CHAPTER 3

ESAC: AN ENERGY AND STABILITY AWARE CLUSTERING TECHNIQUE FOR HETEROGENOUS SENSOR NETWORKS

3.1  INTRODUCTION

This chapter discusses about ESAC, an Energy and Stability Aware Clustering technique proposed for heterogeneous wireless sensor networks. ESAC assumes a two level hierarchy within the network wherein the nodes with advanced hardware act as Cluster Heads (CHs), while other normal nodes function as cluster members. The normal nodes send their observations to their corresponding cluster heads, which then aggregate the reported data from all its member nodes and send a higher level message digest to the base station/sink as shown in the Figure 3.1.

![Figure 3.1 A Typical Clustered Sensor Network Architecture](image-url)
Since the wireless sensor networks typically work in resource-constrained environments, energy efficiency is of paramount importance to the design and development of protocols for these networks. In this thesis, it is proposed that the stability of the network should also be given due consideration in order to maintain the consistency and completeness of the reported results. The network is said to operate in the stable region for the period over which all the CHs remain alive i.e. the time interval from the start of the network operation until the death of the first CH node.

In a network where the energy expenditure of various CHs is not balanced, some of the CHs will deplete their battery energy very soon causing their member nodes get disconnected from the rest of the network. ESAC prolongs the stability period of the network by means of balancing the load at each CH. The proposed work does not make any assumption regarding the node distribution and density; nor does it necessitate the expensive CH reelection process for role rotation. In this thesis, the performance of the proposed approach is studied under two different path loss models, viz. free space model (path loss index=2) and multi path fading model (path loss index=4). The effectiveness of the proposed approaches is verified through simulation studies by assuming valid simulation models and the outcomes of the experiments are subjected to standard statistical tests to verify the credibility of the reported results.

3.2 ENERGY EFFICIENT NETWORK DESIGN

The problem of maximizing the network stability is approached by means of (i) the energy efficient assignment of nodes to CHs and (ii) balancing the load at CHs as described in the following sections.
3.2.1 The Network Model

A square sensing region A of area 100 x 100 square metres is considered for the purpose of the simulation study. The sink is assumed to be located at a remote place from the region. Sensor nodes of varying densities and the required number of advanced nodes are deployed randomly using a homogenous Poisson point process over the sensing region. The advanced nodes automatically become cluster heads. The number of advanced nodes for a given node density is decided according to the following relationship (Heinzelman et al 2002).

\[
N_1 = \sqrt{\frac{N_0}{2\pi}} \sqrt{\frac{E_{fs}}{E_{mp}}} \frac{M}{d_{to\, BS}^2} \quad (3.1)
\]

where

- \( N_1 \) = Number of advanced nodes
- \( N_0 \) = Number of ordinary nodes
- \( E_{fs} \) = RF amplifier energy expenditure in free space model
- \( E_{mp} \) = RF amplifier energy expenditure in multi path model
- \( M \) = Size of the sensing area
- \( d_{to\, BS} \) = Distance to the base station

Once clusters are formed according to the clustering process discussed in subsequent sections, individual nodes start sending their raw measurement values to the corresponding cluster heads on a regular basis; each CH then applies an appropriate aggregation function (which is dependent on the application under consideration) to produce a higher level message digest which is subsequently sent to the base station for further analysis.
The following assumptions are made:

- The nodes in the network are stationary (which is typical to sensor networks)
- The network is heterogeneous: Normal nodes of lower energy level $E_0$ are deployed with intensity $N_0$ and advanced nodes of higher energy level $E_1$ are deployed with intensity $N_1$.
- Nodes use omni directional antenna.
- Cluster heads are well distributed within the sensing region.
- Nodes are left unattended after deployment.
- Applications are of continuous data gathering type.
- The medium is contention and error free.
- All the nodes (both CHs as well as member nodes) know their physical location\(^1\).

### 3.2.2 The Energy Model

The amount of energy spent by a normal node to transmit a single bit of data to its cluster head is,

$$E^{i_0}_t = E^{i}_{elec} + E^{i}_{amp} d^{k}$$  \hspace{1cm} (3.2)

\(^1\) It is assumed that all sensors and cluster heads obtain either their absolute positions from the GPS or relative positions from other location services. In an area without the GPS system, each sensor can estimate its relative location information by measuring the signal strength or angle of arrival from its neighbours.
where,

\[ E_t^{\text{elec}} = \text{energy used by the transmitter circuitry} \]
\[ E_t^{\text{amp}} = \text{energy used by the front end amplifier to counter the} \]
\[ \text{propagation loss} \]
\[ k = \text{path loss gradient; } 2 \leq k \leq 4, \text{ depending on the terrain} \]
\[ \text{used.} \]
\[ d = \text{distance between a node and its cluster head} \]

Energy spent by a cluster head to transmit a single bit of data to the base station is

\[ E_t^{t_1} = E_t^{\text{elec}} + E_t^{\text{amp}} D^k \quad (3.3) \]

where, \( D \) is the distance from the CH to the base station.

