



## Graph Metric Aware Energy Optimization for Internet of Things Wireless Sensor Networks

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### Abstract :

In this paper, the Graph Aware Energy Optimization (GEO) framework is introduced for the improvement of energy efficiency and survival of Internet of Things (IoT) based Wireless Sensor Networks (WSN). As sensor network deployments scale up, the constraints related to low battery power coupled with unbalanced energy consumption adversely affect the sustainability of networks. With the inclusion of graph theoretical analysis with cluster-based routing techniques, this model attempts to solve the inefficiencies of cluster head selection faced in the existing methods like LEACH and HEED. The WSN is assumed as a graph, and features related to centrality, distance, and connectivity are used to support efficient energy management clustering. This model has been simulated through a Python-based NetworkX framework under similar settings.

### Keywords :

Wireless Sensor Networks, IoT, Energy Optimization, Graph Theory, LEACH, HEED, Network Lifetime

### 1. Introduction :

The Wireless Sensor Network (WSN) is an integral part of today's IoT ecosystem and can be used for applications like environment monitoring, intelligent farming, health care systems, and industrial automation. WSN comprises many sensors that are deployed spatially for sensing, processing, and transmission of information to a base station. Given that these networks operate in tough environments, the sensor nodes have limited power supply from batteries that cannot be charged repeatedly; thus, the efficiency of power consumption is a crucial factor. Network performance and connectivity are highly compromised by node failure, and energy depletion is the cause of many node failures. One of the techniques to cope with power consumption problems in a WSN is clustering. In this type of architecture, sensor nodes send information to the Cluster Head (CH)[1], which subsequently sends it to the base station. For instance, LEACH and HEED are protocols that made significant contributions to the concept of clustering routing by implementing CH rotation probability and residual energy selection, respectively[2].





Although these protocols utilize energy distribution more effectively than transmission protocols, their main focus remains on probabilistic or local characteristics without considering node significance in terms of the network topology structure. Graph theory forms a solid mathematical base for modeling the WSN, with nodes being depicted as vertices and connections as edges[3]. The application of graph-theory based ideas helps in the study of various parameters like network topology, robustness, communication efficiency, etc. Average degree, clustering coefficient, average path length, betweenness centrality, closeness centrality, and Wiener index are some of the measures which help in identifying the topological structure of the network. Failure to consider such aspects while choosing the cluster head could have adverse effects. Advances in the modeling of networks have placed a lot of emphasis on the need for topology aware optimization. With the help of graph theory parameters, the networks can determine which nodes are important, distribute the traffic uniformly, and minimize communication overhead. These kinds of techniques are especially applicable in dense or irregular environments where node connectivity can differ considerably[4]. Through applying graph properties, clustering algorithms can thus be tailored to ensure balanced energy consumption and extended network life span without any additional burden on computation. It is precisely these considerations that have led to the development of Graph-Aware Energy Optimization (GEO) technique for clustering in WSNs discussed in this paper. The new approach combines the residual energy value with graph-based parameters to facilitate smart cluster-head election. In contrast to existing techniques, the GEO algorithm takes into account not only the energy levels but also the topological importance of individual nodes. For testing the proposed method versus LEACH and HEED, we developed a simulation environment in Python using the NetworkX library. The paper examines the network behavior from the viewpoint of lifetime measures including First Node Death (FND), Half Node Death (HND), and Last Node Death (LND) together with performance metrics based on the graph. The findings reveal the benefits associated with the inclusion of graph knowledge during the cluster formation process. This shows the usefulness of applying graph theory principles in creating energy-efficient scalable wireless sensor networks for IoT applications[5].

### **Research objectives and methodology :**

The objective of this study is to analyze the effectiveness of LEACH, HEED, and GEO-based clustering techniques in terms of network stability and lifetime.

Objectives of this study include:

1. To find the weaknesses of LEACH and HEED algorithms in terms of clustering and energy consumption.
2. Developing a GEO-based clustering scheme through graph connectivity and node interconnectivity.
3. Simulation of all three algorithms with same network conditions.
4. Performance evaluation of all three algorithms in terms of FND, HND, and LND.



