These capabilities play a major role in reducing casualties and speeding up response activities.

WSNs have many operational issues, the most significant of which being energy management, despite their benefits. Usually powered by batteries, sensor nodes are hard or impossible to recharge or replace once deployed, particularly in remote or dangerous disaster areas. Energy resources are also heavily strained by the requirement for continuous data transmission in emergency scenarios. The lifespan of a network is shortened by energy inefficiency, which can also lead to data loss, decreased coverage, and compromised system reliability at critical times.

The energy management techniques for WSNs are thoroughly reviewed in this research, with an emphasis on disaster applications. In order to determine how effective present strategies—such as data aggregation techniques, adaptive sleep scheduling, energy harvesting techniques, and energy-efficient routing protocols—are under the particular limitations presented by catastrophe settings, it is necessary to synthesize and analyses them. The evaluation also points out important gaps in the literature and provides ideas for future lines of inquiry that can strengthen WSN sustainability and resilience in emergency scenarios.

2. Background on WSNs in Disaster Scenarios

Spatially distributed sensor nodes that cable to monitor physical or environmental variables and send the data they collect to a base station or central node. The components of a typical WSN node are a communication module, a processing unit, a sensing unit, and a power source, usually a battery. Applications like post-disaster conditions, where human participation is hazardous or challenging, have shown particular benefit from these networks.

WSNs provide crucial functionalities such as real-time environmental sensing, event detection, and situational awareness in disaster scenarios. For example, during an earthquake, a WSN can be used to monitor ground vibrations or structural health, while in flood-prone areas, it can measure water levels to issue early warnings. Similarly, in wildfire detection, WSNs deployed across forests can monitor temperature, humidity, and smoke levels, triggering alarms if thresholds are exceeded.

The key requirements of WSNs in disaster applications include, Energy Efficiency, Reliability, Low Latency, Scalability and Coverage areas and Self-Organization. These requirements create significant challenges, mainly in energy management, as sensor nodes must operate under constrained energy budgets while maintaining high levels of availability and responsiveness. To address these challenges, researchers have proposed various strategies including energy-efficient routing, duty cycling, data aggregation, and energy harvesting. The following section surveys these techniques in detail.

3. Energy Management Techniques in WSNs for Disaster Applications

WSN operations depend significantly on effective energy management, especially in disaster situations where battery replacement or recharging is frequently impossible. Several techniques have been developed to optimise energy consumption in WSNs, each focussing on different aspects of the network, including energy sourcing, routing, node activity, and data transmission. This section provides a categorised overview of important energy management strategies used in WSN deployments that are susceptible to disasters.

3.1. Energy-Efficient Routing Protocols

Routing protocols in WSNs play an essential role in determining the paths for data transmission from sensor nodes to the base station. Hierarchical Protocols organize nodes into clusters, where a designated cluster head (CH) aggregates and forwards data to the sink. By rotating CH roles among nodes (e.g., LEACH), energy usage is balanced and prolonged [1]. Location-Based Routing use geographic information to route data, minimizing transmission distances and thus conserving energy [2]. QoS-Aware and Reliable Routing, in event-driven networks (e.g., wildfire detection), threshold-based protocols reduce unnecessary data transmission by reporting only significant changes, conserving energy during stable conditions [3].

3.2. Sleep Scheduling Mechanisms

To minimize idle listening and reduce energy drain, sleep scheduling techniques periodically switch nodes between active and low-power states. In duty cycling, nodes alternate between sleep and active states based on a fixed or adaptive schedule, dramatically reducing energy consumed in idle listening. Adaptive Scheduling is the advanced algorithms dynamically adjust sleep intervals based on node workload, residual energy, and data importance—enhancing both responsiveness and efficiency [4]. S-MAC and T-MAC Protocols are medium access control protocols include sleep modes and are designed specifically for energy-constrained WSNs.

3.3. Energy Harvesting Technologies

Energy harvesting is used to draw power from ambient sources to improve network lifetime beyond battery capacity. Solar and RF Harvesting are the most commonly explored sources, suitable for outdoor deployments such as landslide-prone hillsides or flood zones [5]. Thermal and Vibrational Harvesting are less common but useful in environments with changeable temperatures or mechanical motion, such as post-earthquake building interiors [6]. Hybrid Harvesting Systems combine multiple energy sources for more consistent power availability in uncertain disaster environments.

3.4. Clustering and Data Aggregation

Clustering and data aggregation techniques reduce the amount of redundant data transmitted, thereby lowering energy usage. Data aggregation at Cluster heads, it combines multiple readings before forwarding to the base station, reducing the number of transmissions. Compression algorithms, simple compression at the sensor node or cluster level can further reduce the energy cost of transmission [7]. Energy-Aware Cluster Formation, Protocols like HEED use residual energy and communication cost metrics to form balanced clusters.

