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Toward Sustainable Wireless Sensor Networks: An Integrated Approach to Energy Conservation and Protocol Design

Mr. Sunil Kumar Yadav[1], Dr. Ruchi Sharma [2], Dr. Kiran Mayee Adavala[3]

Research

Scholar[1], Department of CSE, Madhyanchal Professional University Bhopal (M.P.)
Associate Professor[2], Department of CSE, Madhyanchal Professional University, Bhopal (MP)
Associate Professor[3], Department of CSE, Kakatiya Institute of Technology, Warangal

Abstract

Wireless Sensor Networks (WSNs) have become pivotal in enabling real-time monitoring and data acquisition in remote and inaccessible environments. However, the limited energy resources of sensor nodes, typically powered by non-rechargeable batteries, pose a significant constraint on network longevity. This paper investigates the critical factors affecting the lifespan and sustainability of WSNs, including communication overhead, node failures, environmental impacts, and energy dissipation. The study examines how advanced communication protocols—such as LEACH, PEGASIS, and TEEN—contribute to energy efficiency through mechanisms like clustering, dynamic topology control, and adaptive duty cycling. Furthermore, the integration of data aggregation, compressive sensing, and energy harvesting techniques is explored to optimize network performance. The paper also highlights the importance of secure data transmission, adaptive MAC protocols, and AI-driven topology optimization in mitigating energy-related challenges. By synthesizing these strategies, this research provides a comprehensive framework for enhancing the energy efficiency and practical deployment of WSNs in real-world scenarios.

Keywords: WSN, Energy Efficiency, Network Lifetime, Sensor node, Remote Monitoring

1. Introduction

Networks are widely valued for their ability to provide real-time monitoring and data acquisition in remote and inaccessible environments. However, one of the most significant challenges in WSN deployment is energy conservation, as sensor nodes are typically powered by non-rechargeable batteries with limited lifespans.

A Wireless Sensor Network (WSNs) typically has thousands or even millions of sensor nodes. The sensor nodes can use radio transmissions to exchange information with one another. Within a wireless sensor network (WSN), the individual nodes have restricted processing speed, storage capacity, and communication bandwidth due to intrinsic resource constraints. These networks are highly appreciated for their ability to provide real-time monitoring and data acquisition in remote and inaccessible environments. One of the foremost challenges in the deployment of WSN is power saving, where sensor nodes tend to be non-rechargeable with limited lives. The concern of this paper is the topmost factors to be considered that affect the lifespan of WSN. This research focuses on the major factors influencing WSN lifetime. Researchers and engineers can improve the sustainability of WSNs and make it possible for them to be used practically in real-world situations by combining cutting-edge communication protocols, Researchers can optimize the sustainability of WSN so that it will be practically deployed in real-case scenarios by employing advanced communication protocols.

1.1 Features of WSNs

1.1.1 Infrastructure-less: WSNs need no existing infrastructure for communication and can be easily deployed in a variety of environments.
1.1.2 Dynamic Topology: The topology of the network can be altered as nodes leave or enter the network, which is necessary for real-world applications to be flexible.

1.1.3 Low Power Consumption: WSNs are so constituted that they consume low levels of energy, and this is essential in extending the lifespan of sensor nodes.

2. Key Factors Affecting Lifetime of WSN

2.1 Impact of Communication Overhead on Power Usage

2.1.1 Increased Energy Consumption: Communication overhead, such as control messages and wake-up signals, consumes more energy than computation tasks in WSNs. This is because transmitting and receiving data requires significant power, especially when additional control overheads are introduced by security mechanisms or routing protocols [6].
2.1.2 Node Velocity and Overhead: As node velocity increases, communication overhead also rises, leading to higher energy consumption. This is due to the increased need for data transmission and reception as nodes move, which requires more frequent updates and control messages [7].

2.1.3 Routing Protocols: Different routing protocols have varying impacts on energy consumption due to communication overhead. For instance, proactive protocols like DSDV require constant updates, consuming more power, while reactive protocols like AODV are more energy-efficient but may still incur overhead during route discovery [8].

2.1.4 Wake-Up Overhead: In on-demand WSNs, wake-up messages are necessary to activate nodes, but they add to the communication overhead, increasing energy consumption. Techniques like double modulation can help mitigate this by embedding data within wake-up messages, reducing the need for separate transmissions [8].

