Chapter 9

Clustering with Reduced Broadcast

The energy usage estimations during steady state phase of clustering protocols can reduce the requirements of energy information collection from the member nodes. This type of collection becomes increasingly difficult when number of nodes are large in number. The nodes are tightly clock synchronized. Accordingly, they transmit the energy information during the initial stage of setup phase. This energy collection is as per the node-id numbers assigned to every node. A long TDMA frame is announced during which, all nodes send their energy information to the base station. Later, the base station applies the clustering algorithm to create clusters depending on certain criteria as per the specific clustering strategy adopted. The initial energy transmissions can be completely avoided if energy usage estimations can be made more accurate. The proposed Harmony Search based Reduce Broadcast Clustering (HRBCP) approach, aims at completely removing energy information transmissions during the setup phase of centralized clustering strategies.

9.1 Related Work

In LEACHC (Heinzelman, Chandrakasan, and Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks”), all nodes send their energy and location information to the base station in every round. Then base station decides the cluster head and cluster members with the best grouping possible depending on the distance between cluster head and cluster members. Simulated annealing
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Algorithm is applied to create the clusters. The nodes which are having suitable position such that the communication cost is minimum and their residual energy is above the average energy of network are selected as cluster heads. The nodes are well aware of their role, either cluster head or cluster member. Accordingly they schedule their transmissions using TDMA scheme. Cluster head aggregates the information received from member nodes and transmit it to the base station at regular interval, at the end of the TDMA frame in a particular cluster. The process is repeated in every round during setup phase, whereas steady state phase is similar to LEACH protocol.

![Figure 9.1: Round of LEACH and LEACHC](image)

Figure 9.1 shows how the LEACH or LEACHC protocol progresses with time. Initially it forms clusters during the setup phase and then after steady-state phase starts. Every steady-state phase is assigned fixed time interval. In this interval, every cluster member sends data to its respective cluster-head. Depending on the number of members present in every cluster, every member gets a TDMA slot at regular interval as shown in Figure 9.2.

![Figure 9.2: Detailed Layout of LEACHC](image)

In centralized version of clustering protocols, generally the sensor nodes send their energy/location information to the BS. BS then applies suitable clustering technique to group the nodes in clusters and declares the list of CHs and CMs. Afterwards, the CHs and CMs go through the steady state phase of data transmission. The reclustering process is called iteratively at every round. The centralized clustering protocol
suffers from excess energy usage during location or energy information transmission to BS. It severely affects the network lifetime if the base station is located far away from the deployment field. Various schemes are proposed in the literature to reduce such transmissions to conserve the energy. Dunkels et al. (Dunkels et al.) have proved that energy estimation can be used to reduce the energy consumption with hardware specific component level energy modeling. Their estimations are close to the real measurements taken on the sensor hardware. They have applied node level energy estimations. Younis et al. (Younis and Fahmy, “An experimental study of routing and data aggregation in sensor networks”) have proposed linear energy model for node level energy estimations. Instead of collecting raw residual energy data from individual nodes, Zhao et al. (Zhao, Govindan, and Estrin) applied in-network aggregation to generate composite residual energy scans. They applied network-level energy estimation method to reduce the energy consumption. Halgamuge et al. (Halgamuge, Guru, and Jennings) described network-level energy estimation for cluster based routing protocol. They have compared subtractive clustering with FCM based clustering. Halgamude et al. (Halgamuge et al.) have later on analyzed the energy estimation comprehensively and compared their approach with other known LEACH variants. Zhou et al. (Zhou et al.) proposed energy dissipation forecast and clustering management (EDFCM) protocol. EDFCM assumes heterogeneous nodes in the deployment and accordingly applies the energy model to compute the energy drain out of the cluster head nodes and cluster members. It also applies optimal cluster head selection policy while electing cluster heads.

9.2 LEACH-CCB

LEACH Completely Controlled by BS (LEACH-CCB) protocol (Manjula et al.) is proposed by Manjula et al. where, 5% of alive nodes in the network are selected as cluster heads. The energy status message from member nodes is sent only once during the first round, during the remaining rounds the energy is estimated with known parameters like cluster heads, cluster member count, number of frames in the round etc. The base station makes 10% of the nodes in the network to go to sleep mode. This is done before the selection of cluster heads. The nodes in sleep mode neither sense any data nor they receive cluster head information from the base
station. Base station controls the operation of all nodes. The base station chooses 5% of the nodes as cluster heads. The cluster heads of previous rounds are not eligible to participate in the cluster head selection unless all nodes in the network have become cluster heads. This model randomly chooses a set of sleeping nodes for a particular round. This does not guarantee the quality of data even if it preserves the lifetime. Also, the assumptions about initial energy and simulation results are not justified with respect to energy model applied. As 10% of the nodes are in sleeping state, throughput should have been less by that factor but, results are not witnessing this fact. Authors have included the initial status message also as part of throughput which seems irrelevant.

