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Intelligent HEED Algorithm for Energy Optimization in Heterogeneous Wireless Sensor Network

Ayobami O. Adedokun*, Folasade M. Dahunsi
Department of Computer Engineering, Federal University of Technology Akure, Nigeria

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ABSTRACT

Wireless Sensor Networks (WSNs) are deployed in various applications, from agricultural automation to environmental monitoring, where sensor nodes transmit data to a central base station. However, nodes further from the base station face accelerated energy depletion, primarily due to higher communication demands. Energy conservation is critical in these resource-constrained networks to prolong network longevity. This study introduces I-HEED (Intelligent Hybrid Energy-Efficient Distributed) clustering, a novel energy optimization algorithm that merges the energy-efficient HEED (Hybrid Energy-Efficient Distributed) protocol with the Monkey Search Algorithm. I-HEED balances energy distribution by optimizing cluster head selection, enabling efficient data aggregation and transmission to the base station. Through optimized cluster head selection, I-HEED effectively reduces energy consumption and enhances data transmission efficiency compared to LEACH (Low Energy Adaptive Clustering Hierarchy), DEEC (Distributed Energy Efficient Clustering), and HEED. The performance evaluation shows that I-HEED significantly outperforms existing protocols, with improvements of 3,700 more packets transmitted than DEEC, 2,800 more than HEED, and 500 more than LEACH. I-HEED also achieved higher node survivability and fewer dead nodes, making it ideal for resource-constrained WSNs. These findings validate I-HEED's effectiveness as a robust, energy-efficient solution, offering extended operational life across diverse WSN applications in resource-limited environments.

Corresponding Author:

Ayobami O. Adedokun
Department of Computer Engineering, Federal University of Technology Akure
The Federal University of Technology Akure
P.M.B. 704, Akure, Ondo State, Nigeria.
Email: *aoadedokun@futa.edu.ng

1. INTRODUCTION

A typical wireless sensor network (WSN) is a self-organizing network composed of small sensor nodes with limited processing capabilities and energy restrictions. The communication among these sensor nodes is done through radio waves, and these nodes are deployed in large numbers to detect, monitor, and interpret the physical environment [1]. A typical sensor node consists of four main components: a sensing unit, a processing unit, a transceiver unit, and a power unit. Recent advancements in WSN research have led to significant innovations, enabling the development of low-cost, compact, and multi-functional sensor nodes [2][3]. Although the sensor nodes individually have limited energy supply (usually battery), these limited resources need to be managed to have an efficient network system. In WSNs, the energy consumption of the communication transmission protocol is directly proportional to the transmission distance [4][5][6].

The routing protocol that was first implemented is called Direct protocol, in which all sensor nodes are configured to communicate to the base station directly [7]. Moreover, there is no communication order between the sensor nodes and the base station. This method is not economical because of frequent communication between the sensor nodes and the base station. To address the limitations of the direct protocol, the first hierarchical network structure, known as LEACH (Low Energy Adaptive Clustering Hierarchy), was introduced by [8]. In this approach, a cluster head (CH) is selected from among the sensor nodes. The base station designates one sensor node as a representative to gather data from other nodes and transmit it to the base station for further processing, as illustrated in Figure 1.

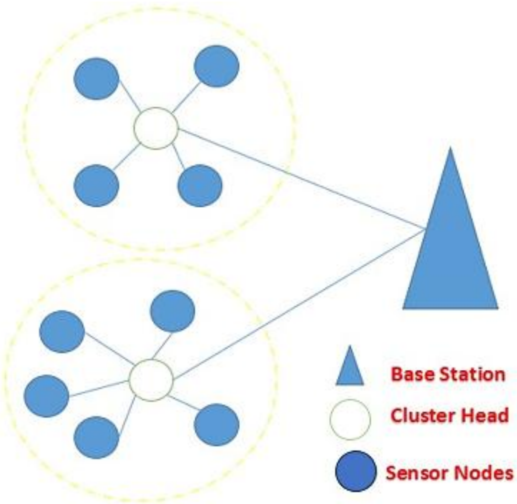

Figure 1. Clustering in LEACH protocol

The primary drawback of this algorithm lies in the method used by the base station to select the cluster head. The random selection of a cluster head makes it non-effective [9]. There are no ways to check if the sensor node elected as a cluster head have enough energy to transmit the data to the base station. The unexpected death of such a cluster head will also lead to the loss of data already transmitted to it [10].

