A Parallel Paths Communication Technique for Energy Efficient Wireless Sensor Networks

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Abstract. A wireless sensor network is a network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions. As sensor networks are large in scale, grouping techniques are required to tackle their scalability issues. The limited energy reserves of the autonomous devices require grouping techniques to be energy-aware and strive to extend the life time of the network. In this paper we propose an energy efficient group communication technique that aims at reducing the energy drain of the group leader nodes and the network as a whole. In our method we introduce a technique for energy efficient packet transfer and define methods to reduce the communication hot-spots in the network. Through the proposed method, we achieve around twenty five percent savings in energy consumption when compared to LEACH method for communication.

Keywords: Wireless Networks, Clustering methods, Energy efficiency.

1 Introduction

Sensor networks are dense collections of small wireless nodes capable of gathering and disseminating physical data about its environment. Sensor networks have a dense deployment topology and are capable of sensing or monitoring remote locations [1, 2]. Sensor networks are usually comprised of nodes that are characterized by limited and finite energy resources. Sensor nodes use wireless communication links to co-ordinate with each other and they are usually low on processing capabilities. Energy consumption is a major factor that determines the life time of the sensor network as the network is driven by nodes of limited and finite energy resources [3]. This makes energy optimization an imperative step in each and every aspect of design and operation of the network.

Hierarchical group based communication paradigms are being proposed to solve the scalability issues in wireless sensor networks [8, 9]. In this paradigm of communication, a set of nodes from the group of sensor nodes deployed in the terrain are chosen as group leaders and the rest of the sensor nodes are assigned to one of these group leaders that satisfy node assignment criteria like node proximity, node energy and node density etc. It has been observed that these group leaders suffer from rapid energy

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drainage and as a consequence, these nodes eventually fall out completely in their energy reserves. This can be attributed to the fact that each group leader handles data from more number of group leaders. Also there is non-uniformity in the number of the group leaders that each group leader is communicating. This non-uniformity in group leader communication topology leads to non-uniform energy loss patterns across the group leader nodes.

Low Energy Adaptive Clustering Hierarchy (LEACH) [8] is a cluster-based protocol that employs randomized rotation of local cluster base stations (cluster-heads) to evenly distribute the energy load among the sensors in the network. LEACH uses localized coordination to enable scalability and robustness for dynamic networks. It incorporates data fusion into the routing protocol to reduce the amount of information that must be transmitted to the base station and is therefore able to distribute energy dissipation evenly throughout the sensors.

Hierarchical Energy-Aware Protocol (HEAP) is an energy efficient and fault tolerant algorithm for routing in wireless sensor networks. The HEAP protocol constructs a hierarchical tree over the sensor network topology and maintains the energy distribution across the nodes by restructuring the hierarchical tree over time. The periodic restructuring of the data path through the communication trees minimizes the effect of bottleneck energy failures.

The cluster heads are responsible for coordination among nodes in the cluster and communication with other cluster heads. The degree of connectivity between the cluster heads is a factor that contributes to communication bottle necks in the sensor network topology. As each group leader is communicating with large number of neighboring group leaders, there is need for larger energy resources to handle the traffic. As energy is consumed for each bit that is transmitted and received, increasing the load on the group leader dissipates its energy resources quickly. It will be worthwhile to limit degree of connectivity between the group leader nodes to minimize the energy utilization of these nodes.

The figures 1 and 2 depict the group leader communication topologies for a wireless sensor network. From the figure 1, it can be seen that the group leader nodes B will be handling the incoming data from two of its children nodes. A direct consequence of the communication setup seen in figure 1 is that more energy is spent by the nodes B in handling data from its children. One solution to alleviate the network communication hot-spots is to untie the congestion areas in the communication topology of the sensor network group leaders. The main idea behind this technique is to limit the number of links between group leaders and arranging the links in a parallelized manner so that data flows efficiently from source to sink. As a result of such paralleling, it was seen that the energy depletion of the sensor network was reduced in comparison to other conventional methods of clustering.

