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Energy-Efficient Clustering Routing Protocol using Quad-Tree Divide and Conquer with Dynamic Multihop LEACH for Enhanced IoT Network Lifetime (EECR-IoT)

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Abstract: - Reducing energy consumption in IoT networks remains a critical challenge in energy-efficient clustering routing protocols (EECR-IoT). Several routing protocols have been developed to address power consumption, with cluster- based protocols emerging as particularly effective. In these protocols, cluster heads are selected to aggregate data from root nodes and transmit it to the base station, optimizing energy usage. Efficient selection of cluster heads is essential to prolong network lifetime. Our proposed protocol employs static clustering for optimal cluster head selection, ensuring effective performance in both large and small areas. To enhance communication efficiency, we divide large sensor fields into rectangular clusters, which are then grouped into zones to facilitate communication between cluster heads and the base station. EECR-IoT involves a vast network of tiny sensor nodes capable of sensing, processing, and transmitting environmental data to the base station. Energy efficiency is crucial for sustaining these networks, and our study introduces an energy-efficient clustering protocol based on the Divide and Conquer Quad Tree dynamic multi-hop LEACH algorithm. This approach optimizes energy efficiency through balanced cluster creation, thereby distributing the load among cluster heads and extending network lifetime. In addition to Euclidean distance, the protocol considers residual energy for cluster head selection. Multi-hop communication between cluster heads and the base station depends on their distance, further improving energy efficiency. Simulations demonstrate that the proposed method outperforms existing heterogeneous protocols, including LEACH-B, BPK-means, Park's approach, and Mk-means, by up to 50% in energy savings. The protocol's effectiveness is evaluated using performance metrics such as throughput, End-to-End delay (EED), Packet Drop Rate (PDR), and node lifespan, showcasing its superiority in enhancing network longevity and reducing energy consumption across various IoT applications.

Keywords: IoT, Divide and Conquer, Quad Tree based DC, Energy Efficient Routing Protocol, EECR IoT

I. INTRODUCTION

The Energy-Efficient Clustering outlines strategies to optimize energy consumption in network design through two main approaches Quad-Tree Structure and Dynamic Clustering, as shown in Figure 1.

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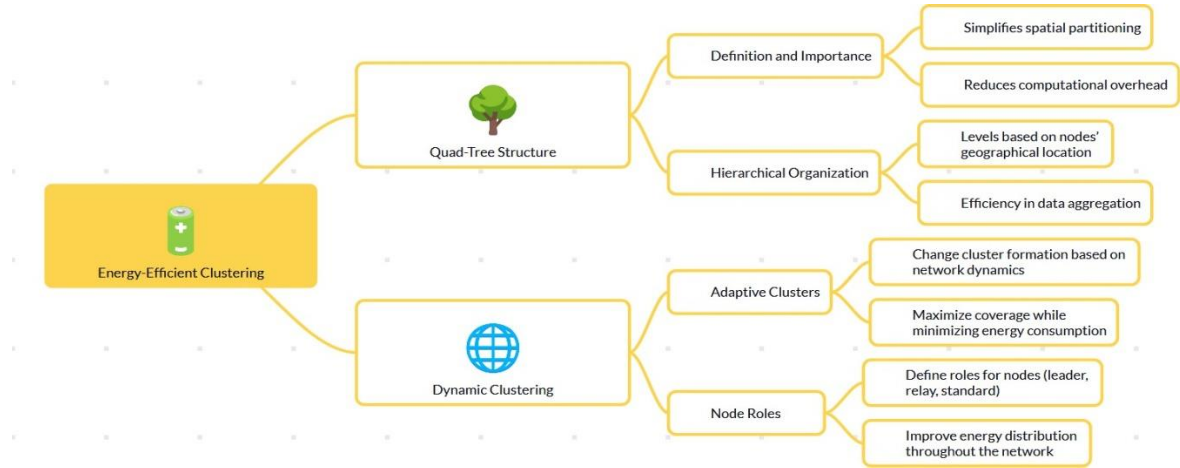

Figure 1: Energy Efficient Clustering Methods architecture

The Quad-Tree Structure simplifies spatial partitioning, reduces computational overhead, and organizes data hierarchically based on geographical location, enhancing data aggregation efficiency. In contrast, Dynamic Clustering focuses on adaptive clusters that can change formation according to network dynamics, aiming to maximize coverage while minimizing energy use. It also defines specific roles for nodes, such as leader, relay, and standard, to improve energy distribution throughout the network, ensuring balanced and efficient operation. The Multihop Communication approach provides a comprehensive overview of routing protocols designed to enhance energy efficiency in net- work communication is as shown in figure 2.

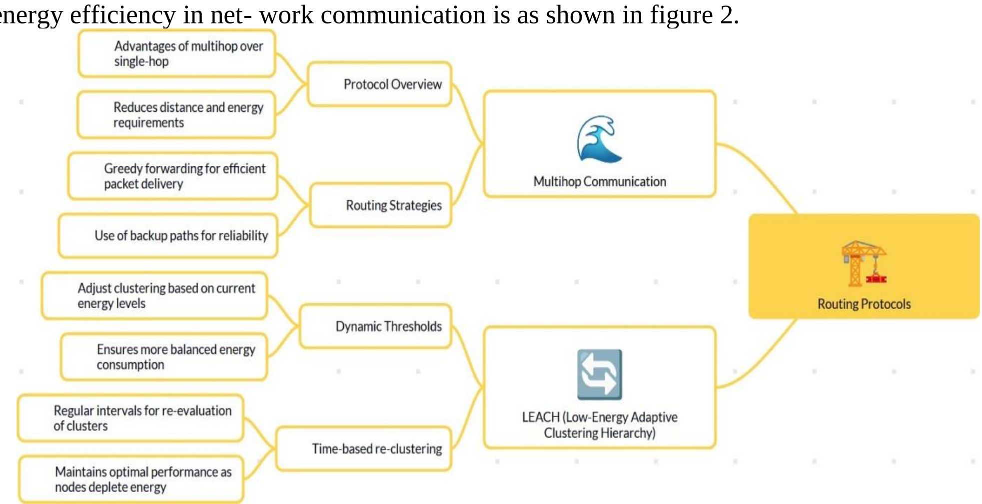

Figure 2: Routing Protocols.

It highlights the advantages of multihop over single-hop communication, emphasizing how multihop reduces both distance and energy requirements, leading to more efficient data trans- mission. Key routing strategies include greedy forwarding for efficient packet delivery and the use of backup paths to ensure reliability in data transfer. The concept of dynamic thresholds is introduced, allowing for the adjustment of clustering based on current energy levels, thereby ensuring balanced energy consumption across the network. Regular intervals for reevaluating clusters and time-based re-clustering are also essential, as they maintain optimal performance even as nodes deplete their energy.

The LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol is mentioned as a specific approach that embodies these principles, focusing on creating a hierarchical structure that optimizes energy use while facilitating effective communication. Network Lifetime Enhancement strategies aim to improve the longevity and efficiency of network systems through two primary approaches:

• Energy Harvesting Techniques
• Performance Metrics

Energy harvesting techniques integrate renewable energy sources, such as solar and wind energy, to power network devices. By incorporating these energy sources, networks can significantly extend their operational time and reduce reliance on traditional power supplies. Additionally, the use of low power communication protocols enhances device battery life, ensuring longer operation without frequent recharging. Furthermore, integrating Internet of Things (IoT) devices for power supply optimizes energy usage across the network. Performance metrics focus on evaluating network effectiveness through various metrics. Network stability is crucial, involving consistency in data transmission and analyzing network degradation over time. Energy consumption analysis is also vital, allowing the tracking of individual node energy levels and aggregating data

to identify trends and areas for improvement. Together, these strategies aim to enhance overall network lifetime and performance, ensuring efficiency and reliability over extended periods.
Recently, EECR-IoT has gained popularity due to its potential applications in fields such as target tracking, localization, environmental monitoring, healthcare, and industrial automation. EECR-IoT, as a foundational IoT technology, consists of smart objects (sensor nodes) deployed in an unstructured manner to capture information. These nodes operate under constraints on energy, computation, memory, and processing power. Clustering is an effective mechanism for data aggregation in EECR-IoT. Efficient clustering and relay node placement can enhance energy utilization and extend network lifetime is shown in Figure 3.