The energy required by the CH to receive a packet of unit length from a node is just,

\[ E_r^{r_1} = E_r^{\text{elec}} \quad (3.4) \]

where, \( E_r^{\text{elec}} \) is the energy used by the receiver circuitry

Figure 3.2 pictorially represents the energy model indicating the various components involved in deciding the energy expenditure of sending a packet of \( L \) bits size to a receiver at distance \( d \).
Let $E$ be the amount of initial energy supplied to a cluster head and $E_x$ be the energy spent by the CH in one round. Here, a *round* specifies the reception of packets containing raw measurement values from all its member nodes, aggregate it to a single packet and send it directly to the sink. The number of such rounds a CH node withstands before depleting its energy decides its lifetime. Hence,

$$T = \frac{E}{E_x} \quad (3.5)$$

where, $T$ denotes the life time of CH and

$$E_x = E[N_v](E^{r_1} + E_d) + E^{t_1} \quad (3.6)$$

where,

- $E(N_v)$ = expected number of nodes lying in each cluster
- $E^{r_1}$ = energy spent in receiving packets from all the normal nodes in its cluster
- $E_d$ = energy spent in aggregating the individual nodes’ packets into a single packet
- $E^{t_1}$ = energy spent in transmitting the aggregated message to the sink
Let $L$ be the size of packet in bits. Therefore, according to Equation (3.4),

$$E_r^i = E_{\text{elec}}^r E(N_v) L$$

(3.7)

Similarly from Equation (3.3), it is evident that,

$$E_t^i = [E_{\text{elec}}^t + E_{\text{amp}}^t D^k] L$$

(3.8)

The transmission and reception energies calculated using Equation (3.7) and Equation (3.8) will be substituted in Equation (3.6) to calculate the total energy spent by a CH in a single round.

### 3.3 THE CLUSTERING PROCESS

Assuming that $N = N_0 + N_1$ are distributed randomly in the sensing field. The goal of any clustering algorithm is to identify an optimal mapping of the nodes to the cluster heads. Each node $N_i$, where $1 \leq N_i \leq N_0$, is mapped exactly to one cluster head $N_j$, where $1 \leq N_j \leq N_1$ (Ossama et al 2003). The clustering process should be made completely distributed - each node should make its own decision based on its local knowledge. The algorithm should also ensure that the load at each cluster is balanced and the total distance between the member nodes and their respective CH nodes is minimized. Balancing the clusters is needed for evenly distributing the relay load at all the CH nodes. Minimizing the total distance helps in reducing the communication overhead and hence the energy dissipation. If the balancing constraint is not enforced, it may lead to the early expiry of certain CH nodes having very high node degree because of their over relaying burden. Once a CH dies, all its member nodes get disconnected from the rest of the network.
The reports generated from such a network will be partial and unreliable since they do not appropriately reflect the status of the entire sensing field.

3.4 THE ESAC ALGORITHM

In this section, the proposed ESAC protocol is described in detail. The definition of the problem is given first which is followed by the details of the protocol design and the simulation results.

3.4.1 The Problem Definition

The principal goal of the proposed algorithm is to construct energy efficient and stable clusters. With this objective in mind, the protocol is designed in such a way that the communication cost of a node is minimized. As discussed earlier in section 3.2.2, the communication cost of a node is primarily decided by the distance over which it needs to transmit. Hence, it becomes obvious that minimizing the communication distance saves the communication cost. Keeping this simple observation in mind, the distance is used as the primary metric to decide the mapping of a given node to a cluster head. That is, a node associates itself with an advanced node that is available at the shortest distance, if there are multiple such nodes available in its communication vicinity. Every advanced node is preprogrammed with a maximum allowable node degree (elaborated in section 3.4.3). An advanced node accepts the affiliation of a member node if and only if its inclusion does not exceed the above said node degree limit. Therefore, the load of a CH is used as a secondary metric and this constraint automatically balances the load on each CH, thus improving the overall stability period of the network.
### 3.4.2 Protocol Design

