

# Energy-Efficient Cluster Formation in Heterogeneous Wireless Sensor Networks: A Comparative Study

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**Abstract**— This paper presents a comparative study of clustering techniques and cluster quality of a single criterion cluster heads election and cluster formation in Wireless Sensor Networks. The HEED, LEACH and Energy-based LEACH protocols are simulated and their performance are compared in terms of the number of cluster head generated, cluster size, cluster head distribution, scalability and coverage. The results of these protocols are presented to show how the cluster formation helps to prolong the network lifetime. We investigated scalability aspects in the presence of advanced nodes in the network and its effect on the network lifetime. We proposed to investigate A-HEED and AE-LEACH protocols, a new approach for cluster heads election that improves network lifetime in the presence of advanced nodes. The simulation shows that having fraction of advanced nodes in the network gives significant improvement in network lifetime as compared with having more homogeneous nodes in the network.

**Keywords**— Wireless Sensor Networks, adaptive clustering, energy-efficient, network lifetime, heterogeneous.

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as recent technologies for data gathering. The sensor devices make up a collection of hundreds or thousands of sensor nodes deployed over a huge geographical area form a networked sensor [1]. These sensors sense data from remote locations by interacting with physical environment and relaying the information by coordinating among the sensors [2]. The sensor node consists of an embedded microprocessor, radio transceiver for communication, limited memory storage and on-board sensors for sensing attributes such as temperature, humidity or pressure [3]. The ability to communicate the environmental data to base station (BS) directly or through neighbouring node (cluster head) makes the sensor network suitable for remote control monitoring and surveillance. A potential application in agricultural industry, such as tiger-shrimps monitoring requires constant monitoring of the pond conditions. The data sensed from the pond such as water temperature, PH level or mineral content can be constantly monitored for ensuring the optimal pond conditions for yielding higher tiger-shrimp production. Considering the resource constrained nature of sensor nodes which depend on un-replenished battery source, the energy should be managed properly to ensure maximum lifetime [4]. In order to

guarantee low energy consumption and uniform load distribution over the network, sensor nodes are organized into clusters [5]. Clustering is one of the most efficient techniques in data forwarding in providing convenient framework for resource management. It can support many important network features within intra cluster such as channel access for cluster members and power control, as well as inter clusters such as routing and code separation to avoid inter-cluster interference [6]. A fix or adaptive approach may be used. In a fix maintenance approach, a cluster membership does not change over time. In an adaptive clustering, nodes may change their associations with different clusters. In adaptive clustering, the load to send data to base station is equally shared among all nodes in the network so that nodes die basically at the same time [7]. This paper investigates the adaptive clustering process on LEACH [8], Energy-based LEACH [9] and HEED [10] and compares different techniques of clustering which result in the cluster quality. The comparative analysis is given to show the cluster quality which are described below:

1. Number of clusters generated
2. Cluster size
3. Number of cluster heads elected
4. Cluster heads distribution
5. Scalability
6. Coverage

The paper presents the scalability aspects in the presence of advanced nodes in the network and compares the cluster quality with existing HEED and energy-based LEACH protocols. The proposed protocols are called advanced HEED (A-HEED) and advanced Energy-based LEACH (AE-LEACH) that take advantages of the advanced nodes. The simulation results show that having advanced nodes in the network improves network lifetime as compared with having more homogeneous nodes in the network. The rest of the paper is organized as follows: Section 2 describes the clustering objectives, clustering phase and cluster quality. Section 3 describes the existing adaptive clustering protocols and section 4 presents the proposed protocols, advanced HEED and advanced Energy-based LEACH, a new approach for cluster heads election and cluster formation. Section 5 presents the simulation results and section 6 concludes the paper.

## II. CLUSTERING IN WIRELESS SENSOR NETWORKS

Adaptive clustering involves grouping nodes into clusters and electing cluster heads periodically such that members of a cluster can communicate with their cluster heads and these cluster heads send aggregated data received from its members to a base station [12].

### A. Clustering Objectives

Nodes are grouped into clusters, based on the cluster objectives which are set to meet certain application requirements. The following presents some of the main objectives for clustering:

1. *Load balancing*: The cluster heads requires extensive energy consumption to aggregate data from member nodes and to transmit the aggregated data to base station which can be located far from the network. Therefore, by rotating the role of cluster heads, the load can be shared equally among all nodes in the network
2. *Optimal number of cluster heads*: In some techniques, the cluster head is determined a priori. Achieving the optimal number of cluster heads ensure the least energy dissipation in the network [9] and therefore, reduce power consumption in order to prolong network lifetime
3. *Maximum network lifetime*: Sensors are resource constraint and dependent on their batteries as source of energy, therefore, the lifetime becomes important consideration in sensor network topology design.

