Heterogeneity-aware Energy-efficient Clustering (HEC) Technique for WSNs

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Abstract

Efficient energy consumption in WSN is one of the key design issues for improving network stability period. In this paper, we propose a new Heterogeneity-aware Energy-efficient Clustering (HEC) technique which considers two types of heterogeneity – network lifetime and of sensor nodes. Selection of cluster head nodes is done based on the three network lifetime phases: only advanced nodes are allowed to become cluster heads in the initial phase; in the second active phase all nodes are allowed to participate in cluster head selection process with equal probability, and in the last dying out phase, clustering is relaxed by allowing direct transmission. Simulation-based performance analysis of the proposed technique as compared to other relevant techniques shows that HEC achieves longer stable region, improved throughput, and better energy dissipation owing to judicious consumption of additional energy of advanced nodes. On an average, the improvement observed for stability period over LEACH, SEP, FAIR and HEC- with SEP protocols is around 65%, 30%, 15% and 17% respectively. Further, the scalability of proposed technique is tested by varying the field size and number of sensing nodes. The results obtained are found to be quite optimistic. The impact of energy heterogeneity has also been assessed and it is found to improve the stability period though only upto a certain extent.

Keywords: clustering, energy-efficient, heterogeneity, phases of network, stability period, wireless sensor network

1. Introduction

Wireless Sensor Networks (WSNs) can be of immense utility for collecting vital information from remote and inaccessible terrains like mountains, oceans, dense forests, and hazardous localities. Quick and cost effective deployment features alongwith flexibility and fault tolerance make WSNs suitable for large number of applications including environment monitoring, agriculture, military, public security and warning, business competitiveness improvement and Quality-of-Life improvement [1]. However, their design is mainly constrained by limited network lifetime, stability period, poor energy utilization besides fault tolerance, scalability, and other issues [2]. Researchers engaged in addressing these issues find efficient energy consumption as the foremost challenge for realizing this technology owing to limited capacity battery of the underlying sensors [3-5]. Different types of energy harvesting mechanisms [3, 6-10] have also been suggested from time to time with their own limits and limitations. Policy-based management framework for self-managed WSNs [11] is proposed to simplify and automate the management of WSNs having reduced energy consumption.

Nodes in a WSN collect data from surroundings and transmit it to the sink directly or through multi-hop communication. Clustering offers an efficient data communication technique by choosing a cluster head in each cluster responsible for communicating with the sink [12-19]. However, the energy-efficient clustering techniques designed for homogeneous networks may not work well when applied to heterogeneous networks, as the former techniques are unable to take full advantage of link, computing power and energy heterogeneity of the network. So, clustering techniques need to be refined and adapted to take full advantage of heterogeneity in heterogeneous WSNs. A network is termed as homogeneous or heterogeneous depending upon the similarity or dissimilarity among sensor nodes. Heterogeneity in sensor nodes may be on account of different energy, computational power and link levels [12]. Since, link and computational heterogeneity ultimately get manifested in the form of energy heterogeneity, so, this work mainly focuses around energy heterogeneity and its impact on WSNs. To simulate energy heterogeneity mostly the researchers have worked by inducing a small fraction of high energy nodes in the network so as to improve the network performance. In this work, however, it is conjectured that with the passage of time, as the network communications progresses, these heterogeneous nodes shall loose energy by different amounts thereby further adding onto the network heterogeneity. This type of heterogeneity is termed as network lifecycle heterogeneity and is broadly divided into initial, active and dying out phases. If energy of heterogeneous nodes (normal and advanced) is efficiently utilized during these different lifecycle phases, which has not been explicitly handled by researchers till now, then it may result in protracting the effective network lifetime, and is the main crux behind this work.

In this paper, we propose and evaluate a new heterogeneous clustering technique, called Heterogeneity-aware Energy-efficient Clustering (HEC), with improved performance over the available clustering protocols and increases the stability period of the network substantially. In HEC, Cluster Head (CH) selection process is divided into three phases depending upon the initial and residual energy. Initially, only advanced nodes participate in cluster head selection process, after some time (based on predefined threshold) all nodes can become cluster head and when minimal energy remains in the network no node will become cluster head and direct data transmission takes place from node to base station as explained in the following subsections. HEC can prolong the stability period by efficiently utilizing the energy heterogeneity of nodes. Simulation results show that HEC achieves longer stable region than the other classic clustering techniques.

The remainder of the paper is organized as follows. In section 2, Heterogeneous WSN model is discussed. Section 3 provides related work and working of related techniques. Section 4 presents proposed technique with a case example. Section 5 presents simulation based performance analysis and comparison. Section 6 gives the concluding remarks.

2. Heterogeneous WSN Model

This section describes the WSN model with energy heterogeneity as used in this work and by various researchers working in the area [13-18]. Network is comprised of T_n number of total nodes having identical computational power and link levels and with uniform random distribution across a $X \times Y$ region. Total nodes, T_n is a combination of N_n number of normal nodes with energy E_0 and A_n number of advanced nodes with enhanced energy E_a. Further, heterogeneity is characterized by m, the fraction of advanced nodes and α, the additional energy factor between advanced and normal nodes. The total energy of the network E_{total} is represented as:

$$E_{total} = N_n \cdot E_0 + A_n \cdot E_a$$

where

$$A_n = m \cdot T_n \quad (1)$$

$$N_n = (1 - m).T_n \quad (2)$$

and

$$E_a = (1 + \alpha) \cdot E_0 \quad (3)$$

Hence,

$$E_{total} = (1 - m).T_n.E_0 + m \cdot T_n(1 + \alpha) \cdot E_0 = T_n(1 + \alpha.m).E_0 \quad (4)$$

2.1 Radio Energy Consumption Model

The radio energy consumption model used in this work is again similar to the one used by other researchers working in the area [13-17, 19].

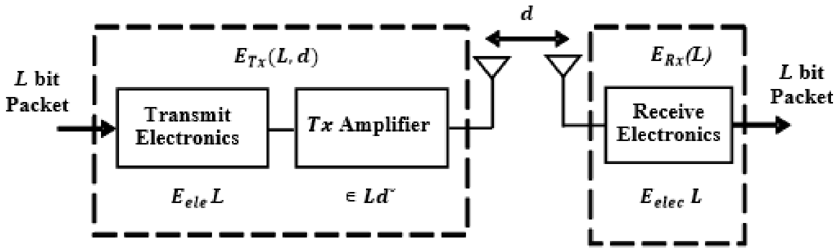


Fig. 1. Radio Energy Consumption Model

According to the radio energy consumption model (**Fig. 1**), for transmitting a L-bit packet over a distance d such that Signal-to-Noise Ratio (SNR) is minimum, the energy expended by the radio is given by:

$$E_{Tx}(L, d) = \begin{cases} L * E_{elec} + L * E_{fs} * d^2 \ if \ d < d_0 \\ L * E_{elec} + L * E_{mp} * d^4 \ if \ d \geq d_0 \end{cases} \quad (5)$$

where E_{elec} is the energy dissipated per bit to run the transmitter or the receiver circuit, E_{fs} and E_{mp} depend on the transmitter amplifier model we use, and d is the distance between the sender and the receiver and maximum distance of any node to the sink is $\leq d_0$.

