

# An Enhanced HEED Clustering Algorithm for Increased Reliability and Network Lifetime of Wireless Sensor Networks

**Amit**

Department of Electronics and Communication Engineering, P. D. A College of Engineering, Kalaburagi, India | Visvesvaraya Technological University, Belagavi – 590018, India | Department of Electronics and Communication Engineering, Vidyavardhaka College of Engineering, Mysuru, India  
amitanilraikar@gmail.com (corresponding author)

**Geeta Hanji**

Department of Electronics and Communication Engineering, P. D. A College of Engineering, Kalaburagi, India | Visvesvaraya Technological University, Belagavi – 590018, India  
geetanjali123@gmail.com

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## ABSTRACT

Wireless Sensor Networks (WSNs) are utilized in several modern applications, however, their exploration suffers from the limited energy resources of the sensor nodes, directly affecting network's lifetime. Energy-efficient routing and clustering protocols are important for solving this problem. In this paper, an enhanced Hybrid Energy-Efficient Distributed protocol with a Vice Cluster Head (HEED-VCH) is proposed to increase the lifetime, reliability, and stability of WSNs. The novel Vice Cluster Head (VCH) mechanism introduces a secondary leader within each cluster to monitor and take over duties seamlessly in the event of a primary Cluster Head (CH) failure, thereby significantly improving fault tolerance over traditional clustering methods. HEED-VCH extends the HEED protocol by incorporating this hierarchical stage, which balances the energy consumption across the network, reduces energy-intensive re-clustering, and enhances reliability by providing an immediate backup path for data aggregation and transmission when the main CH fails. Comparative analysis among HEED-VCH, LEACH, DEEC, and EECB protocols demonstrated that HEED-VCH outperformed the others in residual energy. At 500 rounds, it retained approximately 70%, which was significantly higher than LEACH (50%), DEEC (36%), and EECB (56%). While benchmark protocols exhaust their entire 50 J network energy between 800 and 1200 rounds, HEED-VCH retains considerable residual energy (34%, 24%, and 15%, respectively), indicating prolonged network operation and reduced energy depletion. These results establish the HEED-VCH as a most energy-efficient protocol with enhanced fault tolerance.

*Keywords-WSNs; HEED; vice cluster head; energy efficiency; reliability; network lifetime*

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) have attracted considerable attention as technologies for 21st-century applications in smart cities, industrial automation, healthcare, and environmental monitoring [1]. These networks consist of sensor nodes spread out in an open space with limited resources and provide remote data-acquisition capabilities in various remote environments [2]. However, the basic limitation of WSNs is the finite energy capacity of the sensor nodes, which reduces the lifespan of the network [3]. The consideration of higher priority on network lifetime is a research trend and promotes the further evolution of communication protocols in WSNs [4]. The primary energy-saving strategy employed in WSNs is the Low Energy Adaptive Clustering Hierarchy

(LEACH) method. It organizes the sensor nodes into hierarchical clusters, where each cluster has a Cluster Head (CH) that collects data and sends them to the Base Station (BS). Although LEACH and other similar protocols introduced early concepts of energy-based clustering, they often suffer from the fast depletion of CH energy and improper distribution of energy [6]. Later, improvements were made in the Distributed Energy-Efficient Clustering (DEEC) and Energy Efficient Clustering Based (EECB) protocols to handle the issue, considering both residual energy and backup mechanisms [7]. However, there is still a pressing need for protocols that enhance energy efficiency and system reliability [8].

The flowchart in Figure 1 illustrates the operational cycle of WSN simulations. The process begins with the initialization, where the network parameters, node positions, and energy levels are set. Each cycle starts with a new round, followed by the execution of a clustering algorithm to select suitable CHs. Once the clusters are formed, data transmission occurs, where sensor nodes send data to their CHs, which in turn forward them to the BS. After transmission, the system checks whether all nodes are dead. If yes, the simulation ends. Otherwise, it updates the status of dead nodes and resets the status of active nodes in preparation for the next round. This loop continues until all nodes have depleted their energy, enabling the evaluation of the protocol efficiency and network longevity.