### B. Clustering Phase

Clustering is a process that elects cluster heads and formation of clusters. The following describes cluster formations:

1. *Cluster head election criteria*: Cluster heads are elected among all nodes in the network. The election can be based on single or multiple criteria such as node ID, node residual energy, random round-robin or distance to base station.
2. *Intra-cluster communications*: The communication among neighboring nodes helps create a competitive election of cluster heads. This is because each node can weigh its probability of becoming a cluster head with respect to its neighboring nodes. At the same time it prohibits two cluster heads to be in each other's range and thus give better cluster head distribution.
3. *Cluster selection*: Once cluster heads elected, the non-cluster head nodes have to choose which cluster to join so that no nodes will be left uncovered. The selection can be based on single or multiple criteria. Some protocols introduced mechanism to resolve ties in the case where node falls between more than one cluster heads range.

### C. Cluster Quality

Once the cluster heads are elected, non-cluster head nodes join a cluster head to form clusters. The quality of the cluster formation is described by the attributes defined as follows:

1. *Covered and uncovered nodes*: Covered nodes are nodes that are within a cluster head, whereas nodes not within any cluster heads are called uncovered nodes.
2. *Single-node cluster head*: In single-node cluster head, the cluster has no other members except itself. This single-node cluster heads must be minimized.
3. *Cluster count*: Optimal number of cluster should be achieved as it gives the least energy dissipation in the network.
4. *Cluster head distribution*: Uniform cluster head distribution in the network is important to have long network lifetime.
5. *Cluster size*: A balanced number of cluster members will distribute the cluster heads load uniformly. There will be no cluster head that is overburdened which can cause early death of nodes.

## III. RELATED WORK

In LEACH [8], Energy-based LEACH [9] and HEED [10] protocols use a single criterion to elect cluster heads and to form clusters. LEACH protocol uses a round-robin rotation to elect its cluster head where nodes elect to become the cluster heads base on the threshold defined as:

$$P_i(t) = \frac{k}{N - k * \left( r \bmod \frac{N}{k} \right)} : C_i(t) = 1$$

$$0 : C_i(t) = 0 \quad (1)$$

where  $r$  is the number of rounds that have passed and  $C_i(t) = 0$  if a node has already become a cluster head in the most recent  $(r \bmod N/k)$  rounds and 1 otherwise.  $N$  is the total number of nodes in the network and  $k$  is the optimal number of cluster head. Each node chooses a random number between 0 and 1 and if the number is lower than the calculated probability, the node is elected to become cluster head. Nodes that have not become a cluster head in a specific round will have higher probability to become the cluster heads on the next round.

Energy-based LEACH [9] elects nodes to become a cluster head at time  $t$  with probability:

$$CH_{prob}(t) = \min\left(\frac{E_i(t)}{E_{total}} \times k, 1\right) \quad (2)$$

where  $E_i$  is residual energy of node  $i$ ,  $E_{total} = \sum_{i=1}^N E_i(t)$

and  $k$  is the optimal number of cluster head. Nodes with higher energy have higher probability of becoming the cluster heads regardless whether the cluster heads are within each other's range. Energy-based LEACH protocol demonstrates the same behaviour as LEACH but elects cluster head based on node residual energy with respect to the total energy of the network. Energy-based LEACH shows better cluster heads selection and therefore has longer network lifetime. Once cluster heads announces their status, non-cluster head nodes will join a cluster based on only one criterion which is the strongest received signal strength.

HEED protocol [10] elects the cluster heads based on node residual energy which is defined as:

$$CH_{prob} = C_{prob} \times \frac{E_{residual}}{E_{max}} \quad (3)$$

where  $E_{residual}$  is the energy of the nodes,  $E_{max}$  is the initial energy of each node and  $C_{prob}$  is the initial percentage of cluster heads that is set as 5%. A number of iterations are performed before a final cluster heads are elected. HEED protocol ensures uniform distribution of cluster heads across the network. In its initialization phase, HEED protocol allows sensors to compute a probability of becoming cluster heads, proportional to its residual energy and to a pre-determined percentage of cluster heads. Then, during a repetition phase, sensor seeks the best cluster head to connect to. If no cluster heads is found, the sensor doubles its probability to become cluster head and broadcasts it again to its neighbours. This phase stops either when this probability equals to 1 or when it finds a cluster head to connect to [16].