The contribution of this paper is the development and characterization of a *Parallel path cluster communication technique* that partitions the sensor network into manageable groups and sets up communication links within and across groups. It is established in this paper that by using this parallel path cluster communication technique, the energy consumption of the group leader nodes are minimized and at the same time bounded within a deterministic range.

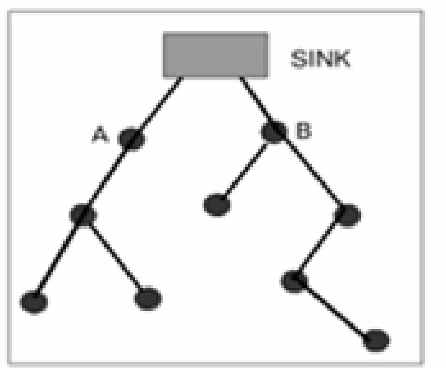

Fig. 1. Conventional cluster head communication

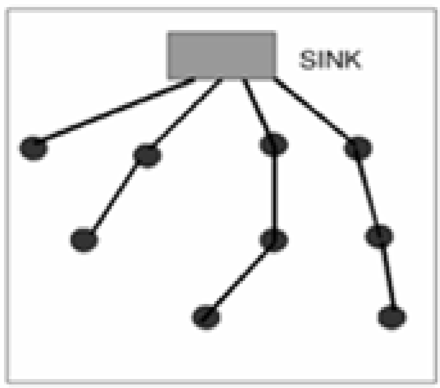

Fig. 2. Parallel path communication technique

2 Network Model and Problem Definition

The sensor communication network comprising of N nodes, distributed in a random manner inside a square area A can be modeled as an undirected unit disk graph $G = (V, E)$ in which V is the set of N vertices and E is the set of M edges. A wireless sensor network is modeled as unit disk graphs under the assumption that each sensor node has a defined range of broadcast reception. A set of N unit disks in the plane can represented by an N node graph, when every node corresponds to a unit disk and there is an edge between two nodes if the corresponding unit disks intersect or tangent [7]. Using the unit disk graph modeling technique, each vertex in the graph represents a sensor node and each edge represents the communication link between two sensor nodes. There exists an edge (u,v) if the two vertices u and v are within either's communication range. The communication range is defined by transmission and reception strength of the sensor nodes. We assume that all the transmitters employ the same transmit power level P. Also there is a single sink node located arbitrarily inside the square region A.

It is assumed that the sensor nodes are stationary throughout the functioning of the network. The sensor network topology can be visualized as a composition of gradient bands starting from the sink node and ending at the topological boundaries of the terrain. The level or gradient of a node can be interpreted as the depth of each node in the network topology starting from the sink node. As the dimension of the network topology is larger than the transmission radius of the sensor nodes, we visualize the sensor topology to be arranged in gradients based on transmission radius. The network topology is divided into k gradient bands and a set of nodes N_i are available in each of the band such that

$$\sum_{i=1}^{k} N_i = N \tag{1}$$

If the average Euclidean distance from the sink to the nodes in a particular gradient band is denoted by d_i and $d_{(i,s)}$ is the distance of an individual i to sink s, then gradient bands are numbered in increasing order starting from the sink node such that

$$d_1 < d_2 < d_3 < \ldots < d_k. \text{ where } d_i = \sum d_{(i,s)} / N_i \tag{2}$$

A general sensor network partitioning method can be described as partitioning the network into C independent subsets $c_1, c_2, c_3, \ldots, c_k$ so that

$$N = c_1 \cup c_2 \cup c_3, \ldots, \cup c_k \text{ with } c_i \cap c_j = \varnothing \text{ ; } |c_i| != \varnothing \text{ and } |c_j| != \varnothing \text{ for any } i \neq j.$$

The first problem that is addressed in this paper is the task of identifying C group leader nodes among the set of N sensor nodes and arranging them in the network so that,

$$|g_1| + |g_2| + |g_3| + \ldots + |g_k| = C, \text{with } C < N \tag{3}$$

where g_i is a set of group leaders in gradient level i. The group leader selection procedure will ensure that the $|g_1| >= |g_2| >= |g_3| >= \ldots >= |g_k|$. The nodes in the gradient level d_1 are involved the selection of the group leader set g_1 and likewise for the other group leader sets g_2 through g_k.