3. Related Work

The pioneering work in the field of energy efficient communication protocol for WSNs was proposed by Heinzelman et al. [19] in the form of Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol for homogeneous WSNs with the assumption that all nodes in the network have equal energy. It selects cluster heads based upon a threshold value having equal probability for all nodes. The crucial point was randomized rotation of local clusters for data fusion and to evenly distribute energy among nodes. In comparison to conventional direct transmission protocols it could improve network lifetime, indicating reduced energy consumption by a factor of three and increased network stability by a factor of eight. Smaragdasik et al. [13] extended the work for heterogeneous WSNs by introducing few high energy nodes having high probability to become cluster head than normal nodes and proposed Stable Election Protocol (SEP). In SEP, clusters are formed in each round and new cluster heads are selected in every round. The probability is higher for advanced nodes to become cluster head than normal nodes, thereby increasing the network lifetime and stability in comparison to LEACH. The concept of FAIR scenario is also introduced where instead of having advanced nodes the equivalent extra energy of the advanced nodes is uniformly distributed among all the nodes. This is basically done to critically analyze whether improvement in results is due to proposed technique or due to extra energy of the network nodes. However, in SEP, it is conjectured that the energy of advanced nodes has not been utilized effectively and there exist a scope of further improvement, as elaborated in subsequent sections. Qing et al. [14] proposed Distributed Energy-efficient Clustering (DEEC) for heterogeneous WSNs considering residual energy of each node and average energy of the network as the major criteria for cluster head selection. As per the claim made by authors the improvement is around 15% in comparison to LEACH-E [20] and SEP for the tested scenario. Rashed et al. [17] proposed a Weighted Election Protocol (WEP), which combines SEP and HEARP, a chain based communication algorithm [21]. It assigns high probability to advanced nodes during cluster head selection process and the cluster heads make a chain between themselves using greedy algorithm for data transmission to the sink. The improvements in stability period are found to be 13%, 6% and 8% over LEACH, SEP and HEARP. Javaid et al. [18] proposed Enhanced Developed Distributed Energy-efficient Clustering (EDDEEC) scheme having three levels of energy heterogeneity in the network nodes corresponding to normal, advanced and super nodes having different probabilities of becoming cluster heads in a dynamic fashion. Super and advanced nodes have more probability to be chosen as cluster head than normal nodes. The results are claimed to be better than the DEEC [14] and its variants [15-16] though not quantified explicitly. However, it is felt that introduction of higher number of hierarchy levels may lead to other issues related to deployment and node identity during the lifetime of the network, which has not been addressed in the work. This work tends to improve the network performance keeping two levels of hierarchy and carefully examining the network lifetime scenario for heterogeneity.

3.1 Motivation for the present work

A node acting as cluster head consumes more energy as it has to receive and aggregate data from multiple surrounding sensing nodes and then transmit it to the sink. To extend effective lifetime, it is desirable to choose high energy nodes as cluster head. SEP seems unable to utilize the energy heterogeneity because normal nodes are given chance to become cluster head even when advanced nodes are present. This increases chances of dying of normal nodes inspite of the presence of active advanced nodes, thereby reducing network stability. Further, it is found that there are three phases of WSN lifecycle: first phase termed as Initial phase is when network is initially established, with both types of nodes (normal and advanced) full of energy; second phase termed as Active phase starts when all nodes are active and have lost a part of their energy due to communications but are not dead yet; and the third phase termed as Dying-out phase is when all nodes start aging and ultimately result in dying out. So, it is conjectured that a single protocol serving in the three phases is not an optimal choice, as is done by most of the researchers as discussed above. For every phase, separate mechanism needs to be developed for efficient use of energy which will lead to increase in the stable period i.e. effective lifetime of the network. Accordingly, the proposed technique works by exploiting this network lifetime heterogeneity during the three different lifecycle phases. It shall be better if initially only advanced nodes are allowed to participate in the cluster head selection process, and at a later stage (when the residual or remaining energy of a fraction of advanced nodes goes below a certain threshold) both- advanced and normal nodes are permitted based on certain weighted probability. To further improve the effective lifetime, cluster formation is relaxed by applying direct (single-hop) communication between the nodes and the sink during the last phase. By this time very less energy is left with the nodes, which may result in early death of a node if made cluster head due to insufficient energy to collect, aggregate and transmit data to the sink. So it will be better to transmit as much data possible to the sink using direct communication without indulging into clustering mechanism. Our proposed HEC technique is developed around this logic. To make the work self sufficient, a brief overview of the working of LEACH and SEP is presented here.

3.2 Working of LEACH

LEACH assigns equal probability to all nodes in the network for being elected as cluster head. Optimal number of clusters (k_{opt}) decides average number of cluster heads per round in the network, where k_{opt} is represented as:

$$k_{opt} = \sqrt{\frac{T_n}{2\pi}} . \frac{2}{0.765} \tag{6}$$

The optimal probability, p_{opt} of a node to become cluster head depends upon the total number of nodes in the network and optimal number of clusters to be formed in a particular round. p_{opt} is represented as:

$$p_{opt} = \frac{k_{opt}}{T_n} \tag{7}$$

LEACH guarantees that every node will become cluster head every $1/p_{opt}$ rounds, also referred as epoch. Nodes which are not elected as cluster head belong to set G and their probability to become cluster head increases after every round. Nodes belonging to set G independently choose a random number in $(0, 1)$ at the start of every round. After that threshold $T(s)$ is calculated to select cluster heads for the current round. $T(s)$ is calculated as:

$$T(s) = \begin{cases} \dfrac{p_{opt}}{\left(1 - p_{opt\left(r \cdot mod \frac{1}{p_{opt}}\right)}\right)} & if\ s \in G \\ 0 & otherwise \end{cases} \tag{8}$$

where r is the current round number. If random number chosen by a node is less than $T(s)$, node is selected as cluster head for that round. In every round probability of nodes ∈ G increases and becomes 1 in last round of the epoch.

3.3 Working of SEP

SEP assigns higher probability to advanced nodes as compared to normal nodes during cluster head selection process. So, advanced nodes become cluster head more frequently than normal nodes. SEP guarantees that every advanced node will become cluster head after every $1/p_{adv}$ rounds where $p_{adv} = p_{opt} . (1 + \alpha)/(1 + \alpha \cdot m)$ and every normal node will become cluster head after every $1/p_{nrm}$ rounds where $p_{nrm} = p_{opt}/(1 + \alpha \cdot m)$; where p_{opt} is optimal probability of a node to become cluster head in each round.

Threshold for normal nodes is given by:

$$T(s_{nrm}) = \begin{cases} \dfrac{p_{nrm}}{\left(1 - p_{nrm\left(r \cdot mod \frac{1}{p_{nrm}}\right)}\right)} & if\ s_{nrm} \in G' \\ 0 & otherwise \end{cases} \tag{9}$$

where, r is the current round, G' is the set of normal nodes that have not become cluster head within last $1/p_{nrm}$ rounds and $T(s_{nrm})$ is the threshold.

Threshold for advanced nodes is given by:

$$T(s_{adv}) = \begin{cases} \dfrac{p_{adv}}{\left(1 - p_{adv\left(r \cdot mod \frac{1}{p_{adv}}\right)}\right)} & if\ s_{adv} \in G'' \\ 0 & otherwise \end{cases} \tag{10}$$

where, r is the current round, G'' is the set of advanced nodes that have not become cluster head within last $1/p_{adv}$ rounds and $T(s_{adv})$ is the threshold.

4. Proposed HEC Technique

Based on the motivations given above, we propose a new Heterogeneity-aware Energy-efficient Clustering (HEC) technique aimed at improving the stability and effective lifetime of a WSN. This approach is a step forward towards well balanced energy consumption of the nodes. As explained in the network model, energy heterogeneity is considered in terms of two types of nodes: normal and advanced. The fraction of advanced nodes is m, and they have α times more energy than the normal nodes. To provide well balanced energy consumption in the network, cluster head selection process is divided into three phases depending upon the initial energy and residual energy of network nodes. These three phases correspond to the three phases of network lifecycle as discussed above. Proposed technique is outlined below:

4.1 Phase 1 of HEC

In phase 1, only advanced nodes are given chance to become cluster head, as they are having higher initial energy. The optimal probability of an advanced node to become cluster head, p_{adv} using Eq. 1 and Eq. 7 is shown in Eq. 11:

$$p_{adv} = \frac{k_{opt}}{A_n} = \frac{p_{opt}}{m} \tag{11}$$

An advanced node can become cluster head at random every $1/p_{adv}$ rounds per epoch and the average number of cluster heads per round per epoch will be k_{opt} . Nodes which are not elected as cluster head belong to set H and their probability to become cluster head increases after every round. Nodes belonging to set H independently choose a random number in $(0, 1)$ at the start of every round. After that threshold $T(S_a)$ is calculated to select cluster heads for the current round. $T(S_a)$ is calculated as:

$$T(S_a) = \begin{cases} \frac{p_{adv}}{\left(1 - p_{adv\left(r \cdot mod \frac{1}{p_{adv}}\right)}\right)} & if\ S_a \in H \\ 0 & otherwise \end{cases} \tag{12}$$

where r is the current round number. If random number chosen by a node is less than $T(S_a)$, node is selected as cluster head for that round. In every round probability of nodes $\in H$ increases and becomes 1 in last round of the epoch.

