A Hybrid Energy Efficient Routing Protocol for Heterogenous Wireless Sensor Networks (HEER)

K.Raghava Rao
Research Scholor

Manoj Kumar
Associate Professor

Department of Computer Science & Engineering

Shri Venkateshwara University, Gajraula, Amroha,

Uttarpradesh, India

Abstract

Multi-level hybrid energy efficient routing protocol algorithm (HEER) for heterogeneous wireless sensor networks (WSNs) is presented. HEER proposed several techniques to prolong the overall network life time and to fairly distribute the energy load among nodes. It logically divides the sensing area into three levels. A centralized selection is proposed for Level One, in which the base station (BS) plays a great role in selecting cluster heads (CHs) for the first round, then the next CH will be independently chosen among the cluster-members (CMs). In Level Two, CH selection is proposed based on the Grey Wolf Optimizer (GWO), were nodes select the best route to the BS for saving more energy. Herein, grey wolves represent the sensor nodes in Level Two and the prey is the CH. Finally, a distributed clustering based on a cost function is proposed for Level Three. The main idea target in HEER is to minimize the communication distance to further prolong the network life time. The algorithm was evaluated through tests of a network's energy efficiency, lifetime, and stability period.

Key words: Energy Efficiency, routing protocol, wireless networks, routing algorithm, Hybrid network

1.Introduction

New infrastructure systems are connecting the world: systems such as smart grid, smart homes, smart water networks, and intelligent transportation. These systems are associated with a single concept, the internet of things, in which sensors are the key components, closely coupled with information and communication technologies; devices are interconnected to transmit useful information and control instructions via sensor networks [84]. WSNs can provide cheap, appropriate solutions for a range of applications from military to medical [82, 109]. Bio inspired metaheuristic algorithms are proposed by researchers as WSN routing becomes more challenging and complex, like Ant Colony Optimization (ACO) [1–11], Particle Swarm Optimization (PSO) [13][14], Artificial Bee Colony Optimization (ABC) [15][16], and Fuzzy Logic [17][18], are used to provide prolonged network lifetime for WSNs.

Grey Wolf Optimizer algorithm (GWO) [19] is a new evolutionary optimizing algorithm that used for modest applications such as optimum feature subset selection [20], when compared with PSO

and genetic algorithms showed better performance. Authors of [21] proposed improved version of GWO for training q- Gaussian Radial Basis Functional-Link nets neural networks and a competitive results were obtained comparing to other metaheuristic methods.

1.1 Grey Wolf Optimizer (GWO)

Bio-inspired metaheuristics have been efficient in solving problems and finding the best solution. GWO is a new bio-inspired metaheuristic introduced in 2014 by Mirjalili et al. [19] [22]. It is inspired by the social hierarchy and hunting behaviour of grey wolf packs. Wolves live in a hierarchical society of 5 to 12 members and can be categorized into four types: alpha (α) wolves are on top of the societal pyramid (Fig. 4.1); they are responsible for making hunting decisions, deciding where to sleep and when to wake up, etc.

α wolves can be male or female and are not necessarily the strongest but rather the best at finding possible prey locations. Beta (β) wolves are the α wolves' consultants, and in the absence of α they take responsibility for the pack. Delta (δ) wolves are the last ones to eat and they play a devotee role. If a wolf does not belong to the

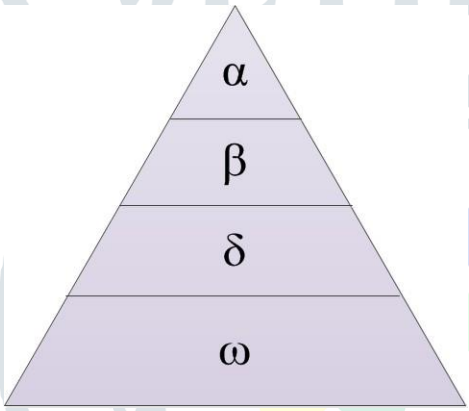


Fig. 1.1 Grey wolf social hierarchy.

previous groups then it is an omega (ω) wolf; ω wolves are responsible for protecting the boundaries and alerting the pack in case of emergency. In the GWO algorithm illustrated in (Fig. 1.2) [19], the search starts with a population of wolves (solutions) randomly generated: α is the best solution, β is the second-best solution, and δ is the third-best solution within the search space. During the hunting (optimization), the prey's location (optimum) is estimated by the three best solutions through an iterative procedure. Each grey wolf's position is denoted in a vector form $X = x_1 + x_2 + \ldots + x_n$, where n is the search-space dimension. Search (hunting) is guided by the α, β, and δ wolves, and the ω wolves follow. The hunting behaviour consists of three main stages: (1) Searching (Hunting), (2) encircling, and(3) attacking the prey.

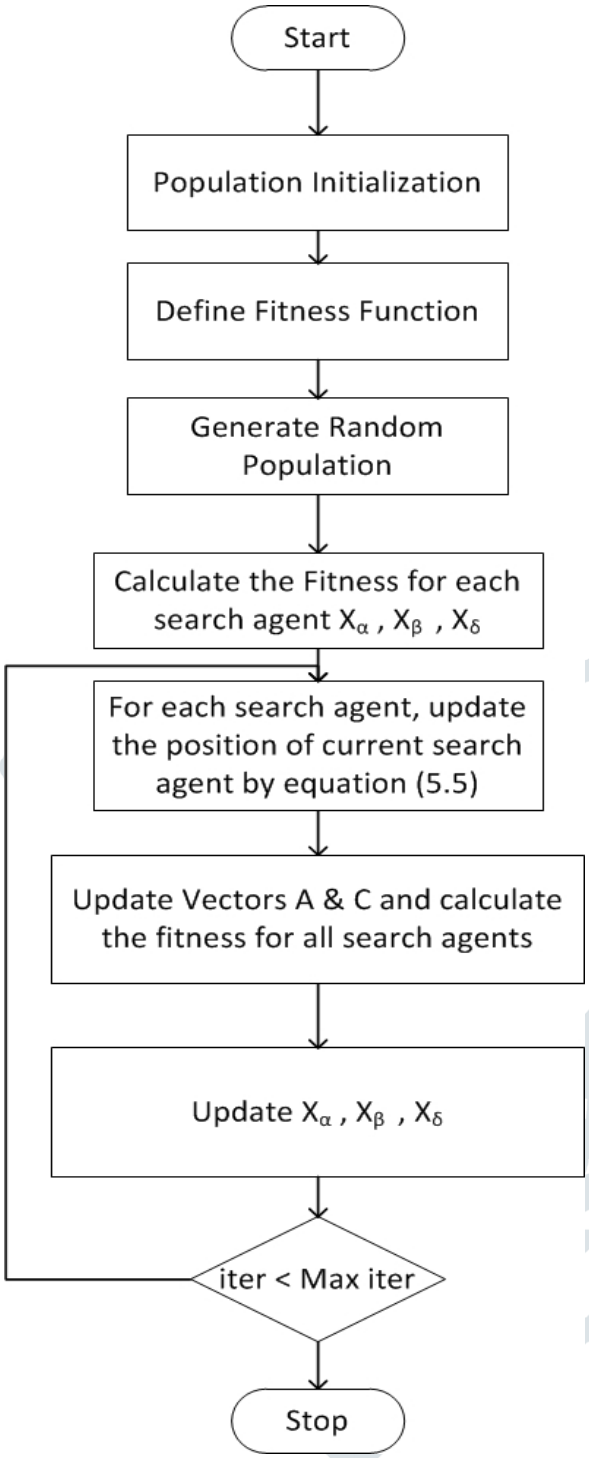


Fig. 1.2 Grey Wolf Optimizer Flowchart

1.1.1 Searching (Hunting) Prey

GWO hunting behaviour is led by the α, β, and δ wolves because they have better knowledge of potential prey locations. Therefore, the three best solutions obtained so far are used by the ω to update their positions as fellows:

$$D_\alpha = |C_1.X_\alpha - X|$$
$$D_\beta = |C_2.X_\beta - X| \qquad (1.1)$$
$$D_\delta = |C_3.X_\delta - X|$$

Where t indicates the current iteration, X represents the position of the current solution, X_a shows the position of α wolf, D_a is the updated α position , X_β shows the position of β wolf, D_β is the updated β position, X_δ shows the position of δ wolf, and D_δ is the updated δ position.

After defining the distances, the final positions of the current solutions X_1, X_2, and X_3 are calculated as follows:

$$X_1 = X_a - A_1.D_a$$
$$X_2 = X_\beta - A_2.D_\beta \qquad (1.2)$$
$$X_3 = X_\delta - A_3.D_\delta$$

$$X^{t+1} = \frac{X_1 + X_2 + X_3}{3}$$

where, A_1, A_2, A_3 are random vectors, and t indicates the number of iterations.

1.1.2 Encircling Prey

Wolves update their positions imitating the encircling behavior during the optimization, around α, β, or δ. The is mathematically modelled by the following equations:

$$D = |C.X^t - X^t_p| \qquad (1.3)$$

X^{t+1} = where t is the current iteration, X_p is the prey position, and X is the wolf's position; D is the distance between the position vector of the prey and a wolf and it is calculated in Eq. 4.4; A and C are coefficient vectors calculated in Eqs. 4.6 and 4.7, respectively:

$$A = 2d.r_1 - a \qquad (1.4)$$

$$C = 2d.r_2 \qquad (1.5)$$

where the a components are linearly decreased from 2 to 0 over the course of the iterations, and r_1,r_2 are random vectors in the range [0,1].