The second problem addressed in this paper is the task of connecting the group leaders across the adjacent gradient bands and assigning of ordinary nodes to the elected group leaders. The node assignment problem is the task of assigning individual ordinary nodes n_i to the group leader nodes g_i, such that each node n_i is connected to exactly one group leader node g_i. The group leader connectivity degree $D(g_i)$ of a group leader node g_i is defined as the number of communication links that the group leader has with adjacent group leaders in the neighboring gradient bands. The setting of the communication topology across the group leaders takes place such that $D(g_i) <= 2$ for any i.

Let g_i^k denote the group leader node i in level k and (u,v) represent a link between u and v, then our communication setup method results in a communication topology that has $(g_i^k, g_j^k) = \varnothing$ for any i and j. There no more than one link established in the gradient level above and below the current gradient level.

To model the radio communication energy consumption, we use a first order radio model in which the radio dissipates E_{Elec} to run the transceiver circuitry and E_{Amp} for the transmitter amplifier to achieve a desired signal to noise ratio. We will use this following energy model in our energy analysis section to find the worst case energy consumption of the proposed algorithm. To transmit a B bit message over a distance of $D_{Euclidean}$, the radio circuitry in the sensor nodes expend $E_{Tx}(B, D_{Euclidean})$ and $E_{Rx}(B, D_{Eculidean})$ for transmission and reception respectively. Since transmission requires both the radio and amplifier circuitry, we have

$$E_{Tx}(B, D_{Euclidean}) = E_{Tx\text{-}Elec}(B) + E_{Tx\text{-}Amp}(B, D_{Euclidean}) = E_{Elec} * B + E_{Amp} * B * D_{Euclidean} * D_{Euclidean} \quad (4)$$

However, for the reception for radio signals, we have only the electronic components that are used and thus we have $E_{Rx}(B, D_{Eculidean}) = E_{Rx\text{-}Elec}(B) = E_{Elec} * B$.

3 A Parallel Path Communication Technique

Sensor networks are characterized by large scale deployment of sensor nodes capable of sensing and network management. The sensor nodes sense physical data about the environment like temperature changes, humidity levels, seismic activity etc. The sensor nodes also possess capabilities to self organize and form a communication network. This paper explores the methods of self organizing and network setup in an aim to achieve prolonged network lifetime.

3.1 Algorithm Description

The algorithm assumes that sensor nodes are stationary from the start of the algorithm to the end of the algorithm. The algorithm comprises of three phases namely the initialization phase, the grouping phase and communication network setup phase.

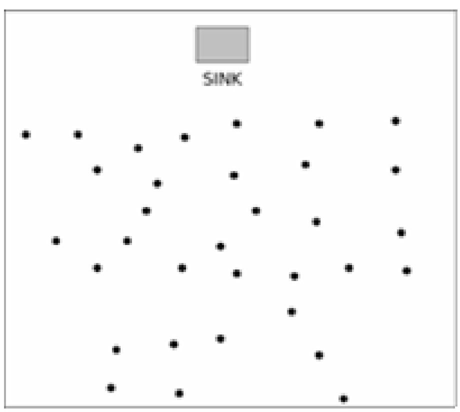

Fig. 3. Network Topology during start

3.2 Forming Gradient Bands

In this phase of the algorithm, the sensor network topology is divided in to gradient bands based on the distance d_i from the sink. The nodes closer to the sink d_i are in a

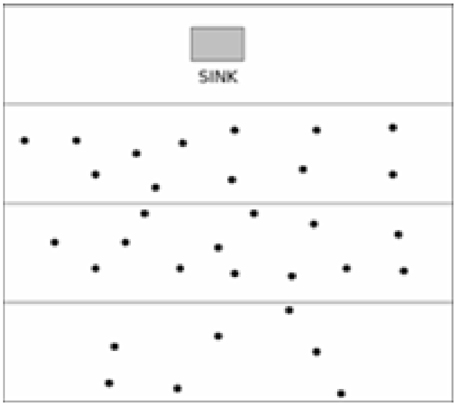

Fig. 4. Division of topology into gradients

higher gradient band than the nodes that are farther away from the sink d_{i+1}. In each gradient band i, there are set of nodes n_i and from this set of nodes, g_i group leaders will be selected.

