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HERP-Next: Hybrid Energy Routing Protocol for Next-Gen Heterogenous Networks

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Abstract. The energy efficiency of the network, as well as its strength and durability, are two of the most significant factors to take into consideration when it comes to the design and operation of Wireless Sensor Networks (WSNs). These are the two most crucial items to take into consideration. In particular, this is the case in ecosystems that are diverse, which are habitats in which nodes have varied quantities of energy and capacity depending on the environment in which they are located. In order to effectively deal with these problems, hierarchical protocols that are based on clustering have emerged as potential solutions that can be of assistance. These protocols make use of better techniques in order to construct routing systems that are more efficient in terms of the amount of energy that they consume. In the course of this investigation, one of the cutting-edge protocols that is discussed is referred to as HERP-Next. This is an abbreviation that stands for Hybrid Energy Routing Protocol for Next-Generation Networks. Another one of the unique protocols that is being investigated is this particular protocol. In order to achieve the goal of maximizing the consumption of energy while simultaneously improving the stability and longevity of heterogeneous wireless sensor networks (WSNs), this initiative is being undertaken. The network is divided into a number of distinct zones for the purpose of the suggested protocol, which takes into consideration the various kinds of nodes and the patterns in which they are dispersed spatially. Following that, these zones are utilized in order to interact with two more zones during the subsequent phase. Due to the fact that this is the case, it is assured that the amount of energy that is utilized by both advanced and normal nodes is the same across the board. Both the amount of residual energy and the density of the nodes that are positioned in close vicinity to the Cluster Heads (CHs) are taken into consideration during the selection process, which is carried out in a dynamic way. The utilization of energy-aware routing and clustering is something that HERP-Next does in order to ensure that data aggregation and communication with the Base Station (BS) happen in an efficient manner. The accomplishment of this work is made possible through the utilization of these two distinct technologies in conjunction with one another. When compared to older protocols such as LEACH and SEP, HERP-Next is undeniably superior in terms of the network lifetime, stability period, and data throughput. This is made abundantly clear by the fact that HERP-Next performs significantly better than various protocols currently in use. The findings of the simulation that was carried out led to the formation of this conclusion. Therefore, it is clear that HERP-future offers a solution that is not only dependable but also scalable for heterogeneous wireless sensor networks of the next generation. This conclusion is based on the findings of the study. Consequently, it is a good choice for applications that demand steady data transfer applications as well as applications that require energy economy. This is because of the fact that it is a combination of the two.

Keywords: HERP-Next, LEACH, WSN, Cluster Heads, SEP, Base Station, Hybrid Energy, Durability, Protocols, Clustering

Introduction:

A Wireless Sensor Networks (WSNs) are widely used in various applications such as environmental monitoring, disaster management, healthcare, and military surveillance. These networks consist of numerous sensor nodes that collect and transmit data to a central Base Station (BS). However, the limited energy resources of sensor nodes pose a significant challenge, especially in large-scale deployments where efficient energy utilization is crucial to prolong network lifetime.

In heterogeneous WSNs, nodes are classified based on their energy levels, with advanced nodes having higher energy compared to normal nodes. This heterogeneity creates opportunities to design energy-efficient routing protocols that balance energy consumption while ensuring reliable data communication. Hierarchical clustering protocols have proven to be effective in reducing energy dissipation by organizing nodes into clusters and selecting Cluster Heads (CHs) to manage communication.

This paper introduces HERP-Next (Hybrid Energy Routing Protocol for Next-Gen Networks), a robust routing protocol designed for heterogeneous WSNs. HERP-Next incorporates region-based clustering and energy-aware CH selection to optimize energy usage and extend network longevity. By considering residual energy and node density during CH selection, the protocol minimizes energy imbalances and enhances network performance. The proposed protocol is evaluated through simulations, demonstrating significant improvements in stability period, data throughput, and network lifetime compared to existing protocols like LEACH and SEP. HERP-Next provides an energy-efficient solution for heterogeneous WSNs, addressing the challenges of next-generation network deployments.

Related Work:

The Energy efficiency in Wireless Sensor Networks (WSNs) has been a prominent area of research, particularly for heterogeneous networks where nodes possess varying levels of energy and computational power. Numerous routing protocols have been developed to address the challenges of energy dissipation, network stability, and lifetime extension.