1.1.3 Attacking Prey

Grey wolves diverge from each other when searching for prey (exploration) and converge when attacking prey (exploitation). A mathematical model of divergence uses A with random values greater than **1** or less than –**1** to oblige the search agent to diverge from the prey, allowing GWO to search globally. That is, |A| > **1** forces the grey wolves to diverge from the prey hoping to find better prey, while |A| < **1** forces the grey wolves to converge and attack the prey.

2.HEER **Network Model**

Nodes that reside far from BS tend to lose their power more quickly due to the far distance communication between nodes and BS. Therefore, the network is logically divided into three equal rectangular spaces based on distance threshold d_{th} to minimize the transmission distance. Level One is closest to the BS and Level Three is farthest away, Fig.2.1 HEER considers a heterogeneous network with three stationary types of nodes in terms of their initial energy and their processing capabilities, m_1 nodes equipped with β times more energy acting as advanced nodes and m_2 nodes equipped with α times

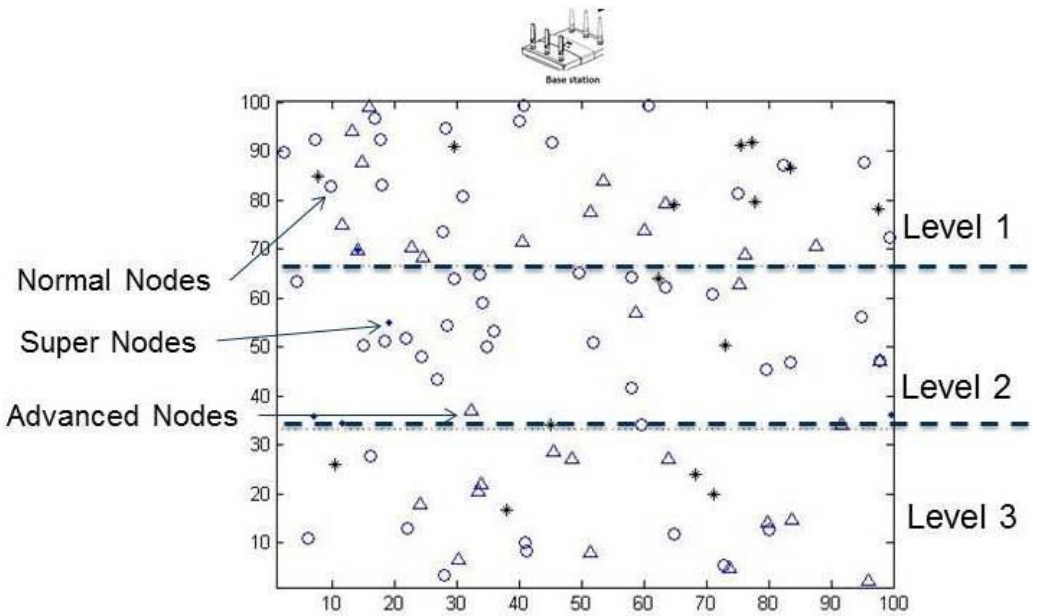


Fig. 2.1 Network Model.

more energy acting as super nodes. The BS is stationary and located in the central upper area. Sensor nodes have a limited and irreplaceable battery. And, sensor nodes can aggregate the l packets into a single packet. In order to keep total energy equivalent with other algorithms for comparison, the total number of nodes is calculated as in Eq.

2.1 . After the network is deployed, the BS asks the nodes for their location by broadcasting a message; it calculates the net distance of a particular node from other nodes and from the BS, Net_{dtoBS}, for every node, plus the maximum Net_{dtoBS}, then broadcasts back (d_{node}, Net_{dtoBS}, D_{Max}, L) once, where d_{node} is the node's distance from the BS, D_{Max} is the maximum Net_{dtoBS}, and L is the node's level, which is determined by the BS depending on the signal transmission.

2.1 Energy Model

The energy model used for this algorithm as previously explained in next section 3.3.2, Fig. 3.3, where the energy consumed to send a k-bit message over distance d is

$$E_{TX}(k, d) = k.E_{elec} + k\epsilon_{mp}d^4, \quad d > d_0 \qquad (2.1)$$

$$k.E_{elec} + k\epsilon_{fs}d^2, \quad d < d_0$$

In LEACH, the cluster formation was created to ensure that the expected number of clusters is k. However, the CH's selection depends on the random number generated by the sensor node, and instability of the random number leads to instability of the number of sensor nodes. Calculation of the optimal cluster number (k_{opt}) gives an expected value that may differ greatly from the value in the real WSN. The proposed algorithm calculates an optimal number of clusters that guarantees a CH in every round for Level One nodes by calculating the real k_{opt}, thus ensuring that nodes in Level Two can forward data if no CH was found in Level Two.

2.2 Cluster Number Calculation

HEER operates in rounds to minimize energy consumption and to evenly distribute energy load over the network. The proposed algorithm suggested several different approaches to improve the network performance and prolong the network life time, which is:

- ***Optimal number of clusters in the network:*** Finding the optimal number of CH's is a key factor that has strong effect on both the life cycle and energy consumption of the network. Lacking suitable number of CH's would cause either redundant selection to nodes or no CH selected, where both situations will lead to power lose.
- ***Different CH selection strategies based on node's level:*** in the proposed schemed three selection techniques were proposed. A centralized CH selection based on node's suitability for Level One, where nodes with the highest suitability make good candidates to be selected as CH. A probabilistic GWO-based CH selection for nodes in Level Two to fairly distribute energy load among nodes.

And, a distributed tree based CH selection is performed in Level Three based on a cost function. The main reason behind the clustering technique is to reduce the energy consumption rate so that the life time of a wireless network extends. For the hierarchical topologies used in WSNs clustering, they are generally preferred to have a fixed (K) number of sensor nodes working as CHs in each round of the collection process to equally balance the energy load and to save more energy.

2.3 Optimal number of CHs (k1) for Level One

In the proposed network, nodes are randomly deployed over the network area. Level One nodes (m) are scattered near the BS over the area ($A = M \times M/3$) with ($d < d_0$) which is set based on the distance threshold (d_{th}). Therefore, the energy dissipation to transmit an l-bit message in the Level One CH is

$$E_{CH} = lE_{ele}\left(\frac{m}{k_1} - 1\right) + lE_{DA}\frac{m}{k_1} + l\epsilon_{fs}d^2_{toBS} \qquad (2.2)$$

where d_{toBS} is the distance from the CH node to BS, and a perfect data aggregation has been assumed:

$$E_{non-CH} = lE_{elec} + l\epsilon_{fs} d^2_{toCH} \quad (2.3)$$

Since nodes are equally distributed, we put d^2_{toCH} to $E[d^2_{toCH}] = A/(2.\pi.k1)$ and

substitute into Eq. 2.10:

$$E_{non-CH} = lE_{elec} + l\epsilon_{fs} \frac{A}{2\pi k1} \quad (2.4)$$

Now, the energy dissipated in a cluster in one frame is

$$E_{Cluster} = l(E_{CH} + \frac{m}{k1} E_{non-CH}) \quad (2.5)$$

and the total energy is

$$E_{total} = k1 E_{Cluster}$$
$$= l(E_{elec}m + E_{DA}m + E_{elec}m + k1\epsilon_{fs} d^2_{toBS} + \epsilon_{fs} \frac{A}{2\pi k1})m \quad (2.6)$$

To find the optimal number of clusters k_1, we equate Eq. 4.13 to zero and differentiate with respect to k_1:

$$k_1 = \sqrt{\frac{m.A}{2\pi}} \cdot \frac{1}{d_{toBS}} \qquad (2.7)$$

where m is the node number in Level One and the average distance from a CH to the BS is given by [23] $E[d_{toBS}] = 0.765 \times \frac{A}{2}$.

2.4 Optimal number of CHs (k2) for the rest of the network

As for the rest of the network (Level Two and Level Three), the same formula as in LEACH-C [30] has been considered:

$$k_2 = \sqrt{\frac{n}{2\pi}} \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \frac{M}{d^2_{toBS}} \qquad (2.8)$$

where $(n = N - m)$, M is the sensed area, and $d_{toBS} = 0.765 \times \frac{M}{2}$.
Given n nodes in a network structured as in Fig. 1.7, the expected energy to send k bits from level 1 SNs to Level 2 CHs will be [124]:

$$E_1 = kE_{elec} + k\epsilon_{fs}d^2_{toCH} \qquad (2.9)$$

The researchers in [24] left the multi-level as an open research issue and this is what we applied in CH Wolf.

2.5 Cluster Heads Selection

Improper cluster formation may results in overload for some CHs; this overload may degrade the performance of the entire network due to the high energy consumption of the CHs. Therefore, proper CH selection is the most important concern for clustering in WSNs and designing an energy efficient clustering algorithm is crucial issue and has many challenges. In this section, the selection of CHs is performed by proposing different strategies depending on the node's level to minimize the energy consumption and enhance the performance of the network.