The network shall continue to work in Phase 1 till the residual energy of at least k_{opt} number of advanced nodes is greater than or equal to 50% of the initial normal node energy E_0, else it shall enter the next Phase 2. It is to ensure availability of minimum number of energy rich cluster heads required for a particular round in Phase 1. In this work, the 50% threshold is taken however in future works refinements on account of varying this threshold can also be worked upon.

4.2 Phase 2 of HEC

In Phase 2 of HEC, to improve the network stability, full potential of available energy of advanced and normal nodes is exploited in a judicious and efficient manner unlike SEP. Till phase 1, initial energy of nodes decides the cluster head formation and only advanced nodes are allowed to participate. While in phase 2, all nodes are given equal chance to act as cluster head based upon the parameter p_{opt} (Eq. 7), as is the case with LEACH. Every node shall become cluster head every $1/p_{opt}$ rounds and the average number of cluster heads per round per epoch will be k_{opt}. Threshold $T(S)$ that is used to select the cluster head from normal as well as advanced nodes in each round is given by

$$T(S) = \begin{cases} \frac{p_{opt}}{\left(1 - p_{opt\left(r \cdot mod \frac{1}{p_{opt}}\right)}\right)} & if\ S \in H' \\ 0 & otherwise \end{cases} \tag{13}$$

where H' is set of normal and advanced nodes that have not become cluster heads within the last $1/p_{opt}$ rounds and $\mathrm{T}(S)$ is the threshold applied to select the cluster heads for current round. It guarantees that each node will become cluster head exactly once every $1/p_{opt}$ rounds.

We have deliberately used LEACH criteria of equal cluster head selection probability unlike SEP which assigns higher probability to advanced nodes. The network shall continue to work in Phase 2 till the residual energy of atleast k_{opt} number of nodes (normal and advanced) is greater than or equal to 10% of E_0, otherwise proposed technique will enter the Phase 3.

4.3 Why LEACH in phase 2 and not SEP?

The logic is, if we implement SEP in phase 2 for the proposed technique, in that case advanced nodes will have high probability of becoming cluster head than normal nodes, which will drain out their energy at a much faster rate leading to their earlier dying. Since advanced nodes have already consumed much of their energy being cluster head in phase 1, some of these nodes are no more advanced due to lower residual energy.

4.4 Phase 3 of HEC

This phase is basically meant for extending the overall network lifetime to its maximum by deciding the mode of data communication judiciously. As pointed out above, the network shall continue to work in Phase 2 till the residual energy of atleast k_{opt} number of nodes is greater than or equal to 10% of E_0, else it will enter Phase 3. The 10% value is chosen as a judicious selection parameter in this work, though possibilities of fine tuning for optimum results do exist and can be further explored.

By the end of phase 2, energy of most of the nodes is depleted enough to become cluster head and send aggregated data to sink. So, in this phase, we propose that no cluster head should be selected, and all nodes should send data directly to the sink. This is done to increase the overall lifetime of the network. If cluster head formation takes place in this phase, then the node elected as cluster head may not have enough energy and may ultimately die out without sending data to the sink, which may result in unreliable and unpredicted behavior of the network. However, on a positive note, it is conjectured that with the left over energy a node may succeed if data is sent directly to the sink.

The pseudo code for the proposed HEC technique is given below:

Algorithm: Heterogeneity-aware Energy-efficient Clustering (HEC) Technique for WSNs
T_n- total no. of nodes
m- fraction of advanced nodes
α- additional energy factor between advanced and normal nodes
E_0 - initial energy of normal nodes
E_a - initial energy of advanced nodes
k_{opt} - optimal cluster parameter (optimal number of clusters desired in the network)
p_{opt} - optimal election probability of a node to become CH
p_{adv} - optimal election probability of an advanced node to become CH
E_{res}- residual energy

/***Initialization*****/**
Step 1: Initialize T_n ;
Step 2: Initialize $A_n = m \cdot T_n$ & $N_n = (1-m) \cdot T_n$;
Step 3: Initialize E_0 &
Step 4: Initialize $E_a = (1+\alpha) \cdot E_0$;

/**** Network Deployment *****/**
Step 5: Distribute nodes randomly uniformly; place sink at center
Step 6: Calculate p_{opt} and p_{adv}

$$p_{opt} = \frac{k_{opt}}{T_n} \; and \; p_{adv} = \frac{p_{opt}}{m} \; ; \; \left(k_{opt} \; is \; calculated \; from \; Eq. 6\right)$$

/**********Beginning of Phase 1 of HEC *****************/**

Step 7: Initialize $H = \{S_{a_i} | 1 \leq i \leq A_n\}$
Step 8: Choose $rand(S_a) = RAND(0,1) \; \forall \; S_{a_i} : S_{a_i} \in H$
Step 9: Calculate $T(S_a)$ from Eq. 11 for $\forall \; S_a : S_a \in H$
Step 10: if $rand(S_a) < T(S_a)$, node is elected as CH. (Choose k_{opt} nodes as CH from *H*)
Step 11: $H = \left\{S_a | S_a \; has \; not \; \text{become CH within} \; \frac{1}{p_{adv}} \; \text{rounds}\right\}$
Nodes transmit data to CH and CH will aggregate data and send to sink.

/********** Transition from Phase 1 to Phase 2*************/**

Step 12: for i= 1 to A_n
```
    if(E_res(S_a_i) > 50 % of E_0 )
        count++
    end if
  end for
  if (count >= k_opt)
     then
        goto step 8
  else
        goto step 13
  end if
```

/**********Beginning of Phase 2 of HEC *****************/**

Step 13: Initialize $H' = \{S_i | 1 \leq i \leq n\}$
Step 14: Choose $rand(S) = RAND(0,1) \; \forall \; S : S \in H'$
Step 15: Calculate $T(S)$ from Eq.13 $\forall \; S : S \in H'$
Step 16: if $rand(S) < T(S)$, node is elected as CH. (Choose k_{opt} nodes as CH from H')
Step 17: $H' = \left\{S \mid S \; has \; not \; \text{become CH within} \; \frac{1}{p_{opt}} \; \text{rounds}\right\}$
Nodes transmit data to CH and CH will aggregate data and send to sink.

/********** Transition from Phase 2 to Phase 3*************/**

Step 18: for i= 1 to T_n
```
    if(E_res(S_i) > 10% of E_0 )
        count++
    end if
  end for
  if (count >= k_opt)
     then
        goto step 14
  else
        goto step 19
  end if
```

/**********Beginning of Phase 3 of HEC *****************/**

Step 19: if $(\sum_{i=0}^{T_n} E_{res} \; (S_i) = 0 \;)$ //checking if all nodes have consumed their energy
```
    then          // If true, HEC will stop
        stop      // otherwise HEC will operate in Phase 3
    else
```

```
            Nodes transmit data directly to sink.
            continue
      end if
```

4.5 Numerical Example

To facilitate the understanding of the proposed HEC technique, a case example is taken up here. Suppose there is a sensor network of 100 nodes ($T_n = 100$) deployed in uniform random manner in $100m \times 100m$ field and the sink is deployed at the center of the field. The desired number of clusters that can be optimally formed in the sensor network will be k_{opt}. We can calculate k_{opt} using equation

$$k_{opt} = \sqrt{\frac{T_n}{2\pi}} \cdot \frac{2}{0.765} = \sqrt{\frac{100}{2\pi}} \cdot \frac{2}{0.765} = 10.4325$$

For this particular network, approx. 10 clusters are desired to be formed per round to get optimal results (the value of k_{opt} will be 7.3769, 10.4325, 14.7538, 19.5174 and 23.3278 for network having 50, 100, 200, 350 and 500 nodes respectively).