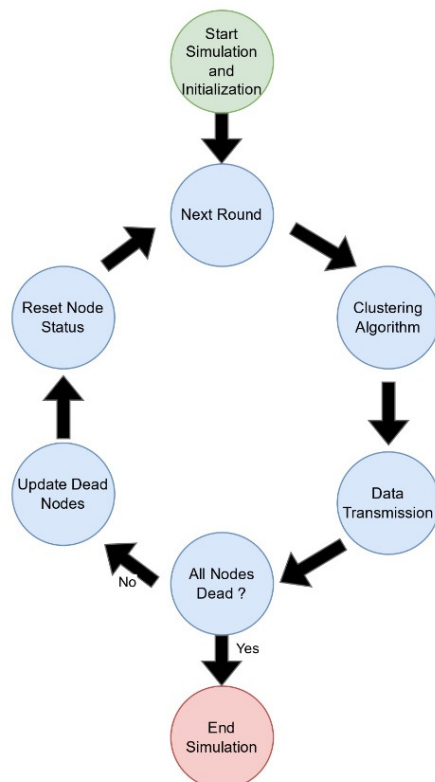


Fig. 1. Iterative simulation procedure for cluster-based WSN protocols.

The main contributions of this work are:

- The modified HEED-VCH protocol is presented, that incorporates a Vice Cluster Head (VCH) feature to enhance fault tolerance and reliable data delivery in WSNs.
- HEED-VCH is compared to the traditional protocols (LEACH, DEEC, and EECB) considering network lifetime and continuity of data delivery.

## II. RELATED WORKS

WSNs consist of spatially distributed autonomous sensor nodes that share a wireless medium for data collection and monitoring physical or environmental conditions, such as pressure, temperature, and sound. WSNs are typically energy-constrained, therefore, energy-efficient routing strategies are

crucial for prolonging network lifetime and ensuring reliable data transmission. The LEACH protocol is one of the most recognized hierarchical routing protocols with the aim to extend the longevity of WSNs. LEACH uses clusters of nodes and has a rotating CH mechanism that distributes node energy consumption, which in turn allows the WSN to last longer [9] and produces less communication overhead [10]. LEACH, like most approaches, considers variability as a threat. The variability for CH selection may provide a low-performance, high-energy imbalance situation [11]. Studies have shown that the performance of LEACH depends on the topology and density of nodes, and simulations have demonstrated that smaller networks can have longer lifetimes [12]. Hybrid-LEACH and RCH-LEACH, which are two more recent versions of LEACH, stress CH selection based on residual energy, stability in the CH number, and network performance improvement [13, 14]. These upgrades collectively provide advances in the sustainability and resiliency of WSNs, which are important in the Internet of Things (IoT) ecosystem [15].

The hierarchical clustering technique is an important part of the DEEC protocol, which seeks to improve the energy efficiency and lifetime of WSNs. The DEEC protocol considers the remaining energy of the nodes and their distance to the BS to improve energy optimization and performance [16]. The ACO-DEEC protocol takes DEEC one step further by utilizing ant colony optimization as the basis for CH selection and achieving better management of energy efficiency and data transmission [17]. The trade-off analysis suggests that from a resource utilization standpoint, the location of the BS could significantly impact energy consumption, with central positioning being optimal for performance [18]. Hybrid frameworks incorporate DEEC for balanced CH selection, EEKA for energy-constrained task allocation, and K-means clustering to minimize intracluster overhead [19].

The EEBC protocol is crucial for performance optimization in WSNs and the IoT. There have been many attempts to improve energy efficiency, and the Divide and Conquer Quad Tree dynamic multi-hop LEACH Protocol improved the energy efficiency in CH selection by considering both a node's distance from the BS and the amount of residual energy in the node, achieving almost 50% savings in energy compared to previous protocols [20]. SDBERP, makes clustering less complicated increasing network lifetime substantially, whereas the ECRP-UCA, utilizing load balance among CHs, and a more efficient route to the sink performs better than more traditional approaches [22]. In [23], a distributed energy-throughput efficient model was proposed for magnetic induction operational WSNs by deploying a hybrid optimization model, demonstrating even greater energy savings and throughput. The EM-RPL protocol [24] employs load balancing in low-power and lossy networks to address energy bottlenecks, thereby increasing network lifetime. The HOAER Hybrid Protocol utilizes ant lion optimization and genetic algorithms to create an efficient clustering and routing model that minimizes energy dissipation [25]. An energy-balancing method using residual-energy-based CH selection and knapsack-based resource allocation has been used in [26] to achieve uniform energy consumption.