9.3 LEACHC with Energy Estimation

LCE [Kim et al.] uses the same centralised clustering scheme as in LEACH-C. It reduces the number of communications between the nodes and base station with an energy efficient clustering scheme through estimation. The energy required to send energy status message is greater than the amount of energy needed to transmit the sensed data to the cluster head. LCE reduces these status message transmissions to the BS. The protocol LEACH-CE achieves greater network lifetime than the previous protocols. The status message is received by the base station only at the setup phase of first two rounds. Third round onwards, the remaining energy level of each node is calculated by the base station itself. The average energy expenditure of the cluster head and the node is calculated and subtracted respectively for the next round. The energy of the nodes in LEACH-CE is utilized better than in LEACH-C. The system

![Figure 9.3: Frequency of energy information collection](image)

lifetime, the live node count in the network at a given time and the useful data received by the base station is greater in LEACH-CE than LEACH-C. Average energy usage by cluster-head and cluster member is derived after observing the energy usage
during these two rounds. Later on, the same is iteratively applied to subtract the 
energy consumption from cluster-heads or cluster members during the consecutive 
eight rounds. The frequency of energy information collection from members is shown 
in Figure 9.3. The LEACH-CE protocol was implemented to examine the standard 
deviation of number of members in clusters. It also shows similar kind of clustering 
behaviour like LEACH-C and its variants. LEACH-CE also has the problem of non 
uniform data delivery at BS.

Figure 9.4: Frequency of data collection

All the centralized clustering protocols actually assign the TDMA slots to dif-
ferent sized clusters as shown in Figure 9.4. This leads to imbalance in the workload 
among the nodes. Some of the nodes do excess data transmission, others are send-
ing very less data. The results shown in Figure 9.5 for per round energy drain for 
LEACHC and its variants suggest that, the estimated usage of energy consumption 
by members may not be accurate. As the clusters may be of different sizes, every 
node may be spending different amount of energy in a particular cluster. This pa-
rameter not only depends on the number of nodes present in the cluster, but also the
distance of member with cluster head and distance of cluster-head with base station. During the cluster formation in every round, cluster-heads also may be placed quite close to each other or they may be far from each other. Cluster-heads may be near to the base-station or they may be far away from the base station. LEACHC-E (Kim et al.) uses estimated energy for 80 % of the rounds. Average energy usage analysis done during the first two rounds may not be directly applied for 80 % of the time. As the clustering process shows large variation in cluster members assignment to a particular cluster, in every round a cluster member gets different share of the total TDMA slots in the cluster. The placement of the nodes may also be different with respect to cluster-head positions. Energy status received during 20% of the rounds can not be directly applied for energy estimations for 80% of the rounds. The nodes may also expire during the 80% of the rounds time. This information will not be available to the BS, till the next two energy collection rounds.

![Figure 9.5: Worst Energy Drain Difference Across Clusters](image)

Due to variations in the cluster sizes (Figure 9.6), the nodes expiry may not be accurately predicted with energy readings of only two rounds as used in LEACHC-E (Kim et al.). A node may expire little earlier than expected or may last longer than the estimated death time. This also depends on the number of TDMA slots assigned to that node during a round and also on the distance of the node with the cluster-head if it is cluster member; and with base station if it is cluster-head. The energy usage estimation needs a refinement here. With Loose Density Control approach, the
clustering process fixes an upper-bound and lower-bound for the highest and lowest number of nodes that is assigned to any cluster at any round. Node death may be more accurately predicted with the integration of Loose Density Control in the energy estimation calculations.

9.3.1 Likely to Die Threshold

To estimate the node death in between a particular round of the protocol, a likely to die threshold can be estimated. This likely to die threshold will suggest whether a particular node will sustain during the round completely or not. The likely to die threshold can be computed in two ways. Base station can find the $LD_{THR}$ using the distance information and TDMA slots assignment to every cluster. Alternatively, cluster-heads can also estimate the $LD_{THR}$ by approximating the average number of members in the cluster and number of TDMA slots given to every node in the cluster. With Direct Broadcast Avoidance approach, the $LD_{THR}$ is computed by cluster-heads for more realistic energy estimation. The threshold is calculated considering the highest number of members being assigned to any cluster using Loose Density Control. The number of cluster members in any cluster in worst case can be computed with careful analysis of LDC based approach. The same worst case member count may be utilized to predict the node survival during a particular round. If the node cannot survive the round as per the Likely to Die Threshold, $LD_{thr}$, it will not be
made member of any cluster during a particular round. Consideration of such nodes will create clusters wherein, few members may die in the beginning of the round itself. So, overall clustering process will be ineffective. TDMA slots of such nodes will also be lost, as the nodes which have expired will not be able to utilize these slots. These TDMA slots may be used by other nodes if the likely to die nodes are avoided from clustering process. To create the clusters where every member survives at least for that particular round, nodes with residual energy less than $LD_{thr}$ should be avoided.

