Energy Efficient Clustering and Data Aggregation in Wireless Sensor Networks

Surender Kumar Soni

Abstract—Wireless Sensor Networks (WSNs) are wireless networks consisting of number of tiny, low cost and low power sensor nodes to monitor various physical phenomena like temperature, pressure, vibration, landslide detection, presence of any object, etc. The major limitation in these networks is the use of non-rechargeable battery having limited power supply. The main cause of energy consumption WSN is communication subsystem. This paper presents an efficient grid formation/clustering strategy known as Grid based level Clustering and Aggregation of Data (GCAD). The proposed clustering strategy is simple and scalable that uses low duty cycle approach to keep non-CH nodes into sleep mode thus reducing energy consumption. Simulation results demonstrate that our proposed GCAD protocol performs better in various performance metrics.

Keywords—Ad hoc network, Cluster, Grid base clustering, Wireless sensor network.

I. INTRODUCTION

IN wireless sensor networks (WSNs), sensors are expected to be deployed randomly in the area of interest by relatively uncontrolled means, e.g. dropped by a helicopter, and to collectively form a network in an ad hoc manner [5]-[8]. Given the vast area to be covered, the short life span of the battery operated sensors and the possibility of having damaged nodes during deployment, large population of sensors are expected in most WSNs applications. Clustering has always been a basic method to organize large number of objects into suitable groups in many fields of science and engineering. Every cluster/group would have a leader, often referred to as the cluster head (CH). A CH may be elected by the sensors in a cluster or preassigned by the network designer. Generally CH is a node that is richer in resources. It can localize the route within the cluster and thus reduce the size of the routing table stored at the individual node [1].

Clustering can also conserve communication bandwidth since it limits the scope of inter-cluster interactions to CHs and avoids redundant exchange of messages among sensor nodes [2]. Sensors would care only for connecting with their CHs and would not be affected by changes at the level of inter-CH tier [9]. The CH can also implement optimized management strategies to further enhance the network operation and prolong the battery life of the individual sensors and the network lifetime [2], [6]. A CH can schedule activities

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in the cluster so that nodes can switch to the low-power sleep mode most of the times and reduce the rate of energy consumption. Furthermore, a CH can aggregate the data collected by the sensors in its cluster and thus decrease the number of relayed packets [11], [29], [30].

In this paper we proposed a technique called Grid based Clustering and Aggregation of Data (GCAD), the sensor field has been partitioned into equal sized grid like small clusters and each cluster is monitored and controlled by a node called cluster head (CH). These CHs can communicate directly with the base station (BS) in a single hop or through other CHs to form multi hop routing of data to the BS. The sensor nodes (SN) within a cluster sense the environment and forward the sensed data to their CH. The CH first aggregates the data received from all the sensor nodes within the cluster and then finally forwards it directly or through other CH to the base station/sink. Since the CH has to collect the data, perform data aggregation and has to involve in long distance transmission as compared to normal sensor nodes, therefore its energy is depleting at faster rate than the other nodes within the cluster. The roll of the CH, therefore, is changed whenever its energy falls below threshold value and can be assigned to other node within a cluster which is more powerful and closer to the centroid of the cluster. Some virtual CHs are also selected to avoid frequent execution of CH election process. The performance of GCAD compared with other existing protocols. Results demonstrate that our protocol behaves better in terms of overall network lifetime, network latency and energy consumption than the existing protocols.

Rest of the paper is summarized as follows. Section II describes the work related to clustering and aggregation of data. Proposed protocol has been explained in Section III. Section IV defines various simulation parameters, performance metrics and explains simulation results. Section V explains the conclusion of the work.

II. RELATED WORK

Clustering algorithms in the literature vary in their objectives [22]-[24]. Nagpal and Coore [25] propose CLUBS, an algorithm that forms clusters with a maximum of two hops through local broadcast and converge in a time proportional to the local density of nodes. Random competition based clustering (RCC) [26] is developed for scenario where few nodes act as backbone nodes or cluster heads and the whole subnet is formed around them. M. Demirbas et al. propose a distributed technique known as Fast Local Clustering service

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:7, No:5, 2013

(FLOC) [27] which produces clusters of approximately equal size with minimum overlap. Low Energy Adaptive Clustering Hierarchy (LEACH) [28] is one of early energy efficient and most popular clustering algorithms for WSNs. It has some main properties; self-organizing, adaptive clustering, evenly distributes load among the sensors, dynamically forms clusters, randomly rotates cluster heads after each round, cluster-heads directly communicate data with the base station and application-specific data processing, such as data aggregation. LEACH has two phases: setup phase and steady state phase.