2.5.1 Centralized selection of CHs for Level One

In level One, the BS calculates the suitability of each node which represents the chance of the node to become CH. BS will only selects K_1 nodes with the highest suitability to be declared as CHs. As depicted in Eq. 4.17, the selection is based on the node's location from the BS, the residual energy, and the energy consumption ratio.

$$Suitability(m) = \frac{E_r}{ECR \times Net_{dtoBS}} \tag{2.10}$$

where E_r is the node's residual energy and $ECR = \frac{E_0}{E_0 - E_r}$ is the energy consumption

ratio. And the net distance is calculated in Algorithm 1. [18]

Nodes will be sent a control message from their BS stating the ID of the CHs, the CHs locations and the nodes suitability ratio, the nodes will send join requests to the nearest CH and form the cluster. This process takes place at the first round of the simulation only and when the current CH reaches a predefined energy threshold, an inner cluster decision to select the next CH among the cluster members will occur. By following this approach, nodes will save communication energy through communicating to their CH instead of with the BS to select the next CH, Fig.2.2 provides a detailed description to the CH selection procedure in Level One.

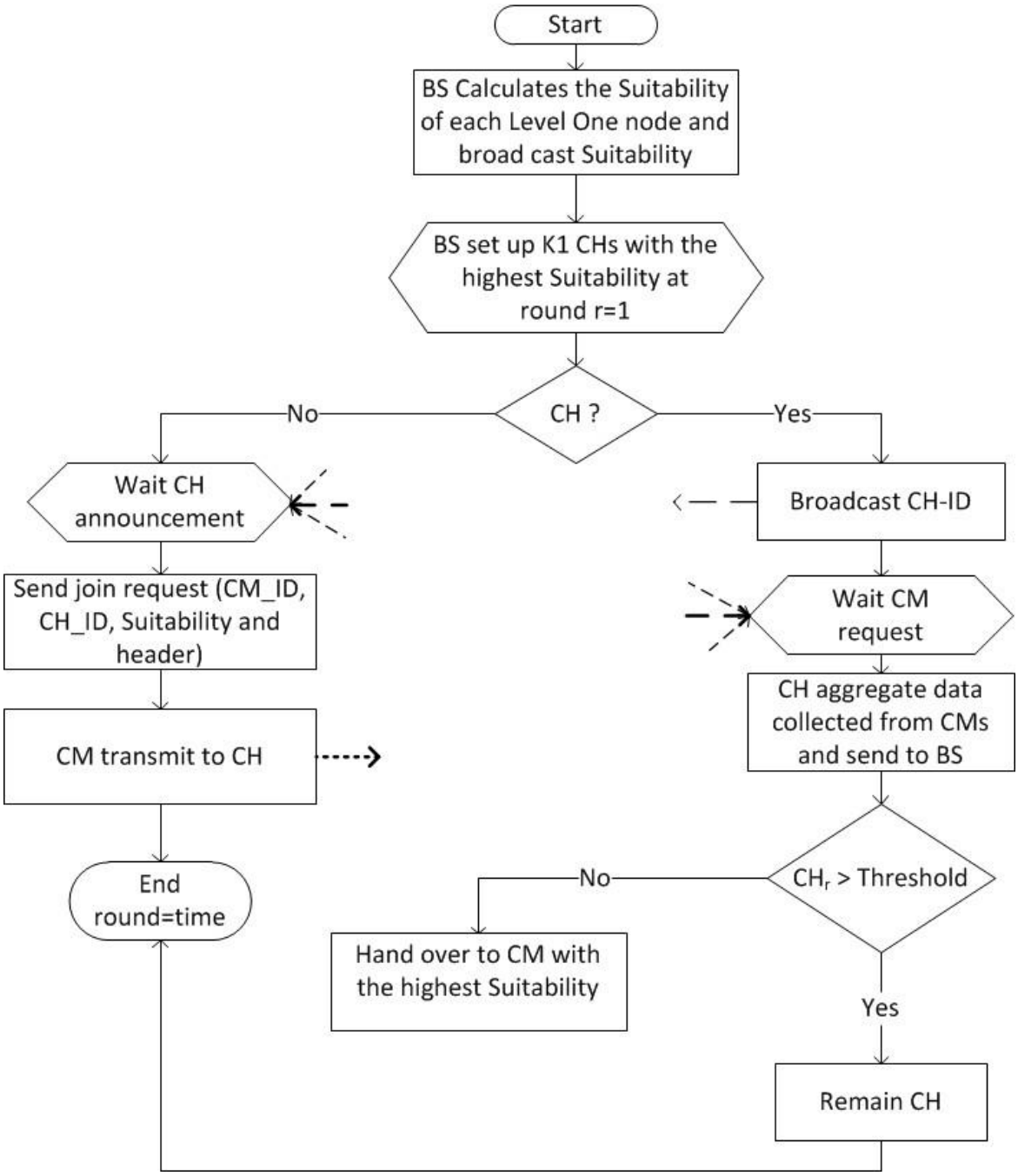


Fig. 2.2Centralized Selection in Level One.

2.5.2 Probabilistic GWO-based selection of CHs in Level Two

The proposed GWO implementation targets the randomly deployed stationary nodes in Level Two. It assumes m nodes that represent the CH search agents (wolves), **(**CH **=** CH_1, CH_2, ..., CH_m**)**. In order to mimic the positions of the wolves in GWO,and since changing the position of a static

sensor node is not possible, the search agent's position (candidate CH) is represented by $\overrightarrow{CH}_i$ in a two-dimensional space that represents the nodes' positions ($Pos_i(t) = x_i(t), y_i(t)$). The final solution is obtained by considering the nearest node to the best search agent position (α position). Algorithm2 describes the Level Two GWO-based CH selection. The CH selection is determined by a fitness function; in the GWO algorithm, the fitness function has the most important role in the searching-for-prey mechanism. The input for this function is the node's characteristics, including its residual energy (E_r) and the number of neighbours; the output is a value expressing how fit the node is to become a CH.

$$f(CH_i) = p_1|N(CH_i)| + p_2 \sum CH_E, \ p \in N_{(CH_i)} \qquad (2.11)$$

where p_1 and p_2 are random numbers in the range [0,1], $N(CH_i)$ is the list of sensor neighbours for a particular CH_i, and CH_E is the neighbour node's residual energy.

The successful candidate is the one with the highest f, meaning the node with the highest residual energy and sufficient adjacent neighbours will declare itself as a CH. After the selection is completed, CHs will broadcast a HELLO_Msg including the CH identification and the CH distance from BS, see Fig. 4.5. Then CH waits for cluster members to join.

bits	32	8	32
	CH_ID	d	CH_Coordinates (X,Y)

Fig. 4.5 *HELLO_M sg.*

When the current α CH reaches an energy threshold, the next CH selection will be in that cluster and the next CH will be chosen from β nodes. This process prevents energy loss in outer cluster communication if CH selection happens on a network level.

2.5.3 Distributed selection of CHs in Level Three

After receiving the HELLO_Msg from Level Two CHs, nodes in Level Three will start CH selection process, this may cause delay in the initialization phase of the algorithm however, it will grantee a maximum life time for the entire network as result for shortening the communication distances.

Algorithm 2 GWO-based CH Selection

```
Input α and β start locations                                  ▷ for each round r
while r < r_max do
    for each search agent CH_i do
        Clone the nearest node to CH_i
        Compute fitness according to (Eq. 4.18)
        Update leader nodes X_α, X_β, X_δ, the best three search agents
        Calculate the coefficient vectors according to (4.6) and (4.7)
        Update wolves' positions using (4.3)
    end for
end while
CH_ID = Nearest node to α obtained.
```

The criteria for selecting the $L3_{CHs}$ depends on the node's distance from $L2_{CH}$ and the its energy. $L3_{node}$ calculates the approximate distance d from each $L2_{CH}$ then build CH_Neighbour_Table as

shown in Table 4.1 below.

Table2.1 CH_Neighbour_Table

CH_Neighbour _ID	d_{toBS}	d
1	62	15
...	...	...

A successful CH candidate will have a minimum communication cost, and its residual energy will be greater than half E_0. None-CH nodes decide its parent within neighbours based on a cost function (Eq. 2.10

Using energy level, HEER chooses the $L3_{CH}$ with more residual energy to transmit data to $L2_{CH}$ if the sensor node cannot find a suitable parent node it will transmit its data directly to BS. Assume the current node is i, the communication radius is R, and the set of its CH_Neighbours is S; then its parent node, P_{arent}, is chosen by the following formula:

$$P_{arent} = \begin{cases} BS, & \text{if } d(i, BS) < R \\ L2_{CH}, & \text{if } \min(\text{cost}(j)) \text{ where } j \in S \end{cases} \quad (2.12)$$

and

$$d(j, BS) < d(i, BS))$$

$$cost(j) = \frac{P \times Net_{dtoBS}}{D_{max}} + ((1 - P) \times (E_0 - E_r)) \quad (2.13)$$

Where, P is a probability factor chosen by CHs, Net_{dtoBS} is the net distance between the CH and BS and between itself and $L2_{CH}$, D_{max} is the maximum distance to BS, E_r is the residual energy and E_0 is the initial energy. The pseudocode for generating the parental tree is given in Algorithm 3.

