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SUSTAINABLE AND SCALABLE WIRELESS SENSOR NETWORK ALGORITHMS

S. Hilda* & C. Kalaiselvi**

* Research Scholar, Department of Computer Applications, Tiruppur Kumaran College for Women, Tiruppur, Tamil Nadu.

** Associate Professor & Head, Department of Computer Applications, Tiruppur Kumaran College for Women, Tiruppur, Tamil Nadu

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Abstract:

The rapid growth of data sources, including audio, video, text, images, cloud storage, web content, RFID, and sensors, has made big data an essential research area. Among the significant contributors to big data are Wireless Sensor Networks (WSNs), which consist of numerous sensor nodes responsible for monitoring environmental and physical conditions such as temperature, pressure, and humidity. However, one of the main challenges in WSNs is energy consumption, as it directly impacts the operational lifespan and reliability of sensor nodes. Efficient energy utilization is crucial for enhancing network performance and sustainability. Various algorithms and protocols have been developed to address this issue by optimizing energy consumption and extending the network's longevity. This paper reviews prominent energy-efficient algorithms used in WSNs, such as LEACH, PEGASIS, and KOCA, discussing their methodologies and impact on network performance. Additionally, it highlights advancements in energy-efficient techniques and explores potential future research directions in WSN optimization. By analyzing existing approaches, this study aims to provide insights into improving energy efficiency in sensor networks, contributing to the development of more robust and sustainable WSNs. The findings can assist researchers and engineers in designing more effective energy management strategies for wireless sensor networks.

Key Words: Network Longevity, Network Performance, Wireless Sensor Network (WSN), Energy-Efficient Algorithms.

Introduction:

Big data can be described as "smaller data, but on a much larger scale." According to an IBM survey from 2012, 90% of the data in the world was generated in just the last two years, and this trend is expected to continue. As a result, there is an increasing need for big data, which is crucial for data analysis, collection, and processing. The primary sources of big data include cloud storage, web content (such as social media), and sensors. Industries, governments, and academia are the main contributors to the generation of big data, with sensors playing a significant role, particularly through Wireless Sensor Networks (WSNs).

WSNs consist of a large number of small sensor nodes that monitor environmental or physical parameters. These networks are designed with low-power nodes that have limited computational and sensing capabilities but are distributed over wide areas. WSNs are cost-effective, fault-tolerant, and flexible, making them suitable for applications such as environmental monitoring, industry, military, mapping, and transportation. The sensor nodes in these networks measure factors such as temperature, pressure, and humidity.

However, WSNs face challenges due to their limited resources, such as computational capacity and energy. Some of the key challenges include time-critical operations, covering large geographical areas, unreliable data due to environmental factors, and the difficulty of maintaining fixed communication paths. Additionally, WSNs often operate with low bandwidth and limited buffer storage.

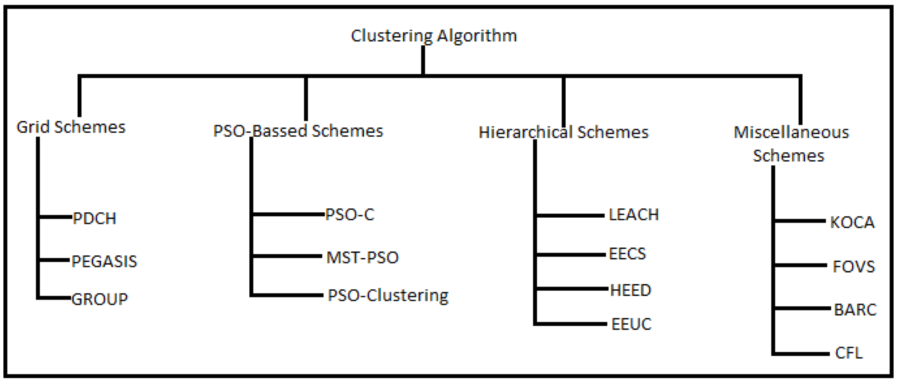


Figure 1: Taxonomy of Clustering Algorithm

To address these issues, various algorithms and protocols have been developed, focusing on reducing complexity, energy consumption, and improving coverage. However, each algorithm or protocol may address specific aspects, with some focusing more on particular challenges. The following section highlights some of the most effective algorithms designed to reduce energy consumption in WSNs.