3.3 Group Leader Election

This phase comprises of the identification of group leaders in each gradient band and assignment of ordinary nodes to the selected group leaders. From the previous initialization phase, we have the network topology that is divided in bands. The objective of this phase is to select a determined number of group leaders for each gradient band. . The group leader selection procedure will ensure that the $|g_1| >= |g_2| >= |g_3| >= ... >= |g_k|$. This is done to ensure that there are maximum number of group leaders near the sink and lesser number of group leaders as we move away from the sink.

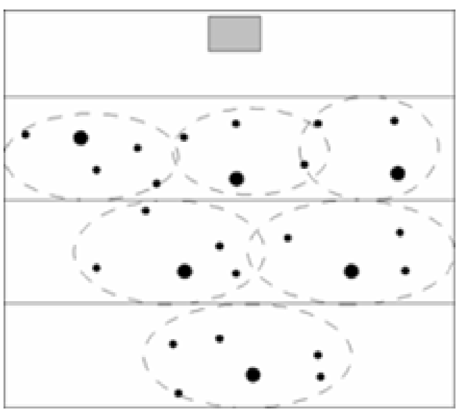

Fig. 5. Selection of group leaders in each gradient band

Once the group leaders are identified in each band the ordinary nodes in each band are assigned to a group leader based on weighing factor of distance and node density in the group. It is not necessary that a node gets assigned to only the group leaders in that level. If the weighing factor is satisfied for group leaders in adjacent bands, assignment to these group leaders can also be done. This will help in uniform node density distribution for the groups. If this relaxation is not made then the nodes in the farthest band from the sink will have very large number of cluster members and this might lead to uneven loading of the groups.

3.4 Communication Network Setup Phase

After the grouping phase is completed, the algorithm then proceeds to the set up the inter-cluster and intra-cluster communication topology. In this setup, each ordinary node will communicate with its respective group leader. And each group leader will handle the data from its own cluster and the data that originate form a single group leader in a lower gradient band. As a result each group leader will handle the data of two groups at the maximum. To setup the communication links the group leaders in each band will select a suitable parent from the higher gradient band. As there is more number of parents available for selection in higher gradients, the decision is based on a weighing factor of the Euclidean distance between the group leaders and the balance energy level. The group leader that has a higher weight is chosen as its parent. Once a leader has locked in its parent, the parent group leader looses the ability to compete for parenthood of other group leaders. The remaining group leaders in the band compete for the remaining parent group leaders. The setting of the communication topology across the group leaders takes place such that degree of connectivity $D(g_i)$ of the group leader node g_i follows the requirement $D(g_i) <= 2$.

From this communication topology, it is can be seen that there will be no bottle necks and the traffic takes a streamlined path from source to the destination sink. Also as there are a determinate number of children for each group leader, the energy dissipation for group leader is more or less uniform. This results in a uniform energy resource drain, unlike the erratic and rapid energy dissipation seen in other grouping mechanisms.

4 Properties of the Parallel Path Technique

We now study the group leader election procedure adopted in our proposed method. Considering the sensor network of N nodes deployed in a square region A, the nodes in the terrain are split into sets of nodes located within differing gradients from the sink node. The sink node can be placed arbitrarily in the square region A. If N_i is the set of nodes in a gradient level i and C_i is the set of group leaders that are selected from the set N_i, the algorithm selects the C_i such that number of group leaders in level i is always greater than the number of group leaders in level $i+1$. In other words, as we move away from the sink, the number of group leaders in subsequent gradient level decreases.

Property 1: The cardinality of the group leader nodes does not increase on increasing gradient.