Based upon the value of k_{opt} the optimal probability of a node to become cluster head can be calculated as:

$$p_{opt} = \frac{k_{opt}}{T_n} = \frac{10.4325}{100} = 0.104325$$

Assume that 20% of total number of nodes are advanced nodes (*m*=0.2) and are equipped with 300% more energy than normal nodes (α=3).

In phase 1, only advanced node will participate in cluster head selection process. So, probability of an advanced node to be elected as cluster head will be

$$p_{adv} = \frac{p_{opt}}{m} = \frac{0.104325}{0.2} = 0.521625 \text{ (0.5 approx.)}$$

Since only advanced nodes are participating in the cluster head selection process, the heterogeneous epoch will be $1/p_{adv} = 2$ rounds, and on an average $k_{opt} = 10$ advanced nodes will become cluster head per round. i.e. 10 nodes will be cluster head in one round and remaining 10 nodes will be cluster head in next round.

If more than k_{opt} advanced nodes are having residual energy greater than or equal to 50% of E_0, the network will remain in Phase 1, otherwise it will enter the Phase 2. In Phase 2, on an average $k_{opt} = 10$ nodes will become cluster head in each round while the standard epoch is $1/p_{opt} = 10$ rounds.

If more than k_{opt} normal and advanced nodes are having residual energy greater than or equal to 10% of E_0, the network will remain in Phase 2, otherwise it will enter the Phase 3.

5. Performance Analysis and Comparison

In this section, the proposed and implemented HEC technique (also referred as HEC-with LEACH) is evaluated and analyzed through extensive simulations and compared based on the following standard performance metrics, as used by the research community in the area.

- *Stability period:* It is the time interval from the start of network operation until the death of first node. This period is also referred as "stable region."
- *Instability Period:* It is the time interval from the death of the first node until the death of last node. This period is also referred as "unstable region."
- *Network lifetime:* It is the time interval from the start of operation (of the network) until the death of the last alive node.
- *Throughput:* It is the sum of number of packets received by cluster heads from nodes and number of packets received by sink from cluster heads of all rounds.
- *Energy Dissipation:* It is amount of energy consumed by the network with increasing number of rounds.
- *Advanced and Normal Nodes Alive per round:* This instantaneous measure reflects the number of nodes of each type that have not yet expended all of their energy.

The other techniques used for comparison are LEACH, SEP, HEC- with SEP (HEC implementing SEP in Phase 2), and FAIR. The radio characteristics and parameters used for simulation are shown in **Table 1** and **Table 2**. It is assumed that no extra bits or messages are required to transmit residual energy information from nodes to sink.

Table 1. Radio Characteristics used in Simulation

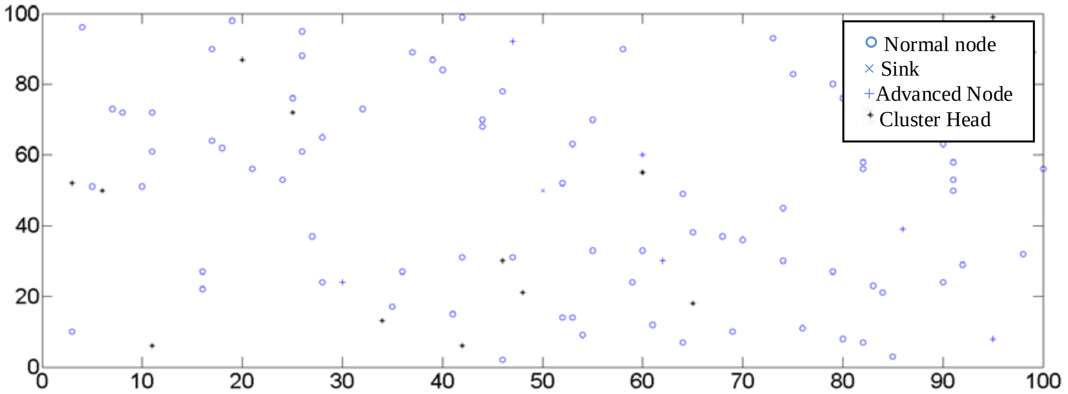
Operation	**Energy Dissipated**
Transmitter/ Receiver Electronics	E_{elec} = 50nJ/bit
Data Aggregation	E_{DA} = 5nJ/bit/signal
Transmit Amplifier if $d_{maxtoBS} \leq d_0$	E_{fs} = 10pJ/bit/m^2
Transmit Amplifier, if $d_{maxtoBS} \geq d_0$	E_{mp} = 0.0013pJ/bit/m^4

Table 2. Parameters used in Simulation

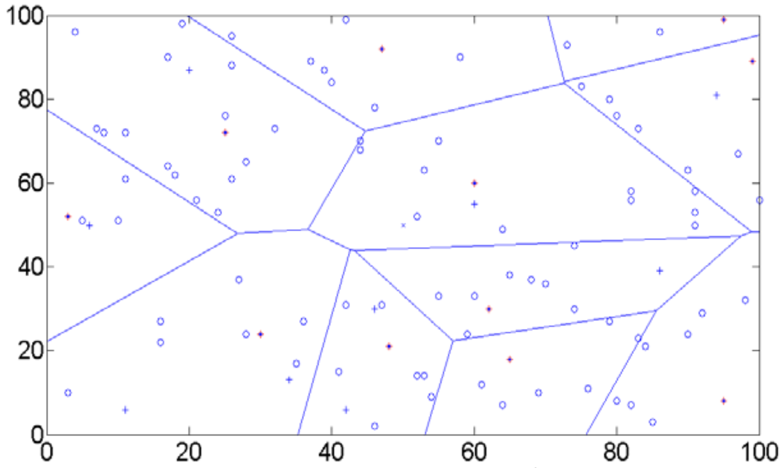
Parameter	**Value**
Total number of sensor nodes (T_n)	50, 100, 200, 350, 500
Area coverage (m^2)	50×50, 100×100, 200×200, 350×350, 500×500
Traffic	1 packet/node/round
m	0.1, 0.2, 0.3, 0.4, 0.5
A	1, 2, 3, 4, 5
E_0	0.5 J
Maximum distance of any node from the sink (d_0)	70 m
Message Size	4000 bits
p_{opt}	0.1
Total number of rounds	6000

5.1 Network Deployment

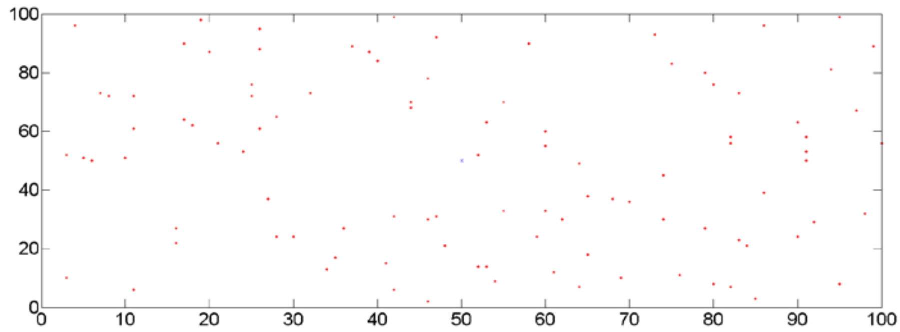
A wireless sensor network having n nodes spread over an area of (X metres $\times Y$ metres) is considered for simulations. Various deployment scenarios are shown in **Fig. 2**. Normal and advanced nodes are deployed in a uniform random distribution manner in the network field while sink is located at the centre of the field as **Fig. 2 (a)**; Cluster formation based on Voronoi cell [22] is depicted in **Fig. 2 (b)** where nodes transmit data to the selected cluster head, which in turn sends it to the sink after aggregation; lastly **Fig. 2 (c)** depicts the network when all nodes are dead.



