An algorithm for energy driven cluster head rotation in a distributed wireless sensor network

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An Algorithm for Energy Driven Cluster Head Rotation in a Distributed Wireless Sensor Network

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***Abstract*— Wireless sensor networks (WSNs) consists of large number of inexpensive, low-power, sensors that can be placed in an ad hoc fashion to form a communication network. Efficient techniques for inter sensor communication and information gathering is critical for prolonging the lifetime of the sensor network. Clustering provides an effective way for extending the lifetime of a sensor network. In this paper we propose a distributed and energy driven clustering algorithm where the cluster heads are selected based on relative residual energy level of sensors. Furthermore the cluster head candidacy selection phase, and the cluster head candidacy rotation among phases is triggered only when any of cluster heads energy drops below a dynamic threshold computed by the algorithm. As a result, the overheads in the inter sensor communications will be reduced and thereby the proposed algorithm will favor more powerful nodes over the weaker ones to prolong the lifetime of the entire sensor network in both homogeneous and heterogeneous sensor networks. The results have shown that the the proposed algorithm performs better when compared to existing algorithms such as LEACH, SEP, HEED and ANTCLUST based on the Percentage Node Alive (PNA) and the First Node Dies (FND) metrics.**

I. Introduction

Recent development in inexpensive and low power micro sensor technology, radio communication electronics and processors have led to mass production of sensor motes [1]. These motes are less reliable and less accurate compared to their high end macro sensor counterparts. However their reliability and usefulness can be improved using data aggregation techniques based on sensor clusters. This has led to the development of WSNs with hundreds to thousands of nodes per sensor bed. These type of sensor networks are used in military applications, hazard environment monitoring and wildlife tracking to name a few. Such applications have two characteristics that we will concentrate on. Namely the random distributed placement of such sensors and the low power availability per node. In such applications once the sensors are deployed they cannot be retrieved, as a result it is difficult to recharge or replace the batteries of these motes. Furthermore, the Radio communication consumes most of the energy of a sensor. Therefore energy efficient communication and data gathering mechanisms are key issues that have to be considered for the successful deployment of such networks in practice.

Clustering based node organization has been the primary method used to ensure energy efficient communication in WSNs. Each cluster thus created will have a cluster head (CH) to coordinate further communication with other similar CHs. Hence a communication hierarchy is formed where local data aggregation is coordinated by each CH within its cluster and the global data aggregation is carried out by all CHs between clusters. Several algorithms that have shown varying degree of success at prolonging the lifetime of the sensor network have been developed. LEACH algorithm [2]- [3] has proposed an algorithm that selects a certain percentage of nodes randomly to become CHs in homogeneous sensor networks. SEP [4] extends the LEACH by adding a small percentage of high energy nodes other than the normal nodes in the network. HEED [6] periodically rotates CHs according to the hybrid of their residual energy and a secondary parameter such as node degree. The energy-efficient clustering method proposed in ANTCLUST [5] is based on the ant model of colonial closure to solve clustering problems. ACE [7] is an emergent algorithm to produce uniform clusters. In all of the above algorithms, the common factor is that the CH rotation mechanism is time driven rather than event driven. That is, the role of CH will be changed after a predetermined number of data gathering rounds.

The LEACH and SEP algorithms have problems with forming well distributed CHs and also has FND/PNA performance issues for heterogeneous energy sensor networks. ANTCLUST assumes that nodes know their location either using GPS or some form of localization technique. Such an assumption is suitable for location based information gathering systems and less applicable to low cost ad hoc sensor networks. HEED has a significant amount of overhead compared to the other algorithms. However HEED can be used in multi-hop networks. EDAC [8] is an improvement over LEACH in heterogeneous networks. EDAC also uses an energy driven CH rotation methodology. However EDAC also has a similar problem found in LEACH where the cluster heads are not uniformly distributed.