III. PROPOSED PROTOCOL

In this section we have described our proposed protocol called Grid based Clustering and Aggregation of Data (GCAD). The main objective is to prolong network lifetime via energy efficient data aggregation protocol that employs grid based clustering and maintains the energy balance among all involved sensor nodes. The sensor field has been partitioned into equal sized grid like small clusters. All sensor nodes are aware of their location either by using GPS or any other localizing method [16], [17]. Each cluster is monitored and controlled by a node called cluster head (CH) [11]. These CHs communicate through other CHs to form multi hop routing of data to the BS. For the first round, CHs are formed on the basis of their distance from the center of the cluster. The SN that becomes the CH advertises itself to other nodes within cluster and to the BS by broadcasting a message. Each CH also creates a time division multiple access (TDMA) table for its cluster. Using TDMA table, CH schedules the data transmission of sensor nodes and also allows sensor nodes to turn off their antennas after their time slot to go to sleep mode and save their energy. A CDMA schedule is assigned to all CHs to perform inter-cluster communication and to communicate with the BS [18]. CH node being much more energy intensive than a non-CH node, the role of being a CH is rotated once its energy falls below some threshold level among the nodes within the cluster in order to balance the load. The strength of GCAD is in its CH rotation mechanism and data aggregation. Whenever the residual energy of CH falls below threshold level, CH announces CH election message. The node with more residual energy and closer to the centroid of the grid is the new CH. Some virtual CHs are also selected to avoid frequent election mechanism.

A. System Model

In this paper, we assume that set of homogeneous sensor nodes are randomly deployed in the square field to continuously monitor the phenomenon under inspection [12]-[15]. The location of the sensors and the base station are set and known apriori. All sensing nodes deployed in the sensing area are assumed to be static and have the knowledge of their location. It is assumed that localization process is carried out just after the deployment of sensor nodes. Nodes are left unattended after deployment; therefore, battery recharge is not possible. Efficient, energy-aware sensor network protocols are thus required for energy conservation. All nodes have similar capabilities and equal significance. This motivates the need for extending the lifetime of every sensor. Each sensor produces some information as it monitors its surrounding area. We suppose that the whole network is separated into a number of clusters; each cluster has a cluster head (CH). We also assume that after the formation of cluster, nodes use power control to tune the amount of transmit power according to the transmission distance. It is assumed that the transmitter electronics of all sensor nodes is capable of transmitting the data with two types of radio ranges: low power broadcast range $r_1 = r/2$ meters and high power range of $r_2 = r$ meters, where r is the maximum transmission range of a node. Low power broadcast range r_1 is used for intra-cluster communication between a sensor node and cluster head. The maximum diagonal distance of any cluster is assumed to be r/2 meters, so that even if a node is located at the diagonal vertex of a cluster, it may be selected as cluster head, and data connectivity is still maintained between the sensor nodes and cluster head within the cluster. High power broadcast range r_2 is used by cluster head node to transmit data either to next hop cluster head or to the sink node, in case the sink node is at a distance of one hop from the cluster head. The proposed model ensures that two neighboring cluster heads are always at maximum distance of less than r from each other, so that connectivity is always maintained between such nodes. Data sensing and data gathering operation of sensor network is divided into rounds. In each round, the, sensor nodes sense the desired variable of interest e.g. temperature, pressure, etc. around its periphery within the sensing area. The sensed data is converted into digital data of k bits length and transmitter electronics sends the data to its designated cluster head within the cluster. We assume that there is perfect MAC layer in the network, i.e. transmission scheduling is so perfect that there is no collision and retransmission. Initially the network is assumed to be well connected. For intra-luster communication, TDMA scheduling is assumed to avoid any collision among the data transmitted by various sensor nodes [18], [19]. It is assumed that in each cluster TDMA schedule is managed by cluster head for its own cluster members. As the data from various sensor nodes arrive at the cluster head, it performs data aggregation or data fusion over the arrived data as per the nature of sensed data to reduce the transmission overhead. The cluster head transmits the aggregated/fused data to its next hop cluster head towards sink node. To avoid the collision of inter-cluster data; BS/sink assigns CDMA scheduling to all CH. CDMA scheme avoids collision of inter-cluster data by assigning different codes for each cluster head within the sensing area.
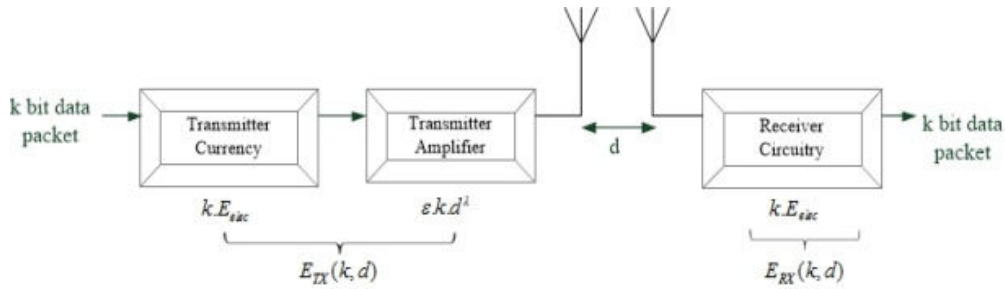
World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:7, No:5, 2013