$$T(n) = \frac{p}{1-p}\left[r\, mod\left(1/p\right)\right], for\ n \epsilon G = 0\ , Otherwise \quad (1)$$

where: p = percentage of nodes that are Cluster Heads; r = current round; G = set of nodes that have not served as cluster heads in the past $1/p$ rounds.

However, LEACH is still more effective than the direct protocol method. PEGASIS (Power-Efficient Gathering in Sensor In-formation Systems) was proposed to resolve the random selection of cluster heads [11]. In PEGASIS, each node communicates solely with a nearby neighbor and alternates in transmitting data to the base station, thereby minimizing the energy consumed per round, as illustrated in Fig. 2. However, this approach introduces significant delays for distant nodes along the chain, and having a single leader can create a bottleneck [12][13].

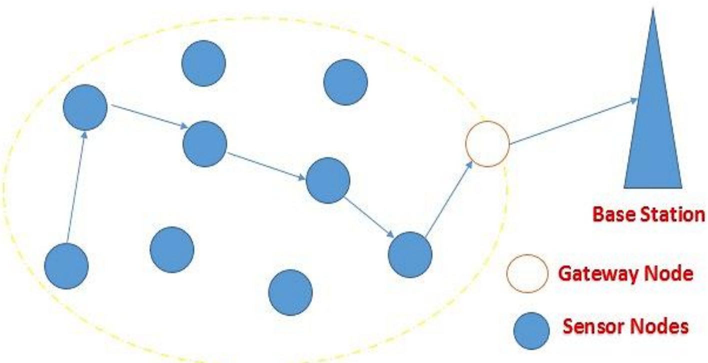

Figure 2. Chain Formation in PEGASIS protocol

To solve the bottleneck of distant sensor nodes in PEGASIS, TEEN (Threshold sensitive Energy Efficient sensor Network) was introduced, where the base station looks at the threshold energy of the sensor node before it can be selected as cluster head [14]. The major setback of TEEN is that the algorithm has a low response time and also not suitable for regular data gathering applications [15]. In order to solve the disadvantages in LEACH, PEGASIS and TEEN, HEED (Hybrid Energy-Efficient Distributed Clustering) was introduced by [16]. HEED considers the residual energy of the sensor node before it can be selected as the cluster head [17]. There is also effective inter-cluster communication in which a particular cluster head that is far from the base station can transmit its data to any cluster head that is close to the base station [18][19].

The four algorithms are only suitable for the homogeneous network. The homogenous network is a type where all the sensor nodes carry the same energy, but sensor nodes have varying energy levels in the heterogeneous network. A homogenous network is not accurate in real-life applications [20]. For easy deplorability of sensor network and real-life application, a heterogeneous algorithm DEEC (Distributed Energy Efficient Clustering) was proposed by [21]. In DEEC, cluster heads are selected probabilistically, based on the ratio of each node's residual energy to the network's average energy [22]. All the routing algorithms aid energy efficiency in Wireless Sensor Network, extending network lifetime. All proposed algorithms have challenges in selecting the best cluster head [23].

This work introduced the Monkey search algorithm developed by [24] to select perfect cluster heads in the network due to its capability to efficiently explore the search space and avoid local optima, it enhances energy conservation and extends network lifespan [25]. The paper is structured as follows: the next section outlines the research methods, Section 3 presents the discussion and analysis of the results, and Section 4 provides the conclusion.