LEACH, DEEC, EECB, and HEED are popular protocols designed to optimize energy consumption in WSNs. Each protocol uses different techniques to optimize system performance with the goal of extending the lifetime of the nodes to address the issue of energy constraints in remote sensor deployment. The protocols mentioned above were developed to improve energy efficiency in WSNs, however, there are also factors such as scalability, reliability, and adaptability to dynamic environments to be considered. The VCH approach with the HEED protocol enhances network reliability by providing backups for CHs if they fail or become energy depleted. The VCH enhances the ability to continuously transmit data by assuaging the amount lost when communication is interrupted, thereby improving fault tolerance during communication deficiencies and, in turn, network lifetime.

### III. THE PROPOSED CLUSTERING ALGORITHM

The proposed HEED-VCH algorithm expands the original HEED protocol by including a VCH selection mechanism to remedy unexpected CH failures, thus enhancing network reliability and lifetime. While HEED uses the residual energy and communication cost to select a CH, HEED-VCH adds a VCH as a redundancy layer to guarantee the fetching of data and minimize the re-clustering overhead. The HEED-VCH approach involves choosing a VCH in each cluster based on the energy consumption and closeness to the CH. Therefore, if the CH is disabled, the VCH can perform an energy-efficient takeover. This functionality conserves energy because CH election occurs less frequently, and redundant control packets are reduced. In addition, when making the assignment of the VCH in the clusters, the distribution of nodes and coverage overlaps will be considered to avoid CH-VCH pairs. This avoids placing the CH and VCH too close to each other, which could lead to ineffective energy utilization.

#### A. Network Model

The simulation modelled a static homogeneous WSN deployed within a defined geographical area.

- Network Area: A two-dimensional area measuring 100 m × 100 m was considered for simulations.
- Sensor Nodes: One hundred sensor nodes were randomly and uniformly distributed across the network area with the same initial energy and identical communication capabilities. Once deployed, the positions of the nodes remained fixed throughout the simulation.
- Base Station: A single, powerful, energy-unlimited base station was centrally located.

#### B. Signal Transmission Model

The signal transmission model dictates how nodes communicate and determines the energy costs associated with sending and receiving data.

- Communication Range: Each node had a fixed communication range of 25 m. Nodes can only communicate directly with other nodes or the BS if they are within its range.

- Path Loss Model: The energy consumption for transmission is governed by a simple radio energy model, which implicitly considers path loss. The model assumes that the energy dissipated to transmit a packet depends on the distance over which data are sent.
- Euclidean Distance Calculation: The communication distance ( $d$ ) for energy consumption between any two nodes is calculated using the Euclidean distance formula

$$d = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2} \quad - (1)$$

where  $a_1$ ,  $a_2$ ,  $b_1$ , and  $b_2$  are the x, y coordinates of Node 1 and Node 2.

#### C. Energy Model

The energy model is crucial for simulating the lifetime of individual nodes, and consequently, of the overall network. It accounts for both the transmission and reception energy.

- Initial Energy: All nodes begin with the same initial energy of 0.5 J.
- Energy-consumption parameters: The energy for electronics represents the energy consumed by the transceiver's electronic circuitry for transmitting and receiving each bit of data. This is independent of the transmission distance. The energy of the amplifier represents the energy consumed by the power amplifier.
- Packet Length: Each data packet had a fixed size of 4000 bits for consistent transmission across the network.
- Energy-consumption equations: The transmission and reception of a  $k$ -bit packet over a distance  $d$  is given by:

$$E_{Tx}(k, d) = (k \cdot E_{elec}) + (k \cdot E_{amp} \cdot d^2) \quad (2)$$

$$E_{Rx}(k) = k \cdot E_{elec} \quad (3)$$

where  $E_{Tx}(k, d)$  is the transmission energy,  $E_{elec}$  is the energy for electronics, and  $E_{amp}$  is the energy for amplifiers.