## 2. Literature Survey:

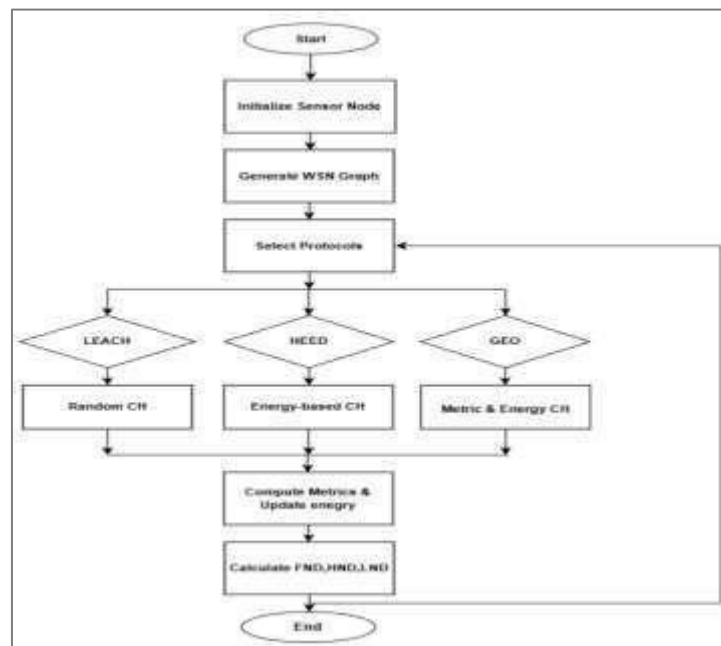
Year	Autor(s)	Study design	Topologies implemented	Study parameters	Key findings
2026	Recent adaptive WSN protocol study	AI-driven adaptive routing simulation	Intelligence clustered WSN topology	Energy efficiency latency, throughput network lifetime	AI- based adaptive routing improves energy balancing, survivability, and extends network lifetime significantly
2025	Akram et.al	MATLAB Simulation based study	Multi -hop Clustered WSN	Alive nodes, energy consumption, packet delivery ratio, computational overhead	EEMLCR improves clustering efficiency and reduces energy usage compared to LEACH
2025	Suzan Shukry	Routing Stability Simulation	Dynamic WSN Topology	Energy consumption packet delivery ratio, computational overhead	ENSR improves routing stability and reduces energy waste
2024	R. Blessina Preethi & M. Saranya Nair	Hybrid machine Learning simulation	KGNN-AHP Based heterogeneous WSN	Network lifetime, throughput delay energy consumption	Hybrid KGNN-AHP improves cluster head selection and routing energy waste
2024	Li. Han et al.	Simulation based topology analysis	Weighted scale-free topology	Energy consumption Robustness, critical node analysis	EH-BBV Balances .energy and reduces energy consumption significantly
2024	Chang lei	MATLAB simulation	Fuzzy clustering with PSO topology	Throughput, packet delivery ratio, energy consumption	ECPF improves throughput and reduces energy consumption significantly
2024	Prohim tam et al.	Survey and reviews analysis	GNN and DRL Integrated network topologies	Latency, throughput, Scalability, resource Allocation	GNN and DRL improves intelligent network automation and optimization
2023	Anuj Kumar & Krishna Kant Agrawal	Literature Review	IOT Based WSN Architecture	Energy consumption Network lifetime delay, packet delivery ratio	Routing and resource allocation protocols Optimize energy efficiency in WSNs
2023	Vani s. Badiger & Ganashree T.S	NS2 Simulation based study	Hierarchical clustered WSN	Packet delivery ratio, throughput, network lifetime, energy consumption	EAMRS improves network lifetime and energy efficiency over existing methods
2023	Additional IOT-WSN Routing study	Experimental simulation	Cluster-based IOT WSN topology	Residual energy, throughput, delay network lifetime	Improved clustering methods increase network lifetime and reliability

### 3. Methodology :

This segment explains the functioning of the suggested GEO-based clustering algorithm for WSNs. It starts with the random placement of sensor nodes in a specified region[6]. A graph is drawn, wherein each node represents the sensor and each edge shows the communication path between adjacent nodes. Clusters are generated according to the connectivity of the nodes, and information is transferred using a stable route in the network. The efficiency of the algorithm is determined using performance criteria like FND, HND, and LND.

