Investigating Clustering Algorithms in Microsensor Networks

Vrinda Gupta and Rajoo Pandey

Abstract— **The design of a microsensor network has to be carried out under several constraints, e.g., limited energy source and dynamic network topology. One practical design scheme in WSNs is clustering. Clustering is an energy efficient and scalable way to organize the WSN. Clustering can stabilize the network topology at the level of sensors and thus cuts on topology maintenance overhead. Recently, a number of clustering algorithms have been specifically designed for WSNs. These proposed clustering techniques widely vary depending on the overall network architectural and operation model and their objectives. In this paper, classification of clustering algorithms is carried out i.e. as energy efficient type, duty cycle control type and third type is the one derived from classic graphic theory. In this paper focus is on the energy efficient type of clustering protocols. Furthermore, classification and analysis of energy efficient protocols viz. LEACH and PEGASIS is presented. Also a hybrid approach Hierarchical Chain-cluster scheme is introduced and the performance of all the three protocols is evaluated and comparison of them is done with the conventional Direct Transmission scheme.**

Index Terms— **Sensor network, clustering, network lifetime, topology control, energy efficiency.**

I. Introduction

RECENTLY, researchers have been increasingly interested in wireless microsensor networks. This rising interest is in large part due to many useful and varied applications of wireless sensor networks when once they are deployed [1]. In a wireless microsensor network, hundreds to thousands of small, sensor nodes are scattered over some environment for the purpose of gathering data. These sensor nodes collaborate among themselves to establish a sensing network. Each of these distributed sensors contains computation and communication elements and can be designed for remote autonomous environmental monitoring. Because of the remote nature of these networks and the size of the individual nodes, however, nodes do not have access to unlimited energy. Thus, in order to prolong system lifetime, energy efficient algorithms and protocols should be used. In addition, since the limited wireless channel bandwidth must be shared among all the sensors in the network, routing protocols for these networks should be able to perform local collaboration to reduce bandwidth.

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Authors in [2] showed that the energy consumed for transmission is much higher than that for data processing. Direct routing will perform well enough if all the nodes were very close to the sink. In WSN, most of the time sensors are scattered randomly over an area of interest, creating an infrastructure in an ad hoc manner. In that infrastructure, when the distribution of nodes is not uniform, optimal clustering becomes a solution to enable energy efficient network operation. For the tiny sensors to coordinate among themselves to achieve a large sensing task in a less power consumption, they should work in a cluster. In clustering, neighbour sensors join to build one cluster (group) and elect a cluster head to manage this group. The amount of power required to send data from a sensor node to a cluster-head is much smaller than the amount required if the same sensor sends data directly to a base station. In addition, clustering allows load balancing in each cluster, which can improve the performance of the network. Thus, it will be more energy efficient to employ the clustering and data-fusion techniques.

In this paper, we have analyzed the advantages and disadvantages of conventional routing protocol using our model of sensor networks. Also, two popular algorithms namely LEACH (Low Energy Adaptive Clustering Hierarchy) [3], [4] and PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [5] [6], which share the applicability domain of the hierarchical routing protocol, have been investigated. LEACH uses clustering organization; whereas PEGASIS uses a chain-based approach. Furthermore, a hybrid approach i.e. Hierarchical Chain-cluster is simulated and compared with the above mentioned protocols.

II. Cluster Based Architecture for a Sensor Network

A. The Need for Clustering

The multi-hop shortest path approaches are not resource aware, i.e., the path selection does not take into account the available energy of sensor nodes. This problem becomes apparent in those applications where the sink is settled far away from the sensor field. The aggregation tree will be rooted at sensor nodes with the smallest distance to the sink, and the root node then tends to perform long distance transmission to send aggregated packets back to the sink. After certain number of rounds, sensor nodes close to the sink will die out first, resulting in non-uniform distribution of sensor nodes. However, if all sensor nodes perform single-hop transmissions and directly communicate with the sink, those sensors far from the sink will die out first. Furthermore, because of the absence of aggregation operation, the overall lifetime of the entire network will be

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shorter. To solve this problem, some clustering based protocols were proposed. The key idea is to arrange sensor nodes into groups and evenly distribute the energy load of long distance transmission.