- Node Death: A node is considered dead when its energy level decreases to zero or below. Dead nodes cannot participate in any network activity.

#### D. HEED with VCH (Proposed Algorithm)

The simulation implements the HEED clustering protocol with a crucial extension: the selection and takeover functionality of the VCH. The simulation proceeded in rounds, with clustering and data transmission occurring in each round.

##### 1) Initialization Phase (Per Round)

At the beginning of each round, all nodes whose energy had fallen to zero or below are permanently marked as dead. For all currently alive nodes, their roles (CH or VCH) and cluster assignments (Cluster Id) were reset to 0. This ensures dynamic reclustering in every round.

##### 2) HEED Clustering Phase

CH selection and clustering for the current round were performed. Each alive node calculates its probability ( $P_{CHI}$ ) of becoming a CH using:

$$P_{CHi} = \max\left(C_{prob} \cdot \frac{E_{residual}}{E_{initial}}, CH_{prob\_min}\right) \quad (4)$$

where  $E_{initial}$  is the initial energy,  $E_{residual}$  is the residual energy,  $CH_{prob\_min}$  is the minimum probability, and  $C_{prob}$  is the desired CH percentage.

Dead nodes have  $P_{CHi} = 0$ . This probability is based on the residual energy, weighted by the desired CH percentage, and capped by the minimum probability to ensure connectivity. The algorithm iteratively selects the final CHs. In each iteration, it finds the minimum  $P_{CH}$  among all live nodes that have not yet finalized their roles. Any unfinalized live node whose  $P_{CH}$  matches this minimum probability declares itself to be the final CH. Upon becoming the final CH, it finalizes its neighbors within the communication range. These neighbors are then prevented from becoming CHs themselves, promoting a uniform distribution of CHs. This process continues until the desired proportion of CHs is achieved, or all live nodes have finalized their roles (either as CHs or by being covered by one). Once CHs are finalized, every live node that is not a CH seeks to join a cluster. Each node identifies the closest live CH within its communication range. If multiple CHs are within the range, they choose the nearest CH. If no CH is found within its range, the node remains unassigned for the round.

### 3) Vice CH Selection

For each active CH, a VCH is designated from the current cluster members. The calculation of the probability ( $P_{Vci}$ ) of a node to be chosen as a VCH is given by:

$$P_{Vci} = \alpha \left(\frac{E_{residual}}{E_{initial}}\right) + \beta \left(1 - \frac{d_{i,CH}}{d_{max}}\right) \quad (5)$$

where  $E_{residual}$  and  $E_{initial}$  represent the residual and the initial energy of the node,  $d_{i,CH}$  is the distance between a node and its CH,  $d_{max}$  is the maximum distance to the CH among the candidate nodes, and  $\alpha$  and  $\beta$  are weights, assigned with values:  $\alpha = 0.6$  and  $\beta = 0.4$ . The total weight should be equal to 1.

### 4) VCH Takeover Mechanism (Pre-Transmission Failure Check)

The VCH mechanism is the core network robustness enhancement of the proposed protocol. Before any data transmission occurs in a round, the system proactively checks the health of designated CHs.

- **CH Monitoring:** Each VCH continuously monitors the status of its corresponding CH through periodic status checks.
- **CH Failure Detection:** For every node currently marked as a CH, the system checks if its energy has dropped to zero or below (e.g., due to the previous round's activity or the VCH selection process itself). If so, the CH is immediately marked as dead.
- **VCH Identification:** If a CH is found to be dead, the system searches for a live VCH previously assigned to the cluster.
- **Takeover Execution:** If an alive VCH is found, the VCH is immediately promoted to CH. All nodes that were members

of the dead CH cluster are immediately reassigned to the newly promoted VCH. If no live VCH is found for a dead CH's cluster, that cluster effectively becomes orphaned for the round, and its members will not transmit data to a CH.