Algorithm 3 Pseudocode for creating the tree

```
Sending HELLO_Msg (CH_ID, d_toBS)
On receiving a HELLO_Msg from node j by node i
Add j to the CH_Neighbour_Table
for i = 1 : N do
    if Node.L == 3 & Node.Energy > E0/2 then
        Node.Live = 1
        Node.p = 0
        Node.d = 0
        min_cost = 1
        for j = 1 : S(i) do
            if Node(i).d_toBS < R then
                Node(i).p = BS
            elseNode(i).d_toBS > Node(j).d_toBS
                cost = P × (Net_dtoBS/D_max) + ((1 − P) × (E0 − Er))
                if cost < min_cost then
                    min_cost = cost
                    Node(i).p = j
                    Node(i).d = d(i, j)
                end if
            end if
        end for
    end if
end for
```

3.Performance Evaluation

The motivation of designing HEER is to further improve the network energy consumption and to extend the network life time than of HRHP. HEER is compared HRHP in terms of network stability (FND), operational time (HND), network life time (LND) and the total remaining energy.

Two cases are conducted to test the performance of both protocols when changing the sensing area and the network density. The base station located in the middle far of the network and the heterogeneity parameters were set to ($\alpha = 2$ and $\beta = 1$) which will give fair testing environment:

3.1 Case1: Area $= 100 \times 100$ m², the number of nodes N $= 100$ and N $= 200$.

3.2 Case2: Area $= 200 \times 200$ m², the number of nodes N $= 100$ and N $= 200$.

HEER reduces the communication distance by dividing the area into three levels and applies a tree-based CH selection for level 3. In the first level of the network, HEER applies the same techniques used in HRHP, however, different CH selection technique is used for the remaining area. Which improved the performance of HEER compared to HRHP. Examining the results obtained from case1, HEER performance outperformed HRHP for the stability period by a percentage change of 78.03%, the operational time for HEER is also increases by a percentage change of 74.06% and the network life was extended by a percentage change of 80.66%, as can be seen in Table 2.2.

Table 3.1 Case1: Network life time, Area= 100×100 m^2

	Results obtained for 100 nodes			Results obtained for 200 nodes		
Algorithm	FND	HND	LND	FND	HND	LND
MLHP	1848	3490	9353	1463	2406	6389
HRHP	1038	2005	5177	116	2096	5034

When increasing the number of nodes to 200, MLHP stability period increases compared to HRHP by a change of 25.58%, the operational time increases by a percentage change of 14.79% and the network life time increases by 26.92%.

Furthermore, MLHP has more energy balanced network compared to HRHP, MLHP successfully maintains higher energy levels for both node deployments. Fig. 3.1 shows the total remaining energy levels for a 100 nodes deployment and Fig. 3.2 shows the remaining energy for network deployment of 200 nodes.

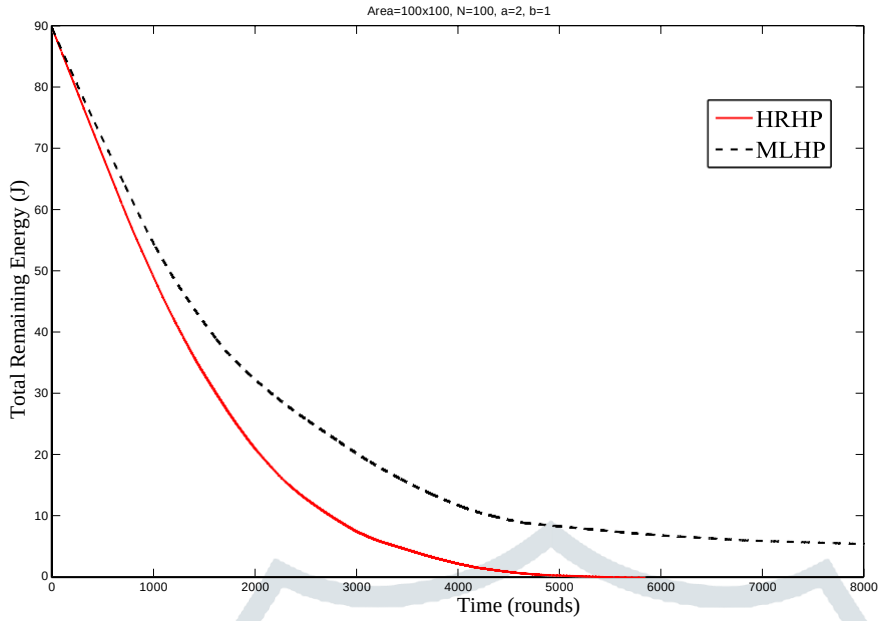


Fig. 3.1 Total network remaining energy for **100** × **100** m^2 area and N **= 100**.

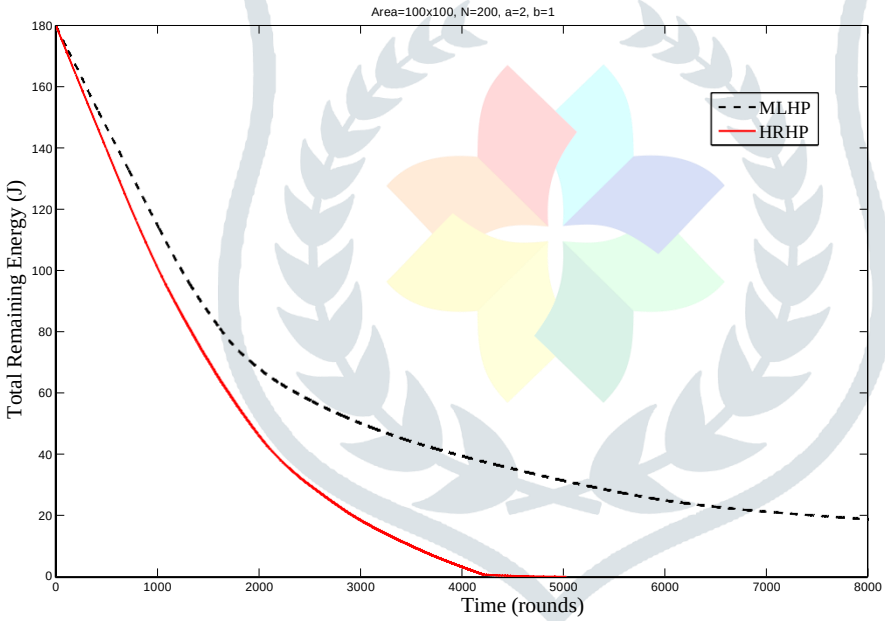


Fig. 3.2 Total network remaining energy for **100** × **100** m^2 area and N **= 200**.

Increasing the sensing area to **200** × **200** m^2 has affected the performance of both protocols in comparison with case1. However, MLHP remains to act better than HRHP.

For 100 nodes deployment, the stability period of HEER increases by increase of 23.47%, the operational time increases by 2.62% and the network life time increases by 28.57%. In addition, when the number of nodes increases to 200, the stability period of HEER increases by 12.2%, the operational time increases by 2.16% and the network life time increase by 43.07%. Table 4.3 presents the results obtained for case2.

Table 3.2 Case2: Network life time, Area= **200** × **200** m^2

	Results obtained for 100 nodes			Results obtained for 200 nodes		
Algorithm	FND	HND	LND	FND	HND	LND
MLHP	605	1212	7277	920	1609	8298
HRHP	490	1181	5660	820	1575	5800

he network remaining energy is further improved in HEER when increasing the sensing area size. Fig. 3.3 presents the results for comparing the remaining energy for 100 nodes deployment and Fig. 4.9 shows the results obtained for 200 nodes deployment. The figures clearly show that MLHP performance in preserving the network energy is better than HRHP for both nodes deployment.

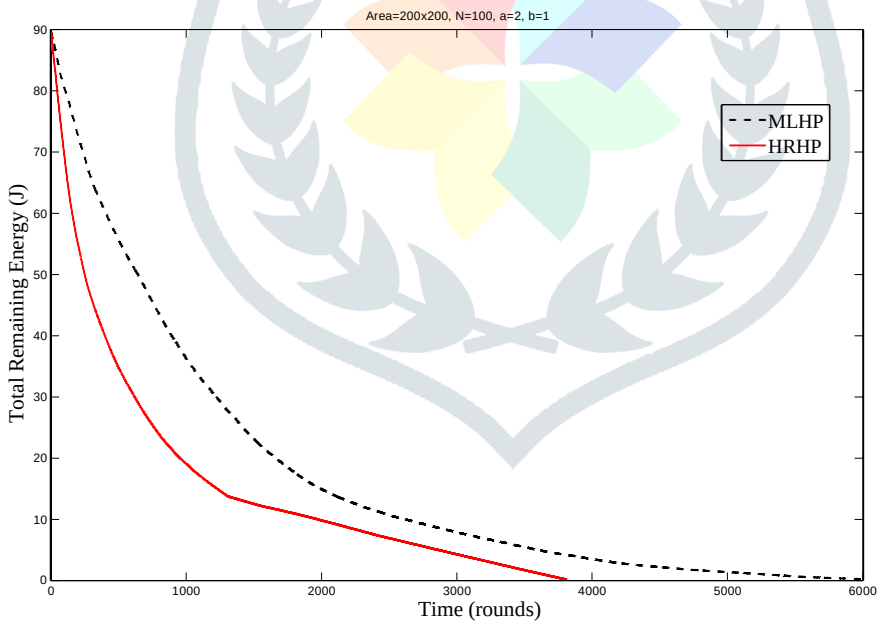


Fig. 3.3 Total network remaining energy for **200** × **200** m^2 area and N **= 100**.