2.1.5 Transmission Power Control: Adjusting transmission power dynamically can reduce energy consumption by minimizing unnecessary communication overhead. This approach can lead to significant energy savings while maintaining network reliability [9].

2.2 Impact of Energy Consumption in WSNs

2.2.1 Limited Energy Resources: Sensor nodes in WSNs are often powered by non-replaceable batteries, which limits their operational lifespan. Energy consumption is primarily due to sensing, processing, and communication activities, with communication being the most energy-intensive [10].

2.2.2 Energy Dissipation: The energy dissipation during network communications is a significant challenge. Strategies such as clustering and efficient routing protocols are employed to minimize this dissipation.

2.3 Environmental Impact on WSN Topology

Environmental factors such as terrain, weather conditions, and physical obstructions significantly affect WSN topology. Complex terrains require advanced methods for topology optimization, as traditional fixed communication radius assumptions are inadequate. A Bayesian approach using LIDAR-derived terrain characteristics can predict good network links, optimizing node placement and connectivity in complex environments1. Additionally, environmental changes like temperature and rainfall can cause temporary connection impairments, necessitating adaptive topology control to maintain network functionality [12].

2.4 Node failures and their effect on network sustainability

Random node failures refer to the unexpected loss of nodes (or devices) in a network due to various reasons such as hardware malfunctions, power outages, or environmental factors. In wireless networks, these failures can disrupt communication and affect overall network performance [13].

2.4.1 Impact on Connectivity: When nodes fail randomly, it can lead to fragmentation of the network. This means that some parts of the network may become isolated, making it impossible for certain nodes to communicate with others. The paper emphasizes that understanding how these failures affect connectivity is crucial for maintaining network reliability.

2.4.2 Node Failure Probability: Each node in a network has a certain probability of failing, which is often assumed to be the same for all nodes. This probability is a key factor in analyzing the network's resilience. The paper discusses how the probability of node failures can be modeled and analyzed to predict the network's behavior under such conditions.

2.4.3 Geometric Distribution and Density: The likelihood of random node failures and their impact on connectivity is influenced by the geometric distribution of the nodes and their density in the network. The paper highlights that these factors play a significant role in determining how many nodes can fail before the network loses its ability to function properly.

2.4.4 Practical Implications: Understanding random node failures is essential for designing robust wireless networks. By knowing how many nodes can fail and still keep the network operational, engineers can create systems that are more reliable and efficient, ensuring better performance even in adverse conditions.

2.4.5 Hardware Malfunctions: Physical components of the nodes may fail due to wear and tear, manufacturing defects, or unexpected operational stresses. Such hardware issues can result in complete or partial node failures.

2.4.6 Network Congestion: High traffic loads can overwhelm nodes, leading to performance degradation or failure. When nodes are unable to handle the volume of data being transmitted, they may become unresponsive or crash.

2.4.7 Power Supply Issues: Nodes rely on power sources, and any disruption in power supply—whether due to battery failure or external power issues can lead to node outages.

2.4.8 Software Bugs: The software that operates the nodes may contain bugs or vulnerabilities that can cause crashes or malfunctions. Regular updates and maintenance are necessary to mitigate this risk.

2.4.9 Interference from Other Systems: In an aviation context, nodes may experience interference from other communication systems or devices, which can disrupt their functionality and lead to failures.

2.4.10 Physical Damage: Nodes can be physically damaged due to accidents, collisions, or other unforeseen events. Such damage can render a node inoperable.

3. Energy-Efficient Communication Protocols

There is various routing protocols were utilized in wireless sensor networks (WSNs) to enhance energy efficiency and prolong network lifetime.

3. LEACH (Low-Energy Adaptive Clustering Hierarchy)

This protocol is a widely utilized routing protocol in wireless sensor networks (WSNs) designed to enhance energy efficiency and prolong network lifetime. By employing a cluster-based approach, LEACH reduces energy consumption through randomized cluster head selection and data aggregation. In the cluster head selection process involves each node randomly determining its probability of becoming a cluster head based on a threshold value. This threshold is calculated considering the desired percentage of cluster heads, the current round number, and the history of which nodes have been cluster heads previously. If a node's randomly generated number is less than the threshold, it becomes a cluster head for that round.