### 5) Data Transmission Phase

After clustering and any potential VCH takeover, data transmission occurs.

- **Member-to-CH Transmission:** All live non-CH nodes that have been assigned a valid, live CH (including those reassigned during a takeover) transmit their packet length data to their respective CHs. Energy is consumed by the members (transmission) and the CH (reception)
- **CH-to-BS Transmission:** All active CHs (original CHs and any newly promoted VCHs) collect data from their members and then transmit their own packet length data directly to the central BS. Nodes are marked dead if their energy drops below zero at any point during transmission. The cumulative data sent to the BS are updated based on successful CH-to-BS transmissions.

## IV. RESULTS AND DISCUSSION

The energy efficiency of the proposed HEED-VCH protocol outperforms the existing protocols (LEACH, DEEC, and EECB) regarding residual energy over multiple simulation rounds. To make the results from the research more objective, we used the same parameters in MATLAB environment. Table I summarizes the set of parameters and baseline settings used in the simulation runs.

TABLE I. SIMULATION PARAMETERS

| Network Parameters           | Values                    |
|------------------------------|---------------------------|
| Sensing area                 | 100m × 100m               |
| Number of nodes              | 100                       |
| Location of the base station | 50,50                     |
| Packet size                  | 4000 bits                 |
| Initial energy               | 0.5 J                     |
| Energy for electronics       | 50 nJ/bit                 |
| Energy for the amplifier     | 100 pJ/bit/m <sup>2</sup> |

The results demonstrate that HEED-VCH consistently outperformed the other protocols in terms of residual energy. At 200 rounds, HEED-VCH retains approximately 41 J (90%) of the initial energy, outperforming LEACH with 36 J (80%), DEEC with 33 J (76%), and EECB with 39 J (84%). At 400 rounds, HEED-VCH maintained 32 J (70%), whereas LEACH dropped to 24 J (50%), DEEC fell to 17 J (36%), and EECB held 27 J (56%), as shown in Table II. The Total Network Energy over multiple rounds is shown in Figure 2, along with the comparative energy consumption of various WSN clustering protocols, highlighting the superior performance of the proposed HEED-VCH algorithm. The proposed HEED-VCH demonstrates the most gradual energy decline, maintaining a significantly higher residual energy level for an extended duration and reaching near zero only at approximately round 1500. The energy consumption with DEEC, LEACH, and EECB reached zero after 800, 900, and 1100 rounds, respectively. The compelling, slower energy dissipation of the HEED-VCH significantly extends the overall operational lifespan of the WSN.

TABLE II. NETWORK ENERGY (J)

| Round No. | HEED-VCH | LEACH | DEEC | EECB |
|-----------|----------|-------|------|------|
| 0         | 50       | 50    | 50   | 50   |
| 200       | 41       | 36    | 33   | 39   |
| 400       | 32       | 24    | 17   | 27   |
| 600       | 24       | 14    | 6    | 15   |
| 800       | 17       | 8     | 0    | 6    |
| 1000      | 10       | 3     | 0    | 2    |
| 1200      | 5        | 0     | 0    | 0    |
| 1500      | 2        | 0     | 0    | 0    |

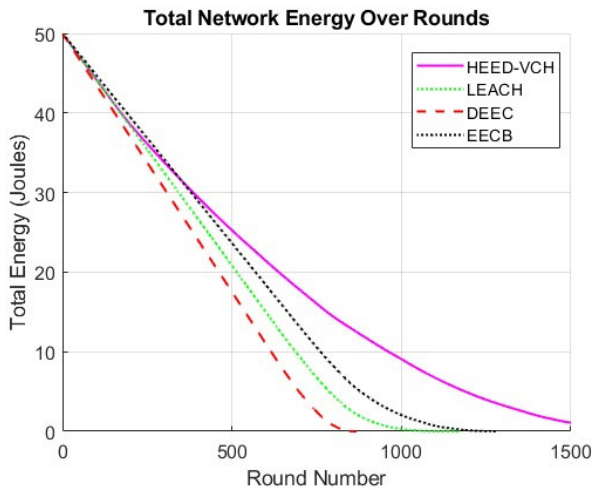


Fig. 2. Total network energy of HEED-VCH, LEACH, DEEC, EECB over 1500 rounds.