(a) Network having all nodes alive



(b) Cluster Formation based on Voronoi cell



(c) Network when all nodes are dead

Fig. 2. Network deployment Scenarios

The phase-wise performance of the proposed HEC technique depicting stable and unstable region is shown in **Fig. 3**. It can be observed that the first node dies near the end of phase 2. So, until then, network remains in the stable state. Afterwards, network becomes unstable as the nodes start dying.

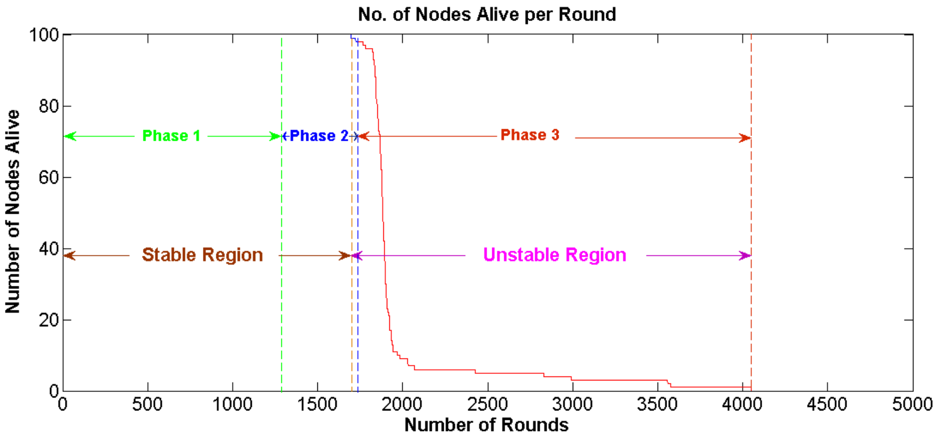


Fig. 3. Phases of HEC for stability period

5.2 Network Stability Comparison

i) Stability Period

The stability period of all the protocols under consideration for the case where *m*=0.2 and α=3 is shown in **Fig. 4**. The stability period, which is indicative of the effective lifetime of the network, is showing significant improvement for the proposed technique justifying our conjecture.

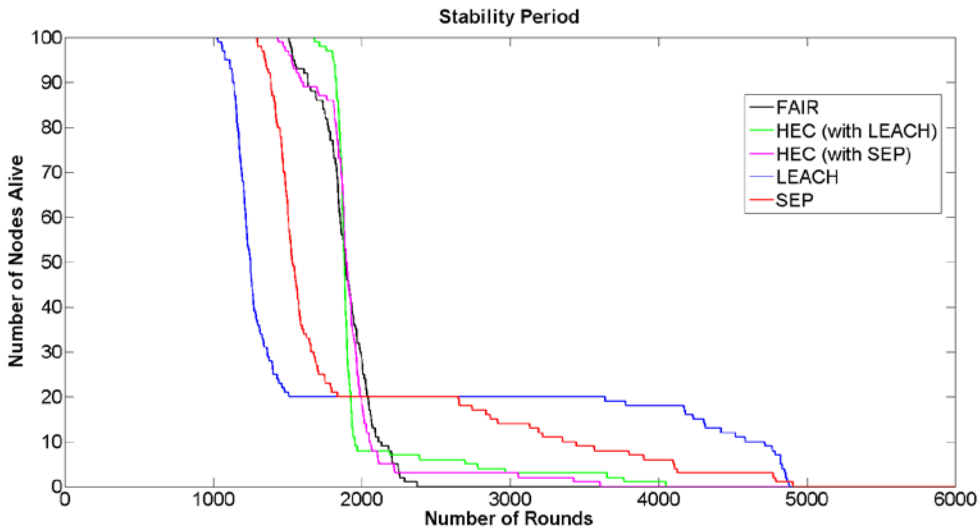


Fig. 4. Stability period comparison for HEC

The stable region of the proposed HEC improves by 65%, 30%, 17% and 15% as compared to LEACH, SEP, HEC-with SEP, and FAIR. Although going by definition, the network lifetime of LEACH and SEP is more than that of the proposed technique, but it is not useful. For example, when more than 80% of nodes are dead in LEACH and SEP, network is still operating for a longer period but data gathered in this unstable period is of no use, so efforts should be made to reduce the unstable region and increase stable region. It can be observed that when 80% of nodes are dead in LEACH and SEP, all nodes are still alive in HEC, improving the stability period. The unstable region is smaller in case of HEC as compared to LEACH and SEP.

ii) Throughput

Performance in terms of throughput of the network is presented in **Fig. 5** in comparison to other relevant techniques. It is observed that in the stable region, HEC technique provides better throughput than other protocols. More succinctly, it is presented in **Fig. 6**.

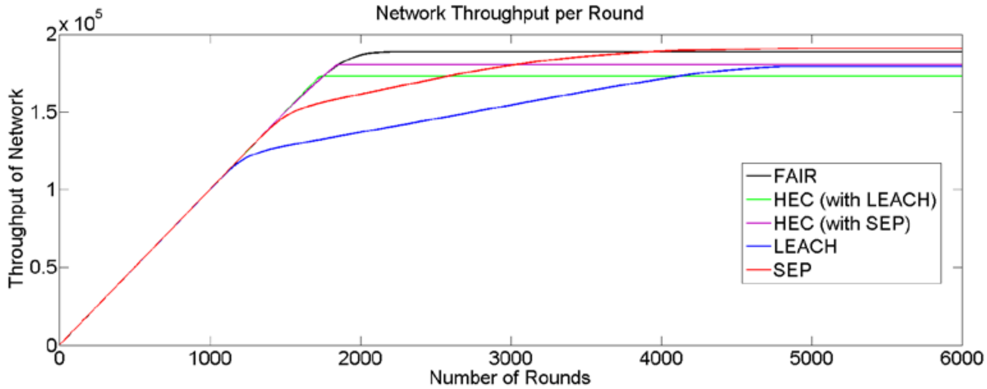


Fig. 5. Overall throughput of the network

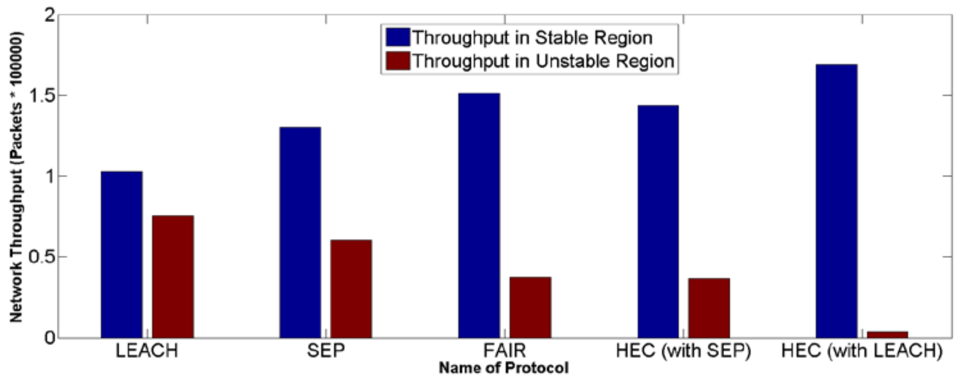


Fig. 6. Throughput in stable region v/s unstable region for all protocols

Though, total throughput of LEACH and SEP is more than the proposed technique in the unstable region, but it is of no use as discussed earlier. For successful communication high throughput in the stable region is desired. Here again, HEC technique takes the lead.

iii) Energy Dissipation

Energy consumed in the stable region is fruitful and should be higher than that in the unstable region. The proposed technique shows a clear cut edge over all others in this respect. The network energy depletes at a uniform rate till the stable period for the HEC technique, and more than 90% of energy gets consumed in the stable period as shown in **Fig. 7**. SEP and LEACH dissipate more energy in the unstable region, reflecting improper utilization of the most scarce resource in WSNs. Energy consumption in the stable region should be more than that in the unstable region as the communication in the unstable region cannot be relied upon and hence of no use especially for the critical engineering applications. So, energy consumed in the unstable region is wasted. The proposed technique is much lesser wasteful in this aspect as well.