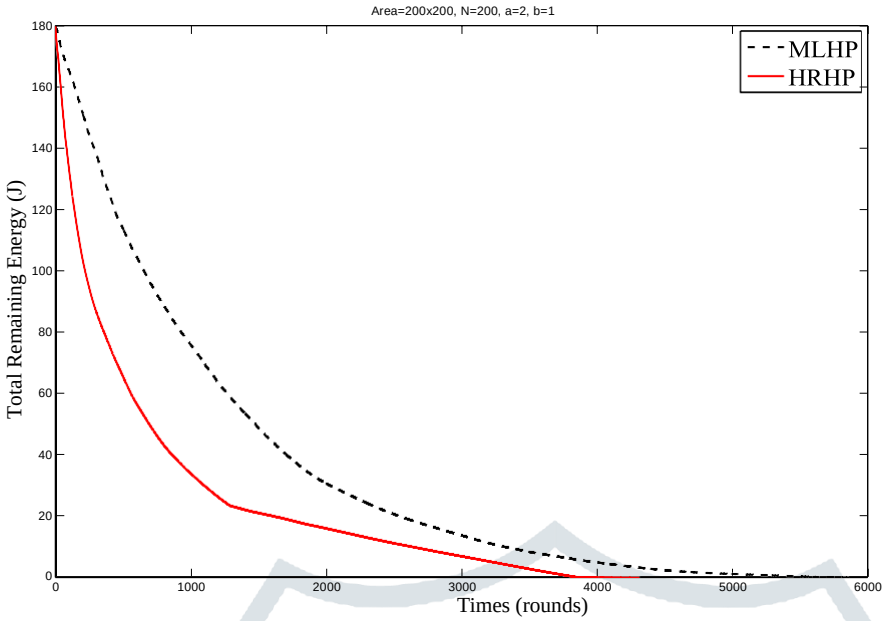


Fig. 3.4 Total network remaining energy for **200** × **200** m^2 area and N **= 200**.

MLHP has fulfilled its purpose in comparison with HRHP. Therefore, we wanted to test MLHP against other protocols. HEER is compared with LEACH, DEEC and SEP protocols in terms of stability period, operational time, network life time and the network remaining energy. In the next section, the simulation parameters and the settings are explained in the next section.

4. Simulation Parameters and Settings

Simulation can be defined as a representation or imitation of a system in its realistic form. It is a powerful tool for the evaluation and analysis of a new system design, modifications to existing systems. Employing simulation to study system performance incorporates different advantages. In networking field, simulation has been widely used to evaluate network algorithms under different conditions, and to provide a critical understanding for their behaviors and characteristics. The main scenarios involve results for different assumptions simulation scenarios and analyses the most significant performance results in terms of network stability, life time, percentage of nodes survival, residual energy, and data packets sent to the BS.

4.1 Simulation Parameters

To evaluate the performance of HEER, three extensive simulation studies was conducted using MatLab R2012b and compared with the performance of best-known algorithms. All simulations were conducted in randomly generated, static networks with different number of nodes and monitoring area size. The metric performance used in simulation is based on the number of *rounds* in which the first node deployed its energy, half of nodes are active and when all nodes are inactive. A *round* is a time interval where all the Cluster Members (CMs) have to transmit their data to the associated Cluster Head (CH). To represent the heterogeneity of the network, three types of nodes are used with different initial energy as illustrated below. The common simulation parameters settings are

listed in Table 4.1 and the performance indicators are defined below:

1. **Network Stability Period:** is the number of rounds lapsed from the start of the network operating till the energy of the *First Node Dead (FND)* is insufficient to transmit data. High value of FND indicates more balanced energy consumption among sensor nodes [125].

2. **Operational Time**: is defined as the number of rounds for which 50% of the total nodes are active, *Half Node Dead (HND)*.

3. **Network Life Time:** referred to as the *Last Node Dead (LND)*, which indicates the number of rounds after which all nodes in the network deployed their energy and no longer able to establish communication with other nodes.

4. **Energy Dissipation:** this parameter indicates the average energy dissipated by the network over the period of operating time.

5. **Packets Delivery:** which is the total data transmitted by CH's and received by the BS.

Table 4.1 Simulation Parameters

Parameter	Value
Initial Energy (E_0 Normal)	**0.5**J/bit
Cluster Head Probability (P)	0.1
Data Aggregation Energy cost **(**EDA**)**	**5**nJ/bit/signal Packet Size 4000 bits
Transmitter/ Receiver Electronics **(**E_{elec}**)**	**50**nJ/bit Transmit amplifier **(**ϵ_{fs}**)** **10**pj/bit/m^2
Transmit amplifier **(**ϵ_{mp}**)**	**0.0013**pj/bit/m^4
Fitness function probability (p_1)	0.7
Fitness function probability (p_2)	0.3

4.2 Simulation Settings

In this work, the scenarios were designed to give proper indication on the algorithm performance in terms of heterogeneity awareness to extend the network life time and thus the network performance. Three main scenarios were set to measure the performance of the proposed algorithm. The stability of the algorithms as well network operational time were tested in scenario-I for small-scale and large-scale networks with the minimum heterogeneity and for different number of nodes (100, 300, and
500) as illustrated in Table 4.2, the performance of the protocols in terms of network life time, energy conception and packet delivery for small-scale networks is examined in scenario-II and the parameters are set accordingly as illustrated in Table. 4.3. Finally, the performance over large-scale networks in terms of network life time, energy conception and packet delivery is measured in scenario-III and the parameters settings are shown in Table. 4.4.

Table 4.2 Scenario-I Settings: Network Stability and Operational Time

Case	Area	Nodes (N)	β	α	m	mo
1	$100 \times 100\ m^2$	100 nodes	0.5	1	0.5	0.4
2	$100 \times 100\ m^2$	300 nodes	0.5	1	0.5	0.4
3	$100 \times 100\ m^2$	500 nodes	0.5	1	0.5	0.4
4	$200 \times 200\ m^2$	100 nodes	0.5	1	0.5	0.4
5	$200 \times 200\ m^2$	300 nodes	0.5	1	0.5	0.4
6	$200 \times 200\ m^2$	500 nodes	0.5	1	0.5	0.4

Table 4.3 Scenario-II Settings: Heterogeneity over Small-Scale Network)

Case	Area	Nodes (N)	β	α	m	mo
1	$100 \times 100\ m^2$	100 nodes	0.5	1	0.5	0.4
2	$100 \times 100\ m^2$	100 nodes	1	2	0.5	0.4
3	$100 \times 100\ m^2$	200 nodes	0.5	1	0.5	0.4
4	$100 \times 100\ m^2$	200 nodes	1	2	0.5	0.4

Table 4.4 Scenario-III Settings: Heterogeneity over Large-Scale Network

Case	Area	Nodes (N)	β	α	m	mo
1	$200 \times 200\ m^2$	100 nodes	0.5	1	0.5	0.4
2	$200 \times 200\ m^2$	100 nodes	1	2	0.5	0.4
3	$200 \times 200\ m^2$	200 nodes	0.5	1	0.5	0.4
4	$200 \times 200\ m^2$	200 nodes	1	2	0.5	0.4

where, m is the ratio of normal nodes, mo is the ratio of advanced and super nodes combined, α is the percentage of energy for the super nodes, and β is the percentage of energy for the advanced nodes.

The usage of these factors are explained in the following **Example**: in scenario-I, when the total number of nodes ($N = 100$) and $m = 0.5$, this means the ratio of normal nodes is 50%, therefore the network will have 50 normal nodes, the same ratio division applies to ($N = 300$ *and* $N = 500$). When $mo = 0.4$, then the number of advanced nodes (N_a) in the network can be calculate as:

$$N_a = N \times m \times (1 - mo) = 30 \text{ nodes} \tag{4.1}$$

And the rest of the nodes are super nodes ($N - N_a \Rightarrow 50 - 30 = 20$ *nodes*), now the initial energy of the advanced nodes is calculated as: $E_a = E_o * (1 + \beta)$, meaning when

$\beta = \mathbf{0.5}$ that means there are 30 advanced nodes equipped with initial energy equals to **0.75** J/bit, and when $\alpha = \mathbf{1}$ that means there are 20 nodes equipped with initial energy equals to **1** J/bit. The same ratio settings apply for (N= 200, 300, and 500).

In scenario-II and scenario-III when $\beta = \mathbf{1}$, the initial energy of the advanced nodes, equals to **1** J/bit and when $\alpha = \mathbf{2}$ the initial energy of the super nodes equals to **1.5** J/bit. Which is the highest energy level allowed for the nodes, this will provide a clear vision for the algorithms behavior under worst case scenarios when the heterogeneity of the network is low.