The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol is one of the earliest and most widely studied hierarchical routing protocols. LEACH operates by randomly selecting Cluster Heads (CHs) in each round, distributing the energy load evenly across nodes. However, it assumes a homogeneous network, making it less effective in heterogeneous environments where nodes have different energy levels.

To address heterogeneity, the Stable Election Protocol (SEP) was proposed, which introduces weighted probabilities for CH selection based on node energy levels. SEP improves the stability period and energy efficiency in two-level heterogeneous networks by favoring advanced nodes for CH selection. However, SEP does not account for the residual energy of nodes during subsequent rounds, limiting its long-term effectiveness.

The Enhanced Stable Election Protocol (ESEP) extends SEP by introducing a three-level node hierarchy (super, advanced, and normal nodes) to further balance energy consumption. While ESEP enhances network lifetime, its static configuration of energy levels may not adapt well to dynamic network conditions.

The Hybrid Energy-Efficient Distributed Clustering (HEED) protocol improves CH selection by considering both residual energy and communication cost. HEED achieves better energy distribution and avoids the randomness of LEACH, but its overhead for iterative CH selection can impact efficiency in large-scale networks.

Recent works have introduced hybrid protocols that integrate clustering with other techniques, such as tree-based routing and fuzzy logic. These approaches aim to optimize CH selection and data routing based on multiple parameters, including energy, distance, and node density. Despite these advancements, challenges remain in achieving a balance between computational complexity and energy efficiency, especially for next-generation heterogeneous networks.

The proposed HERP-Next protocol builds on these existing approaches by incorporating a region-based clustering mechanism and a dynamic CH selection process that considers residual energy and node density. This hybrid approach addresses the limitations of existing protocols and provides a scalable solution for energy-efficient routing in heterogeneous WSNs.

Overview of Network System Models

HERP-Next (Hybrid Energy Routing Protocol for Next-Gen Heterogeneous Networks) is designed to optimize energy efficiency and routing in diverse, next-generation network environments. Below is an outline of typical network system models used within HERP-Next:

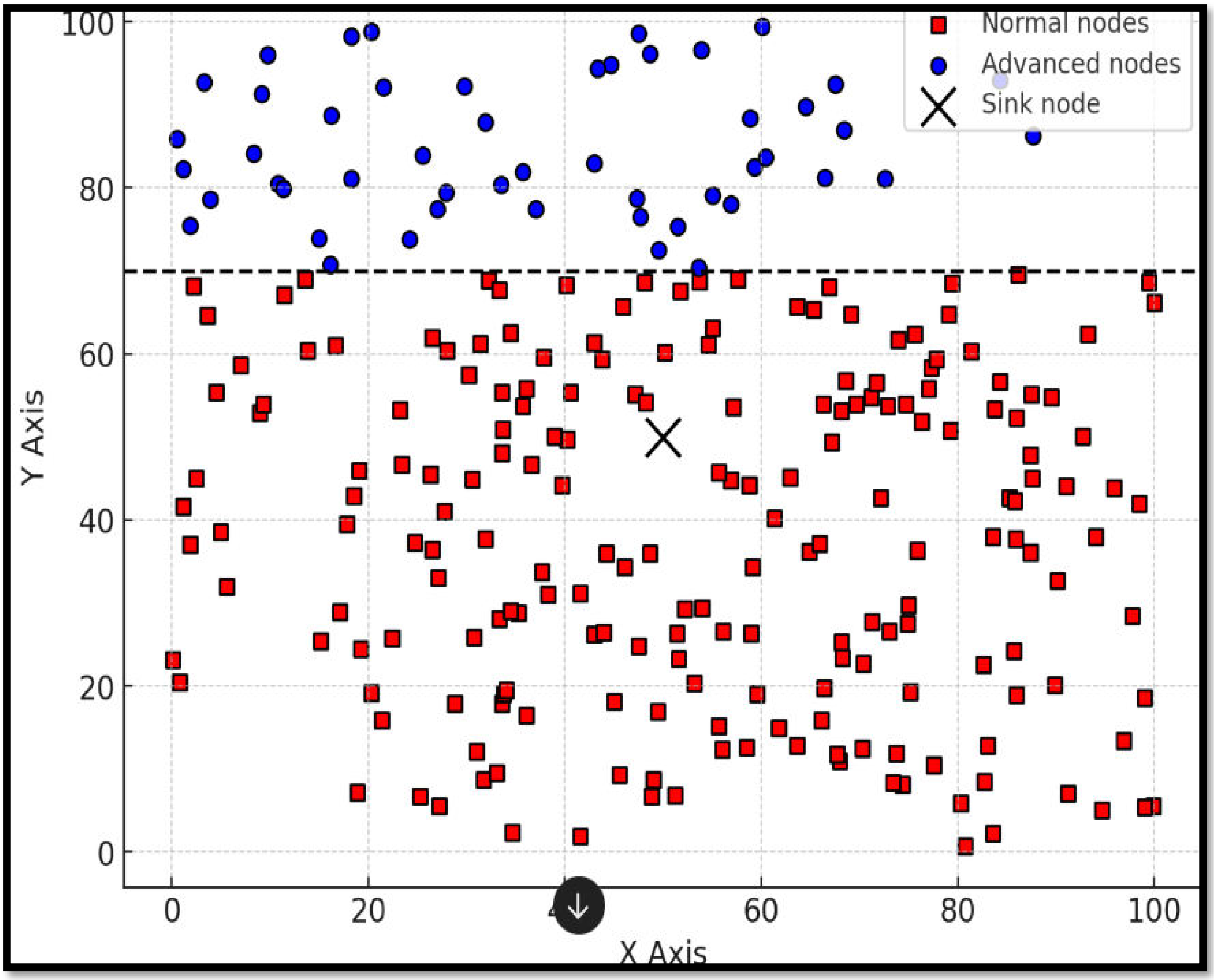


Fig I. Network Architecture

Region number	Dimension	Type of nodes	No.of nodes
1	0<X<=100 25<Y<=75	Normal	100
2	0<X<=100 75<Y<=100	Advanced	50

Table I. Proposed Network Architecture table

1. Network Architecture

- Heterogeneous Network Nodes:
    - Nodes with varying capabilities (e.g., energy levels, processing power, communication range).
- Cluster-Based Hierarchy:
    - Clustering of nodes to reduce energy consumption.
    - Cluster heads act as intermediaries for data transmission, balancing load and optimizing routes.
- Gateway Integration:
    - Gateways bridge clusters or sub-networks, enabling cross-cluster communication.

2. Energy Model

- Residual Energy Considerations:
    - Nodes monitor and share their remaining energy levels for dynamic routing.
- Energy Harvesting Nodes:
    - Some nodes integrate renewable energy harvesting (e.g., solar, wind) to prolong network lifetime.
- Energy Consumption Metrics:
    - Transmission and reception energy costs.
    - Idle energy dissipation for inactive states.

3. Routing Model

- Hybrid Approach:
    - Combines proactive routing (maintains routing tables) and reactive routing (on-demand path discovery) for efficiency.
- QoS-Aware Routing:
    - Prioritizes paths based on latency, throughput, and energy consumption.
- Load Balancing:
    - Distributes data transmission evenly to prevent rapid depletion of high-energy nodes.

4. Communication Model

- Multi-Hop Communication:
    - Data travels through multiple nodes to reach the destination, reducing direct transmission costs.
- Data Aggregation:
    - Intermediate nodes aggregate and compress data to minimize redundancy and save energy.

- Priority-Baed Transmission:
    - Critical data packets (e.g., alerts) are prioritized in transmission queues.

Preferred Strategy

The Hybrid Energy Routing Protocol (HERP-Next) for Next-Generation Heterogeneous Networks is a theoretical or proposed framework that would focus on optimizing energy efficiency in heterogeneous wireless networks. In such systems, nodes often differ in terms of energy capacity, communication range, and computational power. Here's a breakdown of a preferred strategy that such a protocol might adopt:

1. Cluster-Based Hierarchical Routing

- **Cluster Formation:** Group nodes into clusters based on their proximity or similarity in characteristics (e.g., energy level or data needs).
- **Cluster Heads (CHs):** Select nodes with higher energy and computational resources as cluster heads. Use algorithms like Fuzzy Logic, Artificial Neural Networks, or Machine Learning for adaptive CH selection.
- **Inter-Cluster Communication:** Route data between clusters via CHs to reduce redundant transmissions and minimize energy consumption.