#### IV. SCALABILITY ASPECTS IN WSN

In homogenous network all sensor nodes are identical and have the same hardware capabilities and battery energy. On the other hand, in a heterogeneous network, different types of nodes are used with different battery energy and hardware capabilities. Due to this fact, the cluster heads can be assigned among the nodes with higher capabilities or with extra energy as cluster heads require extensive energy usage. Intuitively if fractions of nodes have higher capabilities and are set as cluster heads, the network lifetime can be improved and at the same time reduces the hardware cost as compared to having all nodes with higher capabilities [14].

##### A. Advanced HEED

We propose advanced HEED (A-HEED) and advanced Energy-based LEACH (AE-LEACH), a new approach in election of cluster heads in the presence of advanced node in the network. A-HEED and advanced Energy-based LEACH (AE-LEACH) considers the residual energy to elect the cluster head in the network. The cluster formation follows the original HEED [10] and Energy-based LEACH [8] protocols as discussed before. We assume the residual energy of each node is sent to cluster heads. Each cluster head will aggregate this information and broadcast this information to all other cluster heads in the network. Assume highest transmission power is used for this purpose. All the cluster heads will receive the energy information from all cluster heads in the network. Then, the cluster heads will take the average of the total residual energy of the network and send this information back to its cluster members for next round of election. In the presence of advanced node, consider  $m$ , fraction of the nodes are heterogeneous and having  $\alpha$  more energy.

Thus, A-HEED protocol elects the cluster heads with the following probability:

$$CH_{prob} = \frac{E_{residual}}{E_{average}} \quad (4)$$

and

$$E_{residual} = E_i(1 + \alpha)$$

where  $\alpha = 0$ ,  $E_{residual}$  corresponds to normal node, otherwise is advanced nodes.

This probability gives the advanced node higher chances of becoming the cluster heads than normal nodes. The  $E_{average}$  is defined as the average energy of the network as given below:

$$E_{average} = \frac{1}{k_{opt}} \left[ \sum_{i=1}^{Nm} E_i(t) + \sum_{i=1}^{N(1-m)} E_i(t) \right] \quad (5)$$

and  $k_{opt}$  is the initial number of cluster heads chosen as given in [8].

##### B. Advanced Energy LEACH (AE-LEACH)

Advanced Energy-based LEACH (AE-LEACH) elects the cluster head with the following probability:

$$CH_{prob} = \min\left(\frac{E_{residual}}{E_{average}}, 1\right) \quad (6)$$

and

$$E_{residual} = E_i(1 + \alpha)$$

and  $E_{average}$  is as (5).

Having this probability, the expected cluster head elected per round is as described below. The advanced node will have  $\alpha$  more energy than the normal node therefore, the probability of advanced node to be elected is defined as:

$$CH_{prob} = \frac{E_i(1 + \alpha)}{E_{average}} \quad (7)$$

Probability of normal node to be elected is defined as:

$$CH_{prob} = \frac{E_i}{E_{average}} \quad (8)$$

Therefore, the total probability of the cluster head election is

$$CH_{prob} = m \frac{E_i(1 + \alpha)}{E_{average}} + (1 - m) \frac{E_i}{E_{average}} \quad (9)$$

$$E_{average} = [E_i(1 + \alpha)m + E_i(1 - m)] / k_{opt} = E_i(1 + m\alpha) / k_{opt} \quad (10)$$

Therefore, from (9) and (10) the election probability is derived as:

$$CH_{prob} = \frac{E_i(1 + m\alpha)}{E_i(1 + m\alpha) / k_{opt}} = k_{opt} \quad (11)$$

This equation proves that only  $k_{opt}$  cluster heads will be elected on each round.