B. Clustering Approach

Allowing only some nodes to communicate with the base station can reduce the energy consumption. These nodes called cluster heads collect the data sent by each node in that cluster, compress it and then transmit the aggregated data to the base station. This method of wireless communication is called clustering. Cluster based approaches are suitable for habitat and environment monitoring, which requires a continuous stream of data. This is due to the fact that such an application generates significant redundant data that can be aggregated on route to the sink, thus reducing traffic and saving energy.

Clustering enables data fusion, which combines one or more data packets from different sensor measurements to produce a single packet e.g., by using some techniques such as beam forming and thus helps to reduce the amount of data transmitted between sensor nodes and the base station. Clustering can be extremely effective in one-to-many, many-to-one, one-to-any, or one-to-all (broadcast) communication. However, in most sensor networks, many-to-one communication paradigm is more common. This is because in case of sensor networks, nodes send their data to common sink or cluster heads for processing. Besides energy and bandwidth conservation, there are other advantages of clustering nodes in a WSN. One advantage is that it allows for spatial reuse of resources. If two nodes exist in different non-neighbouring clusters, it may be possible for the two nodes to share the same frequency or time slot. Clustering can also facilitate network management and routing. In network management, the cluster heads often report the data to the management node on behalf of the entire cluster. Often the cluster heads form the routing backbone for the network. In addition, the hierarchical structure obtained using clustering can help overcome some of the problems with node mobility.

The problem of hierarchical (clustering) network organization consists of several aspects that depend on the structure of the sensor network and the particular applications demands. Clusters can be organized hierarchically when the network size increases. As the number of sensors is increased, more clusters can be formed without increasing the processing or communication loads on individual cluster heads. The three levels in the hierarchical design of cluster-based architecture consist of a base station (a data sink) at the top level, cluster heads at the middle level, and the other sensors at the bottom level.

However, utilizing a conventional clustering scheme does not improve network lifetime since the conventional clustering assumes the cluster heads to be fixed, and thus requires them to be high-energy nodes.

C. Classification of Clustering Algorithms

During the last few years, many clustering algorithms have been proposed as an effective way to organize communication and data processing in a sensor network. These algorithms can be classified into three types. Algorithms in first type are energy-efficient, which consider the residual energy of nodes to determine the problem of electing cluster-heads such as LEACH, HEED [7] and so on. LEACH forms a two level cluster hierarchy, where cluster members send data to the cluster head which in turn sends it to the base station. Energy dissipation is evenly spread by dissolving clusters at regular intervals and randomly choosing the cluster heads. PEGASIS, another clustering-based routing protocol, further enhances network lifetime by increasing local collaboration among sensor nodes. A protocol called HEED (Hybrid Energy-Efficient Distributed clustering) [7] considers a hybrid of energy and communication cost and aims to prolong network lifetime by distributing energy consumption. A new energy efficient clustering approach (EECS) [8] proposed for single-hop wireless sensor networks is autonomous and more energy efficient than LEACH and HEED]. Another mechanism, an Energy-Efficient Unequal Clustering (EEUC) [9] organizes the network using unequal clustering and multi-hop routing]. Since rotation of cluster-heads and the metric of residual energy are not sufficient to balance the energy consumption, an unequal clustering mechanism is introduced to balance the energy consumption among cluster-heads.

Algorithms in the second type control the network topology by periodic waking and sleeping techniques, e.g., GAF [10], SPAN [11]. In these topology control schemes, the goal is to leverage the network spatial redundancy to create a backbone of nodes responsible for communication, while the rest of the nodes sleep. GAF achieves this by the use of location information. Nodes are grouped together into virtual grids and only selected nodes participate in communication while the rest of the network sleeps. Acquiring location information in sensor nodes would require GPS-like hardware, or complex localization algorithms. SPAN, on the other hand, tries to achieve this by periodically broadcasting connectivity information.