2. Multi-Criteria Node Selection

- **Energy-Aware Selection:** Prioritize nodes with high residual energy to minimize node failure and extend network lifespan.
- **Node Mobility:** Incorporate dynamic algorithms to handle mobile nodes and ensure connectivity in a heterogeneous environment.
- **QoS Constraints:** Factor in Quality of Service (QoS) requirements like latency, bandwidth, and reliability.

3. Hybrid Routing Protocol

- **Proactive + Reactive Approach:** Combine proactive methods for frequently-used routes (e.g., base station to cluster heads) and reactive methods for rarely-used routes to reduce overhead.
- **Energy-Optimized Route Discovery:** Implement algorithms that discover the most energy-efficient paths based on current network conditions.

4. Adaptive Energy Harvesting

- Integrate renewable energy sources (e.g., solar panels or energy scavenging mechanisms) into high-power nodes.
- Develop protocols to balance energy consumption and harvesting cycles effectively.

5. Data Aggregation and Compression

- Perform data aggregation at CHs to minimize redundant data transmission.

- Use lightweight data compression algorithms for resource-constrained nodes.

6. Cross-Layer Optimization

- Enhance communication efficiency by enabling interaction between layers (e.g., routing, MAC, and physical layers) to share energy metrics, link quality, and load information.
- Employ machine learning techniques for predicting network performance metrics.

7. Fault Tolerance and Scalability

- Design mechanisms to dynamically adjust the network topology in case of node or link failures.
- Use lightweight routing algorithms to maintain efficiency as the network scales.

8. Security Considerations

- Implement lightweight encryption and authentication to secure communication without significant energy overhead.
- Use anomaly detection systems to identify malicious nodes or activities.

A. Types of Communication

There are two different forms of communication:

1. Intra-Cluster Communication

- Definition: Communication within a cluster, typically between normal nodes and their respective Cluster Head (CH).
- Purpose:
  - Normal nodes send sensed data to the CH for aggregation.
  - CH minimizes redundant data before forwarding.
- Features:
  - Short-range communication.
  - Low energy consumption due to proximity.
- Techniques:
  - Time Division Multiple Access (TDMA): Nodes communicate with CH in assigned time slots to avoid collisions.
  - Energy-Efficient Encoding: To minimize energy spent per transmission.

2. Inter-Cluster Communication

- Definition: Communication between Cluster Heads (CHs) of different clusters orregions.
- Purpose:

    - CHs exchange aggregated data or relay information toward the base station.
- Features:
    - Medium-range communication.
    - Requires more energy compared to intra-cluster communication.
- Techniques:
    - Multi-Hop Routing: CHs forward data through neighboring CHs toward the base station.
    - Direct Transmission: Used if CH has sufficient energy and proximity to the base station.

3. Node-to-Base Station (Direct) Communication

- Definition: Nodes (normal or CHs) communicate directly with the base station.
- Purpose:
    - Directly relay urgent or critical data to the base station.
    - Serve as a fallback mechanism when CHs are unavailable.
- Features:
    - High energy consumption, suitable for nodes with high energy reserves.
- Techniques:
    - Direct Line-of-Sight Transmission for advanced nodes with high energy capacity.

4. Cross-Region Communication

- Definition: Communication between nodes or CHs across different regions.
- Purpose:
    - To maintain connectivity and data flow across network regions.
- Features:
    - Involves advanced nodes from different regions acting as bridges.
- Techniques:
    - Hierarchical Routing: Data is relayed through CHs in Region 2 for efficient cross-region transfer.
    - Energy-Aware Path Selection: Routes are chosen to minimize energy consumption.

5. Base Station-to-Node Communication

- Definition: Communication initiated by the base station to nodes or CHs.
- Purpose:
    - For configuration, command dissemination, or updates.
- Features:
    - Generally infrequent and centralized.
- Techniques:

  - Broadcast for all nodes.
  - Targeted unicast for specific CHs or advanced nodes.