In this paper we present the Energy Driven Cluster-Head Rotation (EDCR) protocol which addresses some of the issues related to other algorithms. The proposed algorithm uses the idea of initiating a CH rotation based on an energy driven event instead of predetermine time driven idea of LEACH, SEP, HEED and ANTCLUST. Furthermore the algorithm uses localized communication within a limited neighborhood to select the node which has the most residual energy to become the CH, thus resulting in very low communication overheads during the selection phase of the algorithm. Furthermore, as the results will indicate, this has allowed the formation of well distributed CHs in the system similar to the ones found in HEED and ANTCLUST. Further, the reduction in energy consumption of a node is achieved by initiating this localized communication protocol only at the point of CH rotation. This is the key factor that has lead to reducing the overheads compared to other algorithms. Furthermore EDCR has the characteristic features of an emergent algorithm as defined in the ACE where local communication is used to achieve a predictable global effect.

The paper is organized in the following manner. In Section II we discuss the preliminary details related to the sensor network model, energy consumption model of a sensor and the assumptions related to the lifetime of the network. In Section III we discuss the salient features of the proposed algorithm. In Section IV we present the simulation results in a comparative form for several algorithms including the proposed EDCR algorithm. In Section V we give our conclusions and proposed future work.

II. Sensor Network Model

The preliminary assumptions used to model the sensor network are as follows.

A. Assumptions

1. All nodes have the equal processing and communication capabilities.
2. Base Station (BS) has the ability to guide the existing CH operation asynchronously.
3. TDMA scheduled data transmission from normal nodes to its CH.
4. Symmetric radio communication model.
5. Nodes have the capability of adjusting the transmission power.
6. The required transmitting power is calculated based on the received signal strength.
7. Sensor nodes are uniform randomly distributed in a rectangular region.
8. Sensor nodes can aggregate or fuse multiple data into a single-size data.

However we have relaxed the following two assumptions used in most of the previous literature.

1. Homogeneous energy of nodes.
2. Location awareness of nodes.

B. Energy Consumption Model

We use the same energy consumption model used by the ANTCLUST algorithm. This model assumes free space transmission. Furthermore in this model a sensor node consumes E_{elec} (nJ/bit) energy at the transmitter or receiver circuitry and ϵ_{amp} (pJ/bit/m^2) energy at the transmitter amplifier. A sensor node expends energy $E_{Tx}(\ell, d)$ or $E_{Rx}(\ell)$ in transmitting or receiving a ℓ bit message to or from distance d respectively. These can be computed using equations (1) and (2).

$$E_{Tx}(\ell, d) = E_{elec} \times \ell + \epsilon_{amp} \times \ell \times d^2 \quad (1)$$

$$E_{Rx}(\ell) = E_{elec} \times \ell \quad (2)$$

Furthermore a CH node consumes E_{DA} (nJ/bit/message) energy in aggregating multiple sensor data.

C. Life Time of the Sensor Network

The definition of the life time of a sensor network depends on the application where the sensors are deployed. There are three commonly used definitions in the literature [6], [9].

- *First Node Dies (FND)*: This definition is appropriate in situations where death of a single node deteriorates the quality of the network. E.g. Intrusion Detection systems.

- *Percentage of Nodes Alive (PNA)*: Time until a certain percentage of nodes are still alive. This definition is more appropriate for most of the applications with a requirement for a certain percentage of nodes alive for the network to output credible information. Here we assume that some of the sensors are producing correlated data so that some amount of redundancies are built into the network. For example measuring of environmental parameters in hard to reach places. The half of the Nodes Alive (HNA) metric is a special case of this.

- *Last Node Dies (LND)*: Though this parameter can be considered as a way to measure the lifetime of a sensor network its practical applicability is very limited.

The goal of any good self organizing sensor network protocol is to increase the life time of all sensors in the network. As shown in Fig 1, the ideal situation is represented when all sensors die at the same time. Thereafter a new set of sensors can be deployed without replacing some of them. In general, ad hoc sensor networks are deployed in areas where the sensors are hard to reach after deployment. Hence selective sensor replacement is not practical. Typically aerial dumping of sensor nodes in the interested area sets up such a sensor network. Hence in this paper we use the PNA and FND metrics to measure performance of the sensor network. In the case of PNA we have assumed 95% of nodes alive which balances the quality of the information gathered and the correlation between the information gathered by the sensor nodes in the network. In other words, a shift of the knee point of graph to right while maintaining a right angle at the knee point is our ultimate objective.