5. Simulation Results

In the first stages of the network setup, HEER sets the number of CHs based on the Eq. 4.1, then selects the nodes with the highest suitability using Eq. 4.3 for Level One. In Level Two, the selection is made based on the proposed fitness function (Eq.4.18) which guarantee the selection of the best fitted nodes. Lastly, it reduces the communication distance in Level Three by selecting the nearest CH in Level Two to act as the parent of Level Three CH based on the cost function which is proposed in Eq. 4.20. Three main scenarios were set in Table 4.4 to compare the performance of HEER against three known protocols namely LEACH, DEEC and SEP.

In this, the evaluation performance of HEER and the simulation results are presented. Each result represents an average of 30 simulation runs to provide accurate results. The first set of results investigate the network stability and the operational time in small-scale and large-scale networks.

5.1 Network Stability and Operational Time

In order to test the algorithms' behavior over a scaled network deployed with different node density (100, 300, and 500 nodes) and low heterogeneity parameters ($\alpha = \mathbf{1}$ and $\beta = \mathbf{0.5}$), the stability of the network and the network operational time are evaluated for two different areas ($\mathbf{100} \times \mathbf{100}$ m^2 and $\mathbf{200} \times \mathbf{200}$ m^2). The obtained results are illustrated in Table 4.8 and Table 4.9 respectively.

In Table 4.4, for a small network area (**100** × **100** m^2) deployed with 100 nodes, HEER first node has lost its activity in round 1213, LEACH in round 955, DEEC in round 1205, and SEP in round 1019. This indicates that HEER had the longest network stability, which will give the systems that are implemented in a small area more stable environment to operate. When the number of nodes increases to 300, the stability time percentage change for HEER increases by 12.7%, LEACH by 1.99% and SEP by 16.58% while DEEC decreases by 2.66%. Further, when the deployment of the nodes increases to 500 nodes, the stability time percentage change for HEER increases by 18.47% and SEP by 20.22% while LEACH decreases by 1.57% and DEEC further decreases by 5.39%. HEER and SEP took the advantage of choosing CHs that can support the network which made them maintain higher increase stability regardless of the network density for small scaled networks. However, when we examine the operational time represented by Table 4.9, we can see that HEER HND took place at round 2765 for **100** × **100** m^2 area deployed with 100 nodes, and SEP in round 1753 which represents an increased percentage change by 36.6% for HEER over SEP. When the same area is deployed by 300 nodes, HEER percentage change increased by 15.19% while SEP only increases by 0.74%. The same improvement is noticed when deploying the area with 500 nodes, HEER shows an increased percentage change by 37.03% and SEP by 1.08%. HEER scored better performance because it considers the characteristics of the nodes when selecting a CH, which include the node's location in the network, the node's distance from the BS and the node's residual energy. Therefore, when we increased the number of nodes, HEER had more range of nodes to select from, which is important for IoT applications were there will be billions of nodes connected together.

Moreover, HEER keeps the communication distance to the minimum when considering a CH. Therefore, when the sensing area increases to **200** × **200** m^2, HEER successfully preserve the highest stability period. For an area deployed with 100 nodes, HEER percentage change increased by 16.53%, while LEACH by 0.34%, DEEC by 15.12% and SEP by 4.01%. Furthermore, for deployment of 500 nodes, stability period percentage change increased in HEER by 6.62%, LEACH by 0.68%, DEEC by 8.54% and SEP by 1.34%. This will reflect on the operational time for HND (Table 4.4) were HEER had the highest improvement for operational time, which will guarantee that the system operates HEER have longer time to collect more data from the field. The operational time percentage change has increased for HEER by 49.34% for a network deployed with 300 nodes and 43.65% for a network deployed with 500 nodes.

For LEACH an increase of 13.07% for 300 nodes and increase of 11.7% for 500 nodes. DEEC showed an increase of 25.6% for 300 nodes and 25.16% for 500 nodes. Finally, SEP showed and increase of 19.51% for 300 nodes and 11.67% for 500 nodes.

As a result, HEER successfully preserves good stability period and the longest operational time for both small-scale and large-scale area networks, regardless the nodes number and for minimum heterogeneity. It also has the longest operational time for both areas, which means that HEER has more balanced network.

5.2 Heterogeneity over Small-Scaled Networks

MLHP had high stability period and the longest operational times for a small-scale network sized **100** × **100** m^2, for different node intensities (100, 300 and 500) with the minimum heterogeneity parameters (α **= 1** and β **= 0.5**).

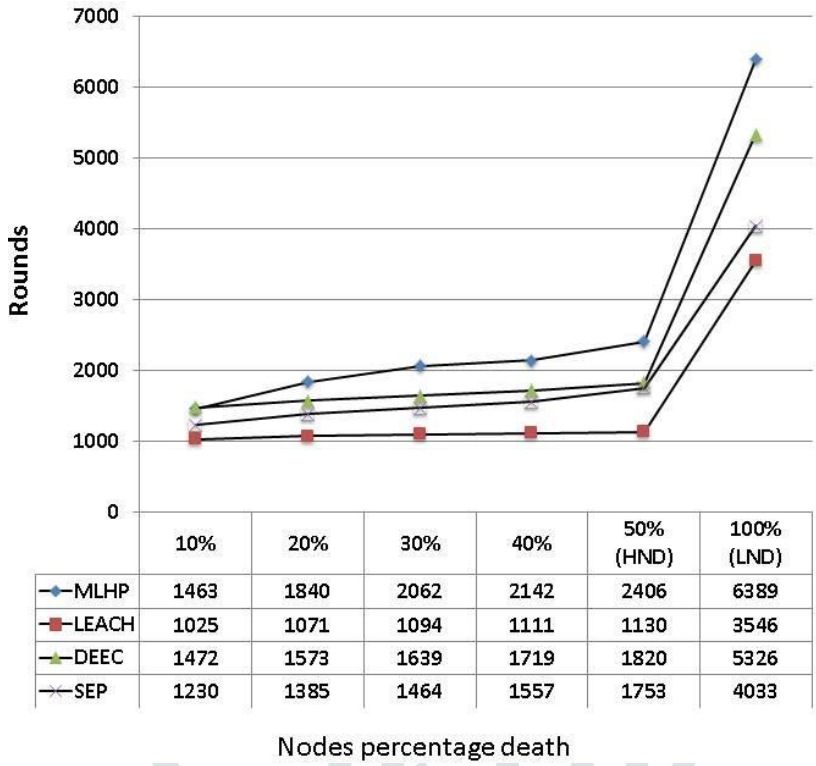
In this section, the results obtained in order to find the affect on the performance of HEER when increasing the heterogeneity parameters. The performance of HEER is compared to LEACH, DEEC and SEP in terms of network life time, network residual energy and the number of packets delivered to the BS.

5.2.1 Network Life Time

The majority of the literature compare the network lifetime in terms of last dead node (LND) only, which may not give a full indication on the performance of the algorithms and the ratio of the active nodes during different life time stages. In the presented results for this scenario, a time slots are set to provide a better image for the number of active nodes during the life time of the network.

Case1: When the network was deployed with 100 nodes with low het- erogeneity parameters (α **= 1**) and (β **= 0.5)**.

Fig. 5.10 illustrates the average communication rounds at which a certain nodes percentage death happen, which is presented by the x-axis. When comparing the nodes' death point of HEER with those of LEACH and SEP, HEER nodes died later for the entire life time points. HEER 10% of nodes died at round 1463, LEACH at round 1025 and SEP at round 1230. However, when comparing with DEEC (at round 1472), the 10% death of HEER happened slightly before that of DEEC because HEER had more active nodes at the first rounds. While when comparing the remaining time slots, we can see that MLHP had slower death than DEEC which means that HEER adjust its selection of CHs to preserve the number of active nodes. The improvement percentage of HEER over all compared algorithms is presented in Table 4.5.



	10%	20%	30%	40%	50% (HND)	100% (LND)
MLHP	1463	1840	2062	2142	2406	6389
LEACH	1025	1071	1094	1111	1130	3546
DEEC	1472	1573	1639	1719	1820	5326
SEP	1230	1385	1464	1557	1753	4033

Fig. 5.1 Network lifetime for small-scale network, N **= 100**, α **= 1**, β **= 0.5**.