6. Opportunistic Communication

- Definition: Communication using opportunistic connections when direct or predefined paths are unavailable.
- Purpose:
  - To maintain robustness in dynamic or mobile environments.
- Features:
  - Data is temporarily stored and forwarded when a suitable node is available.
- Techniques:
  - Store-and-Forward approach.
  - Delay-Tolerant Networking (DTN) protocols.

B. Proposed Model for Data Transmission.

Algorithm: Energy-Aware Communication with Stationary Base Station

Algorithm Steps

1. Initialization Phase

1. **Input:**
   - Network topology NN: A set of nodes $N=\{n1,n2,\dots,nm\}$.
   - Base station BSBS: A stationary sink node located at a fixed position.
   - Node parameters: Initial energy Ei, coordinates (xi,yi), node type (normal/advanced).
   - Communication range RR.
2. **Cluster Formation:**
   - Divide the network into regions based on geographical dimensions.
   - **Cluster Heads (CHs) Selection:**
     - Select CHs based on:

$$F(ni)=w1\cdot Ei/Emax+w2\cdot di,\ BS/dmax$$

where:

- Ei: Residual energy of node ni.
- di, Distance of node ni from the base station.
- $w1,w2$: Weight factors (e.g., $w1=0.7,w2=0.3$).

2. Data Transmission Phase

A. Intra-Cluster Communication

1. Each normal node ni senses data and transmits it to its associated CH.
2. Transmission energy Etx is calculated as:

$$Etx=Eelec+\epsilon amp\cdot d^2$$

where:

- Eelec: Energy to operate the transmitter.
- ϵamp: Amplifier constant.
- d: Distance between n*i* and its CH.

3. Nodes only transmit data when:

Ei>Ethreshold

to prevent premature node failure.

B. Inter-Cluster Communication

4. Cluster Heads aggregate data from intra-cluster nodes.
5. CH-to-CH communication:
    - If CHi,BS>R, use **multi-hoprouting**:
    - *E*multi-hop=min (*E*path)
      where
    - Epath is the total energy of a routing path.
6. If CHi, BS≤R, CH transmits directly to the base station.

3. Energy Balancing Phase

1. **Dynamic CH Rotation:**
    - Rotate CH roles periodically to balance energy consumption among nodes.
    - New CH selection uses the same formula as in initialization.
2. **Load Balancing:**
    - If a CH is overburdened, data is offloaded to the nearest CH with sufficient energy.
3. **Sleep Scheduling:**
    - Nodes alternate between active and sleep modes based on data generation rates to conserve energy.

4. Fault Tolerance

1. **Backup CHs:**
    - Preselect backup CHs based on energy reserves and location proximity.
    - If a primary CH fails, a backup CH takes over.
2. **Re-Routing:**
    - Nodes reroute data via alternative CHs or directly to the base station in case of CH failure.

5. Termination

- Repeat until a majority of nodes have depleted their energy or the network disconnects.