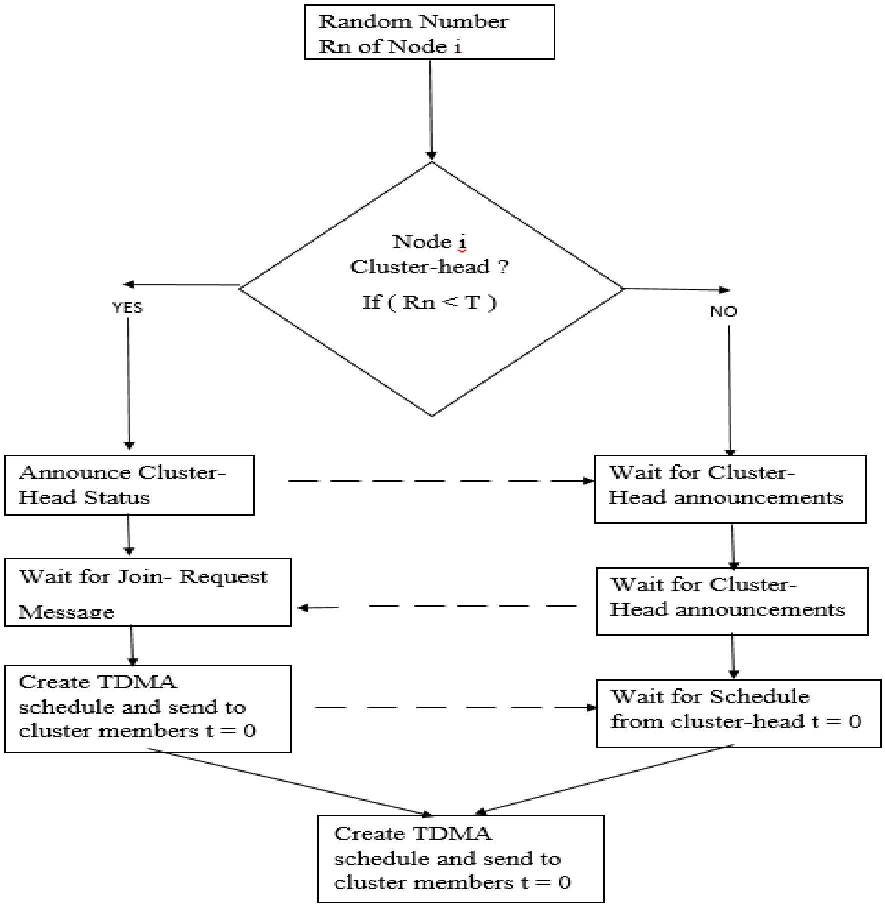

Figure 1 Cluster Head Selection process in LEACH protocol

Table 1: Algorithm

Cluster Head Selection in LEACH
Step-1 Threshold Calculation: The threshold is a crucial component of LEACH's cluster head selection. It's calculated using the following formula: threshold = p * (1 - (r mod (1/p))) ……………… (1) Where p: The desired percentage of nodes to be cluster heads (e.g., 5%). r: The current round number. 1/p: The number of rounds a node can be a cluster head before being excluded from the selection.
Step-2. Random Number Generation: Each node generates a random number between 0 and 1.
Step-3. Comparison and Selection: If the random number is less than the threshold, the node becomes a cluster head for the current round.
Step-4. Advertisement:

Once a node is selected as a cluster head, it broadcasts an advertisement message to its neighbors, informing them of its role.
Step-5. Node Joining: Other nodes (non-cluster head nodes) listen for these advertisement messages and join the cluster that offers the strongest signal.

3.1 Key Features of LEACH

3.1.1 Cluster Formation: Nodes are randomly assigned to clusters, with each cluster having a designated cluster head (CH) that manages communication within the cluster.

3.1.2 Energy Efficiency: The protocol minimizes energy usage by reducing the number of transmissions and hops required for data communication.

3.1.3 Dynamic Adaptation: LEACH allows for the rotation of CHs to balance energy consumption across nodes, enhancing overall network longevity.

3.2 Benefits of LEACH

3.2.1 Extended Network Lifetime: By optimizing energy distribution and reducing communication overhead, LEACH significantly prolongs the operational life of WSNs.

3.2.2 Application Versatility: LEACH has been effectively applied in various domains, including smart agriculture, where it addresses energy management challenges in sensor networks.

3.3 Optimizations and Variants

3.3.1 Enhanced CH Selection: Variants like E-LEACH and RCH-LEACH improve CH selection based on remaining energy, leading to better performance metrics such as coverage and node longevity.