To predict the node death, Likely To Die Threshold is calculated as follows,

$$LD_{thr} = \left( \frac{\text{Round Duration}}{\text{number of CMs} \times \text{slot-size}} \right) \times E_{CMtoCH}^{\text{Average}}$$

(9.1)

Average energy from cluster member to cluster-head is calculated as follows,

$$E_{CMtoCH}^{\text{Average}} = \frac{E_{\text{min}(CMtoCH)} + E_{\text{max}(CMtoCH)}}{2}$$

(9.2)

Round Duration is actually the time period fixed for each round. For example, if we take Round duration to be 20 seconds with slot size 2 seconds and 5 members in the cluster, then $LD_{thr}$ for $X$ Joules of average energy ($E_{CMtoCH}^{\text{Average}}$) can be calculated as,

$$LD_{thr} = \left( \frac{20\text{seconds}}{5 \times 2\text{seconds}} \right) \times X\text{Joule} = 2 \times X\text{Joule}$$

(9.3)

The job of finding the likely to die threshold may be distributed to cluster-heads. As every node receives the cluster formation message in the beginning of setup phase, the same fact may be exploited to determine $LD_{THR}$. Cluster-head finds the minimum number of members and maximum number of nodes in an announced cluster at a particular round. These minimum and maximum member count can be used to find average cluster size. Cluster-head can easily find the energy required by a node to survive one full round. The average cluster size can be used to determine the $LD_{THR}$ as per Equation [9.1] Average energy spent during transmission from CM to CH can be approximated with the unit distance $d_0$.

When Loose Density Control is in place, the $LD_{THR}$ estimations can be more accurate. As the density control is applied, the maximum and minimum member count fluctuates between known upper and lower bounds. This ensures that the estimated average cluster size, closely resembles to actual cluster size. A cluster-head receives the energy information in the last round or it does not receive this
information at all. In the first case, it will compare the node energy with $L_{D_{THR}}$. If it is below $L_{D_{THR}}$, this node is added to the likely to die list. In the second case, the cluster-head simply adds this node to the likely to die list and sends this information to base station in the last TDMA frame of the current round. So base station can use this information that which nodes are to be discarded while applying clustering algorithm.

Nodes learn about the last TDMA slot using the cluster announcement received during setup phase. Nodes are aware that the round time is fixed. After receiving cluster information, nodes can learn the number of member nodes in the cluster and also their TDMA slots. The number of total TDMA slots that are available to the member nodes, depends on the number of nodes in the cluster. This fundamental fact of TDMA technique can be exploited to find the occurrence of last TDMA slot. During last TDMA frame, every alive node will send its energy to the cluster-head, instead of sending data to the cluster-head.

CH discards those nodes with energy below $L_{D_{THR}}$, during average cluster energy calculation. It also discards the nodes from which it did not receive any energy information. This list is shared with base station during the last frame of every round. If base station has made any mistake in predicting energy, this list will help base station in rectifying the same. If a node fails in submitting the energy information during the last frame in a round, it will be eliminated from clustering process from next round onwards.

9.4 Energy Status Collection Delay

The time taken for clustering process and time spent during energy transmission was analyzed for 50, 100, 150 and 200 nodes deployment. Figure 9.7 shows the time consumed by nodes during transmission of energy information to base station. The result shown is the average time taken by 10 different simulation sets for each deployment scenario of 50, 100, 150 and 200 nodes. The time taken for energy transmission is around 16 ms, 38 ms, 74 ms and 118 ms for 50, 100, 150 and 200 nodes respectively. Figure 9.8 shows the time taken by clustering process for various deployment scenarios for different iterations of HSADCP protocol. The time taken for clustering with 100 iterations of HSADCP is about 2 ms for 50 nodes, 4 ms
for 100 nodes, 8 ms for 150 nodes and 16 ms for 200 nodes. When the number of iterations are increased, time required for clustering also increases. But still, the time taken for energy transmission is even larger than 1000 iterations for a particular deployment scenario. For example, simulation of 50 nodes with 1000 iterations took 8 ms time, whereas for the same deployment, energy transmission took almost 16 ms time. From these results, it may be concluded that the time taken for energy transmission is dominating the clustering process time. As the number of nodes increase, the energy transmission time increases linearly with respect to increase in number of nodes. This time delay in setup phase can be completely avoided if energy transmissions are reduced or avoided during setup phase.