D. Objectives

Now we outline the base objectives of our algorithm.

1. A node joins a closest CH with most residual energy using local information.
2. A node initiates the CH rotation algorithm if one of the existing CHs find that it does not have enough energy to continue its role.
3. The CHs should be well distributed.

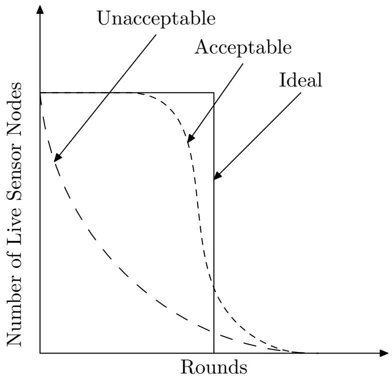

Fig. 1. Number of Live Sensor Nodes at the End of Each Round

Collectively we aim to achieve the sensor network lifetime to follow the ideal situation as shown in Fig 1.

III. Overview of the Algorithm

A. Cluster Head Candidacy

All sensor nodes initially consider themselves as potential candidates of being a CH. However a sensor node with more residual energy has a chance to advertise its candidacy earlier than others within a neighborhood of R. Those sensor nodes that receive an advertisement from any other sensor node will abandon their quest to become a CH. This ensures that a node with a higher residual energy always ends up being a CH within its neighborhood R.

Assume that the CH advertisement phase is limited to a time interval of T time units and that the sensor node i announces its candidacy within a radius of R at a time instance T_i given by (3)

$$T_i = T(1 - P_i) + k_i. \quad (3)$$

Here k_i is a random time unit introduced to reduce the possibility of collisions among sensor node advertisements with identical P_i, and $P_i \in [0, 1]$ represents the relative position of the node i with respect to the other nodes in its neighborhood in terms of its residual energy level. In other words, the node i with the highest residual energy would be assigned the largest value of P_i in a given neighborhood R. Hence from (3), this node will have a T_i which is the smallest in the neighborhood resulting in it being chosen as the CH. Furthermore, the initial conditions that apply to (3) are different for homogeneous and heterogeneous sensor networks.

1) Homogeneous sensor network: For the initial round $P_i = 1$ is assumed $\forall\ i$ since all sensors are considered to be equiped with similar batteries and hence equal in residual energy. Then $T_i = k_i$ from (3). For all subsequent rounds $P_i \leq 1\ \forall\ i$ and the sensor node with the smallest T_i found using (3) will broadcast its CH candidacy.

2) Heterogeneous sensor network: For heterogeneous sensor networks we assume that the initial state will also have $P_i \leq 1\ \forall\ i$ and same as for each subsequent rounds. This is a direct result of the sensor network having dissimilar residual energies at deployment or the algorithm is applied to an already existing sensor network.

Calculation of P_i for different rounds is given in Section III-D paragraph 3. The neighborhood R is computed assuming that the sensor network will consist of an optimum number of clusters k_{opt} as discussed in [2]. For each node j, the set of sensor nodes within a neighborhood of radius μ from j is denoted by $\mathcal{N}_j^{\mu}$. Furthermore we define a set $\mathcal{H}$ where

$$\mathcal{H} = \{i|\ \text{set of all nodes } i \text{ where node } i \text{ is a CH}\}$$

Observation:– For any node i with $j \in \mathcal{N}_i^R$ we have $T_i < T_j \implies E_{\text{res}_i} > E_{\text{res}_j}$. Where E_{res_i} and E_{res_j} are the residual energies of nodes i and j.