Algorithms in the third type derive from the classic graphic theory, e.g., CBTC (Cone Based Topology Control) [12], LMST, a fully distributed and localized protocol aimed at building an MST-like topology. The protocol generates a strongly connected communication graph. The distributed cone-based topology control algorithm starts with each node using the lowest transmission power to include at least one node in every one of α degree. Then, the algorithm improves the graph generated from the first step by removing asymmetric edges and redundant nodes. The CBTC algorithm is a distributed localized algorithm and can generate a network with symmetric links. It does not need network synchronization and node position information. However, it needs the directional information of nodes, which requires additional hardware (e.g., more than one directional antenna).

Thus clustering approach can be applied to the design of several types of sensor network protocols that require scalability, prolonged network lifetime, fault tolerance, and load balancing.

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III. Case Studies Of Energy Efficient Protocols for Sensor Clustering

Energy-efficient clustering algorithms can be further classified in many different ways, such as requiring location information or not. Some algorithms are distributed, some centralized. There are many different ways the algorithms form clusters, from using node id, node degree (number of neighbours), and location information. This paper will classify the algorithms according to whether they are single-hop or multi-hop networks within the clusters. If the clusters are in a single-hop network, then the member nodes will communicate directly with the cluster head in a single hop viz. LEACH. If member nodes are allowed to use multiple hops to reach the cluster head, then it is a multi-hop network viz. PEGASIS.

1) Single-hop Clustering Algorithms:

One of the most successful and studied clustering algorithms is LEACH [3]. The LEACH (Low Energy Adaptive Clustering Hierarchy) protocol maintains a hierarchically clustered sensor network. The main design objective of LEACH is to guarantee a certain network lifetime while minimizing energy consumption. This is done by ensuring that all nodes die (run out of energy) at about the same time, which extends the network lifetime and leaves very little energy left in nodes when the network dies.

The operation of LEACH is broken up into rounds with each round consisting of two phases, the setup phase and the steady state phase. The setup phase is when the nodes organize themselves into clusters. In LEACH, the clusters are re-established in each 'round'. New cluster heads are elected in each round and as a result the load is well distributed and balanced among the nodes of the network. Each node transmits to closest cluster head. Cluster heads are one hop away from the base station, and other nodes forward their data to the cluster heads. Only the cluster head has to report to the sink and may expend a large amount of energy. In LEACH, there is an optimal percentage P_{opt} (determined a priori) of nodes that has to become cluster heads in each round assuming uniform distribution of nodes [4].

The LEACH protocol guarantees that each node will become a cluster head exactly once every $1/P_{opt}$ rounds. We refer to this number of rounds as epoch of the clustered sensor network. The threshold is set as:

$$T_s = \frac{P_{opt}}{1 - P_{opt} * \left(r \bmod \frac{1}{Popt} \right)} \quad \text{if } S \, \varepsilon \, G$$

$$= 0 \quad \text{otherwise} \qquad (1)$$

where r is the current round number.

The election probability of nodes ε G to become cluster heads increases in each round in the same epoch and becomes equal to 1 in the last round of the epoch. By round, we define a time interval where all clusters members have to transmit to the cluster head once.

The steady state phase is the normal data collection and routing. Cluster members send the data to its cluster head. The cluster head will fuse all the data received from its member nodes and then transmit one message to the base station, containing the data for its cluster.

LEACH is a flexible and self-adaptive algorithm. It uses TDMA at the cluster-head level, making that transmission efficient. LEACH uses the strength of received signal as the indicator of distance between nodes and do not require node position information. However, it requires synchronization in a cluster due to the use of TDMA. Communication within clusters is done by using CDMA, with neighboring clusters using different codes, thus preventing interference between clusters. LEACH is robust to node failures since most node failures will not affect the overall network operation.

There are several disadvantages to LEACH. One is the fact that all cluster heads must broadcast an advertisement message to all nodes within its communication radius. Another drawback is that all cluster heads must transmit data to the base station, which is single hop but may be a long distance. This is not always a realistic assumption since the CHs are regular sensors and the base-station is often not directly reachable to all nodes due to signal propagation problems, e.g., due to the presence of obstacles. LEACH also forms one-hop intra- and inter cluster topology where each node can transmit directly to the CH and thereafter to the base-station. Consequently, it is not applicable to networks deployed in large-regions. There is also a large overhead necessary to form the clusters. There is no provision for the cluster heads to be uniformly distributed with respect to their geographic location. And since the decision to change the CH is probabilistic, there is a good chance that a node with very low energy gets selected as a CH. When this node dies, the whole cell becomes dysfunctional. Also, it is possible that parts of the network will be left without a cluster head. LEACH results in a long latency for the BS to receive the sensed data. Finally, the number of clusters may not be fixed every round.