## V. SIMULATION RESULTS

Simulation results are obtained to evaluate the performance of the proposed protocols. Simulation run 100 nodes that are uniformly placed in the network of dimension 100m x 100m. We set the optimum probability of becoming a cluster heads for both LEACH and Energy-based LEACH protocols as 5% as described in [9]. The base station is located at  $x = 50, y = 175$ . The clustering radius is taken at 25m and  $C_{prob}$  is set to 5% as the initial percentage of cluster heads for HEED protocol. On each experiment random topology is generated and each result is the average of 20 experiments. The simulation parameters considered are as described in TABLE 2. The three protocols use single criteria for election of cluster heads and cluster formation. In Energy-based LEACH protocol, the residual energy of nodes is assumed to propagate to the entire network. The round of which the first node dies is defined as the network lifetime [11]. The policy used for cluster formation is described in TABLE 1.

It is observed that the cluster head distribution for both LEACH and Energy-based LEACH protocols are not uniform. The cluster heads can be next to each other or can be at the edge of the network. HEED protocol demonstrates more uniform cluster head distributions as in Figure 1 which results in better average energy dissipation in the network. HEED protocol improves the cluster heads distribution by having additional policy in cluster formation. In the event where contending cluster head nodes received other cluster head messages, this node can withdraw its contention and join the other cluster which has least communication cost. This policy does not exist in LEACH or Energy-based LEACH protocols. However, having periodic local communication within neighbour nodes increases the communication overhead for HEED protocol.

The number of cluster heads elected varies significantly in LEACH and Energy-based LEACH protocols. HEED protocol shows small variation from the number of cluster heads as simulated in [13]. The average relative error is calculated to compare the variation of the number of cluster heads elected on every 100 rounds as shown in Figure 2.

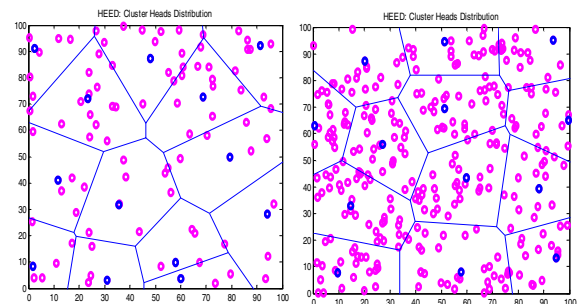
TABLE 1. THE POLICY USED IN CLUSTER FORMATION

|                    | Nodes falls between more than one cluster heads                                           | Nodes not within any cluster heads |
|--------------------|-------------------------------------------------------------------------------------------|------------------------------------|
| LEACH              | Choose a cluster with strongest signal strength                                           | Left uncovered                     |
| Energy-based LEACH | Choose a cluster with strongest signal strength                                           | Left uncovered                     |
| HEED-min degree    | Choose cluster with least cost and if nodes is cluster head then withdraw as cluster head | Become a single-node cluster head  |

TABLE 2. SIMULATION PARAMETERS

| Parameters                   | Values                       |
|------------------------------|------------------------------|
| Network grid                 | From (0,0) to (100,100)      |
| Sink                         | (50,175)                     |
| Initial Energy               | 0.5J                         |
| Eelec                        | 50 nJ/bit                    |
| $\epsilon_{fs}$              | 10 pJ/bit/m <sup>2</sup>     |
| $\epsilon_{mp}$              | 0.00013pJ/bit/m <sup>4</sup> |
| $E_{fusion}$                 | 5 nJ/bit/signal              |
| Threshold distance ( $d_0$ ) | 75m                          |

It is observed that the HEED protocol shows better performance in terms of number of cluster heads elected as it has smaller average relative error. HEED protocol achieves approximately same number of cluster heads on each round and this result in the least energy dissipation in the network. Once the cluster heads are elected, the non-cluster head nodes choose a cluster to join. All three protocols used a single criteria cluster formation. In LEACH and Energy-based LEACH protocols, nodes choose to join a cluster based on the strongest signal strength received from cluster head advertisement messages. This is to ensure the energy dissipated for the intra cluster communication will be the least as the cluster head is closer to its member nodes. In HEED protocol nodes choose a cluster based on the least communication cost which can be the nodes proximity to other nodes. If the requirement of the network is to distribute load among cluster head, nodes join a cluster with minimum degree, or join a cluster of maximum degree to create dense cluster. Additional policy is introduced in the case of cluster heads are within each other range. Cluster heads with minimum communication cost is chosen and other contending cluster heads have to withdraw its position. The simulation result shows that in case of LEACH and Energy-based LEACH protocols, when nodes do not hear any cluster head announcement, those nodes will be left uncovered whereas in HEED protocol these nodes will elect itself to become a single- node cluster head. Although HEED protocol creates single-node cluster, the whole area are covered by nodes in the network. However, for LEACH and Energy-based LEACH, nodes that are not within any cluster head will be left uncovered. If these nodes are the only nodes to cover certain area, there exist unmonitored areas (hole) in the network.