B. Cluster Head Selection

Any node j which is not already a CH will select its CH CH_j using (4).

$$CH_j = \left\{ i \,\middle|\, \max_{i \in \mathcal{H} \cap \mathcal{N}_j^R} D_{i,j} \right\} \quad (4)$$

where

$$D_{i,j} = E_{\text{res}_i} \cdot \frac{P_{Rx_{i,j}}}{P_{Tx_i}}. \quad (5)$$

Here $P_{Rx_{i,j}}$ and P_{Tx_i} represents the received signal power from node i to node j and the transmitted power of the advertisement message for node i respectively. The CH advertisement message will contain both E_{res_i} and P_{Tx_i} which will be used in (4). Furthermore, $D_{i,j}$ will achieve the following:

1. E_{res_i} will allow us to select nodes with higher residual energy over nodes with lower residual energy. For example if we have CH nodes at an equal distance from j, the factor $\frac{P_{Rx_i}}{P_{Tx_i}}$ will be constant. Hence the dominating factor would be E_{res_i}, and as a result the higher energy node will be selected. This will prolong the weaker CH nodes' network lifetime since now the high energy node has taken the burden of processing an additional node.
2. $\frac{P_{Rx_{i,j}}}{P_{Tx_i}}$ allows us to select the closet node which will help to reduce the energy consumption of node j. For example if we have CH nodes' that have equal E_{res_i} but are placed at unequal distances from j, the CH node which is closer will be selected. This will prolong the lifetime of sensor node j since the node j will be using lesser power P_{Tx_j} to reach the CH in all subsequent communications. Furthermore since
$$P_{Rx_{i,j}} \propto \frac{P_{Tx_i}}{d^{\gamma}}.$$
The resulting $D_{i,j}$ can be used with any communication model. γ is a real number. $\gamma = 2$ for the free space model.

The combination of the above facts will ensure that effectively prolong the life time of the entire sensor network.

Furthermore the CH node i calculates a dynamic threshold λ_i based on the present residual energy condition of the network at the time it broadcasts its CH Candidacy and it is defined by $\lambda_i = c.E_{\text{res}_i}$ where $c \in [0, 1]$ is a predetermined constant. The use of such a threshold to generate an event driven CH rotation will be explained in Section III-D. The choice of c is dependent on the topology (size of the network, location of base station and number of sensor nodes) of the sensor network. However we have found that $c \approx 0.7$ provides good results for the sensor bed used in our simulations. The following general rules can be observed when estimating the value for c.

1. If c is chosen arbitrarily high, it will result in frequent CH rotations. This will lead to high overhead which will result in reducing the life time of sensors.
2. If c is chosen arbitrarily low, the CH sensors would not have enough energy to carry out duties as a regular sensor once the CH role is relinquished. This will also lead to drop in the lifetime of the sensor network.

Subsequently a CH j calculates its TDMA schedule and broadcasts it to all the sensor nodes i where $i \in \mathcal{N}_j^R$. Apart from the slots allocated for each node i in the neighborhood $\mathcal{N}_j^R$, the TDMA schedule will have a time slot reserved for the CH to send any messages to its members if any. This slot will also be used to send control information if any. In a normal data gathering round this slot will not carry any communication and will not generate overheads that will expend energy. However, the CH will use this time slot to update its members at the time of a CH rotation.

C. Data Transmission

The next phase of the algorithm is data transmission where the nodes go into normal routine operation of periodic data gathering. Non CH nodes sends their data in the allotted time slot according to the TDMA schedule to the CH. The CH uses a data fusion algorithm to merge the received data before sending the data to the BS. During this period we avoid exchanging unnecessary information such as updates of residual energy to neighbors and also updates of state information to BS. These communication exchanges will only occur at the time of CH rotation which is completely event driven in comparison to existing algorithms. Hence our algorithm has less overheads in communication.

D. Cluster Head Rotation

When a CH node i finds its residual energy falling below the threshold value λ_i, it triggers a new CH candidacy event by informing the BS that it is unable to perform its duties as a CH any more. Subsequently the BS will inform this to all other CHs thus initiating a CH rotation phase. Note that most of the previous Energy Aware Sensor Network Clustering algorithms (LEACH, HEAD, SEP, ANTCLUST, etc.) have a predetermined time point to initiate a CH rotation phase. Then all CHs use their immediate next chance in the TDMA slot to communicate this fact to its neighborhood, and further request nodes to send their residual energy along with the data in its allotted slot.