Initially, once the network is deployed, each normal node broadcasts an ASSO_REQ (Association Request) message, which is then received by all the CHs in its vicinity. Each CH receiving the message replies with an ASSO_RES (Association Response) message containing its ID and geographical location. A normal node may receive multiple such association responses from different CHs, but decides to associate with the nearest CH by calculating the Euclidean distance between itself and each of the CHs in its neighbourhood. It then notifies the selected CH with the ASSO_CNFR_REQ (Association Confirmation Request) message and others with the ASSO_CNFR (Association Cancel) message. Upon receiving the confirmation request, the CH node then checks whether it has reached its maximum node degree. If so, it replies with an ASSO_REJ (Association Reject) message or else with an ASSO_CNFR (Association Confirmed) message and increases its node degree by 1. The node that receives the rejection message from the selected CH, repeats the same procedure with the next nearest CH. Figure 3.3 shows the sequence of operations in ESAC using a timeline diagram.

### 3.4.3 Ensuring Complete Association

Ideally if $N_1$ is the number of cluster heads, the normal node density is expected to be a multiple of $N_1$. Ghiasi et al (2002) makes such an assumption which cannot always be ensured in practice. Therefore, the proposed ESAC algorithm relaxes this constraint whilst attempting to achieve uniform load at each cluster head. Also it does not leave out any node unassociated. To ensure this, the number of cluster heads is fixed according to Equation (3.1), for the given node density of a deployment. Initially, the maximum allowable node degree of each CH is fixed as $\lfloor N_o / N_1 \rfloor$. At the end of association phase, if any ‘uncovered’ node (not affiliated to any CH) is
identified by the base station, it reprogrammes each CH to increase its maximum allowable node degree by 1. So the uncovered nodes are again equally distributed among the CHs, thus leading to uniform load at each cluster head.

Figure 3.3 The ESAC Protocol - Sequence of Operations
3.4.4 The Impact of the Choice of the Transmission Mode

ESAC assumes that each normal node has adjustable transmission power levels and thus being capable of reaching an advanced node in a single hop. If this constraint is relaxed, then a node may try multi hopping to reach the nearest advanced node if no such node is available in its vicinity. However, since the focus of the work is to balance the load at the CHs, it is immaterial whether the member nodes use multi hopping or single hopping. Both of them present the same amount of load for a given CH which depends on the number of nodes in the cluster.

As the distance involved in intra-cluster communication is normally within a few metres, the communication channel is modeled using the free space model with path loss index value (k) as 2. However, the communication channel between the cluster heads and the base station is modeled using both the free space model with path loss index as 2 and the fading model with path loss index value 4. The free space model is applicable when a line of sight (LOS) exists between the cluster heads and the sink, as in the case when an aircraft sweeps through the sensing field to collect the aggregate reports (Mhatre et al 2004). Otherwise, the fading model is used since the communication distance involved is larger and the signal energy is absorbed by various obstacles in the sensing field.

3.5 PERFORMANCE EVALUATION OF ESAC
3.5.1 The Simulation Environment

A square sensing region A of area 100 x 100 square metres is simulated with a population of sensor nodes (N) ranging from 50-250 deployed uniformly across A. For a given node density, the optimum number of advanced nodes are calculated as specified in Equation (3.1). Both the
normal nodes and the advanced nodes are deployed randomly across the given sensing area. The initial energy of a normal node is set to $E_0 = 1\text{J}$ and that of a CH to 2 J. Although these values are arbitrary for the purpose of this study, they do not affect the behavior of the proposed method. The size of the message that nodes send to their CHs as well as the size of the (aggregated) message that a cluster CH sends to the sink after aggregation is set to 4000 bits. The communication is assumed to be noise free. The simulation parameters used in the implementation are summarized in Table 3.1.

Table 3.1 The Simulation Scenario of ESAC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>100 x 100 square metres</td>
</tr>
<tr>
<td>Location of BS</td>
<td>Remote</td>
</tr>
<tr>
<td>N</td>
<td>50-250</td>
</tr>
<tr>
<td>Path loss exponent (k)</td>
<td>2 and 4</td>
</tr>
<tr>
<td>Initial Energy</td>
<td>1 J (Normal node)</td>
</tr>
<tr>
<td></td>
<td>2 J (Cluster Head)</td>
</tr>
<tr>
<td>$E_{\text{elec}}$</td>
<td>50 nJ/bit</td>
</tr>
<tr>
<td>$E_{\text{amp}}$</td>
<td>0.0013 pJ/bit</td>
</tr>
<tr>
<td>$E_f$</td>
<td>5 nJ/bit</td>
</tr>
<tr>
<td>Packet size</td>
<td>4000 bits</td>
</tr>
</tbody>
</table>