2. RESEARCH METHODS

This algorithm aims to provide an optimized energy-efficient protocol in Wireless Sensor Networks and this was inspired by energy distribution method in HEED protocol and selection strategy from Monkey search algorithm for the cluster head selection and thus extending the lifetime of the network. This algorithm is an hybrid of HEED and Monkey Search Algorithm and the system will be intelligent in the sense that over time the system has to learn the process of determining cluster heads that can be selected among the sensors node. In the development of this new hybrid algorithm, this study focuses on five main sections: Cluster formation, cluster head selection, inter and intracluster communication, path establishment and data transfer. A modularized methodology and I-HEED flow chart will be adopted in this research work, as shown in Figure 3 and Figure 4.

The algorithm uses monkey search in the two-way communication between the base station and the field sensor nodes, cluster formation, and determine sensor nodes that will become cluster heads. HEED algorithm was used to estimate inter and intra communication costs between the sensor nodes and cluster heads, path establishments, and transfer data to the base station. The algorithm was evaluated by monitoring the number of alive and dead nodes per round of information exchange and the total number of packets transmitted within the network before all nodes died. It is assumed that the base station remains stationary within the region where the sensor nodes are deployed, with each sensor node having different initial energy levels and symmetric communication links.

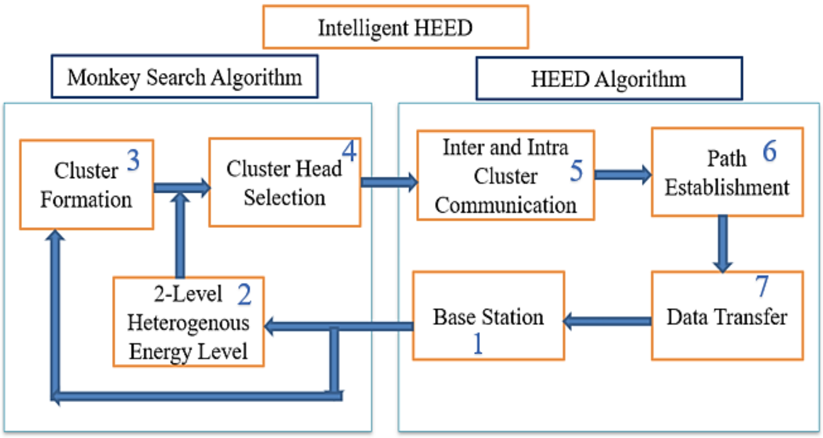

Figure 3. Methodology Module

2.1 I-HEED Cluster Formation

To minimize communication costs between sensor nodes and the base station, clustering is employed. This approach helps to gain insights into the structure of the data by grouping similar data points together. Clustering identifies subgroups (clusters) in which data points are closely related within the same cluster, while differing from those in other clusters. The developed algorithm utilizes the K-means clustering technique due to its simplicity in forming clusters. K-means is an iterative method that partitions the dataset into K predefined, distinct, and non-overlapping clusters, where each sensor node belongs to a single cluster. Each sensor node is assigned to a cluster in such a way that the sum of the squared distances between the data points and their cluster centroids is minimized. This process reduces communication costs between sensor nodes and the base station by first calculating the squared distances between each node and all centroids, assigning each node to its nearest cluster, and then recalculating the centroids by averaging the positions of all sensor nodes within each cluster.