Table 1 – Review Energy Management in WSNs for Disaster Applications.

Ref.	Technique Reviewed	Disaster Context	Energy Strategy	Key Features / Contribution
[1]	LEACH Protocol	General disaster	Cluster-based routing	Reduces transmission energy using CHs
[2]	TEEN Protocol	Wildfire monitoring	Threshold-based routing	Minimizes data transmission using events
[3]	Energy Harvesting WSN	Post-flood monitoring	Solar/RF harvesting	Extends network lifetime using renewables
[4]	Sleep Scheduling (Fuzzy Logic)	Earthquake aftermath	Duty cycling	Dynamic sleep mode based on context
[5]	Drone-assisted Data Collection	Landslide zones	Mobile sink nodes	Reduces node energy use, improves coverage
[6]	Fog Computing with WSN	Urban disaster zones	Edge processing	Offloads task, saves node energy

Each of these techniques contributes uniquely to reducing energy consumption in WSNs under disaster conditions. Routing protocols determine efficient paths, sleep scheduling reduces idle energy loss, harvesting technologies supplement energy sources, and clustering limits transmission overhead. The next section presents a comparative analysis of these methods to guide optimal strategy selection based on specific application needs and deployment conditions.

4. Comparative Analysis of Reviewed Techniques

Disaster environments demand WSN deployments that are not only energy-efficient but also resilient, scalable, and responsive under unpredictable conditions. While several energy management techniques have been proposed, their effectiveness varies depending on network architecture, environmental conditions, and the urgency of sensed data. This section presents a comparative analysis of the primary strategies discussed in Section 3, focusing on key evaluation metrics such as energy efficiency, latency, scalability, fault tolerance, and suitability for disaster scenarios.

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Table 2 – Comparative Table of Energy Management Techniques

Technique Category	Example Protocols/Methods	Energy Efficiency	Latency	Scalability	Fault Tolerance	Disaster Suitability
Clustering-Based Routing	LEACH, HEED	High	Low	Medium	Medium	High
Location-Based Routing	GEAR, GPSR	Medium	Medium	High	Low	Medium
Threshold/Event-Based Routing	TEEN, APTEEN	High	Very Low	Low	Low	High (for real-time alerts)
Sleep Scheduling	S-MAC, T-MAC, Adaptive Fuzzy	Very High	Variable	High	Medium	High
Energy Harvesting	Solar, RF, Hybrid Systems	Potentially Very High	Medium	High	High	High (long-term missions)
Data Aggregation	In-network aggregation	High	Low	Medium	Low	Medium
Mobile Sink / UAV-based	ACO with Sink Mobility	High	Medium	Medium	High	High (urban/wide areas)

Because of their ease of use and energy-saving benefits, clustering-based techniques like LEACH and HEED are frequently employed in disaster applications. However, unless fault tolerance mechanisms are improved, their performance deteriorates in extremely dynamic environments. The biggest energy savings come from sleep scheduling, particularly when paired with adaptive logic. But if not adjusted appropriately, latency can be a problem, making real-time disaster alerts difficult. Energy harvesting has a lot of promise for sustainability in the long run. Reliability, however, is dependent on environmental factors (such as the availability of sunlight), which can change suddenly during emergencies. Data aggregation efficiently saves energy and cuts down on redundant transmissions. It is less efficient in sparse or highly mobile networks, though, and may cause delays. UAV/Mobile Sink Support ACO-based and mobile sink solutions enhance fault tolerance and reduce energy hotspots.

To deploy truly resilient, energy-efficient WSNs in disaster environments, future research must go beyond traditional trade-offs and address multidisciplinary challenges—including hardware reliability, situational adaptability, security, and real-world validation. Bridging these gaps will be essential for building next-generation systems that can function autonomously and reliably in high-risk, resource-constrained settings.

5. Conclusion

The evolving landscape of disaster management demands that WSNs become more intelligent, adaptive, and resilient—without compromising energy efficiency. Building on the challenges identified in Section 5, this section outlines key areas where future research can significantly enhance WSN performance and sustainability in disaster scenarios.

Future WSN protocols should be capable of dynamically adapting to environmental and network conditions. Research should explore hybrid energy harvesting systems that draw from multiple sources (e.g., solar, thermal, RF, kinetic) and intelligently switch based on availability. Swarm intelligence techniques (e.g., Ant Colony Optimization, Particle Swarm Optimization) and deep reinforcement learning (DRL) offer significant potential for developing self-optimizing routing protocols. These approaches can help WSNs autonomously discover energy-efficient paths while reacting to node failures, congestion, or topology changes in real time. The next generation of WSNs for disaster response will be shaped by intelligent, adaptive systems that combine energy efficiency with robustness, security, and scalability. Addressing these future research directions will not only close existing gaps but also pave the way for truly autonomous, self-sustaining networks capable of operating in the harshest disaster environments.

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