C. Flowchart of HERP-NEXT Protocol

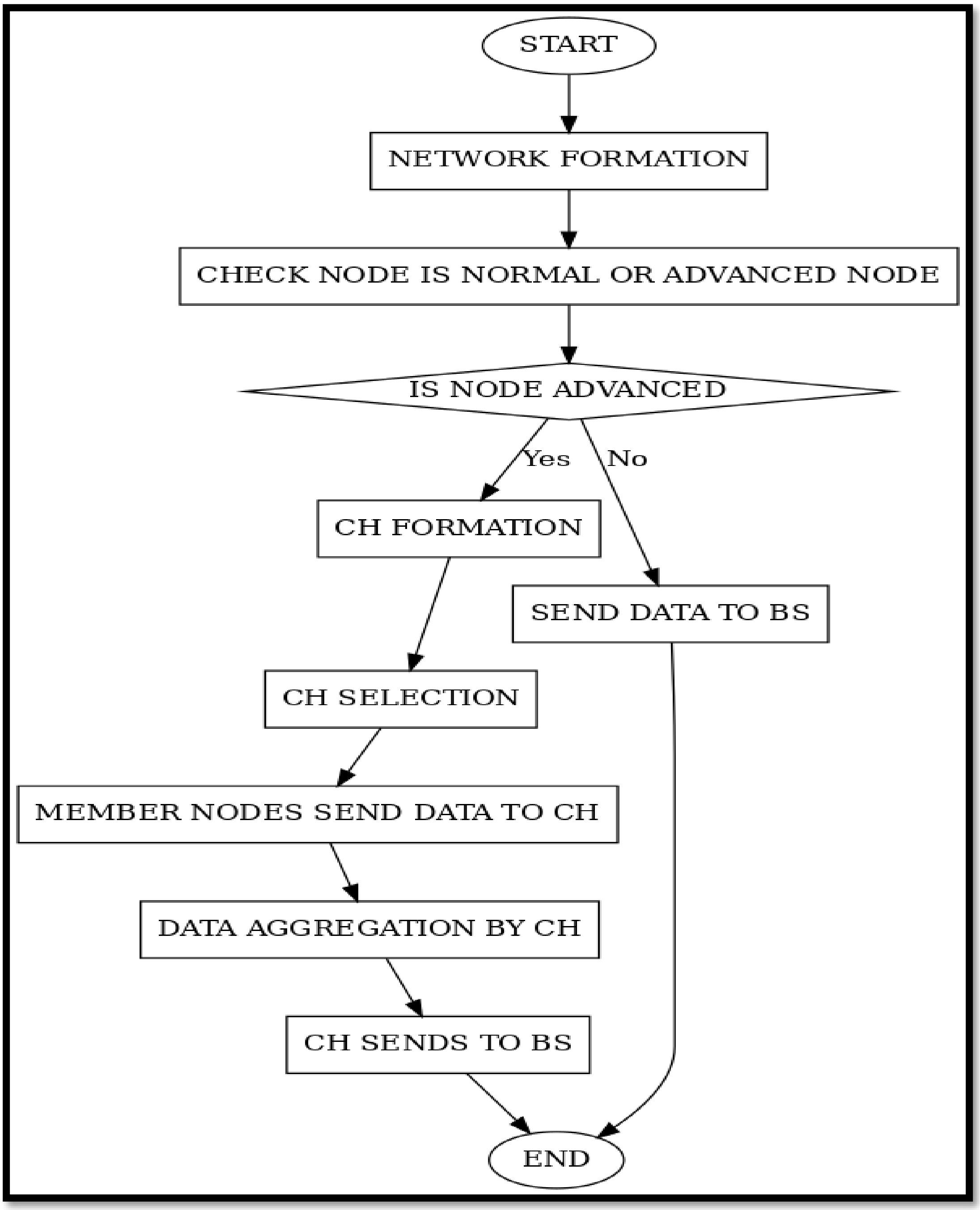


Fig. II. Flowchart of HERP-NEXT Protocol

D. Proposed Algorithm for Cluster Head Selection

Algorithm: ML Based Cluster Head Selection with Energy, Concentration, and Node Centrality

Steps:

1. Initialization

1. Deploy NN nodes randomly in the network area.
2. Assign initial energy Einit to each node.
3. Define thresholds:
    - Eth: Minimum energy required to become a CH.
    - Cth: Minimum concentration of nearby nodes.
    - Dth: Minimum centrality score.

2. Calculate Metrics

1. Energy Ei:
    - Monitor the remaining energy of each node i.

2. Concentration Ci:
    - $C_i = \sum_{j=1}^{N} \text{isNeighbor}(i,j)$, where

$$\text{isNeighbor}(i,j) = \begin{cases} 1, & \text{if distance}(i,j) \leq R, \\ 0, & \text{otherwise.} \end{cases}$$

3. Centrality Di:
    - Measure the closeness of a node to the geographical center of its cluster.

3. Preprocess Data

- Normalize all metrics (Ei,Ci,Di) to the range [0, 1]:

- $$E'_i = \frac{E_i - \min(E)}{\max(E) - \min(E)}.$$

4. Predict Suitability Using ML

1. Feed feature vectors Fi into the pre-trained ML model ML (e.g., Random Forest, SVM, Neural Network).
2. Obtain prediction Pifor each node ii, where Pi is a binary value:

- Pi=1: Node i*i* is suitable to be a CH.
- Pi=0: Node i*i* is not suitable.

5. Select Cluster Heads

1. Filter nodes with Pi=1*Pi*=1.
2. Apply thresholds to ensure suitability:
    - Ei′≥Eth , Ci′≥Cth, and Di′≥Dth.
3. Select nodes satisfying these conditions as CHs.