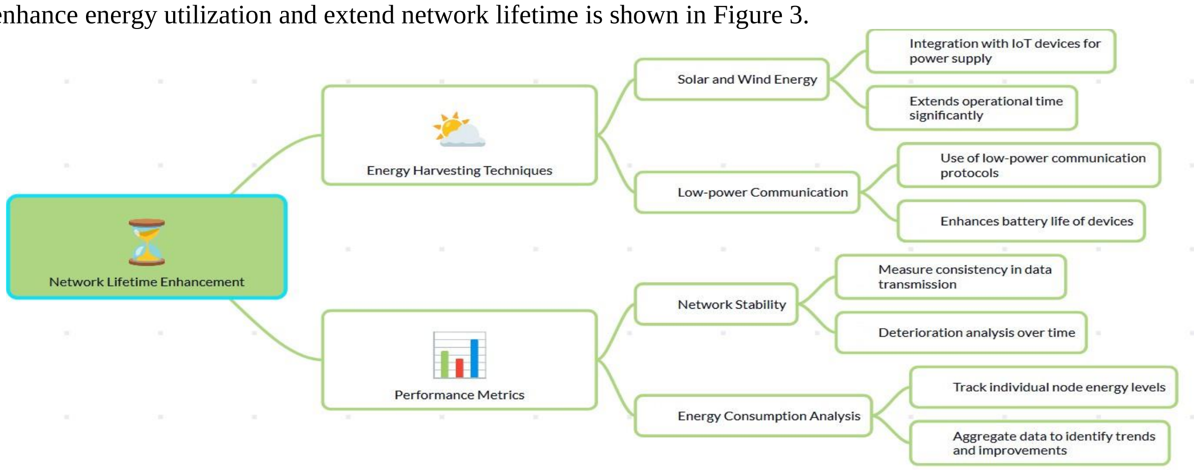

Figure 3: Network life time enhancement.

One critical challenge in clustering is improving cluster structure and optimizing cluster head (CH) selection. Various approaches based on the K-means algorithm have been developed for better clustering. IoT and its protocols have become highly funded topics in both industry and academia, with EECR-IoT receiving widespread attention due to its broad applications. IoT enables interconnections of various objects or devices through the Internet, and currently, over 5 billion intelligent devices are connected globally, with rapid growth expected. Routing techniques in EECR-IoT vary depending on application requirements and node operational conditions. The robustness of the routing strategy depends on network architecture and EECR-IoT design. Numerous clustering strategies, alongside comprehensive routing techniques, have been projected to improve performance. IoT represents a global communication infrastructure comprising various connected objects, providing networking, sensing, and information processing capabilities. The core concept of EECR-IoT is to enable connectivity between homogeneous objects anywhere. Radio frequency identification (RFID) is an early technology for EECR-IoT, allowing electromagnetic fields to transmit identification data to a reader through wireless devices. An RFID system includes two main components: a radio signal transponder (tag) and a tag reader. RFID tags, typically containing electronically stored information, are attached to objects for data collection and monitoring. Due to IoT's complex structure and sensor node constraints, securing EECR-IoT systems is challenging, and communication can be vulnerable to various network attacks. Researchers have focused on enhancing CH selection criteria to improve energy efficiency. LEACH based protocols have been modified to address issues such as throughput, end-to-end delay, packet drop rate, alive node rate (ANR), dead node rate (DNR), power consumption, scalability, security, and packet delivery ratio. This paper provides a comprehensive survey of LEACH based protocols to help researchers understand routing protocols with diverse architectures and enhanced performance.

II.RELATED WORK

The primary objective in IoT networks is to achieve energy efficiency due to the limited energy reserves of sensor nodes. Approaches such as relay node placement, tree based data aggregation, and optimized sensor mobility have been found effective for minimizing energy consumption within sensor networks. A key strategy for IoT energy efficiency is network clustering, as it can reduce power use and ensure extensive, consistent coverage. The quad-tree-based divide-and-conquer method has become particularly valuable in IoT applications, cybersecurity, intrusion detection, and beyond, for optimizing clustering. Hanumanthappa et al. [1] proposed a Quad Tree- based Dynamic Multi-hop LEACH protocol to enhance energy efficiency in wireless sensor networks (WSNs) by implementing a quad-tree structure for dynamic cluster head selection. Additionally, Sharma et al. [2] introduced MHSEER, a meta-heuristic secure and energy efficient routing protocol for industrial IoT, focusing on improving network lifetime while incorporating security mechanisms. Kazadi Mutombo et al. [3] developed EER-RL, a reinforcement learning-based energy-efficient routing protocol that optimizes routing decisions to reduce energy consumption in IoT applications. Sethi et al. [4] reviewed IoT architectures, protocols, and applications, emphasizing cluster based approaches to optimize energy usage.

Heinzelman et al. [5] presented the LEACH protocol, a foundational energy-efficient routing method for WSNs that balances energy consumption by rotating cluster heads. Bhatia et al. [6] improved the LEACH protocol for IoT networks by optimizing cluster head selection, enhancing energy efficiency and network lifetime. Behera et al. [7] conducted a survey on energy efficient routing protocols in WSNs, discussing various strategies for improving energy conservation and data transmission. Dash et al. [8] provided insights into energy aware routing strategies for IoT-enabled WSNs, addressing security and privacy challenges. Ray et al. [9] proposed an energy efficient clustering protocol based on K-means midpoint clustering, which enhances network lifetime by optimizing cluster head selection, particularly in applications like forest fire detection. Godfrey et al. [10] introduced a reinforcement learning- based routing protocol for software defined WSNs that dynamically adjusts routing paths to reduce energy consumption. Kasturi et al. [11] proposed a hierarchical clustering-based routing solution to minimize energy consumption during data transmission in IoT. Yarinezhad et al. [12] developed an energy-efficient routing protocol for IoT networks, incorporating geographical location and link quality to improve routing decisions. Altaweel et al. [13] introduced RSOCK, a resilient routing protocol for mobile Fog/Edge networks, optimizing energy efficiency in dynamic environments. Dogra et al. [14] proposed an energy-efficient routing protocol for next generation IoT, focusing on dynamic cluster head selection and routing adjustments to minimize energy consumption. De et al. [15] compared tree structures in heterogeneous WSNs, identifying energy-efficient architectures for data transmission. Ray et al. [16] also proposed an energy-efficient clustering algorithm for multi-hop WSNs, using gateway nodes to reduce energy consumption. Guo et al.[18] introduced a clustering algorithm for initializing multi-hop WSNs, optimizing energy usage through dynamic cluster sizing. Ray et al. [17] developed a level wise energy assignment strategy to balance energy consumption and extend WSN lifetime.