As we are forming the cluster heads in a gradient based manner and such that the number of group leaders in any level i is always greater than the number of group leaders in the level $i+1$. Assuming only two levels we have, $|C_1| + |C_2| = C$. Our communication setup procedure ensures that the number of group leader nodes in level 1 is not less than the number of group leader nodes in level 2, we have $|C_1| >= |C_2|$. On generalizing the above condition we have $|C_1| >= |C_2| >= |C_3| .... >= |C_k|$.

*Property 2: The minimum number of group leaders at a gradient level nearest to the sink is equivalent to the depth of the gradients **k**.*

The figure 7, depicts a group leader communication network formed using our proposed method. The proposed method aims at parallelizing the data paths by creating a group leader communication topology such that,

$$|C_i| + |C_{i+1}| + |C_{i+2}| + |C_{i+3}| + |C_{i+4}| .... |C_{k-1}| + |C_k| = C$$

or

$$\sum_{i=1}^{k} C_i = C \tag{5}$$

Here C and C_i are the total number of cluster heads in the network topology and the number of cluster heads in gradient level i respectively. As we have arranged the group leaders in the non increasing order of cardinality on increasing gradient bands, we will have at least one group leader in the gradient level k in the worst case scenario. And from the Property 1, we will have at least two group leaders in level $k-1$ in the worst case scenario and so on. On extending the same logic, we will have a minimum of k number of group leaders in the level nearest to the sink node.

Property 3: The maximum gradient depth for a communication network k is a polynomial function of the number of group leaders in the network C.

From property 2, we have $C_k = 1$, $C_{k-1} = 2$ as the minimal conditions for the number of group leader nodes in levels k and $k-1$. Similarly, we have $C_1 = k$ and $C_2 = k-1$ as the minimal conditions for the number of group leader nodes in levels *1* and *2*. From property 1 we have

$$\sum |C_i| = 1 + 2 + 3 .... k - 1 + k \leq C, \tag{6}$$

where C is total number of group leader nodes in the network terrain. Thus we have,

$$\frac{k(k+1)}{2} \leq C \tag{7}$$

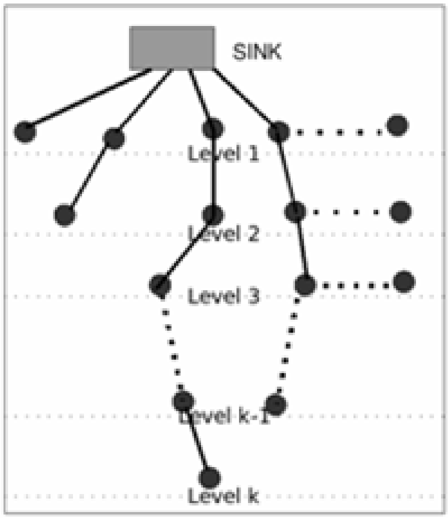

Fig. 6. A typical group leader communication setup

The polynomial inequality between *k* and *C* gives the solution

$$k \leq \frac{\sqrt{1+8C}-1}{2}. \tag{8}$$

As we are dealing with networks, with N typical in range of thousands of nodes and the individual group sizes are in the sub hundred ranges, we can approximate the above solution to

$$k \leq \frac{\sqrt{8C}-1}{2} \tag{9}$$

Thus we have a seen that the maximum gradient depth *k*, is a polynomial function of the number of group leaders *C* in the network with the worst case maximum depth being $k_{\max} = \frac{\sqrt{8C}-1}{2}$.

The above property is an important result that shows that for a given network size and group size, the gradient depth is a fixed value and it is a function of the number of group leaders in the network.

The energy consumption in transmitting a packet from the source node to the base station will be the sum of the energy consumptions across the individual links in the group. In a network of size *N* and *C* group leaders, we will have an average cluster size of *N/C*. In the worst case scenario, we will have all the group members arranged in a chain like manner connecting the group leader node. In this scenario, the group leader node will be *N/C – 1* hops away from the source node.