Fig. 1 Energy Model for Wireless Sensor Network

B. Energy Model

Generalized energy model based on first order radio energy consumption is used for calculation of energy consumption for sensor nodes within the sensing area. The energy/radio propagation model (path loss model) for wireless sensor node is illustrated in Fig. 1. The energy consumption of all nodes is computed. As in [20] the energy consumed for transmission of *k* bits of data over a *d* distance is computed by:

$$E_{Tx}(k,d) = E_{elect\text{-}Tx}(k) + E_{Tx\text{-}amp}(k,d)$$

$$E_{Tx}(k,d) = \begin{cases} k*E_{elec} + k*\varepsilon_{fs}*d^2 & \text{if } d \leq d_0 \\ k*E_{elec} + k*\varepsilon_{mp}*d^4 & \text{if } d \geq d_0 \end{cases} \quad (1)$$

The energy consumption for receiving *k* bits of data is computed by:

$$E_{Rx}(k,d) = E_{elect\text{-}Rx}(k) = k.E_{elec} \quad (2)$$

$E_{elect\text{-}Tx}$ is transmission electronics energy; which is energy consumed by the sensor node for modulation, coding, spreading schemes, filtering operations, etc. $E_{amp\text{-}Tx}(k,d)$ is the power amplifier stage energy consumption of sensor node to transmit k bits of data over a distance of d meter with acceptable signal to noise ratio (SNR). k is the number of bits transmitted over a distance d (distance between transmitter and receiver). E_{elect} (nJ/bit) is energy dissipation per bit to run transmitter and receiver electronic circuitry. ε_{fs} (pJ/(bit-m-2)) is energy coefficient of power amplifier stage of sensor node for free space energy dissipation model, when transmission distance is less than threshold i.e. $d < d_0$. ε_{mp} (pJ/(bit-m-4)) is energy coefficient of power amplifier stage of sensor node for multipath energy dissipation model, when transmission distance is greater than threshold i.e. $d \geq d_0$.

Also energy consumption of data aggregation of CHs is:

$$E_{DA} = 5 \text{nJ/bit/msg}$$

C. Cluster Formation

Cluster formation deals with division of sensor field into suitable size grids. By dividing the entire sensor network into small clusters for easy management, and by putting redundant sensor nodes in particular cluster into sleep mode, the overall energy of the WSN can be conserved. Clustering schemes are promising for wireless sensor networks due to their good scalability and energy conservation potentials. By using geographic coordinates for clustering and routing, grid-based schemes are particularly popular due to their simplicity [3]. However, one problem in grid-based clustering is how to determine a suitable grid size. Significant energy savings can be achieved when more nodes are put into sleep mode. Therefore, a larger cluster is preferable if the coverage and connectivity are still maintained. On the other hand, airborne radio transmissions are attenuated by a path loss factor scaling with the distance in a greater-than-linear fashion, and the total transmission energy can be reduced by dividing a long distance transmission into several shorter ones [4]. The problem is how to determine the optimal transmission range or grid size for energy efficiency, i.e., using the lower amount of energy for data transmission while still allowing many nodes to go to sleep mode.
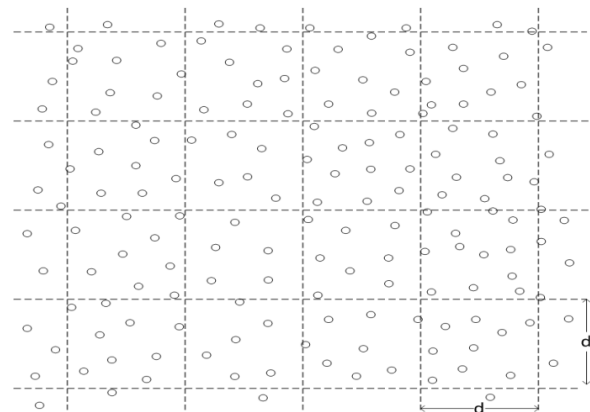

Fig. 2 Formation of Virtual Grids

In our proposed clustering method, location information is used to divide the WSN into virtual grids. Each cluster is a square of grid size d × d as shown in Fig. 2. In the proposed strategy, grid side d is a key factor to the grid formation as given in Fig. 3. For reliable communication, it is to ensure that any two nodes in adjacent grids are within transmission range, r, of each other.

By investigating the worst case scenario, the grid side d should be such that the maximum distance between two nodes

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:7, No:5, 2013

placed at the corner of two diagonally adjacent grids given as l $=\sqrt{(2d)^2+(2d)^2}=2\sqrt{2}d$ must be less than or equal to r. To ensure one hop communication among the nodes between adjacent grids, l should be less than or equal to maximum transmission range (r), i.e., $2\sqrt{2}\,d \leq r$. Hence, $d = r / 2\sqrt{2}$. If d is set to $r/2\sqrt{2}$, all sensors in a grid can communicate to one another in one hop.

For transmission distance r, the side length

$$d \leq r / 2\sqrt{2}$$

Each grid has grid ID [G_x, G_y]. For a node with coordinates (x, y), the grid ID is computed as follows:

$$G_x = \left\lfloor \frac{x}{d} \right\rfloor \quad G_y = \left\lfloor \frac{y}{d} \right\rfloor \tag{3}$$

where $\lfloor k \rfloor$ is largest integer less than k.
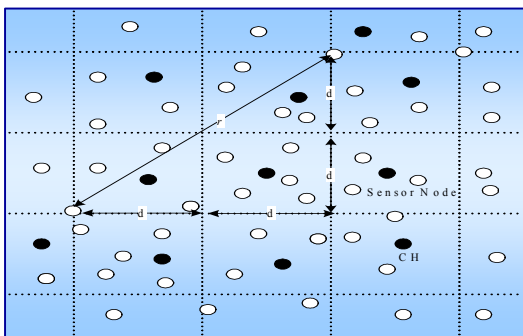

Fig. 3 Formation of Virtual Grids

D. Cluster Head Selection

After dividing the sensor field into equally sized grid like clusters, one cluster head will be selected in each cluster and is responsible for data routing and aggregation. These cluster heads can directly or through other CHs communicate with the base station. Within cluster nodes send the sensed data to CH. CH first aggregates the data from the multiple sensor nodes, and then sends it towards the base station. Hence the cluster head should be powerful in term of its energy and closer to the cluster centroid since the SN nearest to gravity center (centroid) of the cluster ensures least average energy consumption for intra-cluster communications. So a CH can simply act as a relay for the traffic generated by the sensors in its cluster and perform aggregation/fusion of collected sensors data. Sometime, a CH acts as a sink or a base station that takes actions based on the detected phenomena or targets. CHs can be pre-assigned or elected from the deployed set of nodes. In GCAD, concept of backoff timer has been used to select the cluster head where all the nodes compete for this position by setting a backoff timer according to their distance from the center of its grid.