Wang et al. [20] proposed a multi-hop clustering and routing protocol using Enhanced Snake Optimizer and Golden Jackal Optimization to improve energy efficiency through optimal cluster head selection. Ullah et al. [21] combined fuzzy spider monkey optimization with a hidden Markov model to optimize cluster head selection and energy consumption in WSNs. Wang et al. [22] introduced the Enhanced Pelican Optimization Algorithm for cluster head selection, utilizing chaotic mapping and a fitness function to extend network lifetime. Pedditi et al. [23] presented EERP for IoT-based WSNs, designed for forest fire detection by minimizing redundant data transmission and optimizing cluster head selection. Ju et al. [24] developed an energy- efficient routing technology for WSNs that leverages selfish node behavior to reduce energy consumption. Karim et al. [25] proposed the MKFF- midpoint K-means clustering algorithm for forest fire detection, improving accuracy and energy efficiency in high risk zones. Dogra et al. [26] introduced ESEERP, an energy-efficient routing protocol for IoT that optimizes energy consumption through smart routing strategies. Khan et al. [27] proposed AZR-LEACH, an energy-efficient routing protocol using static clustering and residual energy-based cluster head selection to extend network lifespan. Akbar [28] investigated network lifetime maximization techniques in WSNs with mobile sinks, focusing on optimizing routing paths to reduce energy consumption.

III. PROPOSED WORK

Reducing energy consumption in Energy Efficient Clustering Routing for IoT (EECR-IoT) remains a significant challenge, particularly in large-scale sensor networks where power resources are limited. Existing routing protocols, including cluster-based methods, aim to optimize energy usage, but there is still room for improvement in cluster head (CH) selection and overall network efficiency. In cluster-based routing, selecting the right CHs plays a crucial role in minimizing energy consumption. The proposed routing protocol introduces static clustering, dividing large sensor fields into rectangular clusters that are further grouped into zones to improve communication between CHs and the base station (BS). This study presents an energy-efficient clustering protocol based on the Divide and Conquer Quad Tree dynamic multi-hop LEACH algorithm to enhance energy conservation in EECR-IoT systems. The protocol integrates residual energy as a key parameter, alongside euclidean distance, in a modified K-means algorithm for efficient CH selection. Multi-hop communication from CHs to the BS depends on the distance, optimizing energy usage. The proposed method significantly extends network lifetime and reduces energy consumption by up to 50% compared to traditional protocols like LEACH-B and by various margins against other existing algorithms. The research evaluates the protocol using metrics such as throughput, end-to-end delay (EED), packet drop rate (PDR), and node longevity, demonstrating substantial improvements in energy efficiency and network performance.

The proposed work consists of seven layers:

1. Perception
2. Data Preprocessing
3. Network
4. Middleware
5. Data Storage
6. Big Data Analysis
7. Business

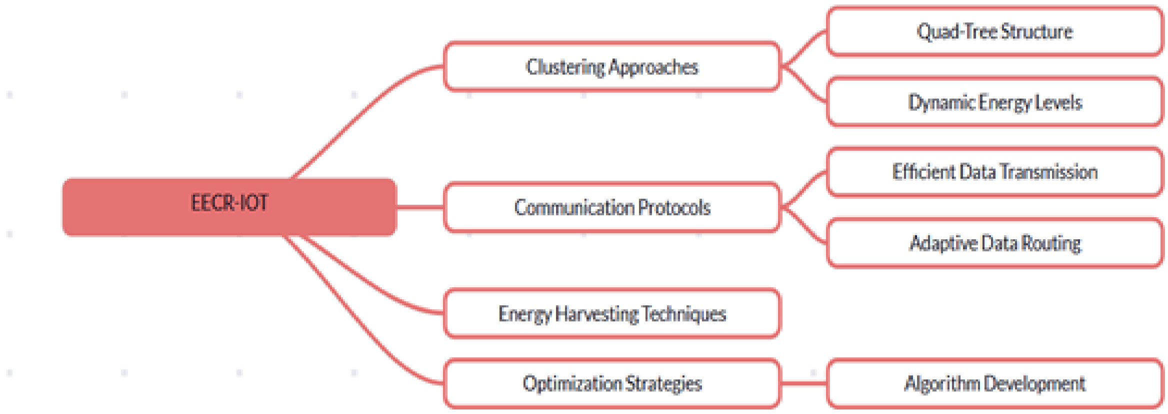

Figure 4: EECR-IOT

A. Energy-Efficient Clustering

the Figure 4 shows the Energy-Efficient Clustering approach includes two main strategies the Quad-Tree Structure and Dynamic Clustering. The Quad-Tree Structure simplifies spatial partitioning, reduces computational overhead, organizes data hierarchically based on geographical location, and enhances data aggregation efficiency. Dynamic Clustering focuses on adaptive clusters that adjust based on network dynamics, maximizing coverage while minimizing energy consumption. This approach also defines specific roles for nodes (leader, relay, standard) to improve energy distribution throughout the network.

B. Multihop Communication

The Multihop Communication strategy highlights its advantages over single hop communication by reducing distance and energy requirements. It emphasizes routing strategies such as greedy forwarding for efficient packet delivery and the use of backup paths for reliability. The concept of dynamic thresholds is introduced to adjust clustering based on current energy levels, ensuring balanced energy consumption. Regular re-evaluation of clusters and time-based re-clustering are essential for maintaining optimal performance as nodes deplete energy, with the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol serving as a key example.

C. Network Lifetime Enhancement

The Network Lifetime Enhancement section discusses strategies for extending the operational time of networks. This includes Energy Harvesting Techniques, such as solar and wind energy integration, which significantly extend operational time, along with the use of low-power communication protocols that enhance device battery life. Performance metrics such as network stability and energy consumption analysis are crucial for measuring data transmission consistency and tracking individual node energy levels, allowing for the identification of trends and areas for improvement.

D. Proposed flowchart

A comprehensive approach to optimizing energy efficiency and extending the lifetime of IoT networks is achieved through structured clustering, effective communication protocols, and innovative energy harvesting techniques. The flowchart begins with energy-efficient clustering, which encompasses two approaches: the quad-tree structure and dynamic clustering.

The Quad-Tree Structure simplifies spatial partitioning by hierarchically organizing sensor nodes based on geographic location, thereby reducing computational overhead and improving data aggregation. In contrast, dynamic clustering adapts clusters based on network dynamics, maximizing coverage while minimizing energy consumption, and assigns roles such as leader, relay, and standard nodes to optimize energy distribution. Following clustering, the multihop communication strategy emphasizes the advantages of reducing energy requirements and distance compared to single hop communication. This strategy includes greedy forwarding for efficient packet delivery and backup paths to ensure reliability in case of node failure. Finally, network lifetime enhancement focuses on extending operational time through energy harvesting techniques such as solar and wind energy, utilizing low-power communication protocols, and monitoring key metrics like network stability and energy consumption to ensure balanced and efficient performance.

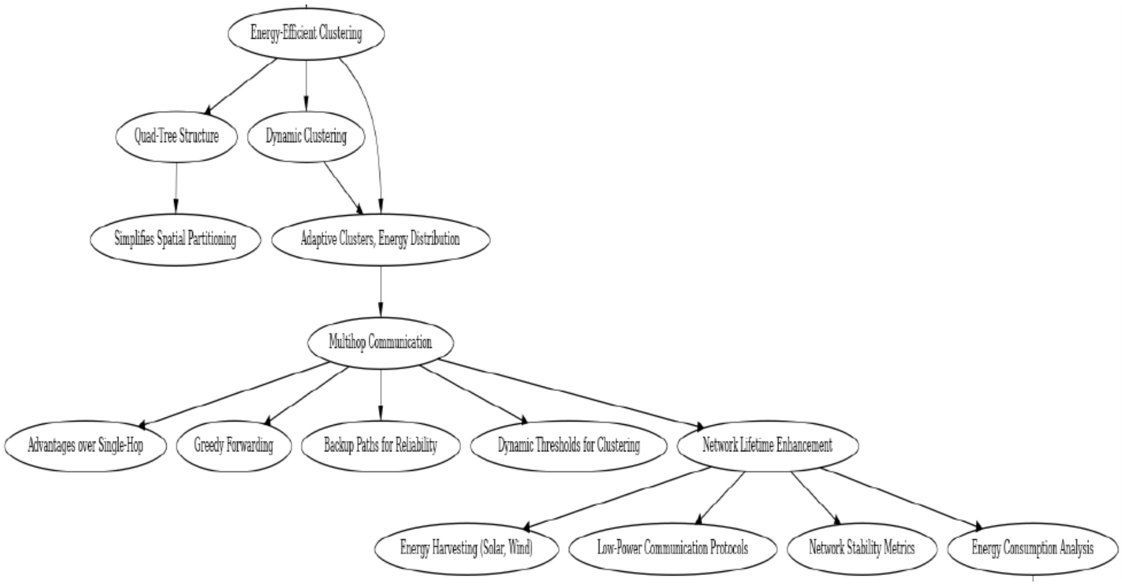

Figure 5: Performance Metrics in Network Stability.