The number of alive and dead nodes over rounds offers complementary insights into the network lifetime and resilience of the various protocols as shown in Figures 3 and 4. Starting with 100 active protocols, the proposed HEED-VCH maintains a significantly higher node count for an extended duration, with a substantial number of nodes still operational beyond 1500 rounds.

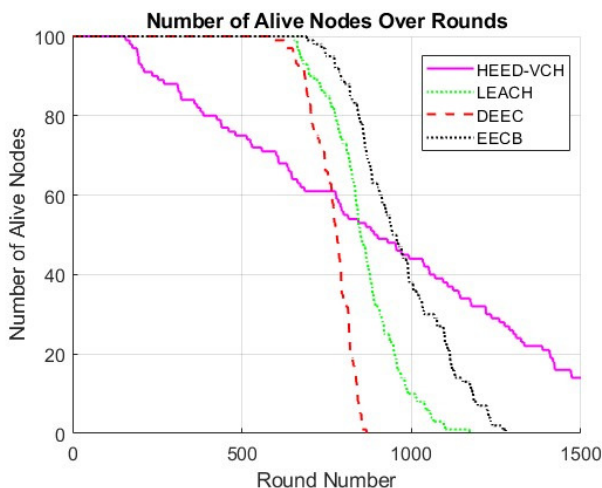


Fig. 3. Alive nodes in HEED-VCH, LEACH, DEEC, EECB over 1500 rounds.

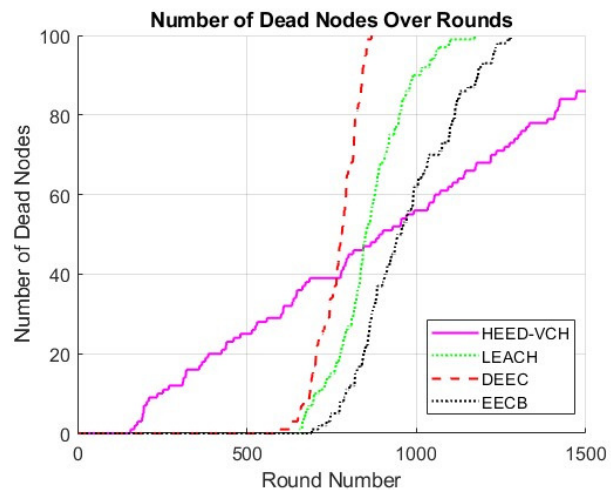


Fig. 4. Dead nodes in HEED-VCH, LEACH, DEEC, EECB over 1500 rounds.

The DEEC experiences a decline in the number of live nodes, with a correspondingly rapid surge in dead nodes, leading to its complete network demise after approximately 900 rounds. LEACH followed a similar, albeit slightly less aggressive, trend, with all its nodes dying off after approximately 1050 rounds. EECB presented an intermediate performance, prolonging the network beyond LEACH and DEEC, with full nonetwork demise occurring after approximately 1200 rounds. Figures 3 and 4 underscore the proposed HEED-VCH's energy-aware CH selection and robust VCH takeover mechanism, which effectively balances the energy load and mitigates single-point failures, leading to a significantly delayed onset of node mortality and a profoundly extended network operational lifespan.