For a node n_i, the backoff timer t_i is set as

$$t_i = \frac{d_i}{r / 4} T_{chs} V_r \tag{4}$$

where, d_i is the distance of n_i from the center of its grid, r is the maximum transmission range of a node, T_{chs} is the time allocated for the first round grid head selection, V_r is a random number whose value is in the range [0.9, 1]

The BS calculates the distance of each node to its cluster centroid. The lesser the distance, the higher the probability that the node will become CH. The maximum distance from the center of a grid to a boundary node is r/4, so the ratio $\frac{d_i}{r/4}$ falls within (0, 1). For a node n_i, if the backoff timer t_i expires and it does not receive any CH declaration message from any other node, it declares itself as a cluster head by broadcasting a message.

E. Medium Access Control

Several MAC protocol for wireless sensor networks have been proposed in the literature. Most of them implement a low duty-cycle scheme for power management [5]. In TDMA based MAC protocols [10]-[21] time is divided in frames and each frame consists of a certain number of time slots. Every node is assigned to one or more slots per frame, according to certain scheduling algorithm, and uses such slots for transmitting/receiving packets to/from other nodes. In our work, TDMA (Time Division Multiple Access) scheme is used which enables a duty-cycle on sensor nodes as channel access is done on a slot-by-slot basis. As nodes need to turn on their radio only during their own slots, the energy consumption is ideally reduced to the minimum required for transmitting/receiving data.

Once the information about members is recorded with the CH, it generates a TDMA schedule and packages it in a message. Then the CH broadcasts its schedule to the cluster members. Each node follows the schedule to transmit the sensed data to the concerned CH. Once the clusters are created and the TDMA schedule is fixed, data transmission can begin. Assuming nodes always have data to send, they send it during their allocated transmission time to the cluster head. The radio of each normal node can be turned off until the node's allocated transmission time, thus minimizing energy dissipation in these nodes. The cluster head node must keep its receiver on to receive all the data from the nodes in the cluster. All the sensor nodes remain in sleep mode most of the times. They wake up according to the schedule implemented, thus leading to lower energy consumption When data from all the nodes has received, the cluster head performs aggregation/fusion to compress the data into a single packet. BS prepares a CDMA schedule for each CH for inter-cluster (CH-CH/BS) communication to avoid collision between inter-cluster and intra-cluster communication.

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:7, No:5, 2013

F. Cluster Head Rotation

Cluster head election rotates the role of cluster head among various nodes in a cluster by making constant adaption to the node energy level. Most of the existing protocols follow the static norm based on time and remaining energy. CH rotation also consumes energy, so it should not be much frequent. On the other hand, assigning the role of CH for longer period will deplete its energy at faster rate thus leading to a partition/hole problem in the network. So in order to balance the load among all the sensor nodes it is essential to interchange the role of CH.

In GCAD, if residual energy E_r of a current CH falls below the given threshold value E_t, the CH declares the cluster head election. Each node having its residual energy greater than E_t participates in the election process by sending E_r value and d_i value (distance from the center of the grid) to the current CH. The CH computes a candidacy factor CF_i for each node n_i as

$$CF_i = \frac{d_i}{E_r} \qquad (5)$$

A node with minimum value of CF_i is elected as next CH. This indicates that the SN nearest to gravity center (centroid) of the cluster and having more residual energy is the next CH. SN nearest to the centroid ensures least average energy consumption for intra-cluster communications while the reduction of CH overhead is not guaranteed. Since election of CH consumes energy therefore in GCAD in addition to the election of CH, some virtual cluster heads (VCHs) in the order of decreasing CF_i value are also elected. From the simulation results the optimal value of three virtual cluster heads has been obtained, thereafter the performance degrades.

Theorem 1: If the numbers of nodes are lower than frequency of rotation is lower.

Proof: CH rotation takes place when its residual energy E_r of current CH falls below threshold value E_t. If the numbers of nodes are lower than the overall traffic from SNs within a cluster to the CH is low which results in lower number of data aggregation operations and workload due to inter-cluster communication will be lower which further results in less number of transmissions from CH to the BS/sink. As a result of which the energy consumption of CH take place at a lower rate and it takes longer time for the residual energy of a node to fall below threshold level. Hence the frequency of CH rotation is low.

Theorem 2: No headship rotation takes place in the time the sensor network is inactive.