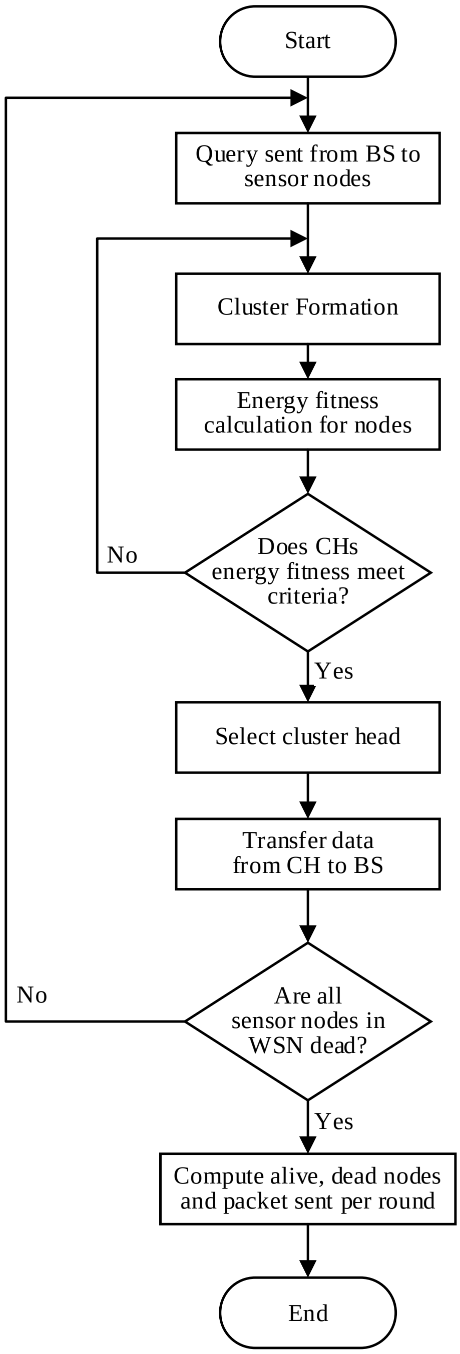

Figure 4. Intelligent HEED flow chat

This algorithm uses K-Mean Expected-Maximization approach in its optimization and the E-step assign sensor nodes to the closest cluster while the M-step compute the centroid of each cluster as shown in Equation 2 and Equation 3.

$$y = \sum_{i=1}^{m} \sum_{k=1}^{K} w_{ik} \parallel x^i - \mu_k \parallel^2 \quad (2)$$

$$\frac{\partial y}{\partial w_{ik}} = \sum_{i=1}^{m} \sum_{k=1}^{K} w_{ik} \parallel x^i - \mu_k \parallel^2$$

$$\Rightarrow w_{ik} = \{ {}^{1 \, for k = \| x^i - \mu_k \|^2}_{0 \, otherwise}$$

$$\frac{\partial y}{\partial \mu_k} = 2 \sum_{i=1}^{m} w_{ik} (x^i - \mu_k) = 0 \quad (3)$$

$$\Rightarrow \mu_k = \frac{\sum_{i=1}^{m} w_{ik} x^i}{\sum_{i=1}^{m} w_{ik}}$$

The assignment of sensor node x^i to the nearest cluster is determined by the sum of its squared distance from the cluster's centroid. Since the K-means clustering algorithm relies on distance-based measurements to evaluate the similarity between nodes, Intelligent-HEED standardizes the data to have a mean of zero and a standard deviation of one. This is necessary because the features of sensor nodes typically have varying units of measurement such as distance and energy level. For the heterogeneity of the sensor, a two-level heterogenous network was introduced.

$$T_{energy} = K(1-m)E_0 + KmE_0(1+g) \quad (4)$$

$$T_{residual\ energy} = KE_0(1-gm) \quad (5)$$

where E_0 is the initial energy of the normal nodes, m is the fraction of the advanced nodes, which have more energy than the normal nodes, g is the fraction of energy enhancement of advance nodes, m is the reference energy of the advance nodes, mK are advanced nodes equipped with an initial energy of $E_0(1+g)$, and $K(1-m)$ are normal nodes equipped with an initial energy of E_0.