### 9.5 HS Based Reduced Broadcast Clustering

The energy collection process from member nodes proves to be time consuming and costly in terms of energy expenditure. This energy information propagation can be completely avoided after the first round using energy prediction with appropriate radio propagation model. The proposed Harmony Search based Reduced Broadcast Clustering Protocol (HRBCP) employs the hybrid approach for clustering process and information collection from the network. There are two types of setup phases in
this approach. During first setup phase, every node sends their location and energy directly to base station. During the subsequent setup phases of the following rounds, the energy information of member nodes is collected via cluster-heads in aggregated form. Figure 9.9 show the progress of the HRBCP which has been proposed. In the last frame of the current round, every node sends energy information instead of data to the cluster-head. During the rest of the frames, member nodes send data to the cluster-head. The startup time required for energy information collection in the beginning of the centralized clustering protocols is eliminated in this approach. The base station discards the nodes with very low energy from repository. It then does clustering using HSADCP approach. Cluster information is announced thereafter. The setup phase and steady state phase of HRBCP is described in the following subsections.
9.5.1 First Setup-Phase

The first setup phase location and energy information collection process is exactly similar to LEACHC protocol. However, the clustering algorithm applied is HSADCP based. It is described in the following steps.

a. Every node sends own location and energy to base station

b. Create clusters using HSADCP based approach

c. Announce the cluster-head nodes and associated cluster-members

d. Cluster-head computes likely to die threshold

e. Steady state phase starts
9.5.2 Regular Setup-Phase

The regular setup phase using energy usage prediction is shown in Figure 9.10. The setup phase is described in the following steps.

a. Base station discards the nodes which were marked as likely to die (if any), by cluster-head in the last frame of previous round.

b. The actual cluster average energy is spread among the nodes proportionately

c. Create clusters using HSADCP based approach

d. Announce the cluster-head nodes and associated cluster-members

e. Cluster-head computes likely to die threshold

f. Steady state phase starts
Centralized clustering protocols expect the energy information from the member nodes in the beginning of the setup phase in most of the cases. For large scale deployments, this may take considerable time and also incur energy expenditure by member nodes. This time overhead for energy information collection is completely avoided in this approach. However, base station does energy prediction and corrections of the same. But the time requirement for this step is significantly lower than the TDMA slots required to send energy information directly to the base station. This strategy also saves considerable amount of energy, which would have been wasted otherwise for sending energy information directly to base station. This approach can be highly beneficial when the base station is located far away from the deployment field.

9.5.3 Steady State Phase

The steady state phase executes fixed number of rounds for a specified period of time as per LEACHC. During all but one TDMA frame, all nodes send data to their cluster-heads. Cluster-heads aggregate the data and send it to the base station for
further processing. During the last TDMA frame of every round, every node sends the residual energy anticipating the cost of the current transmission to the cluster head and goes into sleep mode. As the cluster sizes are uniform and balanced on an average, every CH sends equal amount of information to BS.

Algorithm 8 Steady State Phase

1: for i=1 to $TDMA^n_{frame}$ do
2:   if Node is CH then
3:     if $i < TDMA^n_{frame} - 1$ then
4:       Receive data from Cluster members
5:       Send Aggregated Data to BS
6:   else
7:     Receive Energy information from Cluster members
8:     Find Nodes with Energy $< LD_{THR}$
9:     Calculate Average Energy
10:    Send CH_ACT_AVG_EGY, $LD_{THR}$ list, Energy to BS
11:   end if
12:   else
13:     if $i < TDMA^n_{frame} - 1$ then
14:       Send data to cluster head
15:     else
16:       Send energy information to cluster head
17:     end if
18:   end if
19: end for
20: Get Ready for Setup State

If a node is likely to die in the beginning of the round itself then such nodes are to be avoided so that the cluster formation at BS also can avoid these nodes. Such nodes unnecessarily occupy the TDMA slot which is wasted and CH keeps on waiting for data from these nodes. Such nodes also hamper the algorithm progress, as no activity is there during the TDMA slots assigned to these nodes. $LD_{THR}$ has to be linked with the network size, so that it gives estimated energy requirement for
survival in a round. In LEACH-C and other similar protocols the location/energy announcements does not reach to BS due to many nodes attempting at the same time. Few nodes may fail in transmitting their information to BS, which is avoided in this protocol.

a. CM sends data during designated TDMA slot to CH and CH aggregates the data and sends to base station

b. In the last TDMA frame, CM sends energy information to cluster-head

c. CH sends aggregated energy status (CH_AVG_EGY_ACT) of the cluster, \( LD_{THR} \) list and own energy information to the base station.

d. All the nodes enter into sleep mode till the Cluster formation is announced by the base station.

Algorithm 8 presents the steady state functioning with HRBCP approach. Figure 9.11 shows the steady-state phase of the HRBCP approach.

9.5.4 Cluster-Formation in Setup phase

Base station applies Harmony Search based Auto Density Control approach for clustering process. BS finds the best clusters possible using minimum distance heuristics, actual average energy of the network, predicted energy of individual node and loose density control linked with current network size for grouping of cluster members. Nodes having predicted residual energy more than the actual average energy will be considered as CH candidate.