Proof: In case of no event happening inside a sensor field, majority of times normal sensor nodes may go to sleep mode. In sleep mode, the energy consumption of node is almost negligible. Also the overall traffic from SNs within a cluster to the CH is low which results in lower number of data aggregation operations and workload due to inter-cluster communication will be lower which further results in less number of transmissions from CH to the BS/sink. Therefore it takes very long time for the residual energy E_r of CH to falls

below threshold value E_t. Hence no headship rotation takes place in the time the sensor network is inactive.

G. Data Aggregation and Routing

Ordinary sensor nodes sense the data and deliver to their CH using one hop routing. Each CH first collects the data from its members (ordinary nodes) with one hop routing and aggregates them. Then CH sends the aggregated packet to the BS via multi hop communication.

CH in a particular grid selects the next hop CH out of its 8-neighbours based on greedy strategy. A cluster head CH_i selects its next hop CH_j, such that CH_j has the least distance from the BS/sink. In general the distance between CH_p and CH_q is given as

$$d_{pq} = \max(|x_p - x_q|, |y_p - y_q|) \qquad (6)$$

Thus, by selecting a CH which is nearer to the BS/sink as the next hop node, the overall distance (number of hops) to the BS/sink are reduced.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of proposed GCAD algorithm by simulating in MATLAB. We first define simulation parameters, performance metrics used and scenarios created. We then see the effect of various factors like transmission range, number of nodes and network size on performance metrics to measure the effectiveness of proposed algorithm.

A. Simulation Parameters

We consider a flat and square sized two dimensional sensor field of size 100m×100m in which SNs are randomly deployed. All nodes are homogeneous. Various simulation parameters are listed in Table I.

B. Performance Metrics

1. Network Lifetime

Network lifetime of wireless sensor network is the time span from the deployment to the instant the network works and is able to achieve its objectives. During our simulation, we have used the following parameters to measure network lifetime:
(a) FND: number of rounds after which first node dies.
(b) HND: number of rounds after which 50% nodes die.

2. Energy Consumption

It is energy consumption per round for the operation of whole network. i.e. energy consumed by a set of nodes is the total sum of energy spent by those nodes in performing required network operations (i.e. sensing, transmission, reception and idle state) during one complete round.

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:7, No:5, 2013

TABLE I
SIMULATION PARAMETER

Parameter	Default Value	RanSge
Network size	$(100 \times 100)m^2$	$(50 \times 50) \sim (400 \times 400)m^2$
Number of nodes	400	100~500
Transmission range (r)	100m	20~140m
Sink location	(0, 0)	
Initial Energy of node	2 Joule	
Data packet size	100 byte	
E_{elect}	50 nJ/bit	
ε_{fs}	10 pJ/bit/m^2	
ε_{amp}	0.00134 pJ/bit/m^4	
Data aggregation (E_{DA})	5 nJ/bit/signal	

C. Simulation Results

System model, clustering and data dissemination method described in Section III *C* are used for transmitting the sensed data from SNs to BS/sink through CHs. Different network scenarios are created and energy savings achieved are evaluated for each scenario at overall network level. At cluster level, energy consumed by all active SNs in sensor field is summed up. Similarly at CHs level, energy consumed by designated CHs is summed.

Following basic scenarios are created:

1. Effect of Transmission Range on Network Lifetime

We define network lifetime as the time until a fraction of sensor nodes run out of energy. Figs. 4 and 5 show the results of network lifetime as a function of transmission range of sensor node. Fig. 4 gives the variation of network lifetime calculated in terms of FND and Fig. 5 indicates the variation of network lifetime obtained in terms of HND.

From the Figs. 4 and 5, it is observed that when the transmission range of node is small, the WSN is divided into large number of smaller grids because the grid size is directly related to the transmission range of sensor node.

Therefore the average number of hops for the sensed data to reach the BS/sink increases which results in more consumption of energy. As a result of which the number of rounds for the first node to die and half nodes to die are less. With the increase in transmission range, the grid size increases which decrease average number of hops for the sensed data to reach the BS/sink. Also in a large grid, more redundant nodes can be put to sleep mode. Because of these two factors the energy consumption decreases and the number of rounds for the first node to die and half the nodes to die increase. At this stage, an optimal transmission range is achieved.