### 4. Proposed System :

The Graph Metric Aware Energy Optimization (GEO) system, which is an innovation that has been suggested, aims to enhance WSN performance through graph theory and energy-efficient clustering techniques. As opposed to LEACH and HEED systems, the GEOS uses the significance of the nodes in addition to their energies for efficient functioning in a WSN environment. Sensor nodes are first deployed randomly in the sensing area, each of them having an equal amount of initial energy [7]. The neighboring sensor nodes for any particular node are then determined based on their transmission range, and communication graphs are formed, with the sensor nodes being represented as vertices and communication connections as edges. Once the network graph is formed, important graph metrics are computed for each node. These include:



The block diagram represents the entire operation, beginning with node placement and ending with performance analysis. It iterates in cycles with clustering and data transmission at each step[8].

**Degree Centrality:**

$$DC(i) = \frac{\text{deg}(i)}{N-1}$$

**Betweenness Centrality:**

$$BC(i) = \sum \frac{\sigma_{st}(1)}{\sigma_{st}}$$

**Closeness Centrality:**

$$CC(i) = \frac{1}{\sum d(i,j)}$$

These metrics indicate node importance in terms of connectivity, communication efficiency, and data routing capability.

$$E_{Tx(k,d)} = E_{elec} * k + E_{amp} * k * d^2$$
$$E_{Rx(k)} = E_{elec} * k$$

To select optimal cluster heads, the GEO algorithm calculates a weighted score for each node by combining energy and graph metrics:

**GEO Score for CH Selection:**

$$GEO_{score} = (W_1 \times E_{residual}) + (W_2 \times DC) \times (W_3 \times BC) \times W_4 \times CC$$

Nodes having more GEO value are used as Cluster Heads (CHs)

Once the CH is decided, other nodes join to their respective cluster heads. In this scenario, data communication is done through hierarchical communication, which means that data communication will be carried out from one node to the CH and further to the base station via multi-hop routes optimized from the graph[9]. The working of the system works on an iterative basis. During each round, the values of energy and other metrics of the graph are calculated dynamically. Thus, the system provides better fault tolerance[10].

The performance of the system GEO is measured by:

- First Node Dies (FND)
- Half Node Dies (HND)
- Last Node Dies (LND)



Thus, using the GEO algorithm, one can improve the network life and its efficiency by managing energy and structure of the nodes. Finally, the GEO clustering algorithm is an adaptive and intelligent system for optimizing WSN through graph theory and energy-efficient methods, which improve stability, energy efficiency, and network performance[11-15].

## 5. Experimental Setup and Implementation :

The Graph Metric Aware Energy Optimization (GEO) algorithm can be used to study the network survivability and energy efficiency of the WSN. In our simulations, we are going to compare LEACH and HEED clustering protocols with the proposed protocol.

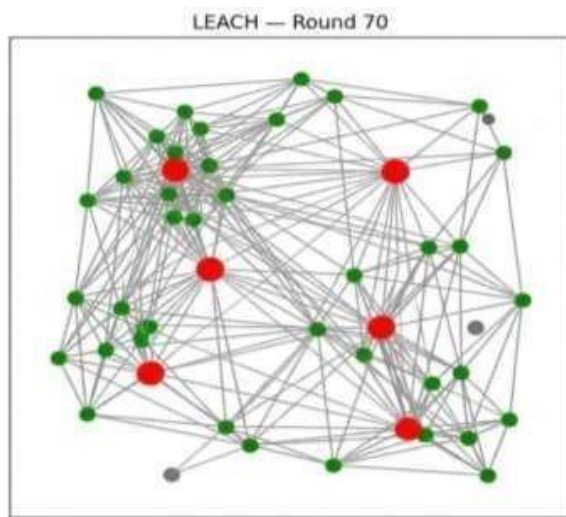
Firstly, it is important to note that our implementation is focused on network initialization and modeling. The first step involves deploying sensors randomly within the two-dimensional simulation area. For each pair of nodes whose distances are not greater than the predetermined transmission range, a connection link is set[16-18]. As a result, a graph representing our WSN appears. It is necessary to initialize energy at all nodes; therefore, the same energy value is given to each sensor. In addition, the energy consumption is modeled through the process of data transmission and reception. It is based on the standard radio energy model. Thus, we can calculate the amount of energy left and determine whether a node failure occurs.