(a)

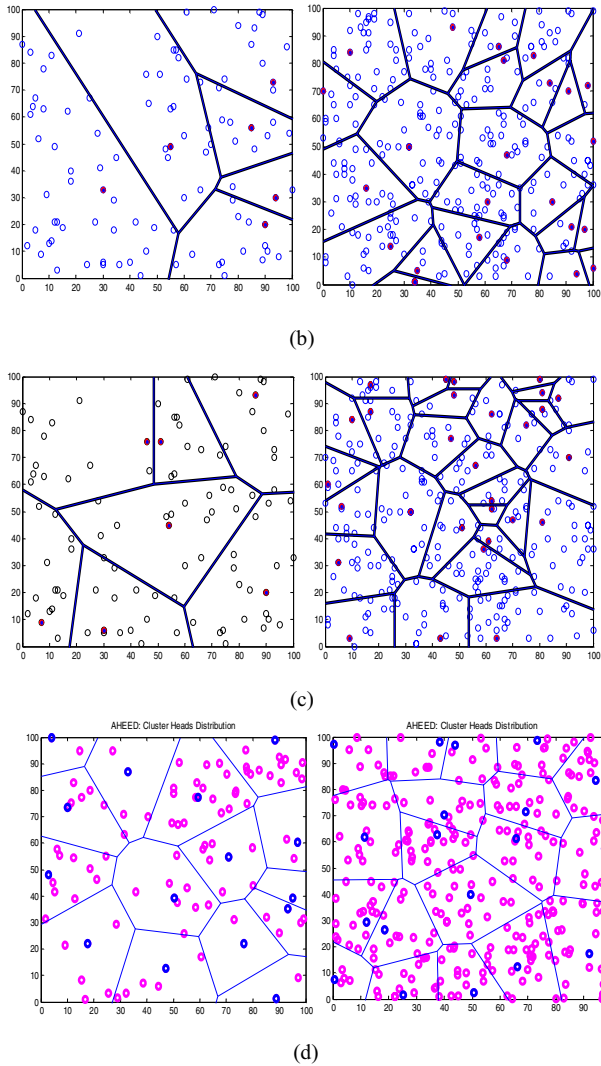


**Figure 1.** The cluster head distribution after 500 rounds with 100 and 300 nodes for (a) HEED , (b) LEACH, (c) Energy-based LEACH and (d) A-HEED protocol

The unbalanced cluster size can be seen in all three protocols as in Figure 1. This simulation results are consistence with the result produced by [17]. Some clusters have far more members than others. This create unequal cluster which causes overburden of cluster heads with higher number of member nodes. These overburden cluster heads might lead to early death.

#### A. Scalability with Advanced Nodes in the Network

We study the effect of having heterogeneous nodes where nodes have more energy at the beginning of network operation. The simulations are performed to observe the network lifetime with the presence of heterogeneous nodes as compared to having more homogeneous nodes network. We conduct experiments with A-HEED and AE-LEACH protocols and compare the result with HEED and energy-based LEACH protocols. We consider fraction of nodes having more energy than normal nodes. We run simulations experiment with

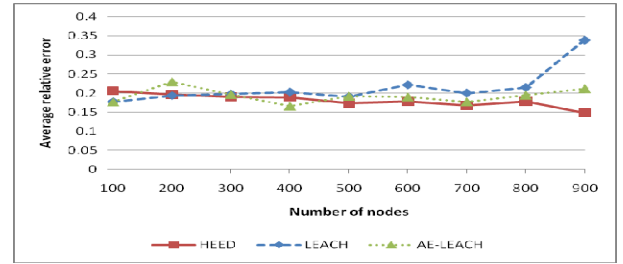


**Figure 2.** Average relative error for HEED, LEACH and Energy-based LEACH

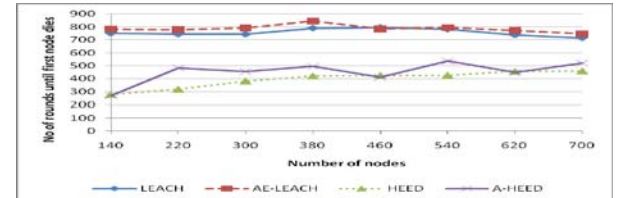


**Figure 3.** The network lifetime for LEACH, AE-LEACH, HEED and A-HEED for different number of nodes, without the presence of advanced nodes.