BS attempts to balance the nodes distribution across the clusters so that there are clusters with close to uniform size. If the grouping is uneven, there will be dense clusters and sparse clusters. In dense clusters, CHs will be required to do excess work compared to CHs of sparse clusters. In sparse clusters, the problem is that, the non-CH nodes continuously transmit data to CH as there are more TDMA frames possible in the same round compared to dense clusters. BS has to wait for more time for the CHs having large sized cluster. This will block the progress of the algorithm and will have effect on the sensing capabilities of the deployed nodes as a region will not be in contact for some time with BS. So algorithm will have overall performance
problem due to asynchronous behavior of the dense and sparse cluster heads and member nodes.

9.5.5 Cluster Announcements

During the cluster information announcement, the cluster-head nodes does an important task that is, identifying the $LD_{THR}$ value. Cluster-heads compute values of $LD_{THR}$ as per the Equation 9.1. This value will keep falling as the number of nodes in the network expire over the time.

a. BS announces the cluster information one by one for every cluster with CH IDs and member node IDs, which is received by all the sensor nodes.

b. After receiving the cluster information, the CH nodes compute the likely to die threshold.

c. CH nodes get ready for the steady-state phase.

d. CM nodes determine their TDMA slots and sleep until the designated time slot.

9.5.6 Estimating Energy Consumption

The location information of CH and CM is already available with base station during the setup phase of every round. BS can estimate the TDMA frame size for every cluster. It can also predict the energy usage of the individual node considering the distance of the individual nodes from CHs. So it will be known to BS by prediction that, how many times a node has transmitted data to CH in a particular round.

- BS estimates individual node energy, $CM_{\text{EST} \_ \text{EGY}}$ and also calculates estimated average energy usage of the cluster $CL_{\text{EST} \_ \text{AVG} \_ \text{EGY}}$.

- The CHs are already receiving the individual nodes energy in the last TDMA frame of the steady state phase. This will help CH in calculating the actual average energy of the cluster, $CL_{\text{ACT} \_ \text{AVG} \_ \text{EGY}}$.

- CHs send this average energy to BS, BS compares the estimated and actual average energy and it spreads the variance to estimated energy of every node with respect to the distance of the node from CH in the particular cluster.
• BS will have the actual average network energy and predicted energy of individual node, those nodes having predicted energy higher than the average network energy will be eligible for CH election process.

Algorithm 9 Cluster-head Energy Usage Predictions

1: Set BW, $\epsilon_{fs}$, $\epsilon_{mp}$, $E_{DA}$, $d_0$.
2: for $j = 0$ to $k$ do
3:   find distance $d$ as $\|CH_j - BS\|$, frame time($ft_j$) and $TDMA_j$.
4:   $ft_j = (|CH_j| + 5) \times$ slot_time
5:   $TDMA_j = Round\_time/ft_j$
6:   if $d < d_0$ then
7:     if $d > 1$ then
8:       $P_t = \epsilon_{fs} \times BW \times d^2$  \(\triangleright\) Free space radio propagation
9:     else
10:        $P_t = \epsilon_{fs} \times BW$
11:     end if
12:    $E_{\text{Round}}^j = TDMA_j \times E_{\text{Packet}} + TDMA_j \times |CH_j| \times (E_{\text{elec}} \times Pkt\_size) + TDMA_j \times E_{DA} \times Pkt\_size$
13:    $E_{\text{Predict}}^j = E_{\text{Residual}}^j - E_{\text{Round}}^j$
14:    $E_{\text{Residual}}^j = E_{\text{Predict}}^j$ \(\triangleright\) Updated residual energy
15:   else
16:     $P_t = \epsilon_{mp} \times BW \times d^4$  \(\triangleright\) Multipath radio propagation
17:     $E_{\text{Round}}^j = TDMA_j \times E_{\text{Packet}} + TDMA_j \times |CH_j| \times (E_{\text{elec}} \times Pkt\_size) + TDMA_j \times E_{DA} \times Pkt\_size$
18:     $E_{\text{Predict}}^j = E_{\text{Residual}}^j - E_{\text{Round}}^j$
19:     $E_{\text{Residual}}^j = E_{\text{Predict}}^j$
20: end if
21: end for

Algorithm 9 shows the cluster-head’s energy usage prediction process. Initially it sets the parameters like bandwidth, free space and multi path propagation amplification parameters, energy used during data aggregation and unit distance. As per the distance between cluster-head and base station, appropriate power requirements
are shown. Here $\|CH_j - BS\|$ represents Euclidian distance between cluster-head $CH_j$ and base station BS. Number of members associated with cluster-head $CH_j$, is represented by $|CH_j|$.