3.3.2 AI Integration: Incorporating artificial intelligence can further optimize CH selection and data routing, enhancing energy efficiency and sustainability in WSNs. While LEACH offers significant advantages in energy management and network longevity, it is essential to consider its limitations, such as the potential for uneven CH distribution, which can lead to network performance issues. Further research into hybrid approaches and optimizations may provide solutions to these challenges.

3.4 PEGASIS (Power-Efficient Gathering in Sensor Information System)
This protocol is a chain-based routing protocol designed for wireless sensor networks (WSNs) that aims to enhance energy efficiency and prolong network lifetime. It operates by forming a logical chain among sensor nodes, where each node forwards data to its nearest neighbors, ultimately reaching the base station. This method reduces energy consumption compared to traditional cluster-based protocols like LEACH. The following sections elaborate on key aspects of PEGASIS and its improvements [16].

3.4.1 Energy Efficiency

PEGASIS minimizes energy consumption by allowing nodes to communicate with their nearest neighbors, reducing the distance data must travel. The protocol's design helps balance energy usage across nodes, preventing premature node failure due to energy depletion.

3.4.2 Cross-Layer Approaches

The CL-PEGASIS protocol introduces a cross-layer scheduling mechanism that enhances load balancing and reduces idle listening, leading to improved energy efficiency and network stability.

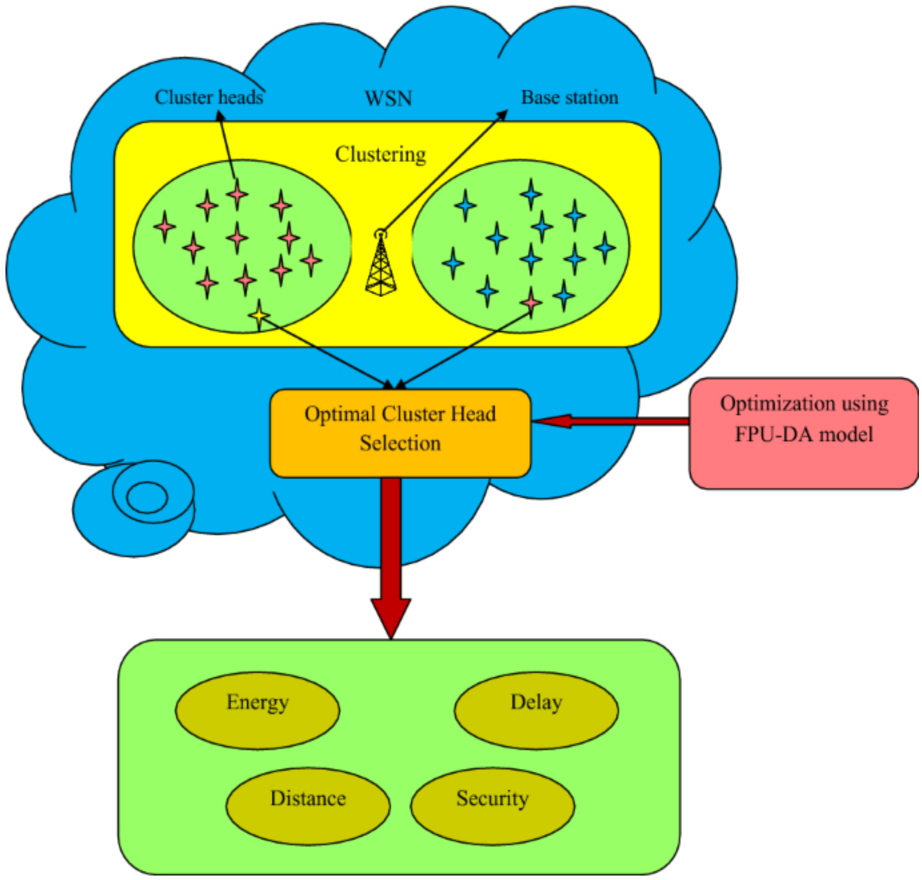

Figure 2: Cluster Head Selection in PEGASIS Protocol

3.5 TEEN (Threshold-sensitive Energy Efficient sensor Network)

It is a hierarchical routing protocol used in wireless sensor networks. It aims to improve energy efficiency by clustering nodes and having cluster heads (CHs) collect data from their members.