The effect of the ESAC algorithm on the life time of the CH nodes and on the stability period of the network is demonstrated under the two path loss models (free space model and multi path fading model). The residual energy of a CH is updated in each round and the simulation is
stopped when the residual energy of each CH falls below the value beyond which it becomes unusable. The following performance measures defined in SEP by Smaragdakis et al (2004) are used to prove the effectiveness of the algorithm:

- **Stability Period:** is the time interval from the start of network operation until the death of the first CH.
- **Instability Period:** is the time interval after the death of the first CH until the death of the last CH.
- **Network lifetime:** is the time interval from the start of the operation of the sensor network till the death of the last CH, beyond which the network is not usable.

### 3.5.2 Results and Discussions

Assuming the simulation scenario given in Table 3.1, a large sample study (sample size > 30) is conducted by choosing purely random and unbiased samples of node distributions. Therefore, according to the Central Limit theorem, the outcomes of the simulation studies follow a normal distribution. For each given node density, 50 statistically independent, pseudo random network topologies are generated and the results shown in the graphs in the Figures 3.5 to 3.9 are the averages of 50 simulation runs. The generated topologies include highly dense to highly scattered node distributions and CH positions across the sensing area. All the results are obtained at 95% confidence interval. The performance of the proposed algorithm is first studied in the free space model by assuming single hop communication mode for both intra cluster and inter cluster communications. i.e., by virtue of its higher battery power, CHs can report data directly to the base station.
In the performance results shown in the Figures 3.4 to 3.9, the term *unbalanced clustering* refers to a class of clustering protocols that do not insist upon balancing the load of CHs, including the work reported by Heinzelman et al (2002) and Duarte-Melo et al (2002). Figure 3.4 compares the individual life times of various CHs in ESAC and the unbalanced clustering techniques for a sample network topology consisting of 100 nodes. From the Figure 3.4, it is evident that all the CHs have nearly uniform lifetime (about 490 rounds) in ESAC. i.e., all the CHs die approximately at the same time, leaving very little residual energy in the network.

In the case of unbalanced clustering, it is apparent from Figure 3.4 that CH 4 dies very soon (in 155 rounds) followed by CH 2 and CH 3, both of which die within 250 rounds. i.e., the network offers complete coverage only for 155 rounds, which is not desirable. Even though CH 1 lasts for more than 600 rounds (i.e., the life time of the unbalanced network is higher than its balanced counterpart), the network offers only a partial coverage for a significant period of time and the reports generated from such a network would be unreliable and incomplete in nature.

Figures 3.5 and 3.6 give consolidated pictures about the differences in the stability periods of the two clustering schemes for varying node densities under the two path loss models. The influence of the proposed ESAC algorithm on extending the stability period of the network is apparent from the Figures 3.5 and 3.6. The results shown are the averages of a sample study conducted with 50 randomly generated node distributions for each node density.
Figure 3.4 CH Life Time Distribution

Figure 3.5 Stability of the Network, Path Loss Index = 2
Statistical analysis of the outcome of the sample study shows that the mean stability period of the proposed ESAC lies in the range of 483 rounds (99% confidence interval) for a 100 node network, while that of an unbalanced network falls in the range of 134 rounds ± 8.68 (95% confidence interval) i.e. the first CH node dies somewhere between 125 and 143 rounds.

The reason for the huge drop and the wide fluctuation in the stability period of the unbalanced clustering technique lies in the way in which the cluster formation is done. In each simulation run, the clustering process is highly influenced by the distribution of the nodes, as the distance alone is considered as the clustering parameter in the unbalanced clustering schemes. It should be noted that in the balanced clustering technique followed by ESAC, the network operates in the stable region for a prolonged period of time which is crucial for many applications where the feedback from the
entire sensor network is required. This is made possible due to the well-distributed and uniform energy expenditure among the CHs, thus avoiding the early expiry of any CH in the network.

Table 3.2 shows the average improvement in the stability period of the network offered by ESAC for both the path loss models as compared to the unbalanced clustering schemes.