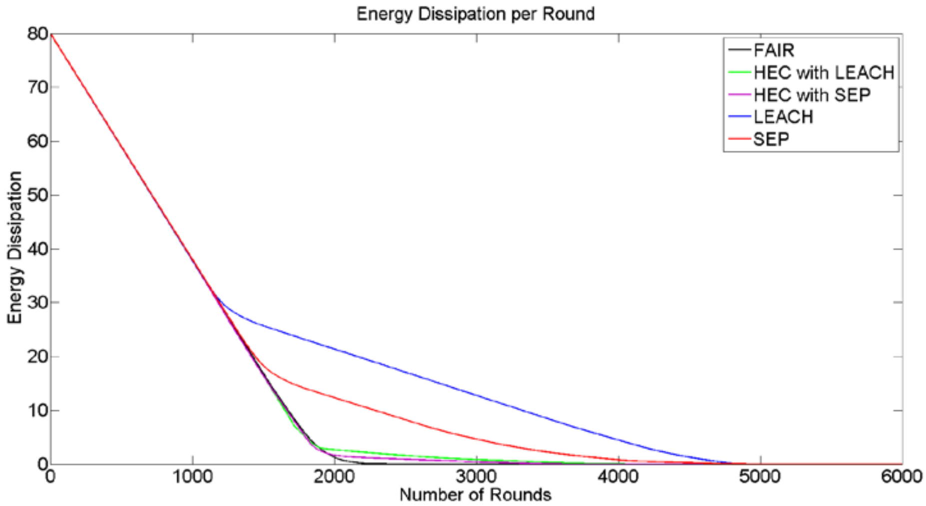


Fig. 7. Energy Dissipation of all protocols

More elaborately, this comparison is presented in **Fig. 8**, that shows LEACH consumes only 54% energy, SEP consumes 68.5%, FAIR consumes 80%, HEC-with SEP consumes 76.25% and proposed technique consumes 90% energy in the stable region.

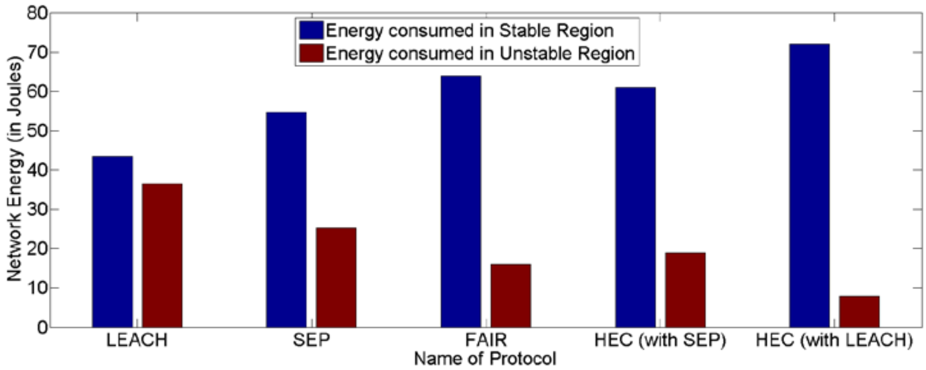


Fig. 8. Energy consumed in stable and unstable regions for all protocols

We can easily observe that in LEACH and SEP large amount of energy is wasted in the unstable region. In the proposed technique, only 10% of the energy is consumed in unstable region while 90% of the energy is used in stable and useful region. This is a major accomplishment of the proposed strategy.

iv) Advanced and Normal nodes Alive

In case of heterogeneous WSN, it is crucial to effectively utilize the energy of advanced nodes prior to the depletion of normal nodes. So, to adjudge the judiciousness of protocols meant for heterogeneous WSNs, we present the results for alive advanced and normal nodes per round in **Fig. 9** and **Fig. 10** respectively. In SEP, advanced nodes die at a very late stage that is in the unstable region as shown in **Fig. 9**. While in the HEC technique, it dies near the beginning of the unstable region, indicating that it has given its worth in the useful period of the network lifetime. In HEC-with SEP also the advanced node dies at the beginning of the unstable region. It can be inferred that SEP is unable to take advantage of the extra energy of advanced nodes and this is the reason for normal nodes to start dying at an early stage resulting in lesser stability of the network. In HEC-with SEP, advanced nodes die earlier because of having a high probability to become cluster head in Phase 2 as compared to HEC-with LEACH technique, as discussed earlier. Proposed technique is thus having wider stable region than all its counterparts.

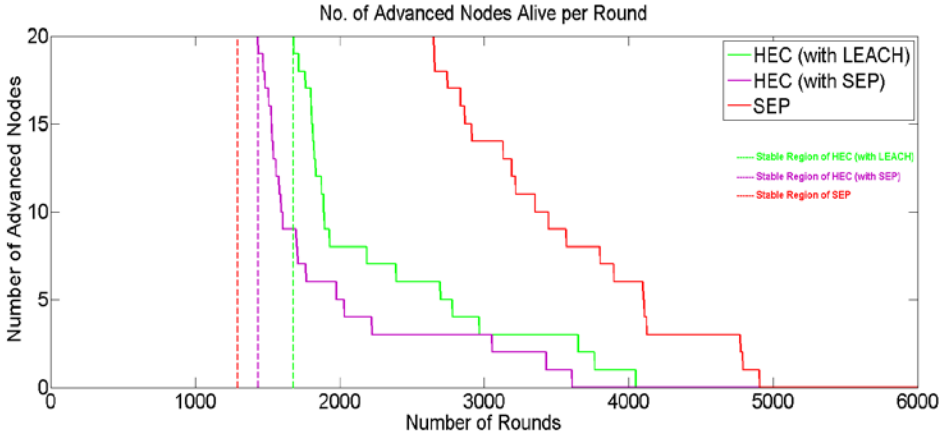


Fig. 9. No. of Advanced nodes Alive

The number of normal nodes alive per round is shown in **Fig. 10**. In case of SEP, first node to die is the normal node. In HEC-with LEACH and in HEC-with SEP, normal nodes are alive beyond stability period. Moreover, all normal nodes in SEP die out soon and only advanced nodes remain alive in the unstable region.