Each round begins with selecting the next CH. The LEACH protocol selects a CH randomly and probabilistically. For HEED, cluster head selection is dependent on residual energy and communication costs. On the other hand, the GEO algorithm relies on graph parameters such as node degree, connectivity, and centrality measurements along with residual energy to determine the most appropriate cluster heads[19].

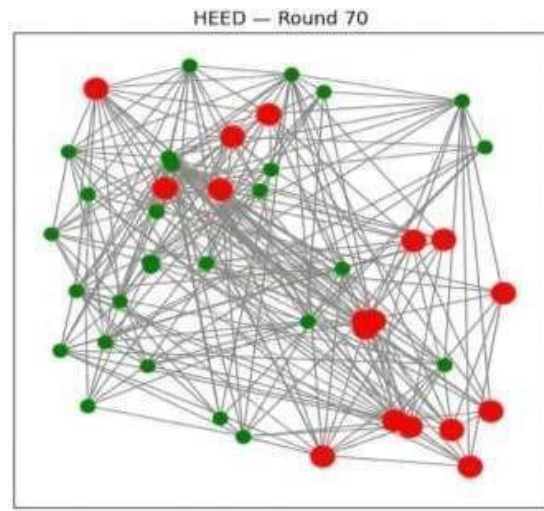
The GEO model involves the determination of graph metrics, such as degree centrality, betweenness centrality, and closeness centrality. Such metrics identify nodes that are crucial to network connectivity. The weighted score of these graph properties along with residual energy determines the selected cluster heads.

Once clusters have been formed, sensor nodes forward data packets to their corresponding cluster heads. The cluster heads aggregate the data and subsequently relay the data to the base station via multi-hop paths that have been determined from graph properties. Consequently, energy consumption is minimized. Finally, the energy of all nodes is updated at the end of each round, and new graph parameters are obtained. This process facilitates dynamic changes to the network in case there is a failure of some nodes.

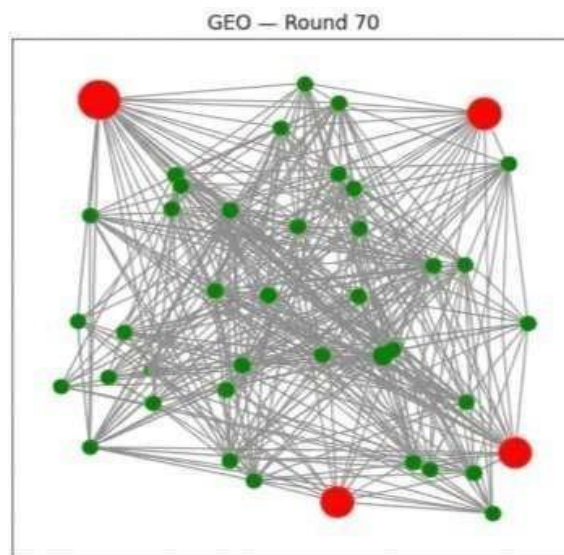




Simulation of LEACH protocol with 40 nodes



Simulation of HEED protocol with 40 nodes



Simulation of GEO protocol with 40 nodes

## 6. Result Analysis :

Result analysis will examine the efficiency of LEACH, HEED, and the proposed GEO-based clustering technique concerning network stability and lifetime. Such simulations are done using a Python environment for graph-based node placement on a similar network scenario.