Table 4.5 Average life time percentage improvement over other protocols for small-scale network (N **= 100**, α **= 1**, β **= 0.5**)

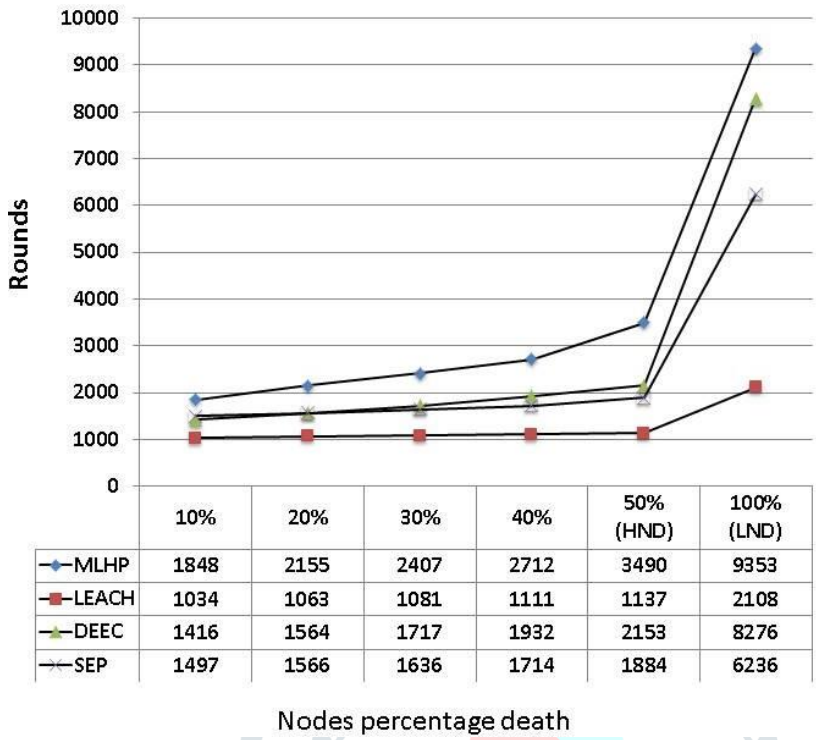
Percentage of dead nodes	Improvement over LEACH	Improvement over DEEC	Improvement over SEP
10%	43%	-1%	19%
20%	72%	17%	33%
30%	88%	26%	41%
40%	93%	25%	38%
50% (HND)	113%	32%	37%
100% (LND)	80%	20%	58%

Case2: When increasing the heterogeneity parameters (α **= 2**) and (β **=**

1) for 100 nodes.

Fig. 5.2 presents the results obtained for the case2. HEER life time extended rapidly to reach round 9353 (for LND) compared to other protocols. LEACH network stopped working early at round 2108 which is even less than the first case, this is

due to LEACH does not consider the heterogeneity of the network, instead it assign random CHs in the network. Network life time in SEP ended at round 6236 and DEEC at round 8276. Table 4.11 presents the average percentage improvement for HEER compared to other protocols.



	10%	20%	30%	40%	50% (HND)	100% (LND)
MLHP	1848	2155	2407	2712	3490	9353
LEACH	1034	1063	1081	1111	1137	2108
DEEC	1416	1564	1717	1932	2153	8276
SEP	1497	1566	1636	1714	1884	6236

Fig. 5.2 Network lifetime for small-scale network, N **= 100**, α **= 2**, β **= 1**.

Table 4.6 Average life time percentage improvement over other protocols for small-scale network (N **= 100**, α **= 2**, β **= 1**)

Percentage of dead nodes	Improvement over LEACH	Improvement over DEEC	Improvement over SEP
10%	77%	31%	23%
20%	90%	38%	38%
30%	113%	40%	47%
40%	165%	40%	58%
50% (HND)	231%	62%	85%
100% (LND)	341%	13%	50%

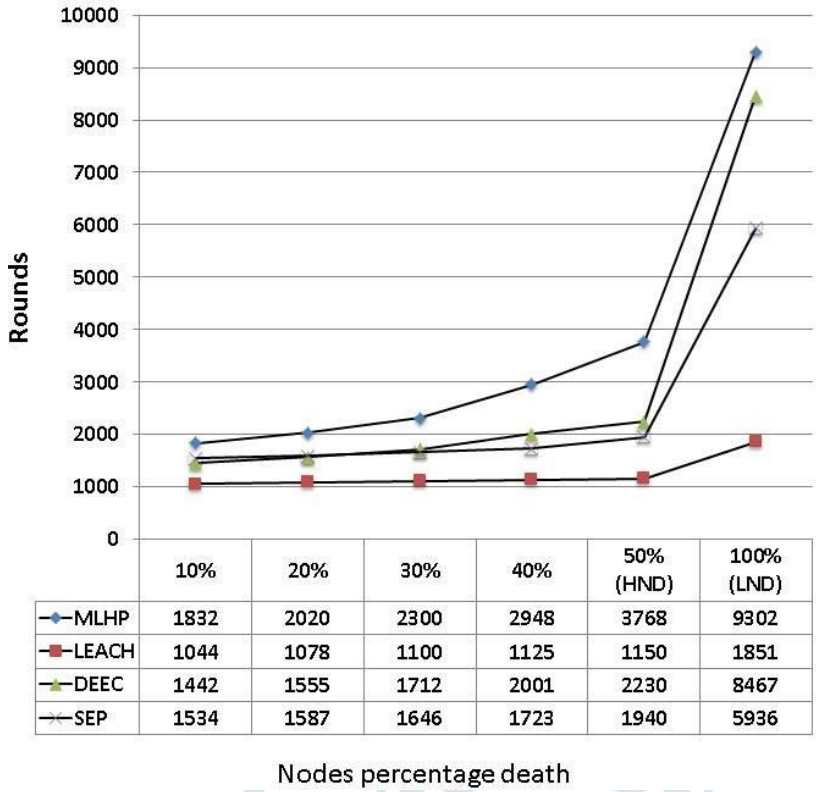
Therefore, when increasing the heterogeneity parameters, the performance of HEER increases compared to case1. For 10% death point, HEER improved by a percentage change of 26.32% which indicates better network stability. For 50% death point, HEER improved by an increase of 45.05% which is longer operational time. As for the entire network life (LND), HEER increased its performance by 46.39%. This behaviour showed that when increasing the heterogeneity, the performance of HEER increases, which is expected and wanted when applying IoT systems.

Case3: When increasing the number of nodes to 200 with low hetero- geneity parameters (α **= 1**) and (β **= 0.5)**.

This case was set to find the affect when increasing the network intensity in regards with changing the network heterogeneity. Fig. 4.12 illustrates the results obtained for the case of low heterogeneity (α **= 1** and β **= 0.5**). When increasing the number of nodes to 200, HEER 10% death point increased compared to case1 by 25.22%, for 50% death point increased by 56.61% and an increase by 45.59% for LND. Based on these results, HEER improved its performance by having longer network stability, operational time and overall network life time.When comparing HEER performance to other protocols, HEER outperformed them in terms of network stability, operational time (HND) and life time (LND) as illustrated in Fig. 4.12. The average life time percentage improvement of HEER over the compared algorithms is presented in Tables 4,7

Table 4.7 Average life time percentage improvement over other protocols for small-scale network (*N* **= 200**, *α* **= 1**, *β* **= 0.5**)

Percentage of dead nodes	Improvement over LEACH	Improvement over DEEC	Improvement over SEP
10%	75%	27%	19%
20%	87%	30%	27%
30%	109%	34%	40%
40%	162%	47%	71%
50% (HND)	228%	69%	94%
100% (LND)	403%	10%	57%



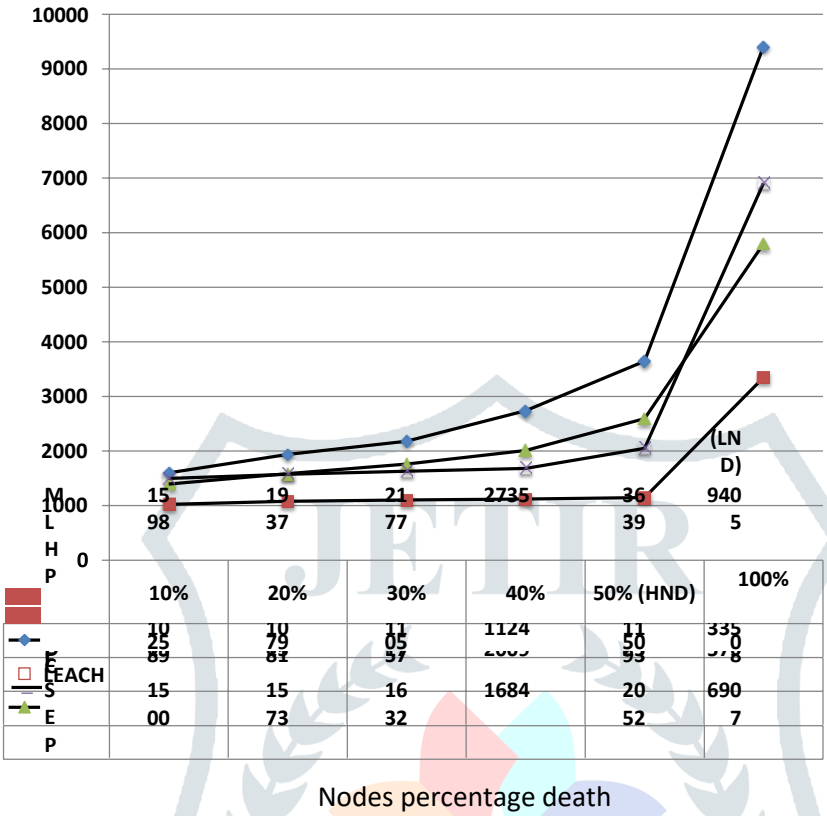
	10%	20%	30%	40%	50% (HND)	100% (LND)
MLHP	1832	2020	2300	2948	3768	9302
LEACH	1044	1078	1100	1125	1150	1851
DEEC	1442	1555	1712	2001	2230	8467
SEP	1534	1587	1646	1723	1940	5936

Fig. 5.3 Network lifetime for small-scale network, N **= 200**, α **= 1**, β **= 0.5**.