The HEED-VCH algorithm demonstrates exceptional performance, achieving the highest total cumulative data transmitted to the BS. It exhibited a consistent and sustained rate of data delivery, reaching over 800 kb, as shown in Figure 5. EECB initially shows a competitive data accumulation rate, even slightly surpassing HEED-VCH in the early rounds, but its transmission plateaus around 750 Kbits, signifying the cessation of effective network operation. Both LEACH and DEEC transmit significantly less cumulative data overall, peaking at approximately 380 and 350 Kbits, respectively, before their curves flatten, reflecting their early network demise. The network lifetime parameters of the considered protocols are presented in Table III. HEED-VCH demonstrated enhanced longevity, with the First Node Dead (FND) found at 500 rounds, Half Nodes Dead (HND) occurring at 1050 rounds, and the Last Node Dead (LND) occurring after 1500 rounds. It also retains over 15 live nodes and maintains a functional network status. In contrast, LEACH shows FND at 750 rounds, HND at 950 rounds, and LND at 1050 rounds, with no nodes retaining energy, indicating a fully dead network. Similarly, DEEC exhibited FND at 700, HND at 800, and LND at 900 rounds. The EECB exhibited FND at 600, HND at 950, and LND at 1200 rounds. Both DEEC and EECB end with fully dead networks and no residual energy.

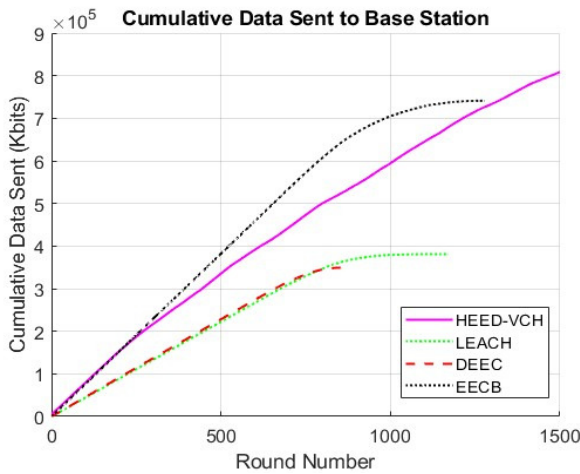


Fig. 5. Data sent to BS in HEED-VCH, LEACH, DEEC, EECB over 1500 rounds.

TABLE III. NETWORK LIFETIME

| Network Lifetime             | HEED-VCH   | LEACH | DEEC | EECB |
|------------------------------|------------|-------|------|------|
| <b>FND</b>                   | 500        | 750   | 700  | 600  |
| <b>HND</b>                   | 1050       | 950   | 800  | 950  |
| <b>LND</b>                   | >1500      | 1050  | 900  | 1200 |
| <b>Alive nodes</b>           | 15         | None  | None | None |
| <b>Active network status</b> | Functional | Dead  | Dead | Dead |

The simulation results of LEACH clearly illustrate the near-total energy depletion within a 100-node WSN. The rapid exhaustion of energy reserves under DEEC resulted in early network fragmentation and operational failure. The network under the EECB protocol collapses after 1100 rounds. The widespread presence of dead nodes indicates a total loss of active nodes, signifying a complete network failure. Table IV presents the selection of nodes being CHs or VCHs in a cluster during both the initial cluster formation and after finalization across five distinct clusters. A CH failure scenario was observed in clusters 2 and 5, where the CH (node 58) of cluster 2 and the CH (node 92) of cluster 5 were considered dead. VCHs were promoted to CHs to keep the network operational. VCH (node 12) of cluster 2 and VCH (node 10) of cluster 5 took over and became CHs, and new VCHs were selected based on the maximum energy that could be provided by the existing nodes in each cluster. The comparison in Table V shows that HEED-VCH outperforms LEACH, DEEC, and EECB across all key metrics. It achieved the lowest handover latency (120 ms), minimal packet loss (7%), and the lowest control overhead (3.2%). HEED-VCH also ensures the highest recovery success (98%) and service continuity (99.9%), making it more reliable and efficient than the other protocols.

