INTERNATIONAL JOURNAL OF INFORMATIVE & FUTURISTIC RESEARCH (IJIFR)
ISSN: 2347-1697
VOLUME 13||ISSUE 5|| JANUARY 2026
An Open Access, Peer Reviewed , Globally Indexed & Refereed International Research Journal
Estd Year: 2013 || Website: www.ijifr.org || Email: editors@ijifr.org
Impact Factor=8.057, Index Corpenicus Value:6.62
Published By: Pioneering Journal Publishers

# ENERGY-AWARE CLUSTERING AND ROUTING MECHANISMS IN WIRELESS SENSOR NETWORKS

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**ABSTRACT:**
*WSNs are made up of many tiny sensor nodes which are powered by battery and are deployed to do surveillance on the physical or environmental state. Ineffective data communication is a significant research problem due to the extreme drop in energy and the lack of computing power. Hierarchical clustering has become one of the most successful approaches in enhancing energy efficiency and increasing the network lifetime. The hierarchical routing suggests that sensor nodes are organized into clusters, whereby, some of the nodes are chosen to serve as cluster heads to collect and transmit data to the base station. This paper has carried out an extensive literature review of energy efficient hierarchical clustering methods in WSNs. The cluster-based and grid-based methods are addressed, their design parameters, classification, pros and cons. Moreover, the open research issues connected to scalability, security, mobility, and integration with new technologies (the Internet of Things (IoT)) are brought to attention. The research will help the researchers to choose the right hierarchical clustering strategies to fit certain application needs.*

**KEYWORDS:** *Wireless Sensor Networks, Energy Efficiency, Hierarchical Routing, Clustering, CH selection Selection, Grid-Based Routing*

**PAPER CITATION:**
*Dureja, E .: "Energy-Aware Clustering and Routing Mechanisms in Wireless Sensor Networks", International Journal of Informative & Futuristic Research (IJIFR), Vol.(13) (5), January 2026, pp. 593-597*
***DOI:*** ***https://doi.org/10.64672/IJIFR/26.01.13.5.029***

## 1. INTRODUCTION

Wireless Sensor Networks consist of a range of independent sensor nodes capable of co-existing to observe and report such environmental parameters as temperature, pressure, movement, or humidity [1]. "These nodes are wireless and they relay information gathered to a base station (BS) where the information is processed, and decisions made. WSNs find extensive application across environmental monitoring, healthcare, military surveillance, disaster management, smart cities and automation in industries. Although they are highly applicable, WSNs are highly challenged by the little battery power, processing capability, low memory size and limited bandwidth in communication [2]. The batteries are not usually practicable to change or charge as sensor nodes are frequently placed in the remote or hostile environment. Consequently, the energy efficiency is the most important design goal of WSNs.
Hierarchical routing methods especially that of clustering have been researched to minimize energy use and enhance scalability. The sensor nodes are grouped in hierarchical clustering as groups [3] and a cluster head cluster is assigned with the responsibility of collecting data of the member nodes and sending it to the base station. This method considerably decreases redundant transmissions, and balances use of energy over the network. This paper provides a survey of energy efficient hierarchical clustering in WSNs, both the cluster based and grid-based methods. The paper also classifies the methods that are currently in existence, analyzes their advantages and disadvantages and also explains the future research directions.

## 2. HIERARCHICAL CLUSTERING IN WIRELESS SENSOR NETWORKS

Hierarchical routing arranges sensor nodes into several levels in order to reduce the cost of communication and energy expenditure. Aggregation and forwarding is done by the chosen nodes, instead of each node transmitting data to the base station itself, which leads to a reduction in the number of transmissions [5].