E. Energy Efficient IoT

In the context of the EECR-IoT (Energy-Efficient Clustering and Routing Protocol for IoT), effective routing is essential for optimizing both data transmission and energy usage across sensor nodes, which typically operate with limited resources.

1) Static Routing

Static routing defines predetermined, fixed paths for communication, where the routes remain unchanged, regardless of any shifts in the network's structure or node energy levels. This method is straightforward and incurs minimal overhead, making it suitable for smaller, stable networks where node mobility and topology changes are rare. However, the rigidity of static routing can lead to inefficiencies in dynamic networks, especially when nodes deplete their energy or become unreachable, as the routes do not adjust to accommodate these changes.

2) Dynamic Routing

Dynamic routing in EECR-IoT adjusts the data paths in real time based on current network conditions, such as node energy reserves, network traffic, and environmental factors. This approach enables the routing algorithm to respond to node failures, congestion, or shifts in network topology by constantly recalculating and selecting the most energy efficient paths. While dynamic routing imposes greater computational and processing overhead, it is far more adaptable and efficient in large or fluctuating IoT environments. Dynamic routing enhances network resilience, balances energy consumption across nodes, and extends the overall network lifetime, making it particularly suitable for large scale, heterogeneous IoT deployments where nodes frequently change their status or location. Thus, the choice between static and dynamic routing in EECR-IoT hinges on the specific needs of the network, with dynamic routing offering superior flexibility and performance in more complex and evolving IoT scenarios.

F. Seven-Layer Model of Proposed Energy-Efficient Routing Protocols

The seven-layer model of our proposed energy-efficient routing protocols for EECR-IoT, utilizing the Quad Tree concept, is illustrated in Table 1. Several network routing protocols have been introduced for EECR-IoT, which can be analyzed within the context of wireless sensor networks. In this study, we examine two heterogeneous routing protocols for EECR-IoT: the direct communication routing protocol, where data is transmitted to the Base Station (Sink), and the minimum multi-hop energy-efficient routing protocol, utilizing EECR-IoT and radio models. Additionally, we explore the conventional heterogeneous clustering technique for routing and discuss its limitations, particularly when all nodes are energy-constrained.

Table 1: Seven-layer energy-efficient routing protocol architecture for EECR-IoT.

Layer No's	Layer Name's
1	Business layer(System management layer)
2	Big data analysis layer
3	Data Storage

4	Middle ware layer (Information Processing layer)
5	Network layer (Routing, Congestion, IP, Subnet/Supernet layer)
6	Data pre-processing layer(Cloud layer)
7	Perception Layer

IV. METHODOLOGY

Network Model and Datasets for Energy Efficient Routing Protocols for IoT using a Graph-Theoretic Clustered Approach An energy-efficient wireless sensor network model for IoT is proposed, focusing on the Energy Efficient Clustering and Routing (EECR-IoT) framework, which operates in heterogeneous networks. These networks comprise a total number of nodes (TN) randomly distributed across an area defined by H×J jurisdictions. Each cluster contains a number of cluster nodes (NCN), with their distribution varying randomly from 1 to a maximum of 4.

The main jurisdiction is subdivided into clusters, which can take the form of rectangles, squares, or a combination of both, depending on the network design requirements. Cluster nodes (CNs) continuously transmit data to a base station (BS). Figure 6 illustrates the EECR-IoT energy-efficient routing protocol, where various cluster heads (CHs) forward compressed data to the BS. This research is conducted on a high-standard wireless sensor network

with varying hop counts, including 30, 120, 126, and 5460. To implement energy-efficient routing protocols using a graph-theoretic clustered approach, we consider different round categories, such as 10, 25, 50, 75, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 5000.

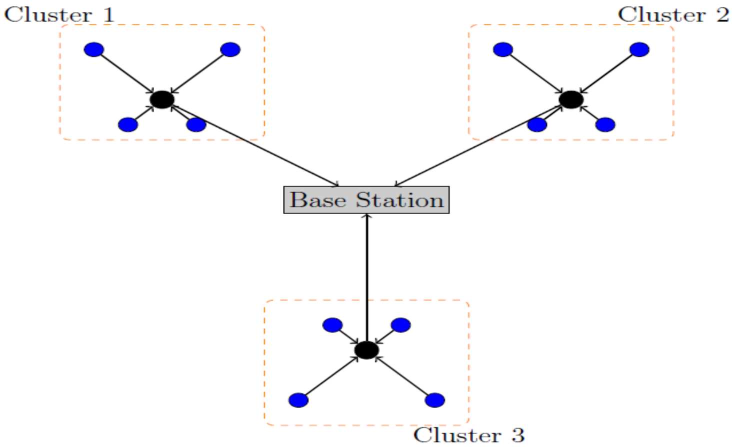

Figure 6: Cluster-based network diagram with Base Station and Sensor Nodes

A. Graph-Theoretic Approach-Based Energy Efficient Routing Protocols for IoT

According to the graph-theoretic technique, one idea to create a sensor network in IoT is represented as G = (V,E), where the vertices V specify the sensors and the set of links E specify the connections between vertices if they are specified within a given domain.

B. Cluster Graph Formation

The graph-theoretic mechanism for the cluster nodes in the Internet of Things (IoT) is specified using the following equation:

$$E_c = \{(u, v) \mid u, v \in C \wedge (u, v) \in E\} \quad (1)$$

The cluster radius is defined as the maximum distance between y (the cluster head) and any other node v:

$$r_c = \max v \in C\ d_c(y, v) \quad (2)$$

The energy computation of each cluster group is denoted as E_{cl}. By using two levels of energy, the cluster energy is calculated using the following equation:

$$E_{cl} = N_{cl}E_0(1 - j) + N_{clj}E_0(1 + h) \quad (3)$$

Where:

- E_0 is the initial energy of a normal node in the IoT network,
- N_{cl} is the total number of normal nodes,
- N_{clj} is the number of advanced nodes, and their energy is $E_0(1 + h)$,
- $E_0(1 + h)$,The sum of nodes present in each cluster is denoted as $N_{cls.}$

The updated energy of each cluster is calculated by the following equation:

$E_{cl} = N_{cl}E_0(1 + h_j)$ (4)

The total initial energy of an entire cluster is provided by the equation:

$$E_{tot} = \sum_{n=1}^{N_{cls}} E_{cl} \quad (5)$$

Where n is the total number of cluster nodes.