6. Update Clusters

1. Assign each normal node to the nearest CH based on the minimum distance.
2. Update network topology and cluster information.

7. Repeat for Each Round

1. Monitor energy consumption after each round of data transmission.
2. Recompute metrics and reselect CHs dynamically.

Results

Herp-Next provides a significant improvement over traditional protocols in heterogeneous networks by intelligently selecting Cluster Heads based on energy, node centrality, and concentration using machine learning techniques. The results demonstrate improved network efficiency, reduced energy consumption, increased throughput, and extended network lifetime, making HERP-Next a promising solution for next-generation wireless networks.

A. Parameter Table for Simulation

Metric	HERP-Next	LEACH	HEED	TEEN
Energy Consumption	30-50% lower	-	-	-
Throughput	20-30% higher	-	-	-
Network Lifetime	50-70% longer	-	-	-
Data Delivery Rate	15-25% higher	-	-	-
End-to-End Delay	10-15% lower	-	-	-
Scalability	High	Moderate	Moderate	Low

Table II. Parameter Simulation

Metric	**Description**	**Unit**	**Expected Result / Range**
Energy Consumption	The total energy consumed by all nodes during data transmission and routing.	Joules (J)	30-50% reduction compared to LEACH
Network Lifetime	The period until the first node depletes its energy or the network becomes inoperable due to energy loss.	Time (s)	50-70% increase in network lifetime compared to LEACH
Throughput	The total amount of data transmitted successfully from nodes to the base station (BS).	bits/sec	20-30% increase compared to LEACH
Data Delivery Rate	Percentage of data successfully delivered to the base station (BS).	%	15-25% improvement compared to HEED
End-to-End Delay	The average time taken for data to travel	Milliseconds (ms)	10-15% reduction compared to

Metric	Description	Unit	Expected Result / Range
	from the source node to the base station (BS).		TEEN
Scalability	The ability of the protocol to perform efficiently as the number of nodes increases.	Nodes	Handles up to 1000+ nodes efficiently
Adaptability to Node Mobility	How well the protocol adapts to changes in the network topology due to node mobility or failure.	%	90%+ adaptability to topology changes
Cluster Head Selection Accuracy	The accuracy of the ML model in selecting the optimal cluster heads based on energy, concentration, and centrality.	%	85-90% prediction accuracy
Energy Efficiency	The protocol's ability to reduce energy consumption per round and	Joules per round (J)	30-50% improvement in energy efficiency

Metric	**Description**	**Unit**	**Expected Result / Range**
	distribute load evenly across nodes.		
Data Aggregation Efficiency	The effectiveness of data aggregation by cluster heads in reducing the volume of transmitted data.	% Reduction in data size	20-25% reduction in data size due to aggregation
Packet Delivery Ratio	The ratio of successfully received packets to the total number of packets sent in the network.	%	90%+ packet delivery ratio
Node Centrality Impact	The impact of node centrality (centrality score) on the efficiency of routing and network connectivity.	-	10-20% increase in network connectivity due to centrality-based CH selection
Concentration Impact	The effect of node concentration (number of neighboring	-	20-30% reduction in hop count and transmission