3.5.1 Key Features of TEEN

TEEN forms clusters of sensor nodes, with each cluster managed by a CH. The CH collects data from its member nodes and then aggregates it, potentially forwarding it to a higher-level CH or the base station (BS). By reducing the amount of direct communication between nodes and concentrating data aggregation at CHs, TEEN aims to conserve energy. TEEN is particularly well-suited for reactive sensor networks, where data collection is triggered by changes in the sensed parameters. The "Threshold-sensitive" aspect refers to the fact that TEEN can use thresholds to determine when data should be collected, further optimizing energy consumption. TEEN builds upon the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol by improving cluster head selection and data aggregation.

3.5.2 Benefits of TEEN

3.5.3 Reduced Energy Consumption

TEEN's hierarchical structure and data aggregation at CHs lead to lower energy dissipation compared to protocols without clustering.

3.5.4 Extended Network Lifetime

By conserving energy, TEEN helps extend the overall operational lifespan of the wireless sensor network.

3.5.5 Scalability & Adaptability

TEEN's hierarchical structure can make it more scalable for large sensor networks. TEEN's reactive nature allows it to adapt to changing environmental conditions and data patterns. In TEEN (Threshold-based Energy Efficient Network) protocol, cluster head (CH) selection is typically a random process. Nodes in the network compete to become a CH, and the one with the highest probability of success, often based on a random number, becomes the CH. The TEEN protocol also incorporates mechanisms to reduce energy consumption, like using thresholds (HT and ST) to control the frequency of data transmission.

3.6 Implementation of TEEN

Similar to LEACH, TEEN uses a random probability-based approach for CH selection. Each node determines its probability of becoming a CH, and the node with the highest probability wins.

3.6.1 Energy Efficiency

TEEN prioritizes reducing energy consumption by implementing thresholds (HT and ST). Nodes only transmit data to the CH if the sensed value is within a specific range of interest (HT) and if the current value differs from the previously sensed value by more than the threshold ST [17].

3.6.2 Cluster Formation

Once a CH is selected, it broadcasts a signal to attract cluster members. Nodes within a certain distance of the CH join the cluster.

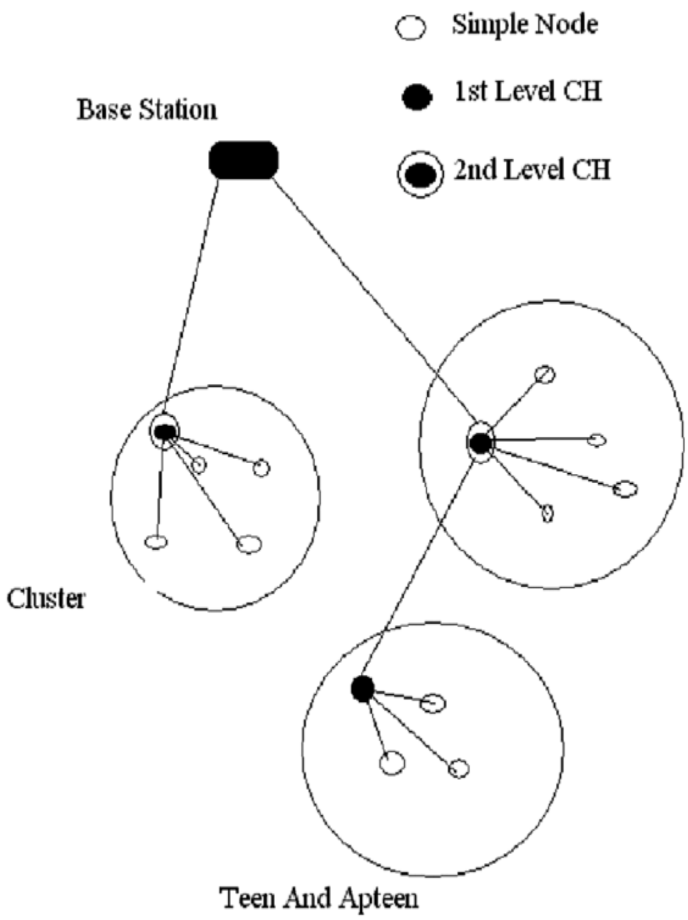

Figure 3: Cluster Head Selection in TEEN protocol

3.6.3 Data Transmission

CHs collect data from their cluster members, aggregate the data, and then transmit the aggregated data to the base station.