2.2 I-HEED Cluster Head Selection

The I-HEED algorithm empower the base station carries out the cluster head selection. Therefore, the intelligent characteristics of this algorithm are embedded in the base station. The base station uses monkey behavior in searching for food (i.e. ripe banana), which denotes the sensor nodes' energy level. The ripe banana denotes the node's fitness (position in the network) and residual energy. For a node to be selected as the cluster head, the base station will analyze the energy level of the sensor nodes and select which one has high residual energy and fitness, which is determined by the base station's distance and proximity. To determine node higher residual energy, there is a need to determine the average energy at each round of communication in the network.

$$\overline{G}(r) = \frac{1}{K}\sum_{i=1}^{K} G_i\,(r) \quad (6)$$

$$p_i = p_{opt}\left[1 - \frac{\overline{G}(r) - G_i(r)}{\overline{G}(r)}\right] \quad (7)$$

$$F_t = \frac{(w \times (T_d - I) + (I - w) \times (K - S_i))}{100} \quad (8)$$

$$I = I_s + I_n \quad (9)$$

$$u_i = \frac{1}{pi} F_t = p_{opt}\frac{G_i(r)}{\overline{G}(r)} F_t \quad (10)$$

where F_t is the node fitness, T_d is the total distance of all the nodes to the target node, K is the total number of nodes, w is a network size. In gives the distances from sensor nodes to cluster head, I_s gives the sum of the distances from all cluster heads to target node and S_i is the number of advanced nodes that can become cluster heads and u_i is the advance node selected as CH and this is based on the residual energy and the node fitness. The nodes with higher residual energy are selected as cluster heads more frequently than those with lower energy.

2.3 I-HEED Energy Consumption

In Intelligent HEED, all nodes exchange information about the total energy and the network's lifetime. The average energy represents the optimal energy that each node should possess in the current round to maintain the network's operation. Ideally, all nodes would deplete their energy at the same rate, consuming an equal amount of energy per round. Consequently, the network's average energy is calculated for each round. Intelligent HEED uses the first-order radio model to estimate energy dissipation among sensor nodes, where energy is consumed when transmitting an n-bit packet over a distance rrr (the communication range between sensor nodes and the base station).

$$E_{tx}(n,r) = E_{tc}(n) + E_{amp}(n,r) \quad (11)$$

$$E_{rx}(n) = E_{tc} \times n \quad (12)$$

$$E_{tx}(n,r) = E_{tc} \times n + E_{amp} \times n \times r^2 \quad (13)$$

where, $E_{tc}(n)$ refers to the energy that the radio circuitry must expend to process an n-bit packet during transmission or reception, and $E_{amp}(n,r)$ is the energy required by the radio amplifier circuit to transmit an n-bit packet over a distance of rrr meters. Since a simple first-order radio was assumed, the radio dissipate E_{tc} = 50nJ/bit to run the transmitter or receiver circuitry and E_{amp} = 100 pJ/bit/m^2 for the transmit amplifier to achieve acceptable energy for transmission. It is also assumed that a r^2 energy loss is due to channel transmission.

2.4 I-HEED Practical Implementation

In today's world, most especially in Nigeria, Agriculture is one of the most important areas of human activity. Due to the surge in population, there is a need to increase agricultural products. Agriculture is increasingly becoming a data-intensive industry where farmers must collect and access vast amounts of information remotely from various devices (e.g., sensors, farming machinery, meteorological sensors) to better organize and connect relevant data. Imagine a 100m-by-100m farmland with 100 wireless sensor nodes distributed randomly throughout the area. Each node is equipped with sensors to measure soil moisture, soil temperature, atmospheric temperature, and relative humidity.