Algorithm 1 Quad Tree Energy Efficient Routing Protocol (EECR-IoT)

Input: E_0: Initial energy, r_1: Rectangular region
Output: Optimized energy, increased lifetime

```
begin
  // Initialization
  E ← E_0  Define r_1
  while Network Active do
    // Partitioning
    r_1 → {q_1, q_2, q_3, q_4}  BS_location ← (width(r_1)/2, height(r_1)/2)
    foreach q_i ∈ r_1 do
      ch_i ← arg max(E)  while q_i contains sub-regions do
        q_i → {q_i1, q_i2, ...} until |q_ij| = 1  ch_ij ← arg max(E)  Link
        ch_ij → ch_i
      Aggregate ∑ Data(q_i) → ch_i
    // Transmission
    foreach ch_i do
      ch_i → BS
    // Update
    E ← E − δE_tx − δE_rx  Update ch_i if E_ch < threshold
```

V. SIMULATION RESULTS AND ANALYSIS

Extensive simulations were conducted using Python and MATLAB to evaluate the performance of the proposed EECR-IoT protocol. The simulations compared EECR-IoT against existing protocols, including Low Energy Adaptive Clustering Hierarchy (LEACH), Multi-Hop LEACH (MH- LEACH), and Stable Election Protocol (SEP). The results indicate that EECR-IoT substantially extends the network lifetime, enhances overall through-put, reduces energy consumption, and optimizes cluster head selection. MAT- LAB 7.7 and Python were employed to simulate the proposed protocol, using a network setup with 100 sensor nodes within a 100 m × 100 m sensing region. By setting the base station distance dBS = 100, the desired number of cluster heads (CH) was four; when dBS was set to 85, the number of desired CHs in- creased to five. Simulations were conducted for both 4-cluster and 5-cluster network configurations. Additionally, our protocol, EECR-IoT, was compared with other energy-efficient routing protocols such as DEEC, DDEEC, EDEEC, and TDEEC, focusing on metrics such as the number of alive nodes, dead nodes, and cluster formations. The comparison also included other approaches under various network parameters within the context of EECR-IoT. This study serves as an innovative attempt to develop a mathematical model for EECR-IoT and assess its implementation and performance in comparison to DEEC and advanced LEACH protocols. The results consistently show that EECR-IoT outperforms competing protocols in extending network life- time, improving throughput, reducing energy consumption, and optimizing cluster head allocation. The comparison with DEEC protocols reveals superior performance in energy dissipation and network longevity.

Table 2 summarizes the performance metrics used to evaluate the energy- efficient dynamic routing protocol of EECR-IoT:

• Number of Dead Nodes per Round: Tracks the count of nodes that have depleted their energy in each round of network operation.
• Stability Period (SP): The time span from the start of network operation until the first node dies, representing the network's stable operation phase.
• Instability Period (ISP) / Unstable Jurisdiction (UJ): The duration between the death of the first node and the last node, indicating the network's unstable phase.

• Number of Alive Nodes per Round: Monitors the count of functioning nodes in each round.
• Throughput: The total number of packets successfully transmitted from the cluster heads (CH) to the base station (BS) over the network.
• Network Lifetime: The period from the beginning of network operation until the last sensor node dies in the IoT network.

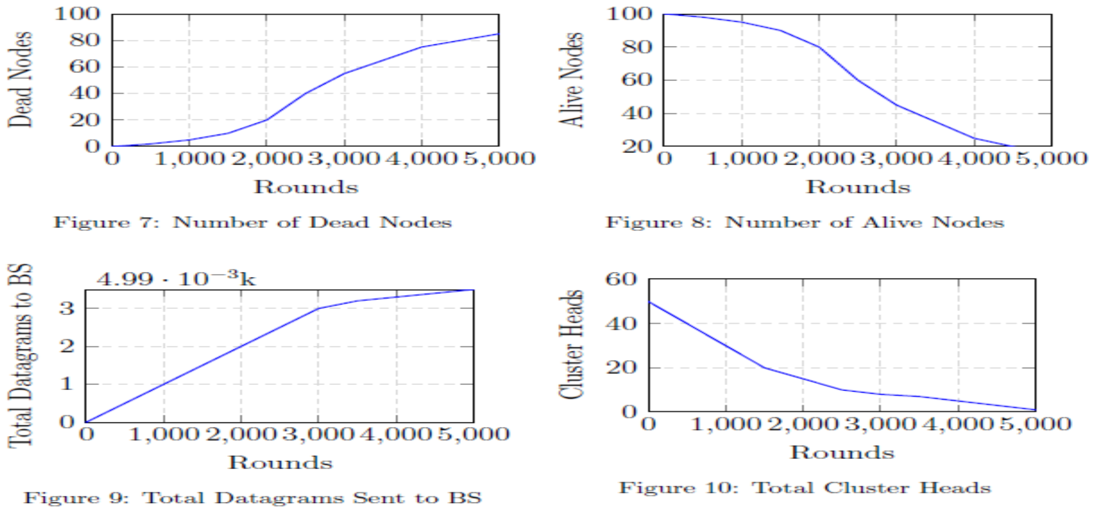

Figure 11: Performance comparison of DEEC, DDEEC, EDEEC, and TDEEC protocols.

• Reliability: A measure of network reliability based on the durations of Stable Jurisdiction (SJ) and Unstable Jurisdiction (UJ). Higher re- liability is achieved when SJ is longer and UJ is shorter.
• Number of Cluster Heads per Round: The total number of nodes selected as cluster heads (CH) in each round, responsible for aggregating and transmitting data from member nodes to the base station.

Table 2: Performance Metrics for EECR-IoT Evaluation

Metric	Description
Dead Nodes per Round	Number of nodes depleted of energy per round
Stability Period (SP)	Time from network start to the first node death
Instability Period(ISP)	Duration between first and last node death
Alive Nodes per Round	Count of nodes functioning per round
Throughput	Total packets transmitted from CHs to BS
Network Lifetime	Duration until the last node in the network dies
Reliability	Based on SJ and UJ durations
Cluster Heads per Round	Number of nodes acting as CHs per round

In this simulation, a heterogeneous energy-efficient IoT network consisting of n = 100 nodes is considered. Among these, m = 0.3 indicates that 30% of the nodes are advanced, possessing additional energy compared to the normal nodes. The simulation takes place within a rectangular field of dimensions 500 m 500 m. Table 1 provides the necessary simulation parameters for simulating the EECR-IoT protocol. In the second phase of this research, a comparison is made between various energy-efficient routing protocols for IoT, including EECR-IoT. In Figure 11, we compare the performance of four energy-efficient routing protocols: DEEC, DDEEC, EDEEC, and TDEEC. Each subfigure highlights a key performance metric:
• Dead Nodes (Subfigure 1): TDEEC and EDEEC protocols result in a higher number of dead nodes as the rounds progress, while DEEC and DDEEC show fewer dead nodes, indicating better energy efficiency 7.
• Alive Nodes (Subfigure 2): DEEC supports the fewest number of alive nodes as rounds increase, whereas TDEEC, EDEEC, and DDEEC perform better by maintaining a higher number of alive nodes 8.
• Datagrams to BS (Subfigure 3): The total datagrams sent to the base station increase over time, showing the network's throughput capacity under different protocols 9.
• Cluster Heads (Subfigure 4): The number of cluster heads de- creases as rounds progress, with DEEC maintaining cluster heads longer than other protocols 10.