**Algorithm 10** Cluster-member Energy Usage Predictions

1: Set BW, $\epsilon_{fs}$, $\epsilon_{mp}$, $E_{DA}$, $d_0$.
2: for $i = 0$ to $N$ do
3:     for $j = 0$ to $k$ do
4:         if $CM_i \neq CH_j \land CM_i \notin \{LD_{THR}\}$ then
5:             $\triangleright$ This node is CM and alive
6:             find distance d as $\|CH_j - CM_i\|$, frame time($ft_j$) and $TDMA_j$
7:             $ft_j = (|CH_j| + 5) \times \text{slot\_time}$
8:             $TDMA_j = (\text{Round\_time}/ft_j)$
9:             if $d < d_0$ then
10:                 if $d > 1$ then
11:                     $P_t = \epsilon_{fs} \times \text{BW} \times d^2$
12:                 else
13:                     $P_t = \epsilon_{fs} \times \text{BW} \quad \triangleright \epsilon_{fs}$ is minimum amplification factor
14:                 end if
15:             $E_{Round}^j = TDMA_j \times E_{Packet}$
16:             $E_{Predict}^j = E_{Residual}^j - E_{Round}^j$
17:             else
18:                 $P_t = \epsilon_{mp} \times \text{BW} \times d^4$
19:             $E_{Round}^j = TDMA_j \times E_{Packet}$
20:             $E_{Predict}^j = E_{Residual}^j - E_{Round}^j$
21:         end if
22:     end for
23: end for

Per round energy ($E_{Round}^j$), usage by cluster-head $CH_j$ is estimated by finding the number of TDMA slots available to every node in the fixed round time. As every cluster has different number of members, frame time ($ft_j$) will be different for every cluster. $E_{Round}^j$ is composed of three different types of energy consumptions. First
part indicates energy required to transmit an aggregated packet at the end of every frame to base station by cluster-head. \( E_{\text{Packet}} \) is the energy (Joules) consumed during packet transmission. It is computed with the following equation.

\[
E_{\text{Packet}} = \text{Number of bits} \times (P_t + E_{\text{elec}})/bw; \tag{9.4}
\]

Second part considers the energy usage by CH to receive packets during every frame sent by every cluster-member. Third part shows the cost of data aggregation for all possible \( TDMA_j \) frames, during a particular round. Once the estimated energy usage by cluster-head is computed during the round, the residual energy \( E_{\text{Residual}}^j \) of cluster-head is reduced by the estimated energy \( E_{\text{Round}}^j \). This reduction gives the predicted energy \( E_{\text{Predict}}^j \) of the cluster-head during a particular round. The predicted energy becomes the new \( E_{\text{Residual}}^j \) of the cluster-head \( CH_j \).

As the cluster-head is sending its own energy consumption to base station, there is no need to predict the cluster-head energy usage. But as and when nodes start expiring, it may happen that cluster-head fails in sending the message during last frame of the round. The cluster-head energy usage estimation algorithm comes into effect when first dead node is reported. At this time, the base station will apply cluster-head energy estimation algorithm. When base station does not hear from cluster-head, it will discard cluster-head node from repository if the energy estimation is less than or equal to zero. The similar treatment is also given to the cluster-members associated with this cluster-head, which fails in reporting average energy at last frame.

Algorithm 10 shows the cluster members energy usage prediction process. This algorithm also considers the distance between cluster-head and cluster members for energy estimations. Frame time \( ft_j \) and total number of TDMA frames \( TDMA_j \) are calculated. As per the distance between cluster-member and cluster-head the appropriate power requirements are computed. Here \( \|CH_j - CM_i\| \) represents the Euclidian distance between cluster-head \( CH_j \) and cluster member \( CM_i \). Cluster member transmits a packet every time when the designated TDMA slot becomes available to the node. Per round energy usage by cluster members \( E_{\text{Round}}^j \) is calculated accordingly. The residual energy of the cluster member is updated accordingly with the estimated energy used by the cluster-member during the round.

As the energy estimation methods in algorithms 9 and 10 rely purely on the computation, these estimations may not be close to the real energy expenditure. So
these energy estimations are applied with energy correction procedure as shown in Algorithm 11. For the accuracy of energy estimation process, cluster-head is collecting residual energy from all members during the last TDMA frame of the particular round. After collecting residual energy from members, cluster-head sends the actual cluster average energy to the base station, during the last TDMA frame of the current round. Likely to die nodes are marked by CH at this time. This received actual cluster average energy is reflected on to the estimated node energy consumptions, as shown in the the Algorithm 11. The energy correction is applied to the cluster members initially, as the cluster-head is sending its own energy consumption to base station in the last frame of the round. The estimated residual energy of the node is updated as per the distance of the node with cluster-head.