For the above scenario, we have the worst case energy loss for intra cluster communication to be

$$E_{node\text{-}CH} = \Sigma E_{inter} = (N/C - 1) * E_{node\text{-}node} , \quad (10)$$

where $E_{node\text{-}node}$ is the average energy consumption per communication link seen in the group.

Similarly, to communicate across the group leader nodes in the network, the worst case number of hops required to connect to the base station will be *C – 1*. Thus we have the worst case energy loss for inter cluster communication will be

$$E_{CH\text{-}BS} = \Sigma E_{inter} = (C - 1) * E_{CH\text{-}CH} \quad (11)$$

Where $E_{CH\text{-}CH}$ is the average energy consumption per inter cluster communication link. Since the inter cluster communication links are more longer in distance than the intra cluster communication links, we have $E_{CH\text{-}CH} > E_{node\text{-}node}$

The total energy loss expended in transmitting a B bit message over a network setup will be the sum of the inter cluster and intra cluster communication energy losses.

$$E_{Total} = E_{node\text{-}CH} + E_{CH\text{-}BS}$$

$$= (N/C - 1) * E_{node\text{-}node} + (C - 1) * E_{CH\text{-}CH}$$

$$= (N/C - 1) * [E_{Elec} * B + E_{Amp} * B * D_{Avg\text{-}Intra} * D_{Avg\text{-}Intre}] +$$

$$(C - 1) * [E_{Elec} * B + E_{Amp} * B * D_{Avg\text{-}Inter} * D_{Avg\text{-}Inter}] \quad (12)$$

Here $D_{Avg\text{-}Intra}$ and $D_{Avg\text{-}Inter}$ are the average intra cluster and inter cluster distances respectively.

5 Simulation Setup

In our system model we assume that the network topology remain unchanged through the execution of the network setup phase of the algorithm. Using the unit disk graph modeling method, each sensor node in the network is modeled a computational object with its set of capabilities like communication range, timing components, transmitters and receivers. The wireless protocol stack provided by JiST is used to define the network interfaces for each node in the program. The network topology is defined a 1000 by 1000 meter range area and wireless sensor nodes are placed at random in this network topology. Thus the location of each sensor node is purely random and two nodes are capable of communication with each other if the nodes fall with either's communication range. The communication range is a variable parameter that is set according to the requirements of the simulation experiment, with values ideally ranging from 300 to 700 meters. Each sensor node is assigned an initial energy value which translates to the real world equivalent of remaining battery time of the sensor node. Also the numbers of nodes that are placed in the terrain are based on the simulation experiment requirements, with values ideally ranging from 100 to 1000 nodes. During simulation setup, the desired number of nodes per cluster was set to be 15 for our algorithm.

In our comparison studies we will be discussing the advantages of using our method over LEACH and HEAP in aspects of energy characteristics and cluster characteristics. In the study of energy characteristics, we simulate the algorithms and track the energy expenses of the nodes in the terrain. We study the energy consumption of the cluster heads in the two algorithms and establish the advantages of the proposed method. In the study of cluster characteristics, we plot number of clusters formed and the cluster densities of the two algorithms for various network scenarios.

6 Performance Comparison

Figure 7 depicts the group leader energy loss comparison between the algorithms and it can be observed from the plot that the energy loss in our proposed algorithm is almost 25% lesser than the LEACH algorithm. This reduced energy loss is attributed to the fact that our algorithm limits the load on each group leader by having at most two communication links with adjacent leaders. It can be noted that the energy savings through our proposed algorithm increases as the number of nodes in the terrain increase.