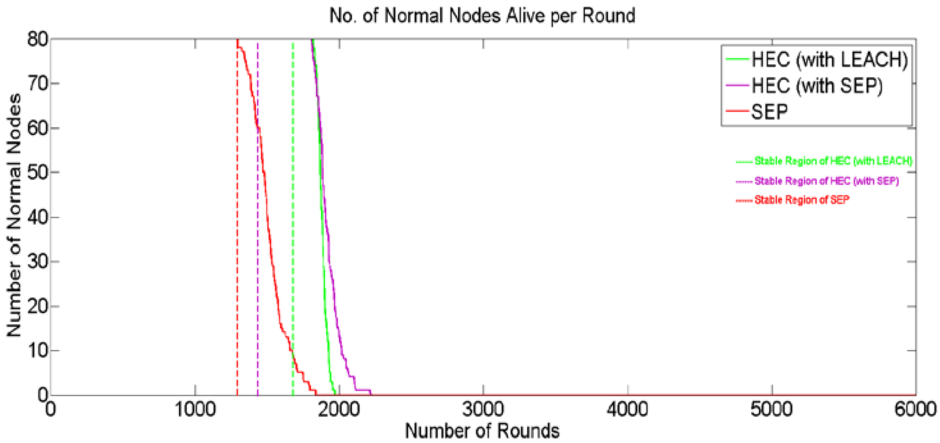


Fig. 10. No. of Normal nodes Alive

So, from these results it gets reflected that SEP has not taken benefit of heterogeneity or increased energy of advanced nodes. Protocol should consume energy in such a way that nodes do not die out soon. Since normal nodes have lesser energy, their energy should be preserved by compromising the energy of advanced nodes. Proposed technique has an edge in this respect over all others.

Keeping in view the goodness of results, the proposed HEC was analyzed for scalability as well as heterogeneity.

5.3 Scalability Analysis

To have a more rigorous analysis of the consistency of the proposed technique, we have tested its performance in comparison to others: i) with increasing number of nodes in the same field, and ii) with increasing field size keeping number of nodes and initial energy fixed, and lastly iii) with varying field size as well as number of nodes.

i) With Increasing number of nodes

The stability period of various protocols with varying number of nodes having field size (100m × 100m) is shown in **Fig. 11**. It is gathered that even when the number of nodes are increased the performance of the proposed scheme in terms of the stability period is quite consistent for all the five scenarios and is also higher as compared to all other protocols.

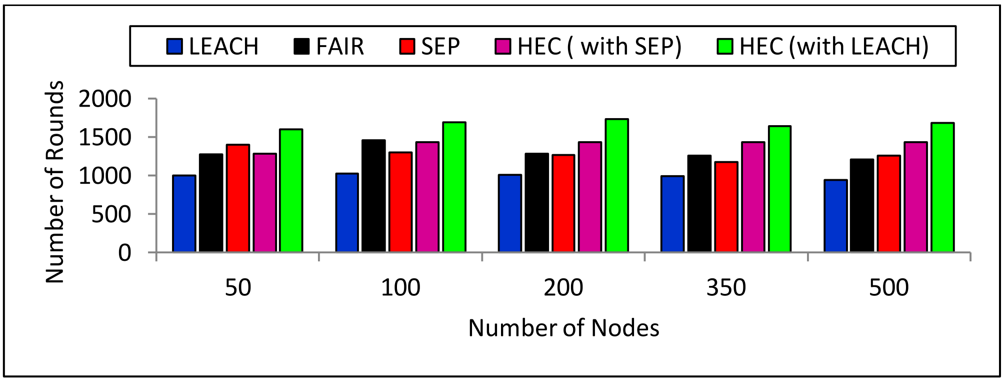


Fig. 11. Increasing number of nodes with field size 100 × 100

ii) With Increasing field size

The stability period of various protocols with varying field size having fixed number of nodes (=100) is shown in **Fig. 12**. With the field size increase, the distance between sink to nodes and between two nodes also increases and hence energy consumed in transmitting and receiving packets also increases resulting in lowering network lifetime considerably. However, the proposed technique is resulting in better stability period than all other protocols for the five scenarios.

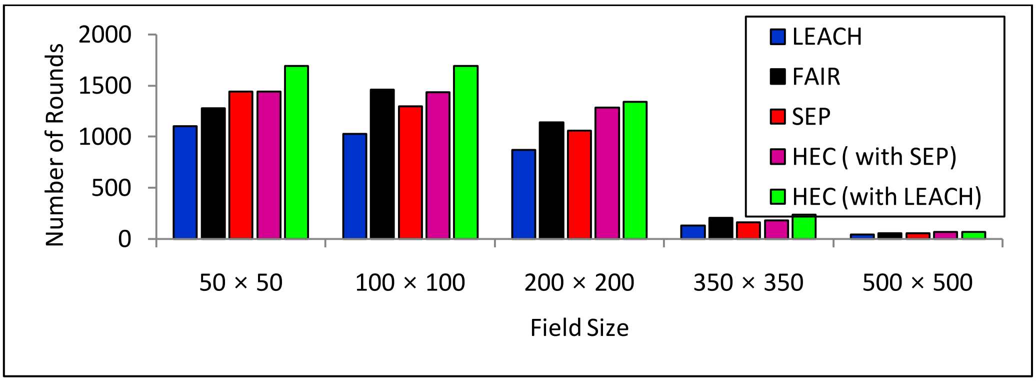


Fig. 12. Increasing Field size with 100 nodes

iii) With Increasing field size and number of nodes

The stability period of various protocols when both field size as well as number of nodes are increased is shown in **Fig. 13**. Deploying large number of nodes in the smaller field size gives the consistent stable period but deploying small number of nodes in a larger field size is of no use. Stability period drastically lowers down. When field size is 50m × 50m and 100m × 100m with number of nodes 50, 100, 200, 350 and 500 stability period of proposed technique outperforms all others.

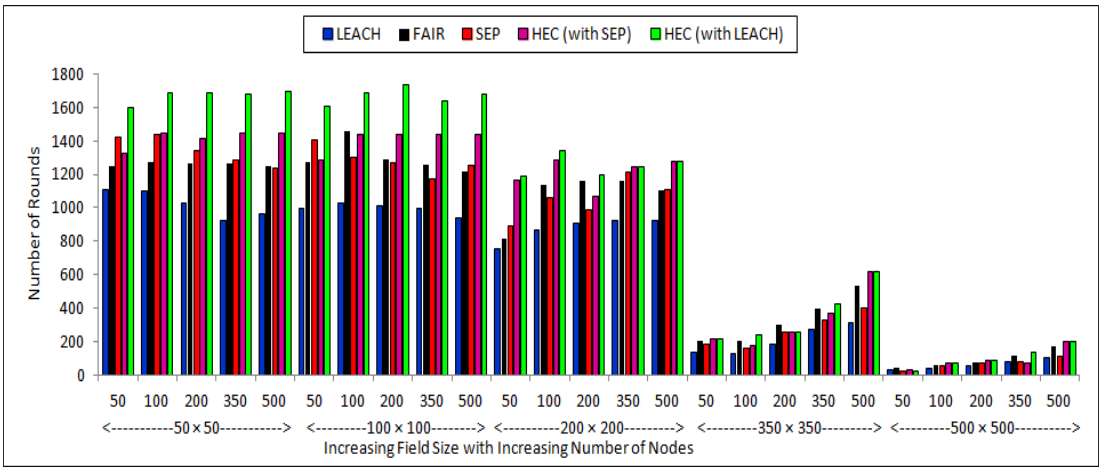


Fig. 13. Increasing Field Size with Increasing Number of Nodes

As the field size grows the stability period increases with the increase in number of nodes though its value is quite less as compared to smaller field size. This is due to the long distance between sink (located at the center) and nodes at the boundary. If all nodes are having more initial energy then in that case stability period can improve. Optimum relationship between field size and initial energy needs further attention of researchers.

5.4 Effect of Heterogeneity

In this section, effect of increase in heterogeneity in terms of m and α is presented. The idea is to ascertain the impact of heterogeneity on the network behavior. Will it turn out to be helpful in improving the stable period or not? And upto what level α and m can be increased? These are the major points that need to be kept in mind before deploying a WSN in the real world.

i) Effect of increase in heterogeneity

The effect of increase in heterogeneity on the proposed technique for the stability period of network is shown in **Fig. 14**. It is observed that when m=0.1, the stability period improvement is only marginal for different values of $\alpha = 1, 2, 3, 4, 5$ indicating that just 10% advanced nodes are not sufficient enough to reflect their impact on the network performance.