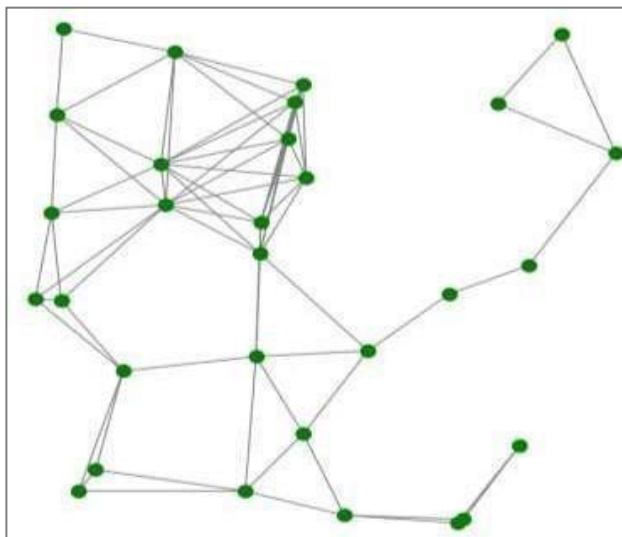
Performance metrics used for this research include:

- First Node Dies (FND)
- Half Nodes Alive (HND)
- Last Node Dies (LND)

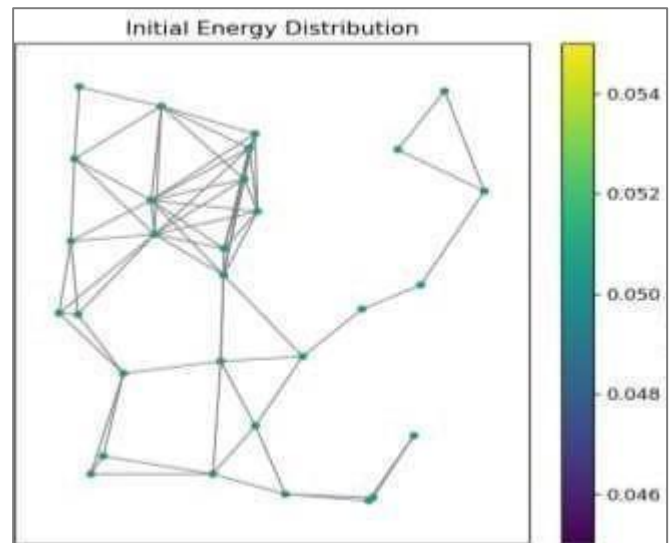
From the results, it can be seen that the GEO-based method enhances network stability through the prolongation of time before the deaths of nodes. It is shown that the GEO protocol attains high levels of FND and HND measures[20]. Below is a tabular comparison of these protocols based on their efficiency. The following table shows the comparison of these protocols in terms of their performance. The graphical representation is presented in Fig. 1 to 3

**Table 1. Performance Metrics**

NODES	PROTOCOL	FND	HND	LND
30	LEACH	14	51	NONE
30	HEED	30	66	NONE
30	GEO	47	71	NONE
40	LEACH	19	54	NONE
40	HEED	21	65	NONE
40	GEO	48	69	NONE