**Algorithm 11 Apply Energy Correction**

1. Set BW, $\epsilon_{fs}$, $\epsilon_{mp}$, $E_{DA}$, $d_0$.
2. for $i = 0$ to $N$ do
3.   for $j = 0$ to $k$ do
4.     if $CM_i \neq CH_j$ then \hspace{1cm} $\triangleright$ This node is CM
5.     find distance $d$ as $\|CH_j - CM_i\|$, frame time($ft_j$) and $TDMA_j$.
6.     $ft_j = (|CH_j| + 5) \times $ slot_time
7.     $TDMA_j = (Round\_time/ft_j)$
8.     if $E_{i,\text{Predict}} \neq 0$ then
9.       if $d > 1$ then
10.      $E_{i,\text{Predict}} = E_{i,\text{Predict}} + (E_{i,\text{Predict}} - E_{j,\text{Cluster\_Avg}}) \times$
11.        \hspace{1cm} $(E_{j,\text{Cluster\_Avg}}/|CH_j|) \times ((E_{j,\text{Cluster\_Avg}} - d)/d^2)$
12.      $E_{i,\text{Residual}} = E_{i,\text{Predict}}$
13.     else
14.      $E_{i,\text{Predict}} = E_{i,\text{Predict}} + (E_{j,\text{Cluster\_Avg}}/|CH_j|) \times (E_{j,\text{Cluster\_Avg}} - d)$
15.      $E_{i,\text{Residual}} = E_{i,\text{Predict}}$
16.     end if
17.   end if
18. end for
9.6 Simulation and Results Analysis

The HRBCP protocol was implemented and simulated in NS 2.34. It was compared with other two protocols, LEACHC and LCE. Tables 9.1 and 9.2 show the setup phase time usage of HRBCP and LEACHC. The dominating time here, is the energy information collection time. The FCMCP takes less time during clustering compared to LEACH-C, but it is still more than the time taken by HRBCP. As the proposed HRBCP approach avoids energy transmissions completely, that time can be utilized for sending more data in unit time.

Table 9.1: HSADCP - Setup Phase Time Analysis

<table>
<thead>
<tr>
<th>HRBCP - Setup Phase Time Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
</tr>
<tr>
<td>Spread (µ sec)</td>
</tr>
<tr>
<td>Predict (µ sec)</td>
</tr>
<tr>
<td>Clustering (µ sec)</td>
</tr>
<tr>
<td>Total (µ sec)</td>
</tr>
</tbody>
</table>

Table 9.2: LEACH-C - Setup Phase Time Analysis

<table>
<thead>
<tr>
<th>LEACHC - Setup Phase Time Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
</tr>
<tr>
<td>Energy Tx (µ sec)</td>
</tr>
<tr>
<td>Clustering (µ sec)</td>
</tr>
<tr>
<td>Total (µ sec)</td>
</tr>
</tbody>
</table>

As shown in Figure 9.12, HRBCP shows controlled variation in members count in the clusters. Figure 9.13 shows that HRBCP achieves significant improvement
in lifetime compared to LEACH-C and LEACH-CE. Tables 9.3 and 9.4 show the alive nodes comparison for the three protocols for two BS locations. The alive nodes snapshot was taken at a particular instance of time during the simulation. When the BS is at center position, more nodes are alive as compared to BS position at (50, 175). CH nodes have to spend more energy in sending data to the BS located at (50, 175) after the end of every frame as compared to centrally located BS. Due to this, the number of alive nodes are falling for the case when BS is at (50, 175). HRBCP is showing linear increment in the number of nodes alive with the rise in number of nodes deployed. However, the other two protocols exhibit inconsistent rise in alive nodes with increased number of nodes. The consistency of HRBCP is due to the auto controlled cluster density during clustering process.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>100nodes</th>
<th>150nodes</th>
<th>200nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEACHC</td>
<td>23</td>
<td>27</td>
<td>51</td>
</tr>
<tr>
<td>LCE</td>
<td>30</td>
<td>28</td>
<td>61</td>
</tr>
<tr>
<td>HRBCP</td>
<td>50</td>
<td>69</td>
<td>112</td>
</tr>
</tbody>
</table>

Table 9.3: HRBCP No. of nodes alive - BS Center


**Figure 9.13: HRBCP Alive Nodes - 200 nodes deployment**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>100nodes</th>
<th>150nodes</th>
<th>200nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEACHC</td>
<td>16</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>LCE</td>
<td>28</td>
<td>21</td>
<td>33</td>
</tr>
<tr>
<td>HRBCP</td>
<td>42</td>
<td>62</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 9.4: HRBCP No. of nodes alive - BS 50,175

Figures 9.14, 9.15, 9.16 and 9.17 show the per node data delivery for various node deployments. HRBCP is showing minimum variance in per node data delivery as compared to other two protocols.