3.6.4 Node Rotation

TEEN aims to distribute the load of CH duties evenly, meaning different nodes take turns being the CH to avoid any one node draining its energy too quickly.

1. **Strategies for Energy-Efficient WSNs**
   Data aggregation and compression techniques in wireless sensor networks (WSNs) are crucial for enhancing energy efficiency and network longevity. These methods aim to minimize data transmission overhead while ensuring data integrity. Various approaches, including clustering, compressive sensing, and advanced compression algorithms, have been explored to optimize performance in resource-constrained environments.

4.1 Data Aggregation Techniques

4.1.1 K- Clustering

K-means clustering optimizes the selection of cluster heads, reducing the number of transmissions required from sensor nodes to the sink, thus conserving energy.

4.1.2 Compressive Sensing (CS)

This method allows for efficient data collection by sampling fewer data points while still reconstructing the original data accurately, significantly improving energy efficiency.

4.2 Data Compression Methods

4.2.1 Lempel-Ziv-Welch (LZW) This algorithm compresses aggregated data, reducing the amount of data transmitted and minimizing energy consumption.

4.2.2 Lossless Compression: Approaches that ensure data integrity while reducing redundancy in the aggregated data stream, leading to lower bandwidth usage and enhanced network lifetime.

4.3 Security Considerations

Integrating security measures with data aggregation can protect against adversarial attacks, although it may introduce additional complexity and energy costs. While these techniques significantly enhance WSN performance, challenges remain, particularly in hostile environments where security and energy efficiency must be balanced. The integration of advanced security protocols may complicate the aggregation process, potentially impacting overall network efficiency. Adaptive duty cycling and sleep scheduling are critical strategies in optimizing energy efficiency and prolonging the lifespan of Wireless Sensor Networks (WSNs). These techniques enable sensor nodes, which typically operate on limited battery power, to minimize energy consumption while maintaining network connectivity. The following sections outline key aspects of adaptive duty cycling and sleep scheduling in WSNs.

4.4 Energy Efficiency through Sleep Scheduling

Sleep scheduling algorithms allow nodes to enter low-power sleep modes, significantly reducing energy usage during idle periods. The self-adaptive sleep/wake-up scheduling approach enables nodes to autonomously determine their operational modes, enhancing energy conservation without compromising packet delivery efficiency.

4.5 Adaptive Duty Cycling Mechanisms

Adaptive duty cycling optimizes the active/sleep schedules of nodes, balancing energy consumption and network reliability. This is achieved through dynamic adjustments based on traffic load and node utilization. The AEH-MAC algorithm exemplifies this by allowing nodes to coordinate wake-up times and dynamically adjust sleep durations, thus minimizing idle listening and maximizing energy savings.

4.6 Performance and Reliability

Implementing adaptive duty cycling and sleep scheduling has shown to improve network performance metrics, such as throughput and energy consumption, while extending the overall network lifetime.

Simulation results indicate that these adaptive mechanisms can significantly enhance the efficiency of WSNs under various operational conditions. While adaptive duty cycling and sleep scheduling present numerous advantages in energy management, they may introduce complexities in synchronization and coordination among nodes, potentially affecting real-time data transmission. Balancing these trade-offs remains a challenge in the design of efficient WSN protocols.

4.7 Energy Harvesting Techniques

Energy harvesting techniques in Wireless Sensor Networks (WSNs) are crucial for enhancing the operational efficiency and sustainability of sensor nodes by converting ambient energy into electrical power. These techniques are particularly significant in extending the lifespan of WSNs, which are often deployed in remote or inaccessible locations. The integration of energy harvesting with IoT and deep learning further optimizes energy management by predicting energy availability and adjusting operational parameters accordingly. Below are the key aspects of energy harvesting techniques in WSNs. Following are the harvesting approaches: (i) Solar energy harvesting (ii) Vibration and RF energy harvesting (iii) Hybrid energy harvesting approaches.

4.8 Optimization of Network Topology

4.8.1 Clustering Techniques

Clustering techniques are crucial for enhancing Wireless Sensor Network (WSN) performance by optimizing energy consumption, extending network lifespan, and improving data transmission efficiency. These techniques involve organizing sensor nodes into clusters, with each cluster having a designated Cluster Head (CH) responsible for data aggregation and communication with the base station. Various clustering algorithms and optimization strategies exist, each with its own strengths and weaknesses. Examples: LEACH, HEED, TEEN, DEEC etc. Benefits Reduces data transmission distances and saves energy.