Table 3: Simulation Parameters for Energy Efficient Cluster Routing Protocol for IoT (EECR-IoT)

Sl. No	Parameters	Values
1	Max number of Sensor Nodes (SNs)	5460
2	Network Size	500 m × 500 m
3	BS Location	-
4	Number of Cluster Heads (CHs)	2 to 4
5	Initial energy of a node	500 mJ
6	Data Packet Size	4000 bits
7	Energy for Normal Nodes	0.5 J
8	Probability of Cluster Heads (P)	0.1
9	E_0 (Initial Energy)	0.5 J
10	Network Size	500 m × 500 m
11	H_{opt} (Optimal Probability)	0.1
12	E_{DA} (Data Aggregation Energy Cost)	5 nJ/bit/message
13	ε_{fs} (Transmit amplifier) if $d_{\max}$ to BS $\leq d_0$	10 pJ/bit/m^2
14	ε_{mp} (Transmit amplifier) if $d_{\max}$ to BS $\geq d_0$	0.0013 pJ/bit/m^4

Table 4: Comparison of Our Propounded Approach Network Lifetime (NLT) with Respect to FND, LND, and 10th ND

Clustering Algorithm	Round FND	Round LND (AND)	10th ND	Packets Sent to BS	Packets Sent to CH	Max Number of Rounds
DEEC	1339	3054	1477	68134	42000	5000
E-DEEC	1206	2950	1388	265797	39884	5000
D-DEEC	1287	3219	1421	89486	114752	5000
Threshold-DEEC	1250	3100	1400	105000	43000	5000
SEP	4437	7468	4500	40021	15866	8000
Z-SEP	943	1500	1000	27000	15000	9000
Z-SEPREP	1044	2000	1100	24613	18000	9000
T-DEEC	1100	2800	1250	95000	40000	5000
LEACH	600	2000	700	12000	10000	2000
Multi-Hop LEACH	800	2500	900	18000	15000	3000
EECR-IoT (Our Proposed Protocol)	1500	3500	1600	310000	50000	9000

Figures 7 and 8 present further comparisons between energy-efficient routing protocols. The research confirms that the TDEEC protocol outperforms EDEEC, DDEEC, and DEEC. In Figure 7, TDEEC is evaluated against the other protocols in terms of the number of packets sent to the base station (BS) as the rounds progress. The results show that TDEEC consistently sends the most packets, demonstrating its superior performance. In Figure 8, the research compares the number of cluster heads (CHs) selected per round across the protocols. DDEEC emerges as the most efficient, selecting more cluster heads than EDEEC, TDEEC, and DEEC, thereby demonstrating better overall performance. Figure 9 highlights an energy comparison between the proposed DCQMS-Leach protocol and DEEC using bar charts, with parameters set at m = 0.3 and a = 1. The results indicate that the DCQMS-Leach protocol outperforms DEEC, maintaining energy efficiency up to approximately 4000 rounds. As shown in Figure 10, the energy consumption of the Leach, DEEC, and EECR-IoT protocols is illustrated, con- firming that EECR-IoT is more energy-efficient than both Leach and DEEC.

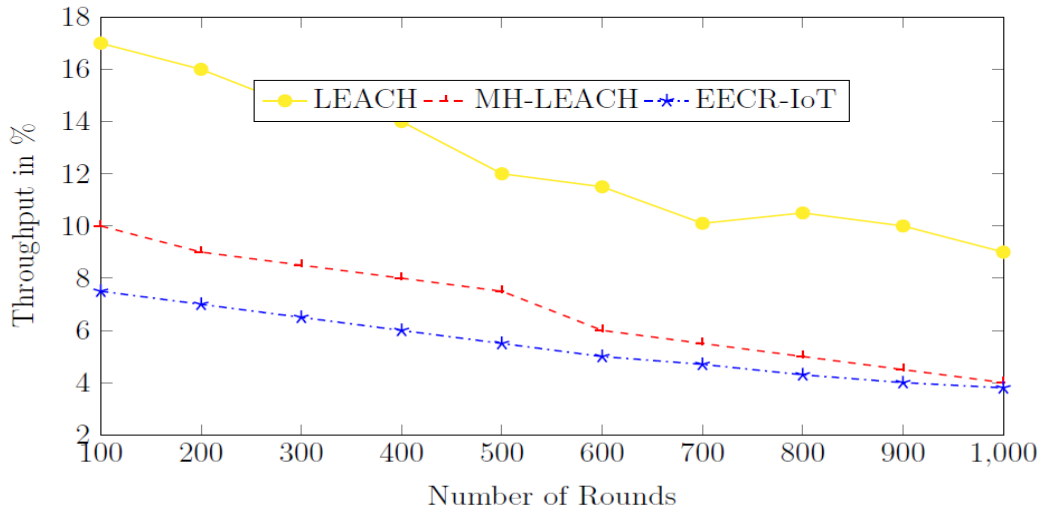

Figure 12: Comparison of throughput for Leach, MH-Leach and EECR-IoT (Quad Tree) energy efficient routing protocols

Clustering is an effective approach for data aggregation in EECR-IoT networks, significantly reducing energy consumption and promoting uniform coverage. Although energy-efficient routing protocols are widely adopted in EECR-IoT and WSNs, single-hop communication limits their effectiveness. In this research, we demonstrated that throughput and packet loss rate are inversely proportional to the number of rounds, while the dead node rate is directly proportional. This study evaluates tree-based static multi-hop Leach energy-efficient routing protocols for EECR-IoT, using graph-theoretic approaches like binary tree-based static multi-hop routing and quad tree- based dynamic multi-hop routing. The Comparison of throughput for Leach, MH-Leach and EECR-IoT (Quad Tree) energy efficient routing protocols is as shown in Figure 12.

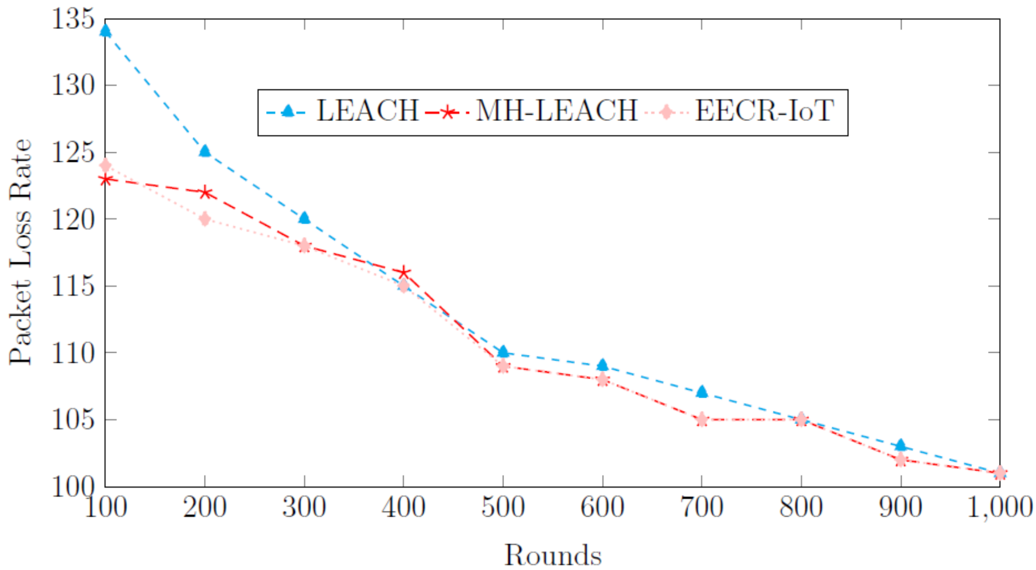

Figure 13: Comparison of Packet Loss Rate (Packet Drop Rate) for Leach, MH-Leach and EECR-IoT (Quad Tree) energy efficient routing protocols.