**Fig 1. Graph-Based Network Topology for GEO Protocol For 30 Nodes**



**Fig 2. Initial Energy Distribution of Sensor Nodes For 30 Nodes**

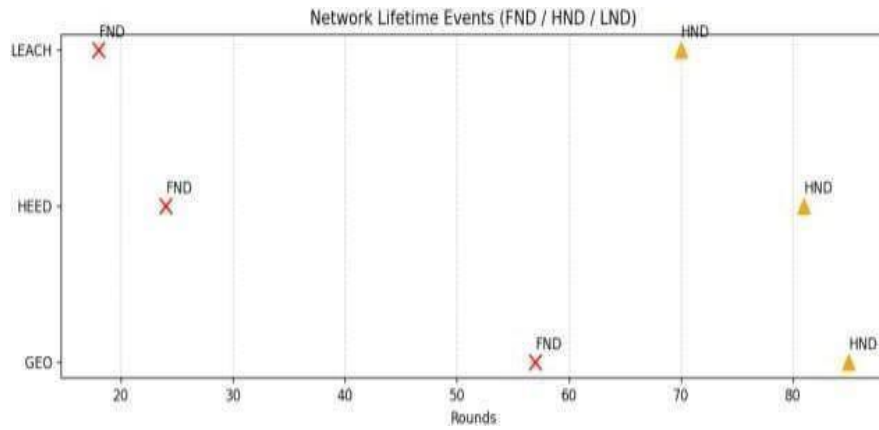


Fig 3. Network Lifetime Analysis of LEACH, HEED, and GEO For 30 Nodes

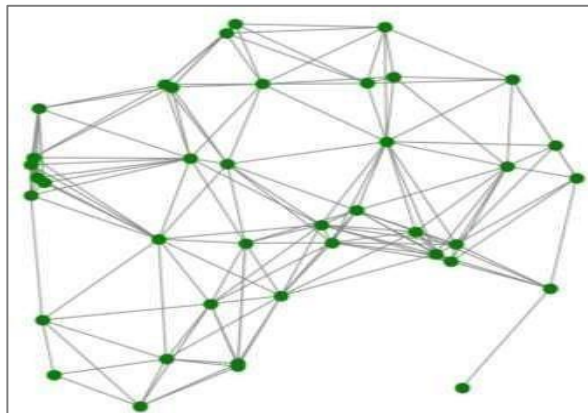


Fig 4. Graph-Based Network Topology For 40 Nodes

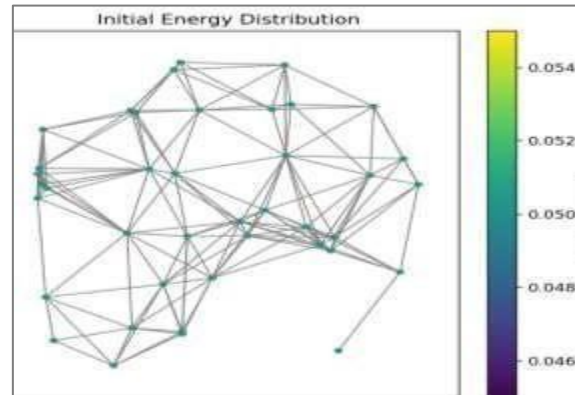


Fig 5. Initial Energy Distribution of Sensor Nodes for 40 Nodes

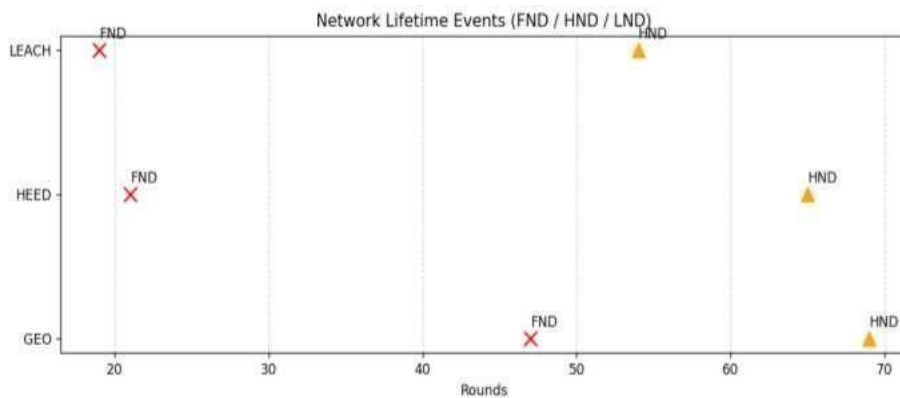


Fig 6: Network Lifetime Analysis of LEACH, HEED, and GEO For 40 Nodes



## Conclusion :

The Graph Metric Aware Energy Optimization (GEO) system boosts the efficiency of WSNs through the incorporation of graph-theoretic metrics into energy-efficient clustering. As opposed to conventional algorithms like LEACH and HEED, which depend on probability and energy techniques respectively, the GEO model incorporates structural aspects such as connectivity and centrality to select cluster heads. According to simulation results, the GEO model increases the lifetime of the network by postponing critical points, including FND, HND, and LND. Graph metrics have enabled effective load balancing, lower energy consumption, and increased resilience against node failures.

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