Algorithms:

Clustering Techniques for Energy Efficiency:

A significant portion of research on Wireless Sensor Networks (WSNs) focuses on energy-efficient clustering algorithms, where nodes are grouped together to optimize communication. One of the earliest and most impactful algorithms is Low-Energy Adaptive Clustering Hierarchy (LEACH). LEACH reduces energy consumption by rotating the role of the cluster head, ensuring an even energy load across the network and minimizing the energy spent during transmission. Studies have shown LEACH's effectiveness in extending the network's lifetime by reducing energy-intensive transmissions.

PEGASIS for Power Efficiency:

The Power-Efficient Gathering in Sensor Information System (PEGASIS) algorithm further refines energy efficiency by organizing sensor nodes into a hierarchical structure. Unlike LEACH, PEGASIS reduces the total number of transmissions to the base station by introducing a chain-based topology. This minimizes the energy required for long-distance communication. Research has demonstrated that PEGASIS can achieve longer network lifetimes, especially in dense sensor networks where energy consumption is critical.

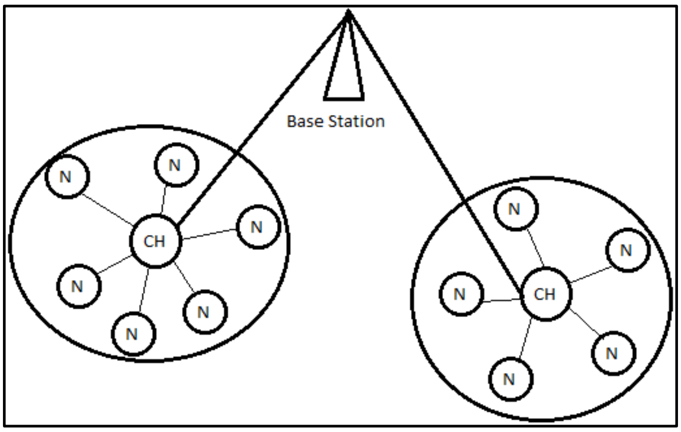
KOCA: K-Means Optimization for Clustering

K-Means Optimization Clustering Algorithm (KOCA) focuses on improving the clustering process by leveraging the K-means algorithm to optimize the selection of sensor nodes based on their energy levels and proximity. KOCA aims to create efficient clusters that minimize energy usage by selecting optimal cluster heads, ensuring data is aggregated and transmitted with minimal energy loss. This approach has been found effective in reducing energy consumption while maintaining data accuracy.

The algorithms mentioned above are discussed in detail in the following sections. Section A provides an explanation of the LEACH algorithm and its operational mechanism. Section B covers the PEGASIS algorithm, while Section C presents an overview of the KOCA or multi-hop clustering algorithm.

A. Low-Energy Adaptive Clustering Hierarchy:

The Low-Energy Adaptive Clustering Hierarchy (LEACH) is a self-organizing, adaptive clustering protocol that aims to distribute the energy consumption evenly across all sensor nodes in a network. LEACH uses a randomized technique to assign nodes to clusters, each headed by a local cluster-head or base station. Once a cluster-head is selected, the other member nodes send their data to it. Unlike conventional clustering algorithms, where the selected cluster-head quickly depletes its energy, LEACH employs a strategy called randomized rotation of the cluster-head. This ensures that the cluster-head role shifts periodically to nodes with higher energy levels, thus prolonging the network's lifetime. The algorithm also compresses the data gathered by the cluster-head before sending it to the base station, reducing energy consumption. Each cluster-head broadcasts its status to the other nodes in its cluster, and member nodes are assigned specific time slots to transmit their data, keeping the radio components off during idle times. This greatly reduces energy waste during non-transmission periods. Despite occasional high-energy transmissions when the base station is far from the cluster-head, LEACH remains more energy-efficient than traditional methods, ensuring the longevity of sensor nodes and the network.



N - Member Node, CH- Cluster Head Node

Figure 2: Simple LEACH Cluster Forming Approach

The cluster formation and functions, as shown in Figure 2, clarify the role of cluster heads. Nodes (N) are member nodes, and CH represents the Cluster-Head in the Wireless Sensor Network.

B. Energy-Efficient Data Gathering in Sensor Networks:

As described earlier, the LEACH protocol forms clusters where the cluster head collects data from all member nodes, compresses the data, and transmits it to the base station. LEACH uses a randomized approach to reduce energy consumption, but it still has limitations. For instance, if the base station is far from the cluster heads, the cluster heads consume more energy to transmit the data, which leads to faster depletion of their energy. This could result in network failure if too many cluster heads die prematurely due to high energy consumption. While LEACH is an effective algorithm, some nodes may still fail because of its limitations.