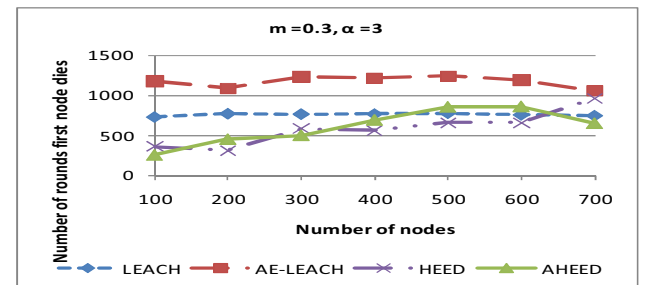
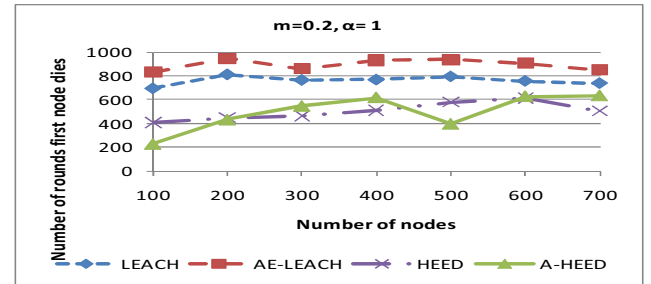


**Figure 4.** The network lifetime for LEACH, AE-LEACH, HEED, A-HEED with presence of advanced node  $m = 0.2, \alpha = 1$  and  $m = 3, \alpha = 3$ .

fraction of nodes  $m$  having extra energy  $\alpha$  as given below, where  $\alpha = 1, m = 0.2$  with increasing number of nodes in the network from 100 to 700 and with interval of 100 nodes. The simulation results are given in Fig 3 and 4. The optimal cluster heads  $k_{opt}$  is assumed to be 11 as calculated based on [9] for node size greater or equal to 300 and set to 5 when node size less than 300. For HEED protocol  $C_{prob}$  is set to 5%. We run the experiment again with same setup but different value  $\alpha = 3, m = 0.3$ .

We summarize the observation based on simulation results in Figure 3 to Figure 4 for network lifetime as follows:

1. LEACH, Energy-based LEACH and HEED protocol do not take full advantage of increasing number of nodes in the network as shown in Figure 3 and Figure 4. When network is dense (more number of homogeneous nodes), sensing ranges (areas) of neighbouring sensors usually overlapped. This overlapping area causes redundant transmission which results in useless energy consumption [15]. The round of the first node dies for Energy-based LEACH protocol is always much later than LEACH protocol as in Figure 3.
2. LEACH protocol has no effect in the presence of advanced node, although given  $m = 0.2$  and  $\alpha = 1$  or  $m = 0.3$  and  $\alpha = 3$  as shown in Figure 4.
3. AE-LEACH protocol takes advantage of the presence of advanced node as the round of the first node dies shifted to higher round. However, the protocol has no effect on the increased number of nodes in the network lifetime as in Figure 4.
4. A-HEED and AE-LEACH protocols take full advantage of the presence of advanced nodes as shown in Figure 4. For given  $m = 0.3$  and  $\alpha = 3$ , where 30% of nodes having three times more energy, the round of first node dies for AE-LEACH protocol increases to about 400 rounds. However, the increase number of nodes in AE-LEACH does not give significant effect to the network lifetime as shown in Figure 4.
5. For the same value of  $m = 0.3$  and  $\alpha = 3$ , A-HEED protocol shows that as the number of node increases, the lifetime also increases. As node increase to 500, the lifetime is better than LEACH protocol as shown in Figure 4.

## VI. CONCLUSIONS

This paper presents a comparative study of clustering techniques and cluster quality of a single criterion cluster heads election and cluster formation in Wireless Sensor Networks. The existing protocols are simulated and their performance are analysed in terms of the number of cluster heads generated, cluster size, cluster head distribution, scalability and coverage. A-HEED and AE-LEACH protocols are proposed, a new approach for cluster heads election and cluster formation, are presented. Simulation results are provided to show the effect of presence of advanced nodes in the network which give significant improvement in network

lifetime as compared to having more homogeneous nodes in the network.

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