Case4: When increasing the number of nodes to 200 with higher het- erogeneity parameters (α **= 2**) and (β **= 1)**.

When increasing the heterogeneity of the network, HEER showed a decreased percentage change for 10% death point compared to case2 by 1.89%, and increase for the HND by 4.27% and by 0.56% for the network life time. This is due to larger number of nodes deployed over small-scale network, which will shorten the distances between nodes and the BS. Therefore, more nodes to be treated as best nodes in Level Two and this means larger number of working CHs in the first rounds. However, after 30% of nodes death point, HEER shows better control and longer life time.

Comparing HEER to the other protocols, HEER have outperformed other protocols in terms of stability, operational time and network life time as shown in Fig. 5.4. Table 4.8 provides the average life time percentage improvement of HEER over the compared algorithms.



5.4 Network lifetime for small-scale network, N = **200**, α = **2**, β = **1**.

Table 4.8 Average lifetime percentage improvement over other protocols for small-scale network (N = **200**, α = **2**, β = **1**)

Percentage of dead nodes	Improvement over LEACH	Improvement over DEEC	Improvement over SEP
10%	70%	2%	-10%
20%	98%	1%	-6%
30%	98%	1%	1%
40%	125%	11%	8%
50% (HND)	214%	50%	60%
100% (LND)	431%	26%	48%

5.2.2 Energy Consumption

Fig. 4.6through Fig. 5.7 show the per-round energy consumption of the four cases mentioned in the previous section. In all different cases, HEER has a higher level of remaining energy in the network compared to LEACH, DEEC and SEP during the operational time after (HND) and through the end of life time (LND). HEER preserved the network energy by reducing the

communication distances between the nodes and the BS, it also reserve the energy through the selection of CHs which guarantees only the best nodes to be selected.

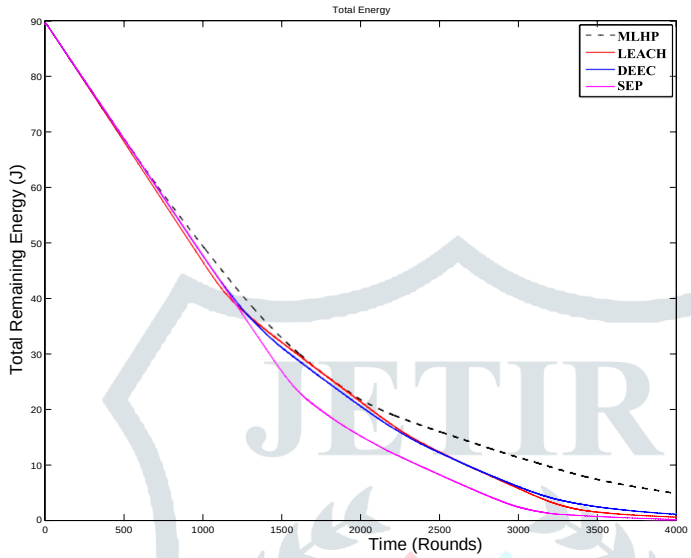


Fig. 5.5 Case1: Total residual energy, N = **100**, α = **1**, β = **0.5**.

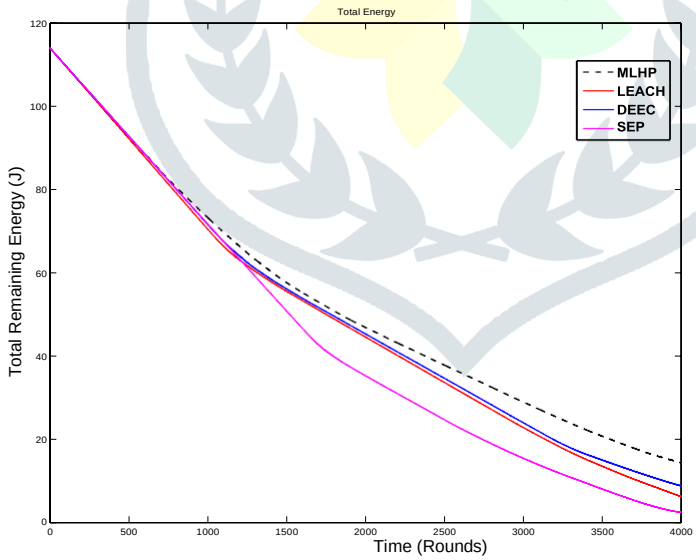


Fig. 5.6 Case2: Total residual energy, N = **100**, α = **2**, β = **1**.

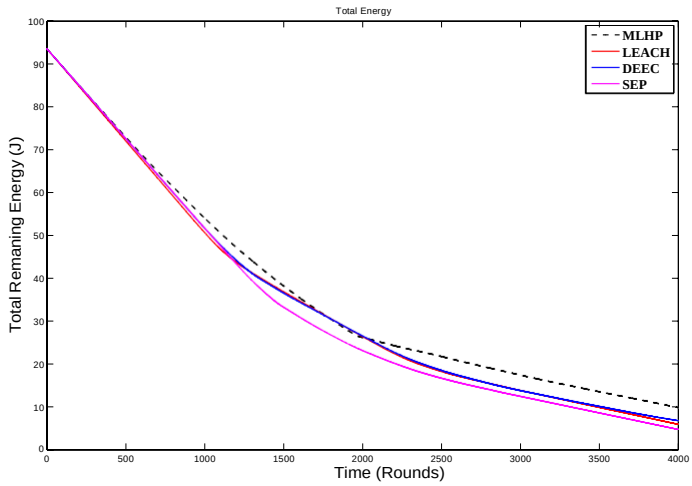


Fig. 5.7 Case3: Total residual energy, N **= 200**, α **= 1**, β **= 0.5**.

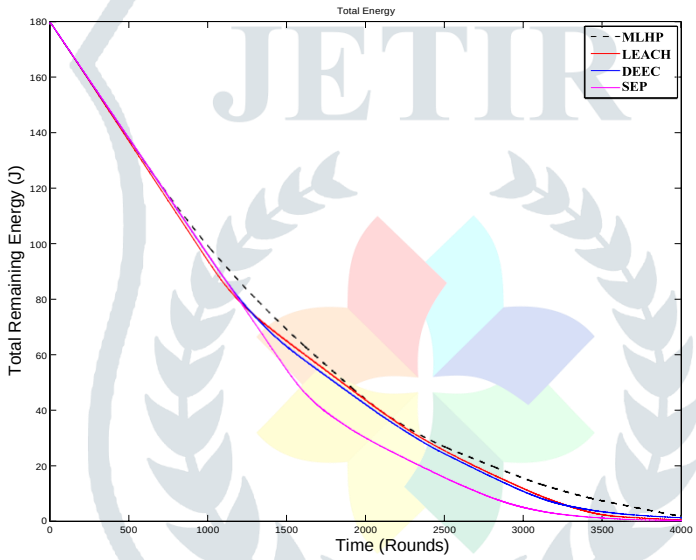


Fig. 5.8 Case4: Total residual energy, N **= 200**, α **= 2**, β **= 1**..

6.Conclusion

In conclusion, a multi-level hybrid hierarchical energy efficient routing algorithm (called HEER) was presented for the use in heterogeneous wireless sensor networks. It combines the advantages of clustering in hierarchical and tree-based routing techniques with the metahuestic technique, it takes the power of centralized as well distributed cluster-heads (CH) selection.

The key idea in HEER is to keep a low transmission distances between CH and the BS and among the cluster-members and their associated CH. The algorithm significantly extends the network lifetime, network stability beyond that achieved with existing protocols and kept energy consumption to the minimum. The performance of the algorithm was tested in three different scenarios. The first scenario presented the stability of the network for two sizes networks deployed with different number of nodes with the minimal heterogeneity. The results showed that HEER has the highest stability period for FND and HND for both small-scale and large-scale area

networks with different node density, which means that HEER has more balanced network by having the highest ratio of active nodes. The two other scenarios showed the affect of changing the network heterogeneity in small-scale and large-scale networks respectively. The performance of HEER was tested against other protocols in terms of network life time, energy consumption and packet delivery ratio. In all the different cases, HEER has more surviving nodes over time than other protocols and hence longer life time. HEER had more surviving nodes over time than other protocols and hence longer life time in all different cases. However, the best performance of HEER in terms of network life time for small scale networks was when the network heterogeneity parameters are set to ($\alpha = 2$ and $\beta = 1$) with 100 nodes and when ($\alpha = 1$ and $\beta = 0.5$) with 200 nodes, this confirms that HEER can operate in crucial cases with enough amount of heterogeneity for small number of nodes and with the minimal heterogeneity for larger number of nodes. Finally, HEER had higher levels of remaining energy in the network compared to LEACH, DEEC and SEP during the operational time after (HND) and through the end of life time (LND). However, for the stability time in the first few rounds, not all the nodes are active in HEER to preserve the energy for the longer time, therefore it show less average energy than DEEC and SEP but always show more energy than LEACH.

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