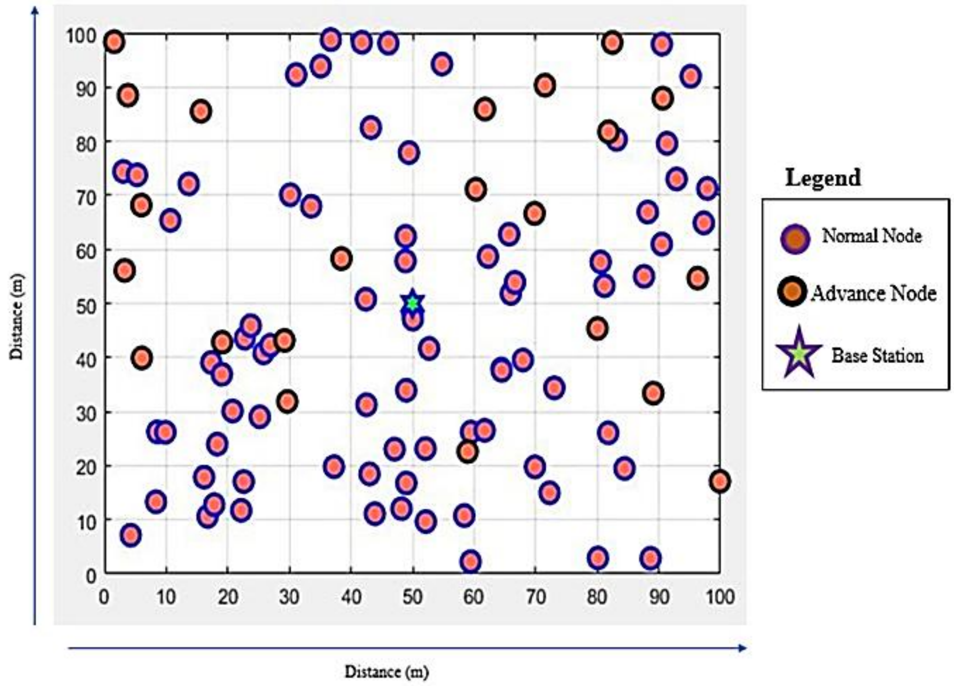

Figure 5. Simulation Sensor Field

Each node periodically monitors all parameters and forms clusters, with the selected cluster heads reporting the data to the base station. This setup facilitates communication between all sensors on the farm and the base station, which helps to quickly deplete the energy of sensors, especially those located far from the base station. It is assumed that the base station is centrally located on the farm, making it easier for all cluster heads to transmit their data, as they effectively function as regional base stations. The I-HEED algorithm also suggests that if a cluster head is far from the base station, it should seek out the nearest cluster head to transfer its data. The closer cluster heads then relay this data to the base station. This approach reduces communication costs among nodes and helps to extend the battery life of the nodes, thereby prolonging the overall network lifespan.

2.5 Simulation Parameters

The experiments were conducted in MATLAB R2019a, and the following assumption made:

a) Base Station has a central position to the region in which sensor nodes are distributed
b) All sensor nodes have different energy initially, i.e. heterogeneous, and are energy-constrained.
c) All links are symmetric and first-order radio the energy analysis used.
d) The base station assigns a unique identifier to each node.
e) The base station can communicate directly to all nodes, and nodes call also communicate among themselves.

It is assumed that the location of the Base Station to (50,50) corresponds to the (p, p)-coordinates of the sensor field. A hundred nodes (K=100) were randomly distributed in 100m by 100m field. Nodes are heterogeneous and equipped with an initial energy of 0.5J. Other simulation parameters are shown in Table 1. Parameters used to simulate other existing protocols (LEACH, HEED, DEEC) are according to the protocol.

Table 1. I-HEED Simulation Parameters

S/N	Parameter	Description	Value
1	P	Network size	100 m by 100 m
2	K	Number of Nodes	100
3	E_{fs}	Amplifier energy for free space model (Joules per bit per meter square)	10 pJ/ bit/ m2
4	E_o	Initial Energy (Joules)	0.5 J
5	E_{DA}	Data Aggregation Cost (Nano Joules per bit per message)	5 nJ/bit/Message
6	d_o	Threshold Distance between CH and member nodes (meters)	70 m
7	Message size	Total Message Size (bits)	4000 bits
8	E_{elec}	Radio electronics energy (Nano joules per bit)	5 nJ/bit
9	E_{amp}	Amplifier energy for multipath fading channel model (Joules per bit per meter square)	0.0013 pJ/bit/m^2

3. RESULTS AND DISCUSSION

This paper considers three key performance indicators for energy optimization in wireless sensor networks: the number of alive nodes, dead nodes, and packets sent to the base station. The analysis of the results is organized into three sections based on these indicators. The first section compares the time until the first node dies for Intelligent HEED against LEACH, HEED, and DEEC. The second section examines the number of alive nodes for the new algorithm in comparison to LEACH, HEED, and DEEC. The third section evaluates the number of packets sent to the base station before node death in the new algorithm relative to the previously mentioned algorithms.