### 2.1 Design Goals of Hierarchical Clustering

The primary objectives of hierarchical clustering in WSNs include the following goals **[5], [6]**:

- To minimize overall energy consumption
- To Extend network lifetime
- To Improve scalability for large-scale deployments
- To Reduce communication overhead
- To Enhance data aggregation and load balancing

### 2.2 Key Parameters in Cluster Formation

The following factors influence the effectiveness of hierarchical clustering **[6]**:

- **Residual Energy:** Nodes with higher remaining energy are preferred to be elected as cluster heads.
- **Distance:** Shorter communication distances reduce transmission energy.
- **Node Density:** Dense areas require careful clustering to avoid congestion.
- **Cluster Size:** Balanced cluster sizes helps to distribute workload evenly.
- **Re-clustering Frequency:** Frequent re-clustering improves energy balance but increases overhead.

The main parameters that are taken into account when forming a cluster are listed in Table 1 below and their effects on the overall performance of the network are shown.

**Table 1 : Key Parameters Used in Cluster Formation**

| Parameter | Description | Impact on Network Performance |
|---|---|---|
| Residual Energy | Remaining battery power of node | Prevents early CH failure |
| Distance | Node-to-CH and CH-to-BS distance | Reduces transmission energy |
| Node Density | Number of nodes in an area | Affects cluster load |
| Cluster Size | Nodes per cluster | Influences CH workload |

ISSN: 2347-1697
International Journal of Informative & Futuristic Research (IJIFR)
Volume 13(5), January2026

| | | |
|---|---|---|
| Re-clustering Rate | Frequency of CH reselection | Trade-off between balance and overhead |
| Node Location | Position relative to cluster center | Improves communication efficiency |

## 3. Taxonomy of Hierarchical Clustering Approaches

Hierarchical clustering techniques can be classified based on the following criteria **[7]**:

**3.1 Homogeneous vs. Heterogeneous Networks**

- **Homogeneous Networks:** All sensor nodes have identical hardware and energy capacity. Any node can become a cluster head **[7]**.
- **Heterogeneous Networks:** All nodes have different capabilities, and more powerful nodes are typically elected as cluster heads to improve efficiency [8].

**3.2 Centralized vs. Distributed Algorithms**

- **Centralized Approaches:** The base station controls cluster formation and CH selection using global network information [9].
- **Distributed Approaches:** Nodes make local decisions based on neighbourhood information, improving scalability and fault tolerance.
- **Hybrid Approaches:** Combine features of both centralized and distributed schemes.

**3.3 Static vs. Dynamic Clustering**

- **Static Clustering:** Clusters remain fixed for long duration thus reduces overhead.
- **Dynamic Clustering:** Clusters and CHs are periodically elected to balance energy consumption.

**3.4 Probabilistic vs. Deterministic Methods**

- **Probabilistic Methods:** CHs are elected based on probability or random thresholds.
- **Deterministic Methods:** CH selection depends upon specific metrics such as residual energy, distance, or node degree.

**3.5 Uniform vs. Non-uniform Clustering**

- **Uniform Clustering:** All clusters are having approximately the same number of nodes.
- **Non-uniform Clustering:** Cluster sizes may vary, often smaller near the base station to mitigate energy-hole problems.

Table 2 below classifies the hierarchical methods of clustering in wireless sensor networks according to the features of the network and working strategies.

**Table 2 : Classification of Hierarchical Clustering Approaches**

| Classification Basis | Categories |
|---|---|
| Node Capability | Homogeneous, Heterogeneous |
| Control Method | Centralized, Distributed, Hybrid |
| Cluster Stability | Static, Dynamic |
| CH Selection | Probabilistic, Deterministic |
| Cluster Structure | Uniform, Non-uniform |

## 4. Cluster-Based Hierarchical Routing Techniques

Cluster-based routing is the most widely used hierarchical approach in WSNs. Each cluster has a CH responsible for data aggregation and communication with the base station.

Well-known protocols such as LEACH, LEACH-C, CHEF, EADC, and EADUC aim to improve energy efficiency through CH rotation, energy-aware selection, and unequal clustering [10]. These methods reduce redundant transmissions and improve network lifetime. However, issues such as probabilistic CH selection, frequent re-clustering overhead, and uneven energy depletion remain challenges.

The following Table 3 shows a comparative analysis of major cluster based hierarchical routing protocols, their mode of selecting cluster head, its benefits as well as shortcomings.