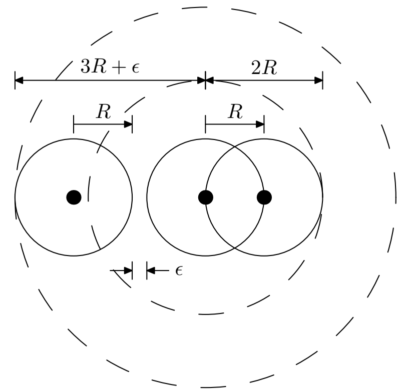

Fig. 2. Second Degree Neighborhood

A CH i computes the maximum residual energy component in its neighborhood using

$$E_{\text{res}_i,\max} = \max_{j \in \mathcal{N}i_i^R} \left\{ E_{\text{res}_j} \right\}.$$

It will then broadcast this information to all nodes $j \in \mathcal{H} \cap \mathcal{N}_i^{2R+\epsilon}$. Here ϵ is a small positive number which represents a degree of uncertainty when computing the distance to neighbor CHs. Furthermore $2R + \epsilon$ would be the maximum expected distance from one CH to its closest neighbor CH as seen from Fig 2. Based on this CH i can get access to the maximum residual energy information of its second degree neighborhood $\mathcal{SN}_i$. where

$$\mathcal{SN}_i = \left\{ j \,\middle|\, j \in \cup_{k \in \mathcal{H} \cap \mathcal{N}_i^{2R+\epsilon}} \mathcal{N}_k^R \right\}$$

This $\mathcal{SN}_i$ can extend up to $3R + \epsilon$ in any direction to the CH i. Then the CH i updates its member base with the highest available residual energy level of its $\mathcal{SN}_i$ in the immediate next TDMA slot and triggers a cluster formation phase.

The use of $\mathcal{SN}_i$ information to derive the relative energy position P_i of a node i is more meaningful since it will dispel any ambiguity when it comes to nodes at a border of two clusters. Furthermore it guarantees that a given node will know its residual energy level with respect to its immediate neighborhood or even further. The relative residual energy level is computed using

$$P_i = \frac{E_{\text{res}_i}}{E_{\text{res}_i,\text{sup}}}, \tag{6}$$

where

$$E_{\text{res}_i,\text{sup}} = \max_{j \in \mathcal{H} \cap \mathcal{N}_i^{2R+\epsilon}} \left\{ E_{\text{res}_i,\max} \right\}. \tag{7}$$

The next step would be to initiate a CH candidacy phase as explained previously.

E. Algorithm Pseudo Code

Setup()
if Initial round **then**
  Compute P_i using immediate neighbor information.
end if
CH Candidacy()

if $T_i < T$ **then**
  Compute T_i from (3)
  if based on T_i its your turn **then**
    Broadcast Candidacy to nodes in $\mathcal{N}_i^R$
  end if
else if Hear Message from j with $i \in \mathcal{N}_j^R$ **then**
  Abandon quest to be CH
  Identify all reachable CHs based on received CH candidacy messages
end if
CH Selection and join()
if $i \notin \mathcal{H}$ **then**
  identify the most cost effective CH
  Send a join request message to it
else if $i \in \mathcal{H}$ **then**
  Collect all the join requests
  Prepare the TDMA schedule and Broadcast to members
end if
CH Rotation()
if $i \in \mathcal{H}$ and $E_{\text{res}_i} < \lambda_i$ **then**
  Request BS for a CH change
end if
if BS request a CH Change **then**
  Find the $E_{\text{res}_i,\text{sup}}$ from (7)
  Initiate a CH selection phase
end if

IV. Simulation Experiments

To evaluate the effectiveness of the proposed algorithm we choose the following cases:

Case 1: Homogeneous Network of 200 nodes each with 0.5J energy randomly dispersed in a 100×100 region with BS located at (50,50).

Case 2: Homogeneous Network of 200 nodes each with 0.5J energy randomly dispersed in a 100×100 region with BS located at (50,150).

Case 3: Heterogeneous Network of 200 nodes with energies 0.3J to 0.8J (randomly assigned) randomly dispersed in a 100×100 region with BS located at (50,50).

Case 4: Heterogeneous Network of 200 nodes with energies 0.3J to 0.8J (randomly assigned) randomly dispersed in a 100×100 region with BS located at (50,150).