Tables 9.5, 9.6, 9.7 and 9.8 show the data delivery analysis for 50, 100, 150 and 200 nodes deployment respectively. HRBCP shows significant reduction in standard deviation and coefficient of variation for average data among all three protocols.
Figure 9.14: HRBCP Per Node Data Delivery 50 Nodes
Figure 9.15: HRBCP Per Node Data Delivery 100 Nodes
Figure 9.16: HRBCP Per Node Data Delivery 150 Nodes
Figure 9.17: HRBCP Per Node Data Delivery 200 Nodes
As per the simulation results in Tables 9.5 to 9.8, the data delivery observed for the HRBCP approach is higher than LCE. As the energy usage estimations for HRBCP are more accurately computed compared to LCE, the death of nodes are more precisely calculated. This has an indirect effect on clustering process, as likely to die nodes are avoided from becoming members. The TDMA slots which would have been wasted otherwise, are now used by the live nodes. This results in effective clustering, delivering additional amount of data in the same amount of time. So data delivery process is more effective, assuring data reporting in uniform way with Loose Density Control based approach. Due to this, HRBCP shows the maximum average data per node for each deployment. HRBCP delivers more data per unit time as compared to LEACHC and LEACH-CE approaches.

Figures 9.18 to 9.21 show per round standard deviation in data reported by nodes.
Table 9.7: Data Delivery - 150 Nodes with Energy Estimations

<table>
<thead>
<tr>
<th>Protocol</th>
<th>mean(µ)</th>
<th>Stdev(σ)</th>
<th>Cv(σ/µ)%</th>
<th>Max-Min(Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEACHC</td>
<td>530.58</td>
<td>89.45302</td>
<td>16.85948</td>
<td>373</td>
</tr>
<tr>
<td>LCE</td>
<td>533.4667</td>
<td>92.97954</td>
<td>17.42931</td>
<td>544</td>
</tr>
<tr>
<td>HRBCP</td>
<td>535.9933</td>
<td>83.91889</td>
<td>15.6567</td>
<td>325</td>
</tr>
</tbody>
</table>

Table 9.8: Data Delivery - 200 Nodes with Energy Estimations

<table>
<thead>
<tr>
<th>Protocol</th>
<th>mean(µ)</th>
<th>Stdev(σ)</th>
<th>Cv(σ/µ)%</th>
<th>Max-Min(Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEACHC</td>
<td>407.08</td>
<td>64.09925</td>
<td>15.74611</td>
<td>287</td>
</tr>
<tr>
<td>LCE</td>
<td>409.25</td>
<td>66.15344</td>
<td>16.16455</td>
<td>301</td>
</tr>
<tr>
<td>HRBCP</td>
<td>407.88</td>
<td>56.45632</td>
<td>13.8414</td>
<td>238</td>
</tr>
</tbody>
</table>
Figure 9.18: HRBCP Per Round Standard Deviation in Data - 50 Nodes

Figure 9.19: HRBCP Per Round Standard Deviation in Data - 100 Nodes
Figure 9.20: HRBCP Per Round Standard Deviation in Data - 150 Nodes

Figure 9.21: HRBCP Per Round Standard Deviation in Data - 200 Nodes
for different network sizes from 50 to 200 nodes. HRBCP shows controlled variation in per round data delivery by every node as compared to HSACP. As HRBCP applies auto density control approach, the number of nodes assigned to every cluster remains in control and does not vary much. Due to this, HRBCP shows less variation in per round standard deviation in data reported by every node in the network.

Figures 9.22, 9.23 and 9.24 show per node data delivery with time for LEACH, LCE and HRBCP respectively. It is observed that HRBCP consistently delivers data from every node during the lifetime of the network. However, LEACHC and LCE exhibits significant variation in the data delivery and number of alive nodes during the lifetime of the network.

To observe the effect of BS location on the energy consumption during setup phase, BS was placed far away from the field at (75, 600). The energy consumption
Figure 9.24: Data per Node over time - HRBCP

Figure 9.25: HRBCP Setup Phase Energy Consumption
during setup phase is compared for two BS positions, center and (75, 600). The energy usage during setup phase is shown in Figure 9.25. When the BS is located in center, HSADCP shows 0.7 to 0.8 Joules extra energy usage as compared to HRBCP. But when the BS is far away, HSADCP shows four times more energy usage than HRBCP. This sudden rise in energy usage is due to the energy collection happening in setup phase of every round. HRBCP does this only once during the first setup phase. That is why the energy consumption is less during setup phase of HRBCP.

9.7 Summary

Centralized clustering protocols expect the energy information from the member nodes in the beginning of the setup phase in most of the cases. For large scale deployments, this may take considerable time and drains energy of the member nodes. This overhead of energy information collection is completely avoided in proposed HRBCP approach except the first round. However, base station does energy prediction and correction of the same. But the time requirement for this step is significantly lower than the TDMA slots required to send energy information directly to the base station. Loose Density Control based approach when integrated with energy usage estimations using likely to die threshold creates more effective clusters. It helps in improving the quality and amount of data delivered to the base station via cluster-heads. This strategy also saves considerable amount of energy which would have been wasted otherwise, for sending energy information directly to base station. This approach can be highly beneficial when the base station is located far away from the deployment field.