TABLE IV. CH AND VCH NODES

| Cluster | Initial cluster formation |     | Final CHs and VCHs |     |
|---------|---------------------------|-----|--------------------|-----|
|         | CH                        | VCH | CH                 | VCH |
| 1       | 27                        | 11  | 27                 | 11  |
| 2       | 58                        | 12  | 12                 | 43  |
| 3       | 68                        | 32  | 68                 | 32  |
| 4       | 84                        | 35  | 84                 | 35  |
| 5       | 92                        | 10  | 10                 | 67  |

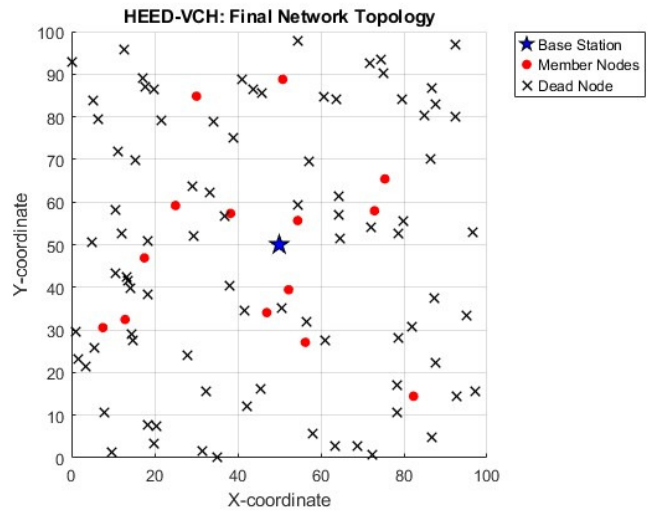


Fig. 6. Final network topology of HEED-VCH after 1500 rounds.

The profound difference in the final network state is directly correlated with the previously observed performance metrics. Figure 6 shows the sustained presence of live nodes in the HEED-VCH topology, which explains its higher overall residual energy, extended network lifetime, and ability to achieve the highest cumulative data transmission. Conversely, the widespread dead nodes in the LEACH, DEEC, and EECB topologies precisely reflected their faster energy depletion rates and earlier cessation of data collection.

TABLE V. FAULT TOLERANCE METRICS COMPARISON

| Metric                    | HEED-VCH | LEACH  | DEEC   | EECB   |
|---------------------------|----------|--------|--------|--------|
| <b>Handover latency</b>   | 120 ms   | 250 ms | 350 ms | 300 ms |
| <b>Packet loss rate</b>   | 7%       | 15-25% | 20-30% | 18-22% |
| <b>Control overhead</b>   | 3.20%    | 8-12%  | 10-15% | 9-13%  |
| <b>Recovery success</b>   | 98%      | 75%    | 70%    | 78%    |
| <b>Service continuity</b> | 99.90%   | 85%    | 80%    | 83%    |

## V. CONCLUSION AND FUTURE WORK

The current paper presents a comprehensive analysis of an enhanced HEED clustering protocol, specifically engineered with a VCH takeover mechanism, to mitigate the critical issue of finite node energy and its consequent impact on WSN longevity. The simulation framework reveals that HEED-VCH maintains a substantially higher residual energy across the network. Specifically, at 400 simulation rounds, HEED-VCH maintains 32 J (70%) of the initial energy, in contrast to LEACH (24 J), DEEC (17 J), and EECB (27 J). The protocol extends network functionality beyond 1,500 rounds, whereas the other protocols exhibit total node death significantly sooner: DEEC by 900 rounds, LEACH by 1,050 rounds, and EECB by 1,200 rounds. The cumulative data throughput further underscores the protocol's efficacy, with HEED-VCH delivering in excess of 800 Kbits to the base station, surpassing EECB (~ 750 Kbits), LEACH (~ 380 Kbits), and DEEC (~ 350 Kbits). Moreover, HEED-VCH retains more than 15 nodes with residual energy after 1,500 rounds, whereas the other considered protocols report no nodes with energy at the end of

the simulation. These findings validate the technical merits of the HEED-VCH in terms of energy management, load balancing, fault tolerance, and sustained connectivity, demonstrating its suitability for deployment in resource-constrained, long-lived WSN scenarios.

Future work will include a comprehensive scalability study to evaluate the performance and efficiency of the HEED-VCH protocol in larger networks with 150 or 200 nodes and integrated energy-harvesting mechanisms. By leveraging dynamic energy replenishment from ambient sources, the inherent energy-efficient design of the HEED-VCH could be further optimized, potentially leading to truly perpetual WSN operations and significantly expanding its applicability in long-term, autonomous monitoring environments.

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