**Table 3.2 Improvement in the Network Stability Period**

<table>
<thead>
<tr>
<th>Network size</th>
<th>k=2</th>
<th>k=4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ESAC</td>
<td>Unbalanced Clustering</td>
</tr>
<tr>
<td>50</td>
<td>622</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>483</td>
<td>134</td>
</tr>
<tr>
<td>150</td>
<td>434</td>
<td>116</td>
</tr>
<tr>
<td>200</td>
<td>362</td>
<td>93</td>
</tr>
<tr>
<td>250</td>
<td>362</td>
<td>80</td>
</tr>
<tr>
<td><strong>Average gain (Rounds)</strong></td>
<td><strong>328</strong></td>
<td><strong>302</strong></td>
</tr>
</tbody>
</table>

Figures 3.7 and 3.8 compare the instability periods (time interval between the death of the first CH and the last CH) of both the schemes. The figures show how much of the time the network operates in the instability period in the unbalanced clustering schemes. The effect of the instability period in very well evidenced for larger node densities as indicated in the figures. Therefore, the prime goal of any balanced clustering technique should be to reduce the instability period, which is successfully achieved by ESAC as shown in the Figures 3.7 and 3.8.
Figure 3.7 Instability of the Network, Path Loss Index =2

Figure 3.8 Instability of the Network, Path Loss Index =4
The accuracy of energy balancing can be measured by calculating the Coefficient of Variation (CV = Standard deviation/Mean) of the stability periods of the balanced (ESAC) and unbalanced clustering techniques for varying node densities. Presumably, the smaller the value of CV, the more balanced is the power consumption across the different CHs. Table 3.3 and the corresponding Figure 3.9 indicate that the value of CV in the case of ESAC is zero for all the node deployments considered.

<table>
<thead>
<tr>
<th>No. of nodes</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESAC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Unbalanced clustering</td>
<td>20.6</td>
<td>20.9</td>
<td>21.6</td>
<td>18.6</td>
<td>8.5</td>
</tr>
</tbody>
</table>

**Table 3.3 ESAC vs Unbalanced Clustering-Coefficient of Variation**

**Figure 3.9 The Accuracy of Balancing**
Figure 3.9 clearly indicates that the energy expenditure of all the CHs is well-balanced, irrespective of the node density and distribution; its unbalanced counterpart results in a much larger value of CV. This clearly displays how prominently the node distributions influence the cluster formation process and consequently the life time of the CHs.

### 3.5.3 Numerical Results Vs Simulation Results

In order to verify whether the simulation results obtained match with the theoretical model assumed in section 3.2.2, the stability periods obtained as a result of the random simulations are compared with their corresponding theoretical values i.e. because of the formation of balanced clusters in ESAC, the expected number of normal nodes in each cluster, $E[N_1]$ is $(N_1/N_0)$. Therefore, the energy expenditure of a CH, according to Equation (3.6) becomes,

$$E_x = (N_1/N_0) \left( E_r + E_t \right) + E_t$$

The dimensions of the sensing area, the number of nodes and the other simulation parameters are taken identically for theoretical analysis and simulations. Figures 3.10 and 3.11 depict the results of the comparison for the two path loss models under consideration. It is observed that the gap between the theoretical results and the simulation results is reasonably small in all the examined cases; the disparity between the two is attributed to the fact that, $N_0$ not being an exact multiple of $N_1$ and the extra load should be shared among a few CHs. Because of the randomness in the node distributions, the number of nodes assigned to the different CHs are not always exactly equal in the simulation studies.
Figure 3.10  Comparison of Theoretical and Simulation Results, k=2

Figure 3.11  Comparison of Theoretical and Simulation Results, k=4
3.6 SUMMARY

This chapter discussed about the proposed energy efficient clustering protocol for heterogeneous wireless sensor networks called ESAC. The proposed clustering technique prolongs the stability period of the overall network by means of balancing the relay load of each cluster head. Simulation results show that the proposed balanced clustering technique improves the stability period of the network by more than 300 rounds on the average. The clustering process in ESAC is terminated within $O(1)$ iterations, irrespective of the size of the network and the distribution of the nodes in the sensing field.

In order to demonstrate the efficacy of the proposed ESAC algorithm, detailed simulation studies were conducted assuming valid simulation models. Well distributed random network topology samples were taken for the purpose of the study. The outcomes of the simulation studies were subjected to standard statistical tests. All the reported results were taken at 95% confidence level. Besides, simulation studies are supported by theoretical models.

The limitation of the present work lies in its assumption of the heterogeneous network architecture. The proposed clustering technique is less robust against CH failures because the failure of a CH necessitates immediate replacement and a subsequent reelection process.