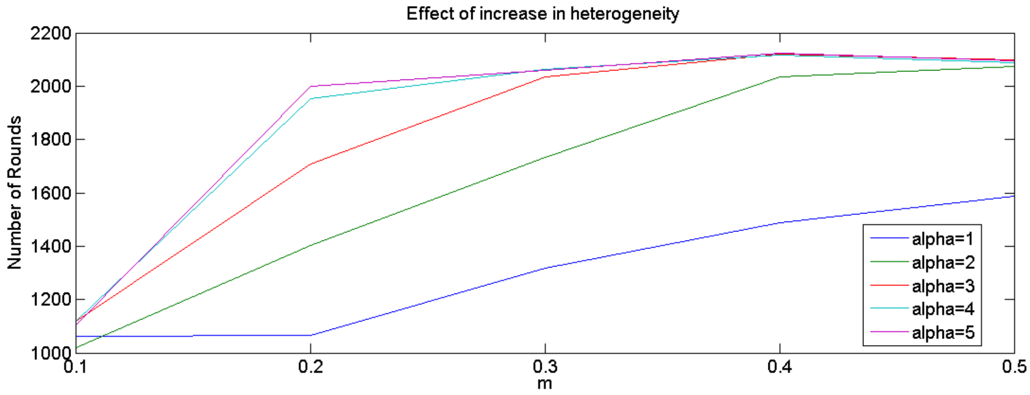


Fig. 14. Effect of increase in heterogeneity on proposed technique

As the number of advanced nodes and their energy is increased; upto m=0.4, this heterogeneity is best utilized by the technique, as reflected by significant improvement in the stability period. Though, this improvement reaches a saturation stage when number of normal and advanced nodes becomes almost equal as seen for m=0.5, where stability period is converging for all values of α. So, after this point there is no use of adding any further heterogeneity in the network.

ii) Effect of increase in $\alpha \times m$

The combined impact of increased heterogeneity ($\alpha \times m$) can be gauged for the proposed technique from **Fig. 15**. As $\alpha \times m$ is increasing the stability period is also improving. Here also at high values of $\alpha \times m$ (=1.2) we can observe no further improvement in stability period. This is due to the fact that initial energy of normal nodes remains same while number and energy of advanced nodes is increased, established network cannot utilize the increased energy of advanced nodes and the death of normal nodes is inevitable.

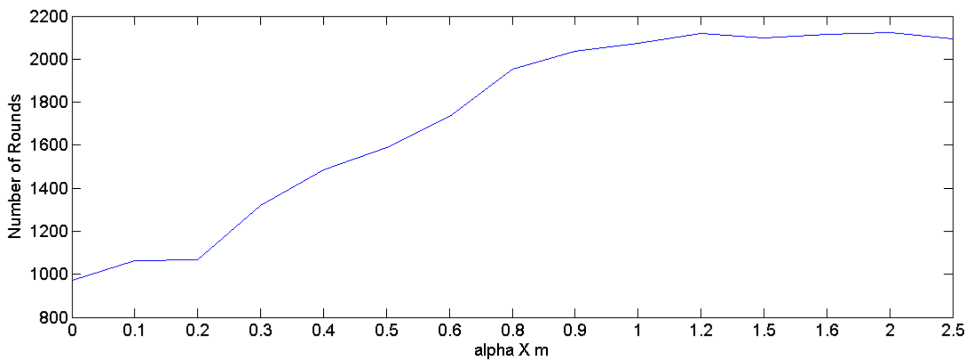


Fig. 15. Effect of heterogeneity (α × m) on proposed protocol

iii) Gain in stability

The gain in stability period of the proposed technique over other relevant protocols like LEACH, SEP, HEC–with SEP, and FAIR is shown in **Fig. 16**. The proposed technique is having a distinctive edge over the LEACH and SEP protocols. Maximum gain observed over SEP is 45% and over LEACH is 117%.

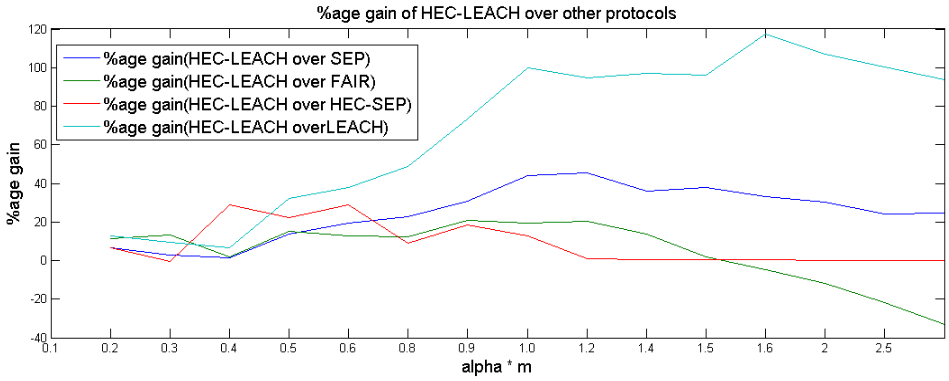


Fig. 16. Percentage gain of proposed technique over other protocols

The proposed strategy which also takes network lifetime heterogeneity into account is quite befitting, as is reflected in the performance of HEC-with SEP as well, which suffers lesser degradation (maximum 29% at $\alpha \times m$=0.4 with respect to proposed technique) as compared to LEACH and SEP with increasing heterogeneity. High number of advanced nodes present in the network tends to make both HEC-with LEACH and HEC-with SEP equivalent. The improvement over FAIR is around 20% at $\alpha \times m$ =0.8, though for higher values of heterogeneity, for $\alpha \times m$ >= 1.5, FAIR protocol surpasses the proposed technique. Again this is because of dyeing of normal nodes before advanced nodes, as the normal nodes' initial energy is same and advanced nodes energy is increasing a lot.

6. Conclusion

Researchers have proposed various solutions for energy conservation in heterogeneous WSN environment. As the network passes through three main phases- initial, intermediate and dying - during its lifetime, data aggregation and communication protocol need to be adopted accordingly to prolong the stability period of the network. Keeping it in mind, in this work, we proposed and analyzed a three-phased heterogeneity-aware energy-efficient clustering technique, HEC, for increasing the stable region of a WSN. Simulation results establish the basis of our approach as the proposed technique is found to outperform LEACH, SEP, HEC-with SEP and FAIR protocols by 65%, 30%, 17% and 15% respectively in terms of stability period. For successful and useful communication, high throughput in the stable region is much desired. HEC technique provides better throughput for the stable region than all other protocols considered. Further, for better performance network should be able to consume most of its energy in the useful stable region; HEC consumes more than 90% of its energy in the stable region while LEACH, SEP, HEC- with SEP and FAIR consume only 54%, 68.5%, 76.25% and 80% respectively. Proposed technique exploits the energy of advanced nodes more judiciously and the first node to die is advanced node rather than a normal node as is the case with SEP protocol, which fails to utilize the energy of its advanced nodes effectively.

Scalability analysis shows that performance of the proposed technique remains quite consistent and better as compared to its counterparts. Though, the overall performance degrades beyond particular range of field size and for very large number of nodes owing to increased distance between nodes and the sink. In a real scenario, very large WSN is feasible only if initial energy of the nodes is first optimized with respect to field size and it needs to be explored further.

Heterogeneity analysis reveals that increase in number of advanced nodes and their initial energy can significantly boost the stability region, though, only up to a certain range beyond which heterogeneity does not help. The proposed technique not only improves the stability period but also utilizes the available energy in the most judicious way and thereby maintains the quality of service by enhancing throughput of the network in this region. Based upon the exhaustive simulations and superiority in comparison to other available relevant schemes, the proposed HEC technique seems to be a potential candidate for usage in the design of energy-efficient wireless sensor networks in heterogeneous environment.

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