It can be seen from Figure 8 that the group leader energy consumption is lesser in the proposed algorithm when compared to the LEACH and HEAP algorithms. This is similar to the pattern seen in Figure 7, when increasing the number of nodes in the terrain. Also, the cluster head energy loss increases as the transmission range increases. More energy is expended in communicating to farther nodes, as energy expense is proportional to the communication distance. Irrespective of increasing the

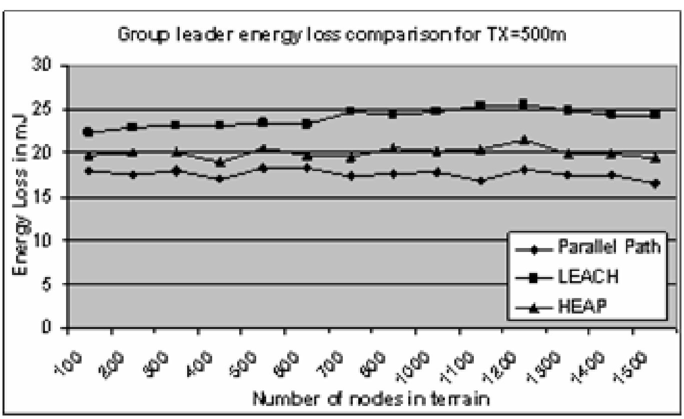

Fig. 7. Cluster head energy loss comparison for increasing nodes in terrain

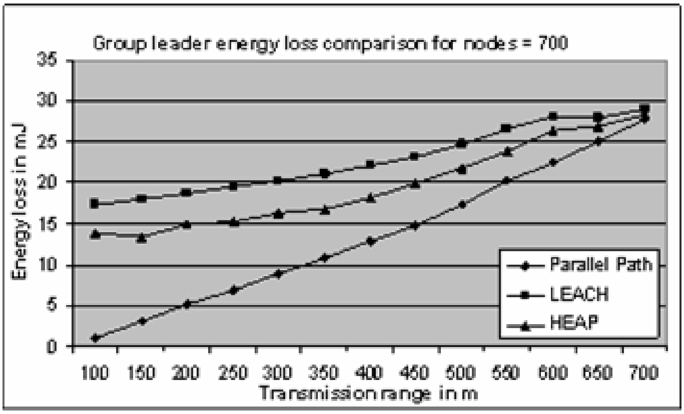

Fig. 8. Cluster head energy loss comparison for increasing transmission power

transmission power or the number of nodes in terrain, the proposed method out performs LEACH and HEAP. As it is crucial to prolong the life time of the network, it is prudential to conserve energy reserves of group leaders.

Figure 9 shows the overall network energy loss comparison between the algorithms while increasing the number of nodes deployed in the terrain. LEACH spends more energy, almost more than 4 to 5 units greater than the proposed algorithm. It can also be observed that energy consumption for LEACH and HEAP increases for the increase in the number of nodes while for the proposed method, the energy loss is more or less consistent. This is due to the deterministic number of nodes each leader handles in our proposed method. Deterministic number of neighbors translates to deterministic network traffic that the group leader handles. Since there is no restriction placed on the neighboring group leader links for LEACH and HEAP, the energy expense does not have any bound and results in increases in energy dissipation for increasing nodes in the terrain.