In this comparison, in Figure 13 we evaluate the packet loss rate of three energy-efficient IoT routing protocols: LEACH, MH-LEACH, and EECR- IoT (Quad Tree). The packet loss rate indicates the percentage of data packets that do not reach their destination, affecting network reliability and efficiency. The LEACH protocol shows a high packet loss rate at first, which decreases as the rounds progress, indicating initial inefficiency that improves over time. MH-LEACH has a slightly lower initial packet loss rate than LEACH but also trends downward, stabilizing around the same rate by the 1000th round. In contrast, the EECR-IoT protocol maintains a lower packet loss rate throughout all rounds. It starts slightly higher than MH-LEACH but quickly stabilizes, demonstrating its effectiveness in minimizing packet loss over time. This comparison shows that while all three protocols even- tually achieve similar packet loss rates, EECR-IoT performs more efficiently, maintaining lower rates consistently and reaching stability earlier than the others. This analysis can aid in choosing the right protocol based on network stability and energy efficiency needs.

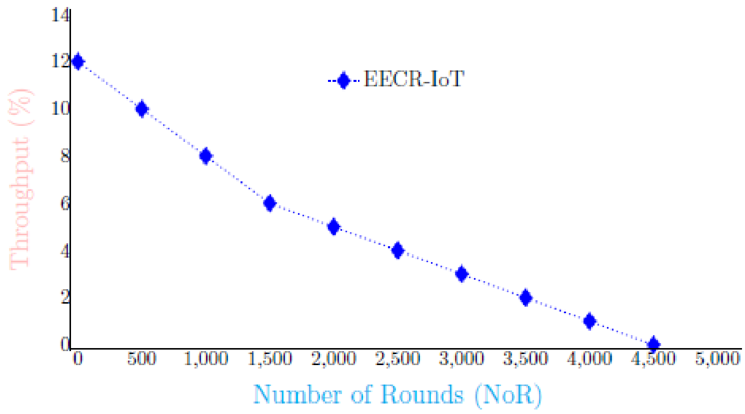

Figure 14: Calculation of Throughput for EECR-IoT (Quad Tree) energy efficient routing protocols when Number of Sensor Hops (SHs) are 120, CHs=3, and Number of Levels=3.

The Figure depicts the throughput of the EECR-IoT (Quad Tree) energy- efficient routing protocol across a range of rounds, from 0 to 5000. The x-axis represents the number of rounds (NoR), while the y-axis indicates throughput, measured in percentage (%), ranging from 0 to 14%. The data shows an initial throughput of 12% at round 0, which gradually declines as the number of rounds increases. Specifically, the throughput drops to 10% by the 500th round and continues to decrease to 1% by the 4000th round. By the end of the 4500th round, the throughput reaches 0%, indicating a complete loss of effective communication. This downward trend illustrates the challenges faced by the EECR-IoT protocol in maintaining data transmission efficiency over extended periods. The analysis suggests that while the protocol starts with a reasonable throughput, its performance diminishes significantly with the increase in rounds, highlighting the need for optimizations to enhance its long-term operational capabilities in IoT networks.

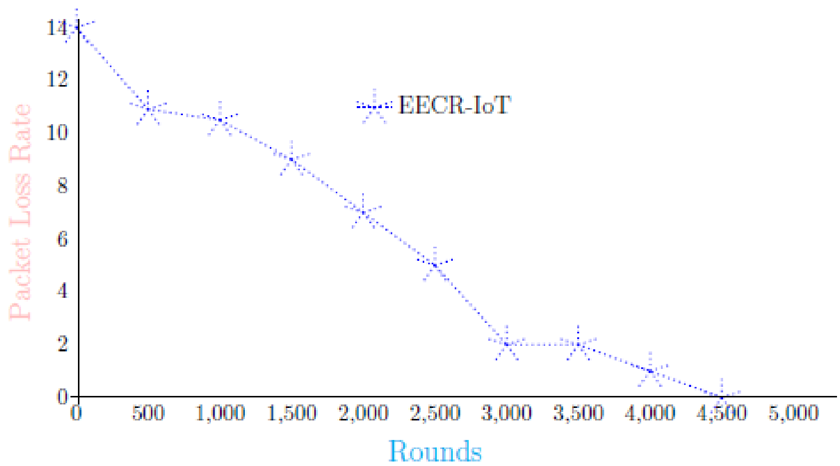

Figure 15: Calculation of Packet Drop Rate (Packet Loss Rate) for EECR-IoT Quad Tree) energy efficient routing protocols when Number of Sensor Hops (SHs) are 120, CHs=3, and Number of Levels=3. Calculation of DNR (%) for EECR-IoT when Sensor Hops=120, CHs=3, Number of Levels=3.

The Figure 15 illustrates the packet loss rate of the EECR-IoT (Quad Tree) energy-efficient routing protocol as the number of rounds increases. The x-axis represents the number of rounds, ranging from 0 to 5000, while the y-axis indicates the packet loss rate, measured from 0 to 14 percent. As shown, the EECR-IoT protocol begins with a packet loss rate of 14 percent at round 0, which signifies an initial level of inefficiency. However, as the rounds progress, the packet loss rate decreases significantly. By round 500, the rate drops to approximately 10.9 percent, and it continues to decline steadily to reach around 0 percent by round 4500. This consistent decrease in packet loss rate demonstrates the protocol's effectiveness in minimizing data loss over time, indicating its reliability for long-term network operations. Overall, the EECR-IoT protocol's performance highlights its capability to maintain efficient communication in IoT networks, making it a suitable choice for applications requiring robust data transmission.

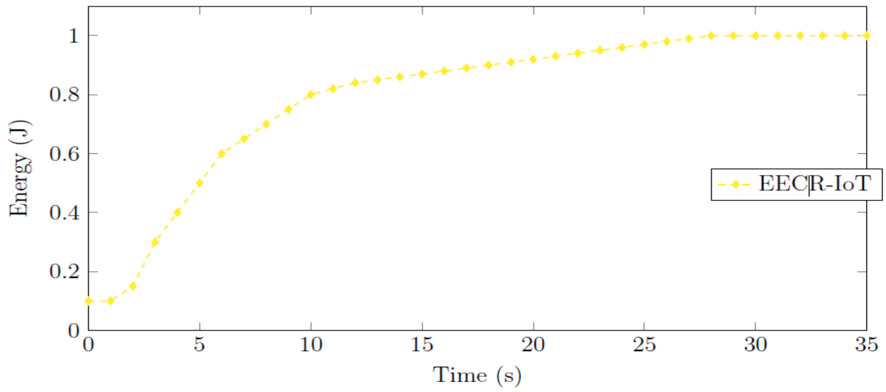

Figure 16: Calculation of Dead Node Rate for EECR-IoT (Quad Tree) energy efficient routing protocols when Number of Sensor Hops (SHs) are 120, CHs=3, and Number of Levels=3

The Figure 16 illustrates the Dead Node Rate (DNR) for the EECR- IoT (Quad Tree) energy-efficient routing protocol over a time span of 35 seconds. The x-axis represents time in seconds, while the y-axis indicates energy consumption in joules, ranging from 0 to 1.1 J. As shown in the graph, the energy consumption starts at 0.1 J and gradually increases over time. Notably, there are significant incremental increases in energy usage during the initial seconds, particularly from 0.1 J at 0 seconds to 0.5 J by the 5-second mark. As time progresses, the energy consumption continues to rise, reaching 1.0 J by the 28-second mark and stabilizing thereafter. The consistent growth of energy utilization indicates the protocol's efficiency in managing energy resources, crucial for prolonging the operational lifespan of IoT devices. This analysis suggests that the EECR-IoT protocol effectively maintains energy efficiency while handling increased communication demands in IoT networks, making it suitable for applications that rely on extended device uptime.