We set E_{elec} at 50 nJ/bit, ϵ_{amp} at 100 pJ/bit/m^2 and E_{DA} at 5 nJ/bit/message. Advertisement or setup packets were chosen 60 bits in length and normal data packets were chosen to be 2000 bits long. These values have been chosen to consistent with [2] and [5].

For simulation purposes we set LEACH as having on average 5% nodes as CHs. EDCR and ANTCLUST is assumed to have a Broadcasting Radius of 25m and 37m respectively for scenario where BS was at (50,50) and (50,150). Additionally for the ANTCLUST algorithm we have assumed 10% as social nodes having a broadcast radius of 15m and 18m for base station locations (50,50) and (50,150) respectively. In computing λ_i we have assumed $c = 0.7$.

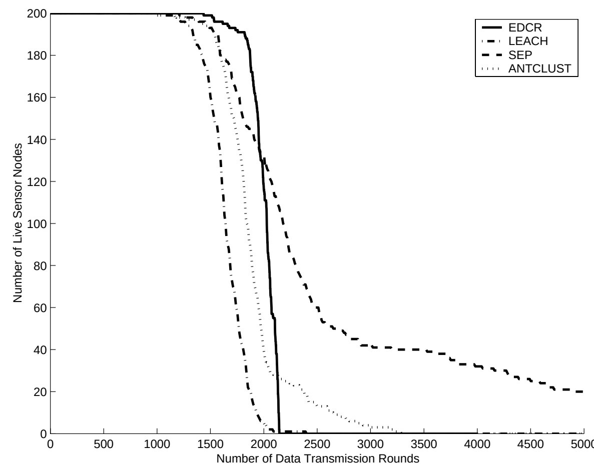

Fig. 3. Number of Live Nodes vs. Data Transmission Rounds for Case 1

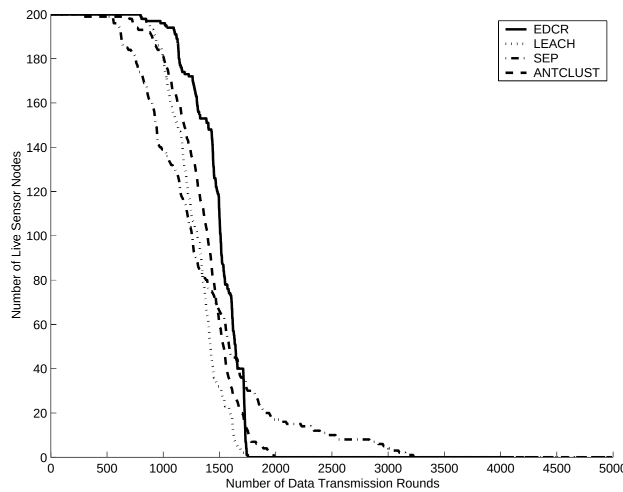

Fig. 4. Number of Live Nodes vs. Data Transmission Rounds for Case 2

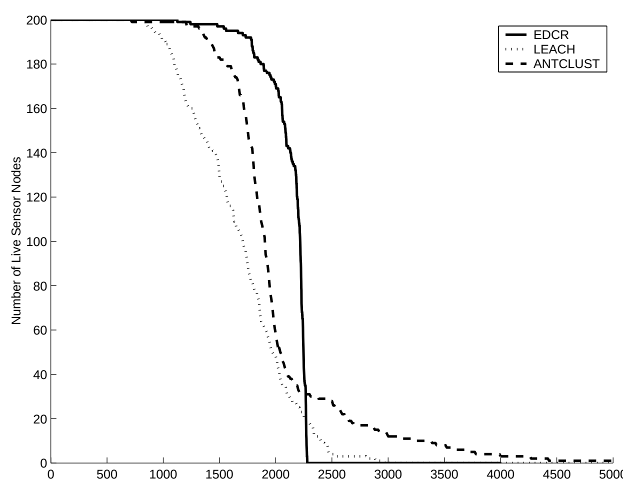

Fig. 5. Number of Live Nodes vs. Data Transmission Rounds for Case 3

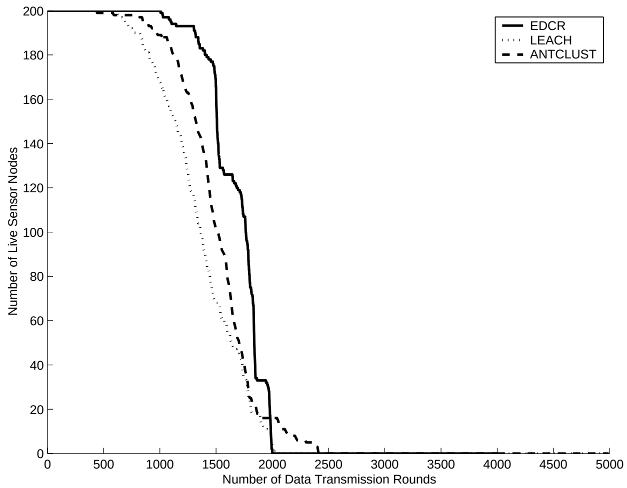

Fig. 6. Number of Live Nodes vs. Data Transmission Rounds for Case 4

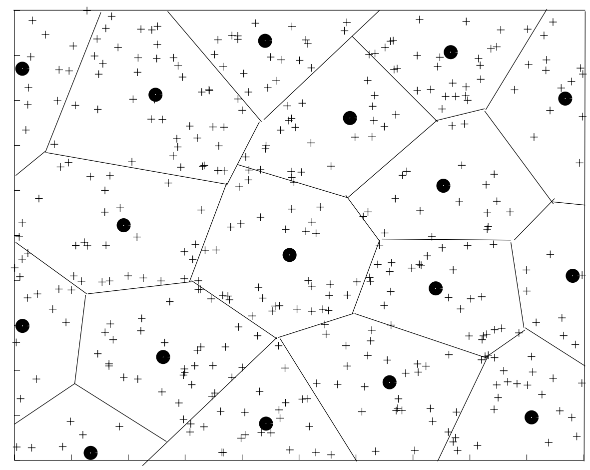

Fig. 7. Distribution of Clusters and CH Positions

The simulation results for homogeneous as well as heterogeneous networks shown in Fig 3 to Fig 6 shows that the proposed EDCR algorithm performs better with respect to the performance metrics FND and PNA (with 95% nodes alive) when compared to algorithms such as LEACH, ANTCLUST and SEP in homogeneous network scenarios.

Remark:– Note that SEP algorithm assumes two types of energy nodes. Hence it cannot be considered in a strict homogeneous network. On the other hand it cannot be also considered in a heterogeneous network where random energies are assigned to nodes. To overcome this issue we have considered SEP in a homogeneous network where some nodes are assumed to have 20% nodes having 4 times (0.5J× 4 = 2J) extra energy. AS results indicate even under these conditions EDCR outperforms SEP.

Furthermore, it is seen that the simulations for EDCR algorithm consistently compares with the ideal situation shown in Fig 1 for both homogeneous and heterogeneous networks. This indicates that the EDCR algorithm is capable of retaining all nodes for a far longer period and die rapidly than other algorithms as a result of it being energy efficient. The performance enhancement is obtained as a result of EDCR preferring to use high energy nodes as CHs than low energy nodes hence balancing the residual energy of all nodes thus equally prolonging the life time of all nodes in the sensor network.

The results in Fig 7 indicate that the EDCR algorithm gives well distributed CHs. This is a direct result of using (3) and using a $\mathcal{SN}_i$ to compute P_i for each round.

V. Conclusion and Future Work

In this paper we have presented a new algorithm that uses the residual energy of sensor nodes for selection and rotation of CHs. The algorithm uses local information up to the second degree neighborhood in order to make these decisions. The algorithm is event driven during the CH rotation phase which ensures that the resulting operation is energy efficient. The CH selection mechanism which is based on network topology has ensured that high energy nodes are favored over weaker ones which results in extending the useful lifetime the entire sensor network.

The investigation of the performance of the EDCR algorithm in hierarchical multi-hop network will be a useful addition to the work proposed in this paper.

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