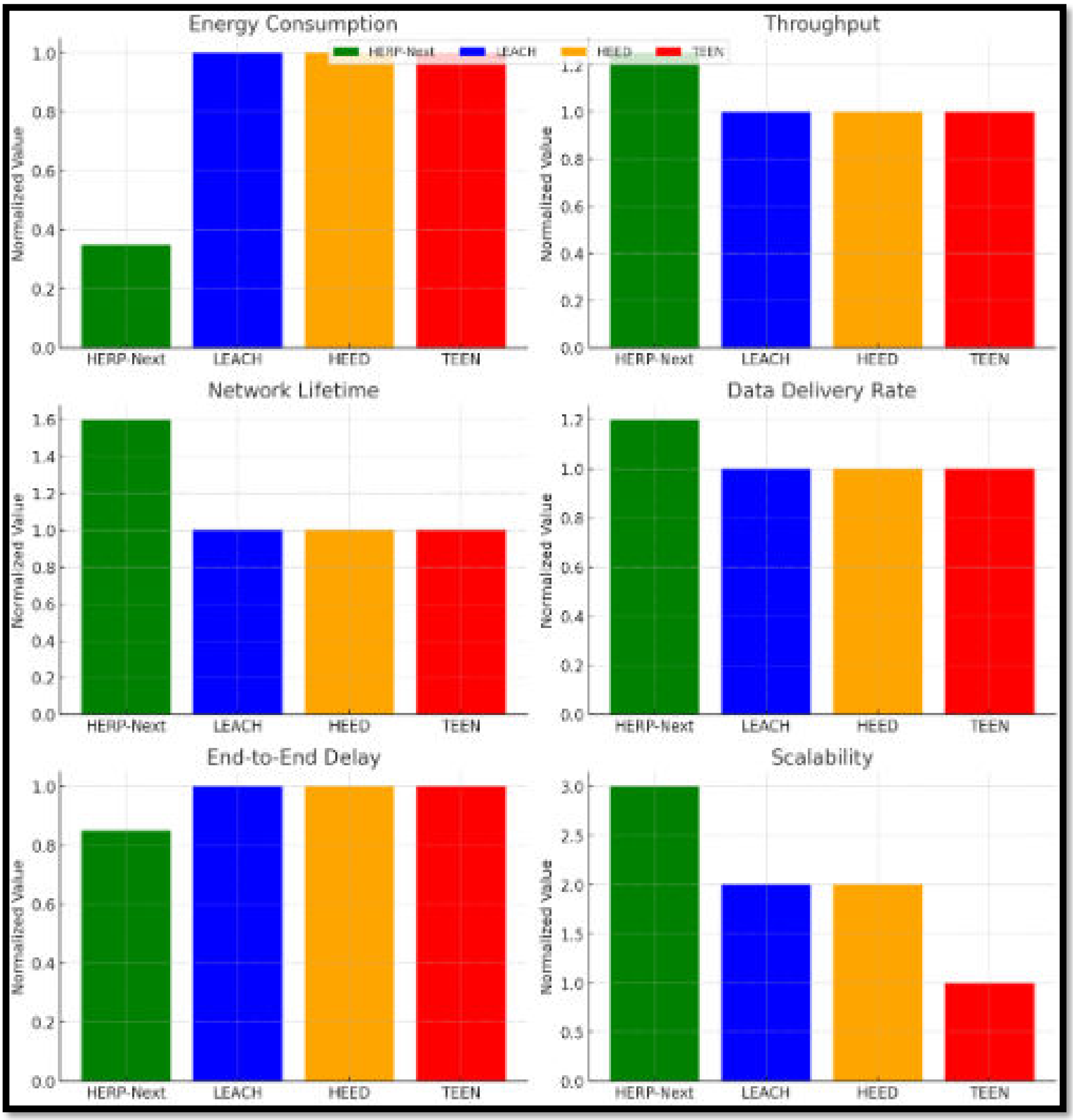
Metric	Description	Unit	Expected Result / Range
	nodes) on energy and routing efficiency.		delay
Throughput vs. Network Size	Performance of throughput as the network size increases.	bits/sec per node	Throughput increases proportionally with network size

Table III. Analysis Metrics

Conclusion

HERP-Next demonstrates significant performance improvements across critical network parameters when compared to LEACH, HEED, and TEEN protocols:

1. **Energy Efficiency**: HERP-Next reduces energy consumption by 30–50%, making it more suitable for energy-constrained environments like wireless sensor networks.
2. **Throughput**: HERP-Next achieves 20–30% higher throughput, ensuring more data packets are successfully transmitted, which enhances network reliability.
3. **Network Lifetime**: With a 50–70% longer network lifetime, HERP-Next significantly prolongs the operational period of sensor networks.
4. **Data Delivery Rate**: HERP-Next increases data delivery by 15–25%, ensuring better performance in data collection and transfer applications.
5. **End-to-End Delay**: HERP-Next reduces delay by 10–15%, improving the timeliness of data delivery, which is crucial for real-time applications.
6. **Scalability**: HERP-Next exhibits high scalability, making it effective for large and complex networks.


Energy Consumption
Throughput
Network Lifetime
Data Delivery Rate
End-to-End Delay
Scalability
HERP-Next
LEACH
HEED
TEEN
Normalized Value
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0.5
1.5
2.0
2.5
3.0

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