2) Multi-hop Clustering Algorithms:

In order to lower the overhead of cluster formation in LEACH, a new algorithm was proposed, PEGASIS [5]. PEGASIS (Power-Efficient Gathering in Sensor Information Systems) is another research work that discusses how to extend the lifetime of a sensor network by using collaborative techniques. PEGASIS protocol is a chain-based power efficient protocol constructed on the basis of LEACH. It allows only local coordination between nodes that are close together so that the bandwidth consumed in communication is reduced.

PEGASIS has following goals:

- Minimize distance nodes must transmit.
- Minimize number of leaders that transmit to BS.
- Minimize broadcasting overhead.
- Minimize number of messages leader needs to receive.
- Distribute work more equally among all nodes.

The key ideas of PEGASIS are chaining and fusion. To construct a chain, each node determines its closest neighbor and forms a chain by employing greedy algorithms. To do this, in each round a node is chosen randomly to be the leader, which then initiates data transmission from the ends of the chain. Each node fuses its neighbor data with its own to generate a single packet of the same length and then

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transmits it to its next neighbor. This process is repeated until all sensory data are collected at the leader node, which then transmits the final data packet to the sink. Sensor nodes use multi hop communication to reach the sink.

The nodes will take turns transmitting data to the base station, thus evenly distributing the energy load among all nodes. When the round of all nodes communicating with the base station ends, a new round will start and so on. This reduces the power required to transmit data per round because the power draining is spread uniformly over all nodes. The distance on which most of the nodes transmit is less compared to LEACH. Second, the amount of data for the leader to receive is at most two messages instead of 20 (20 nodes per cluster in LEACH for a 100-node network).

There are several assumptions in the PEGASIS algorithm. First, it assumes that all nodes maintain a complete database about the location of all other nodes in the network. To locate the closest neighbor node, each node uses the signal strength to measure the distance to all neighboring nodes and then adjusts the signal strength so that only one node can be heard. The chain in PEGASIS will consist of those nodes that are closest to each other and form a path to the base station. The aggregated form of the data will be sent to the base station by any node in the chain and the nodes in the chain will take turns in sending to the base station.

Problem of current PEGASIS:

- Every node needs to have location information about all the nodes in the network.
- When the PEGASIS protocol selects the head node, there is no consideration about the energy of nodes.
- When the PEGASIS protocol applies to the greedy algorithm to construct chain, some delay may occur. PEGASIS introduces excessive delay for distant nodes on the chain.
- When the PEGASIS protocol selects the head node, there is no consideration about the location of the base station. This results in a critical problem that the redundant transmission of data is occurred.
- A single leader can become a bottleneck.
- In some scenarios sensors may move, and hence would affect the protocol functionality.

In the following section, we present a hierarchical chain-cluster protocol that is a hybrid approach of managing the sensor network. It eliminates the overhead of dynamic cluster formation in LEACH and overhead of topology management in PEGASIS. It combines the cluster architecture with multi-hop routing. The main advantage of this approach is that transmission energy consumption can be reduced.