If the range continues to increase, the data communications are subject to d^4 attenuation and the energy consumption associated with transmission increases super linearly with the radio range, so the total energy consumption grows exponentially with node separation which results in the decrease in network lifetime. From the simulation it has been observed that the transmission range of node should be between 110m to 130m in order to optimize the network lifetime. Results of GCAD are better than Zhuang et al. because in Zhuang et al., cluster heads are elected after every

round so the frequency of head rotation is quite high. Moreover in Zhuang et al., all the nodes participate in cluster head re-election process irrespective of their current residual energy, whereas in GCAD only those nodes having current residual energy greater than some.

Fig. 4 Effect of Transmission Range on FND

If the range continues to increase, the data communications are subject to d^4 attenuation and the energy consumption associated with transmission increases super linearly with the radio range, so the total energy consumption grows exponentially with node separation which results in the decrease in network lifetime. From the simulation it has been observed that the transmission range of node should be between 110m to 130m in order to optimize the network lifetime. Results of GCAD are better than Zhuang et al. because in Zhuang et al., cluster heads are elected after every round so the frequency of head rotation is quite high. Moreover in Zhuang et al., all the nodes participate in cluster head re-election process irrespective of their current residual energy, whereas in GCAD only those nodes having current residual energy greater than some threshold value are allowed to take part in cluster head re-election process.
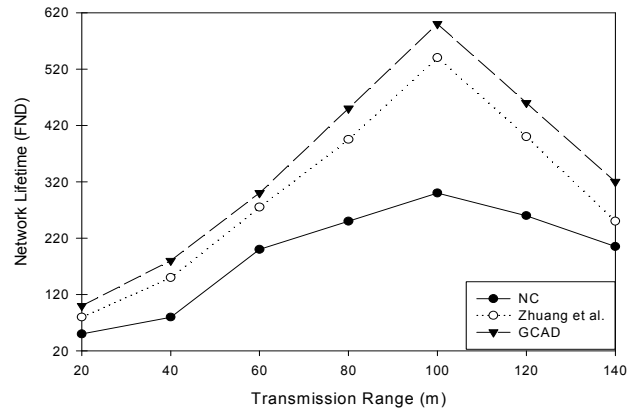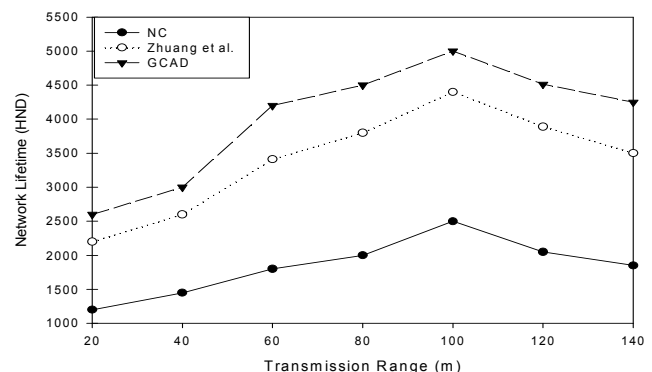

Fig. 5 Effect of Transmission Range on HND

Both GCAD and Zhuang et al. results are better than no clustering (NC) approach. In NC approach all sensor nodes transmit data continuously without going into sleep mode therefore consume more energy. Also in NC approach,

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:7, No:5, 2013

aggregation of data does not take place and data collected by all sensor nodes is transmitted to BS/sink. This requires more number of transmissions.

V. CONCLUSION

A Grid based Clustering and Aggregation of Data (GCAD) for supporting efficient data sensing and forwarding has been developed. GCAD organizes sensor nodes into clusters and puts nodes not involved in forwarding into sleep mode. The proposed grid based clustering strategy is simple and scalable that uses low duty cycle approach to keep non-CH nodes into sleep mode thus reducing energy consumption. An optimal grid size has been considered that leads to minimum energy consumption. Election of virtual CHs reduces the overhead of CH rotation and thus increases the energy efficiency. Simulation results demonstrate that our proposed GCAD protocol performs better in various performance metrics than grid based approach proposed by Zhuang et al. [4] and the naïve approach having no clustering (NC).

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