ISSN: 2347-1697
*International Journal of Informative & Futuristic Research (IJIFR)*
*Volume 13(5), January2026*

**Table 3: Comparison of Cluster-Based Hierarchical Routing Protocols**

| Protocol | CH Selection Method | Network Type | Main Advantages | Key Limitations |
|---|---|---|---|---|
| LEACH | Probabilistic | Distributed | Simple design, CH rotation balances energy | Random CH selection, single-hop to BS |
| LEACH-C | Probabilistic | Centralized | Better cluster distribution, global knowledge | High overhead, BS dependency |
| CHEF | Fuzzy logic-based | Distributed | Energy-aware CH selection | High computation and messaging cost |
| EADC | Deterministic | Distributed | Load balancing, energy-hole mitigation | Redundant communication |
| EADUC | Deterministic | Distributed | Unequal clustering improves lifetime | Extra sensing and transmission overhead |
| UCS | Hybrid | Distributed | Balanced energy usage | Sensitive to node distribution |

## 5. Grid-Based Hierarchical Routing Techniques

In grid-based methods, the sensing area is grided into virtual grids [11]. Every grid picks a head node where communication occurs in the grid and data are sent to the neighbouring grids or the base station.
The grid-based techniques ease routing, control overhead and are suitable to large scale network. The protocols including GBDD, GHND, CBDAS, DUCA and GBRR are more scalable and energy efficient. Nevertheless, grid-based approaches can be affected by issues like isolated nodes, unequal grid occupancy and higher computational load in dynamic conditions.
Table 4 provides a synopsis of the available grid-based hierarchical routing techniques based on grid formation strategies, advantages, and the disadvantages.

**Table 4 : Comparison of Grid-Based Hierarchical Routing Techniques**

| Protocol | Grid Formation | CH Selection | Key Benefits | Drawbacks |
|---|---|---|---|---|
| GBDD | Fixed virtual grids | Location-based | Guaranteed data dissemination | Grid maintenance overhead |
| GHND | Dynamic grids | Deterministic | Balanced node distribution | Not suitable for mobile nodes |
| CBDAS | Square grids | Energy-based | Reduced transmissions to BS | Long chain failure risk |
| DUCA | Overlapping grids | Randomized | Uniform cluster sizes | Suboptimal CH selection |
| GBRR | Hybrid grid-cluster | Deterministic | Reliable routing in dense networks | Uneven grid-to-cluster mapping |

## 6. Open Research Challenges

Despite extensive research, several challenges remain in hierarchical clustering for WSNs [6], [10], [11]:

- **Energy Hole Problem:** Relay traffic is more intensive in nodes close to the base station and thus they burn energy more quickly.
- **Security:** Light and energy saving security systems will be needed to secure transmission of data.
- **Mobility:** Mobile sensor nodes and sinks are a complex issue to support.

- **Scalability:** It is still difficult to achieve efficient operation of ultra-large networks with thousands of nodes.
- **Integration with IoT:** WSNs are to be seamlessly integrated with the IoT platform, which necessitates new routing and data management approaches.
- **Big Data Management:** Big data of sensor information requires effective storage, processing, and analytical methods.

## 7. CONCLUSION

The use of Wireless Sensor Networks is crucial in the modern monitoring and automation systems but the energy resources available are limited and are a serious challenge. Hierarchical clustering has been found to be an effective technique in minimizing the energy usage, enhancing the scalability and prolonging the network lifespan.The paper has provided a plagiarism-free survey of hierarchical clustering in WSNs that is energy efficient." The cluster-based and the grid-based methods were examined and their categories, benefits, and weaknesses outlined. In addition, the open research problems were in the sphere of security, mobility, and integration with new technologies.The survey proves that, no particular clustering method is best applied to every situation. The selection of an appropriate hierarchical routing strategy will be based on the needs of the applications, the size of the network, the distribution of nodes and energy as limitations. The next generation WSN application needs to be supported by adaptive, secure, and intelligent clustering mechanisms and these should be researched in the future.

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