To overcome these issues, the PEGASIS protocol (Power-Efficient Gathering in Sensor Information System) proves to be more efficient. In PEGASIS, each node communicates only with its nearest neighbor, reducing energy consumption during data transmission to the base station. Data fusion also plays a critical role in reducing the data transmission load. It combines packets from different sensor nodes into a single packet, which is sent to the base station by the cluster head.

PEGASIS improves on LEACH by constructing chains of sensor nodes, where each node sends and receives data from its closest neighbor. The chain-based method, similar to the traveling salesman problem, reduces the transmission distance and increases energy efficiency. Additionally, PEGASIS allows for multi-hop communication when nodes are outside each other's range, ensuring that no data is lost. Compared to LEACH, PEGASIS is more efficient in transmitting data to the base station, as it covers shorter distances and reduces energy consumption.

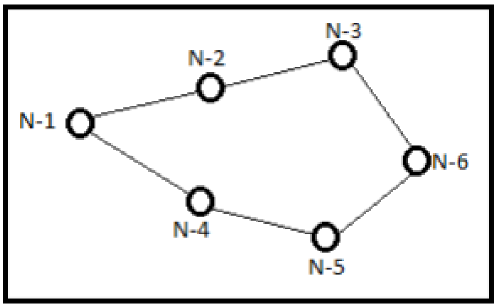


Figure 3: Simple Chain and Token Passing Method

Thus the PEGASIS is the extension of the LEACH in an efficient manner.

C. K-Hop Clustering Approach:

Clusters are commonly used in wireless sensor networks to improve energy efficiency and flexibility. However, it's important to note that cluster stability cannot always be guaranteed. In some cases, sensor nodes may inadvertently enter the range of another cluster, leading to collisions. This phenomenon is known as the overlapping cluster issue, where nodes from one cluster interfere with another cluster. Although this overlap can be beneficial in certain scenarios, such as inter-cluster routing, node localization, and time synchronization, it can also cause congestion and should be avoided in many cases. The K-hop clustering algorithm can address such situations effectively.

Unlike other clustering algorithms like LEACH and PEGASIS, which typically form disjoint clusters with limited criteria, the K-hop clustering approach allows for overlapping clusters, enabling more flexible energy management. In traditional clustering methods, each node belongs to only one cluster, but multi-hop or overlapping clustering algorithms allow a single node to be part of multiple clusters. The K-hop Clustering Algorithm (KOCA) introduces three types of nodes in each cluster:

- Cluster Head (CH)
- Boundary Node (BN)
- Member or Normal Node

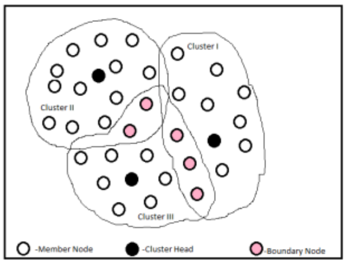


Figure 4: Overlapping Clusters

The cluster head is chosen based on a specific probability, and it has knowledge of neighboring clusters, including how to communicate with them. A boundary node, on the other hand, belongs to more than one cluster and acts as a gateway between them. The process of selecting cluster heads is similar to that in LEACH and PEGASIS, with no centralized control, and like these protocols, KOCA nodes broadcast the selected cluster head to other non-cluster head nodes.

KOCA is a complex algorithm designed to create connected overlapping clusters that cover the entire sensor network, with boundary nodes placed in overlapping regions. The algorithm is more efficient than LEACH and PEGASIS because it incurs lower overhead and supports bidirectional communication links. To prevent collisions, KOCA uses multiple access collision avoidance protocols, including TDMA for communication at the MAC layer.

In networks with a large number of sensor nodes, the multi-hop or overlapping clustering approach is a more suitable choice than traditional methods. While LEACH and PEGASIS are effective for energy reduction within single clusters, KOCA ensures efficient coverage across the entire sensor network, effectively handling overlapping areas and providing better performance in larger networks.

Conclusion:

There are various algorithms developed to reduce energy consumption in Wireless Sensor Networks (WSNs). As data generation from sensor nodes increases, it becomes essential to focus on energy-efficient solutions to extend the network's lifespan. The protocols discussed here aim to address the challenge of energy optimization, each with its own strengths and limitations. Some algorithms excel in reducing energy consumption in specific scenarios, while others may face challenges when applied to larger or more complex networks. The effectiveness of these algorithms depends on several factors, including the size of the sensor network, the communication delay, and the number of clusters present. By carefully considering these aspects, the most suitable energy-efficient protocol can be chosen to optimize the network's performance. Ultimately, selecting the right algorithm ensures that the network operates efficiently, minimizing energy usage and improving the overall lifetime of the wireless sensor nodes.

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