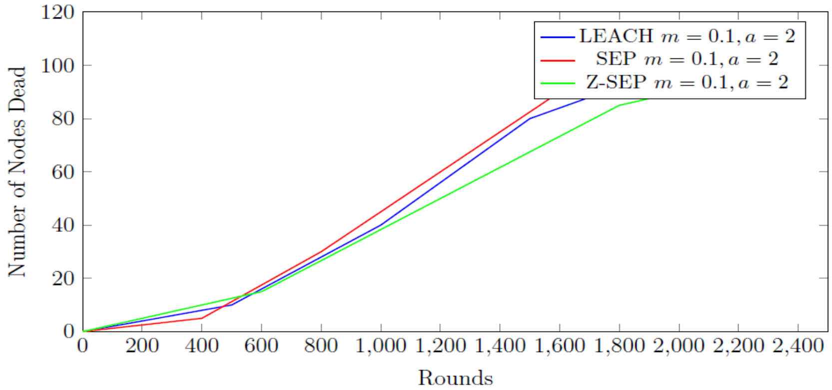

Figure 17: Comparison between LEACH, SEP and Z-SEP Packet sent to BS when m=0.2 and a=1

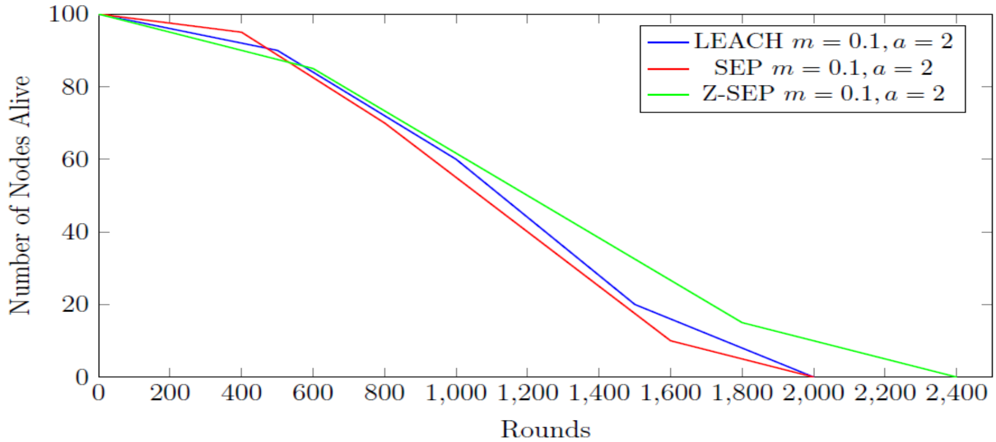

Figure 18: Comparison between LEACH, SEP and Z-SEP alive nodes when m=0.2 and a=1.

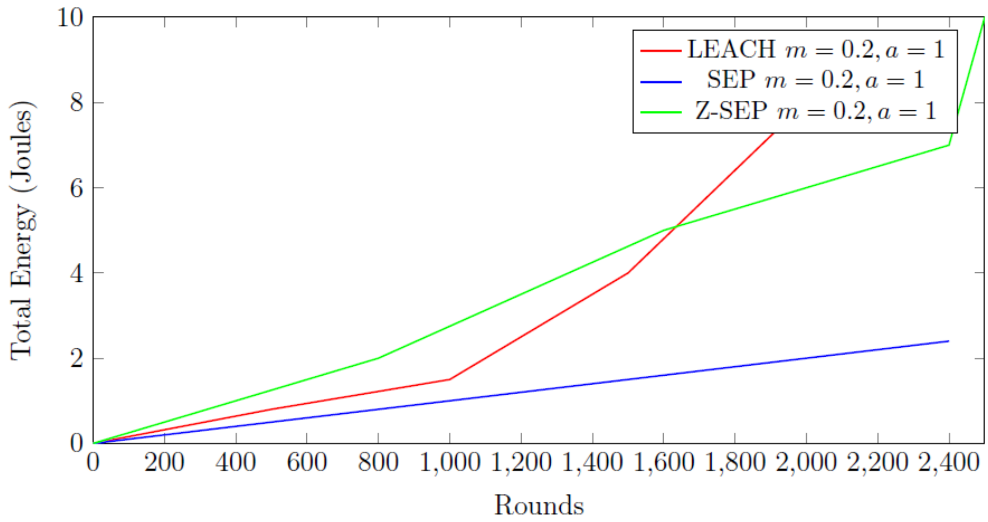

Figure 19: Comparison between LEACH, SEP and Z-SEP Dead nodes when m=0.2 and a=1.

Using MATLAB for the simulations, the experiments included 1500 rounds to compare EECR-IoT with LEACH 17, MH-LEACH 18, and SEP 19. The results, depicted, show that EECR-IoT has a longer stability period com- pared to LEACH and SEP, though slightly shorter than MH-LEACH. The first node in EECR-IoT dies after approximately 80 rounds, while the first nodes in LEACH, MH-LEACH, and SEP die after around 39, 107, and 62 rounds, respectively. Over 1500 rounds, the stability periods for LEACH, MH-LEACH, SEP, and EECR-IoT are 2.6%, 7.1%, 4.13%, and 5.33%, respectively, with MH-LEACH having better stability but a shorter overall network lifetime compared to EECR-IoT. Comparison between LEACH, SEP, and Z-SEP alive nodes when m = 0.2 and a = 1. the energy consumption com- parison among LEACH, DEEC, and EECR-IoT protocols in wireless sensor networks (WSNs) is shown. The final node in LEACH, MH-LEACH, SEP, and EECR-IoT dies after 1079, 1113, 1284, and 1401 rounds, respectively, in- dicating that EECR-IoT's network lifetime is 23%, 20.56%, and 8.35% longer than that of LEACH, MH-LEACH, and SEP. In terms of throughput, EECR- IoT significantly outperforms LEACH, MH-LEACH, and SEP in both stable and unstable regions, delivering 23.39%, 31.51%, and 47.42% more packets to the base station. This is due to EECR-IoT's static clustering and efficient selection of cluster heads, proving that it offers higher throughput than the other protocols. Comparison between LEACH, SEP, and Z-SEP dead nodes when m = 0.2 and a = 1 illustrates the prediction of throughput when m = 0.3 and a = 1, highlighting the total number of packets forwarded to the base station (Sink) for the protocols:

- LEACH
- DEEC
- EECR-IoT

This comparison of throughput for LEACH, DEEC, and EECR-IoT routing protocols indicates the efficiency of EECR-IoT. Depicts the total number of alive and dead nodes in energy-efficient routing protocols over different rounds.

VI. CONCLUSION

Clustering is an effective approach for data aggregation in EECR-IoT networks, significantly reducing energy consumption and promoting uniform coverage. Although energy-efficient routing protocols are widely adopted in EECR-IoT and WSNs, single-hop communication limits their effective- ness. In this research, we demonstrated that throughput and packet loss rate are inversely proportional to the number of rounds, while the dead node rate is directly proportional. This study evaluates tree-based static multi-hop LEACH energy-efficient routing protocols for EECR-IoT, using graph-theoretic approaches like binary tree-based static multi-hop routing and quad tree-based dynamic multi-hop routing. We also examine the challenges of maximizing network lifetime under constraints such as throughput, end-to-end delay, and packet loss rate. These analyses and simulations lay the groundwork for future research on tree-based dynamic multi-hop routing protocols for EECR-IoT, applicable to various scenarios such as audio, video, and multimedia transmissions. This article addresses the implementation of tree-based energy-efficient routing protocols using binary, ternary, and quad trees in a wireless sensor network context. The dynamic and evolving nature of WSN performance metrics makes this a complex area of study.

VII. FUTURE WORK

Future work will focus on enhancing these protocols by incorporating additional performance metrics, refining algorithms, and extending the research to static multi-hop protocols using advanced data structures like singly linked lists, doubly linked lists, circular linked lists, reverse linked lists, and concepts like dynamic programming, divide-and-conquer, and minimum spanning trees. A critical next step is testing and validating the proposed algorithms using real-world data.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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