4.8.2 Node Deployment Optimization

In order to optimize application performance, lower latency, and increase overall efficiency, node deployment optimization focuses on carefully placing and configuring nodes (servers, instances, etc.). This calls for approaches like caching, load balancing, asynchronous processes, and effective resource use. Optimal placement of nodes for maximum coverage and connectivity. Techniques: Grid-based, Random, Gaussian, or Optimization Algorithms (e.g., Genetic Algorithm, Particle Swarm Optimization).

4.8.3 Topology Control Algorithms

Algorithms for topology control serve as crucial for network structure optimization, especially in wireless networks, to improve reliability, speed, and energy efficiency. In order to improve network performance, these algorithms try to modify the physical connection of the network by regulating data rates, radio frequencies, or transmission power. Reducing interference, increasing network longevity, and enhancing wireless channel spatial reuse are important objectives.

4.8.4 Mobile Sink/Node Optimization

The goal of mobile sink/node optimization in Wireless Sensor Networks (WSNs) is to enhance network performance by carefully relocating a sink node to gather data from sensor nodes. This entails minimizing data gathering delays, balancing energy usage, and optimizing the sink's moving path. Clustering, path planning, and using algorithms inspired by nature are important tactics.

4.8.5 Machine Learning and AI Techniques

Techniques for artificial intelligence (AI) and machine learning (ML) have a lot of promises for effective deployments. boosting Wireless Sensor Network (WSN) performance. Such techniques can be used to improve the security, data management, energy efficiency, and network optimization of WSNs, leading to more reliable and efficient deployments. ML algorithms can forecast how much energy will be harvested in a given period of time, improving resource allocation and energy management. By analyzing network conditions and usage patterns, ML can optimize energy consumption for sensor nodes, extending the network's lifespan. By continually updating clustering and routing protocols in response to current network conditions, machine learning algorithms can reduce energy consumption during data transmission.

4.8.6 Efficient MAC Protocols

Efficient MAC protocols are crucial for optimizing the performance of various wireless networks, including Wireless Body Area Networks (WBA), Terahertz networks, and Wireless Sensor Networks (WSNs). These protocols aim to enhance reliability, throughput, energy efficiency, and quality of service (QoS) while minimizing delays and energy consumption. The development of such protocols involves innovative approaches to address the unique challenges posed by different network environments. Below are key aspects of efficient MAC protocols as discussed in the provided papers.

4.8.6.1 Dynamic Super Frame Structure in WBA Networks

This method proposes a dynamic Super frame structure-based MAC protocol for wireless body area (WBA) networks, enhancing the standard IEEE 802.15.6. It utilizes a prioritization mechanism called Criteria Importance Through Inter-criteria Correlation (CRITIC) for slot allocation among sensor devices. The proposed protocol demonstrates improved performance in reliability, throughput, energy efficiency, and packet delivery delay, achieving over 50% increased reliability in data transmission compared to the standard IEEE 802.15.6 MAC protocol. MAC protocol, indicating its effectiveness in supporting reliable data transmission in WBA networks [21].

4.8.6.2 Efficient Synchronous MAC Protocols for Terahertz Networking in Wireless Data Canter

In wireless data centers, terahertz (THz) networking requires effective asynchronous MAC protocols to achieve low latency and high throughput. These protocols must minimize energy usage while addressing the difficulties posed by THz communication's high data speeds and short connection distances. A number of strategies are being investigated to maximize performance, such as traffic-intensity-based models, receiver-initiated handshakes, and "CSMA+TDMA" techniques.

2. CONCLUSION

This study highlights the critical factors affecting the energy efficiency and lifetime of Wireless Sensor Networks (WSNs), including communication overhead, node failures, environmental conditions, and limited energy resources. Energy-efficient routing protocols such as LEACH, PEGASIS, and TEEN, along with strategies like data aggregation, adaptive duty cycling, and energy harvesting, play a vital role in prolonging network lifetime. Additionally, intelligent topology optimization and advanced MAC protocols further enhance network performance. By integrating these approaches with AI-driven techniques, WSNs can achieve greater sustainability, reliability, and practical applicability in real-world scenarios.

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