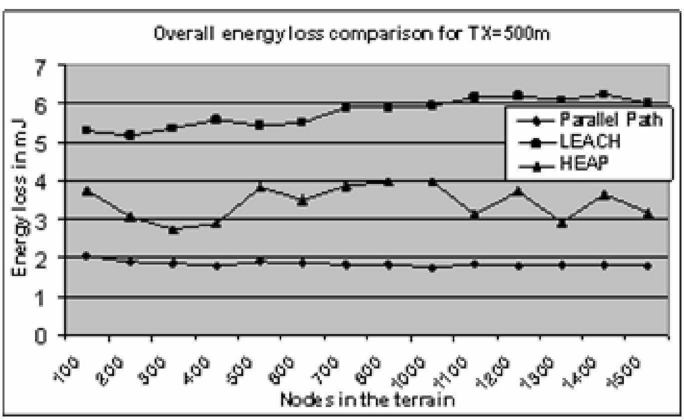

Fig. 9. Overall network energy loss comparisons fr increasing nodes in terrain

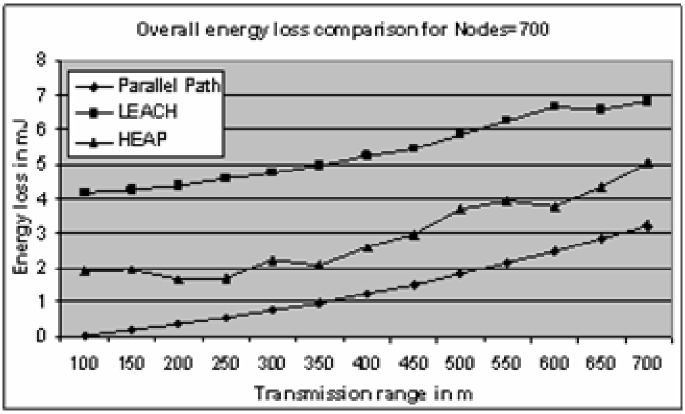

Fig. 10. Overall network energy loss comparison for increasing transmission power

Figure 10 shows the overall network energy loss comparison for LEACH, HEAP and the proposed algorithm. It can be observed that even though the network energy loss increases for increase in the transmission range, the energy loss is lesser in the proposed algorithm. As it is expected that more energy be expended network wide for transmitting packets through larger distances, we have an increasing trend on energy expenses for increasing the transmission ranges. Having seen the energy characteristics of the algorithms, the next section compares the delay characteristics of the two algorithms. The average end-to-end delay for a packet to be sent to the sink is captured for various simulation scenarios and they are compared between the two algorithms.

The cluster density of LEACH and the proposed algorithm is compared in Figure 11. The number of nodes in each cluster is more and is closer to the desired

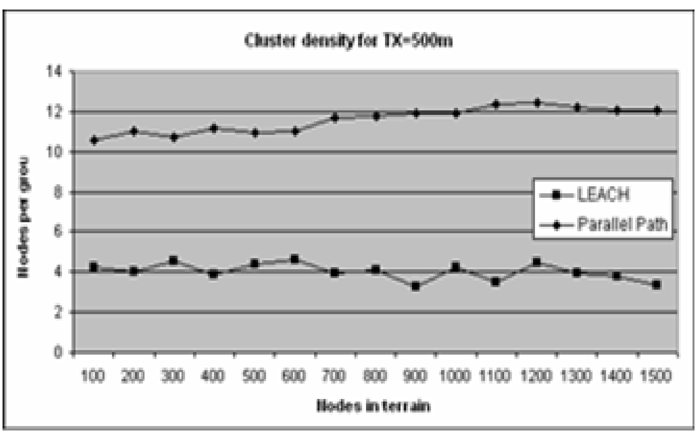

Fig. 11. Cluster density comparison for increasing nodes in terrain

range of 15 nodes per cluster. As there is no provision of specifying the desired cluster size for LEACH, the cluster density results for LEACH will be purely non-deterministic. Although LEACH maintains a consistent number of nodes per cluster, the smaller value means that there will be more number of groups in the terrain.

The larger number of groups and smaller group size does not contribute to the goals of grouping, as they contribute only marginally to the maintainability of the network. The large number of clusters formed for LEACH is seen the following figure. It can be seen that the proposed method maintains a lower number of densely packed groups, thereby aiding in better management of resources of the network.

It can be seen that the proposed method outperforms the LEACH algorithm in all the frontiers of comparison. Also there is a definite advantage of using out proposed method, in terms of energy savings and the average end-to-end delay. The comparisons are carried for a wide range of network scenarios, and the performance of out method was seen to consistently better than that LEACH. Specifically we are able to achieve approximately 25% energy savings of our cluster heads.

6 Conclusion

Clustering techniques are used to tackle the scalability issues in wireless sensor networks. Inter-cluster and intra-cluster communication designs form the key factor in extending the lifetime characteristics of the wireless sensor network. This paper investigates a parallel path cluster communication technique, which helps in extending the lifetime of the network. Our strategy offers a generic two-stage algorithm comprising of a gradient based group formation technique and an inter-group and intra-group communication set up technique. The proposed grouping technique, partitions the wireless sensor network topology into groups of specific size based on pre-determined design requirement. The group communication set up technique, results in energy efficient group leader communication topology. The simulation results show that the proposed techniques perform better than LEACH and HEAP for a wide range of network scenarios.

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