3.1 Dead Nodes

Figure 6 illustrates the graphical representation of dead nodes for each round across the I-HEED, DEEC, HEED, and LEACH algorithms over 9500 iterations. All nodes remain active in all four algorithms up to 1000 rounds. After 200 rounds, nodes begin to fail, with energy levels dropping to zero, particularly in the HEED algorithm. In the I-HEED and DEEC algorithms, nodes start to fail after 1500 iterations. For the initial 1000 rounds, all four algorithms perform exceptionally well.

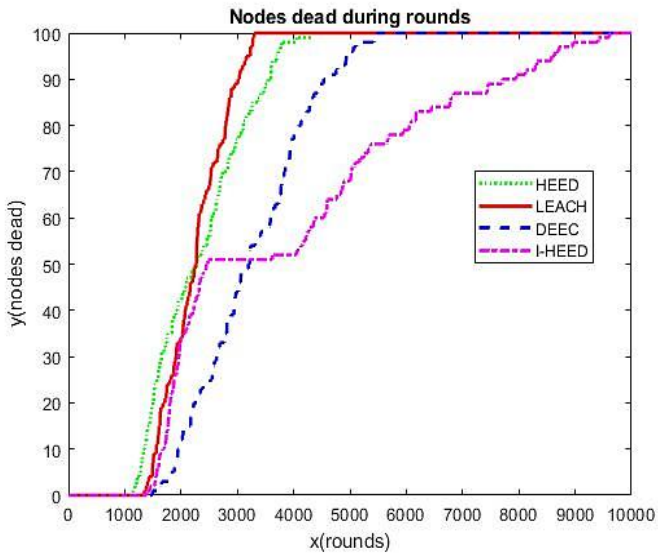

Figure 6. I-HEED Dead Node Performance.

For LEACH, all the sensors' nodes died at 3000 rounds, and no communication occurred within the nodes after 3000 rounds of communication. This happens because, in the selection of cluster head, LEACH just picks a particular sensor node without checking the initial energy of the node if it has the actual power for the required transmission. HEED considers initial energy before picking the cluster heads, and it could perform better than LEACH. In heterogenous DEEC, all the nodes died after 4500 rounds. In Intelligent HEED, all the nodes died after 10000 rounds, which performed better than LEACH, HEED, and its heterogenous algorithm DEEC. The protocol looks for best the CH before picking it to transmit the data bit to the base station.

3.2 Alive Nodes

In Figure 7 all nodes were alive for the first 1500 rounds for LEACH, DEEC, HEED and Intelligent HEED. For LEACH, all the sensors' nodes were alive till 3000 rounds in which no communication occurred within the nodes after 3000 rounds of communication due to effects of probability in cluster head selection. In HEED, all the nodes were alive till 4500 rounds of communication, and in DEEC, all the nodes were alive till 5500 rounds. Intelligent HEED performs better than LEACH and HEED in the number of alive nodes because it could sustain the nodes in communication till 10000 rounds. This shows that Intelligent HEED performs better in energy optimization than other clustering protocols compared. However, 50% of the sensor nodes died after 4000 rounds, and the remaining 50% could sustain the simulation till 10000 rounds. The optimization algorithm can only be effective with fewer sensors.

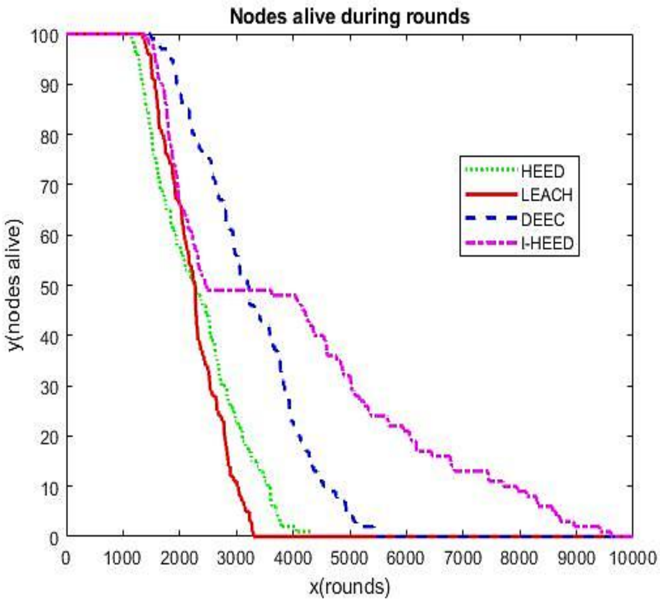

Figure 7. I-HEED Alive Node Performance

3.3 Packet Sent

I-HEED perform better in the number of packets sent to the base station compared with LEACH and HEED. The Intelligent HEED could send close to 400,000 packets in 10000 rounds while DEEC sent 350,000 packets at 4500 rounds, HEED sent 85000 packets at 4000 rounds, and LEACH sent 70000 packets in 3000 rounds. Comparing the packets sent in 5000 rounds for Intelligent HEED and HEED, Intelligent HEED sent close to 350000 packets while HEED sent 85000.

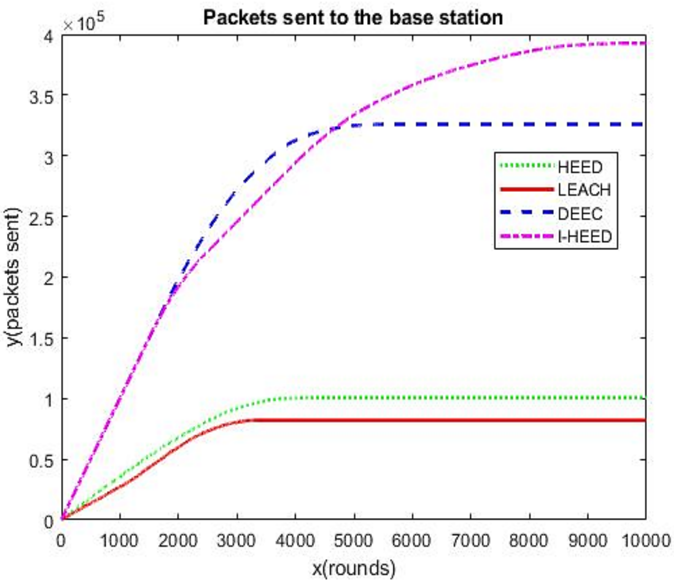

Figure 8. I-HEED Packets Sent to the Base Station

This shows that the new algorithm is 50% better than DEEC, 315 % better than HEED and 330% better than LEACH.

4. CONCLUSION

This study presents an innovative approach to energy optimization in Wireless Sensor Networks (WSNs) through the Intelligent HEED (I-HEED) algorithm. Designed as a hybrid of the HEED protocol and the Monkey Search Algorithm, I-HEED effectively selects optimal cluster heads, ensuring efficient data transmission to the base station. The hybrid system learns network dynamics over time, balancing energy distribution to reduce energy depletion in sensor nodes located farther from the base station. I-HEED exhibits superior performance compared to LEACH, HEED, and DEEC protocols across key metrics. It maintains a higher number of alive nodes over time, reflecting extended network longevity. Moreover, it also effectively minimizes dead node accumulation, delaying node failures more efficiently than the other algorithms. In terms of data transmission, I-HEED outperforms by delivering a significantly greater number of packets to the base station. These findings validate I-HEED's potential as a robust solution for energy-efficient WSN operations, supporting prolonged network lifespan and reliable data delivery in resource-limited conditions.

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