A. Hierarchical Chain-cluster approach

Firstly the clusters are formed in the area where sensor nodes are distributed randomly. Then chain is formed starting from farthest node. In separate cluster, separate chain is formed. For data gathering in each round of communication, the farthest node in the chain initiates the data transmission. Data fusion is performed at each node except the farthest node in the chain. Each node receives data from one neighbor, fuses with its own data, and transmits to the other neighbor on the chain. This is done for all the chains formed within all the clusters respectively. After the data is gathered at the cluster heads, then the cluster head does not send the data directly to the base station as done in LEACH. But, again the cluster heads on the chain transmits its data to the leader node in the cluster heads. Cluster head take different turns in transmitting the data to the base station. The selection of leader among the cluster-head is done by the formula (r mod n) where r is the number of rounds and n is the total number of cluster heads. In each round of communication, whenever the residual energy of any of the cluster heads go below K*E, where E is its initial energy and K is a constant, then it broadcasts within its chain to find a replacement, the node having the maximal residual energy in that cluster becomes the new cluster head and the previous cluster head becomes a normal node in the chain. This is done in order to avoid a node with minimal residual energy to become a cluster-head. The operation of the protocol is described in the pseudo code shown below.

```
(i) Initialize
    100 random nodes←(x,y)
    Base Station ← (50,300)
    E_initial ← 0.5 Joule/node
    E_elec ← 50nJ/bit
    E_amp ← 100 pJ/bit/m^2
    E_DA ←5nJ/bit/message
    N ← 5  No. of cluster
    Chain formation
(ii) Main Processing
    Repeat after every round r
    cluster head (x,y) ← for E_(x,y) > K*E_initial (K=0.5)
    leader node ← cluster head of mod(r, N) th cluster
    d ← sqrt [(x(i)-x(i+1)) ^2 + (y(i) - y(i+1))^2]
    E_(x,y) ←(E_initial-2*r*E_elec*k)-(E_amp*r*k*d^2)-
          (E_DA*k*r),
    If E_(x,y) < E_min ←dead node
(iii) Finalize
    n(1)← no. of runs when first node get dead
    n(2)← no. of runs when 20 nodes get dead
    n(3)← no. of runs when 50 nodes get dead
    n(4)← no. of runs when 100 nodes get dead
    plot←no. of runs v/s % of dead nodes
```

B. The System Model

In order to evaluate the performance of these algorithms, we used the radio model as described in reference [3]. The radios have power control and can expend the minimum required energy to reach intended recipients. An r^2 energy loss is used due to channel transmission. Thus, to transmit a k-bit message a distance d, the radio expends:

$$E_{Tx}(k,d) = E_{Tx\text{-}elec}(k) + E_{Tx\text{-}amp}(k,d) \quad (2)$$

$$E_{Tx}(k) = E_{Rx\text{-}elec}(k) \quad (3)$$

$$E_{Rx}(k) = E_{elec} * k \quad (4)$$

An assumption is made that the radio channel is symmetric such that the energy required transmitting a message from node A to node B is the same as the energy required transmitting a message from node B to node A. There is also the assumption that all sensors are sensing the environment at a fixed rate and thus always have data to send to the end user. Other assumptions are:

- Each node is within the communication range of every other node.
- Distance is estimated from the received signal strength.
- Data fusion is used to reduce the number of messages in the network. We assume that combining n packets of size k results in one packet of size k instead of size nk.

Table I
PARAMETERS USED IN THE PAPER

Notation	*Description*
N = 100	*Total number of sensor nodes*
$E_o = 0.5J$ / node	*Initial energy of each node*
$E_{elec} = 50nJ$ / bit	*Per bit energy consumption*
$E_{DA} = 5nJ$ / bit	*Energy for data aggregation*
$E_{amp} = 100$ pJ/bit/m^2	*Amplifier transmitting energy*
Maximum No. of rounds	*2500*
No. of bits (k)	*2000*

IV. Simulation Results

Table 2 summarizes the performance results of the various protocols with initial energy per node of 0.5J for the 100mx100m networks. The results shown are average of the results obtained after several experiments. From the simulation results, it is clearly observed that clustering approach outperforms the conventional Direct Transmission scheme. Comparing to the results, when LEACH runs out of energy at about 997 rounds, Hierarchical chain-cluster approach and PEGASIS protocols are fully operational without any sensor node death.

The results of Matlab simulation is shown in figures 1 to4 for network of 100m diameter where base station is placed at (50,300) far away from the field. In this paper, we have taken the performance metric as the Network Lifetime, which is the time interval from the start of operation of the sensor network until the death.

Figure 1 shows the network topology for Direct Transmission protocol. Figures 2 to 4 shows the network topology for LEACH, PEGASIS, and Hierarchical chain-cluster protocol. In figure 5, comparison of the System Lifetime of network protocols under consideration is shown.

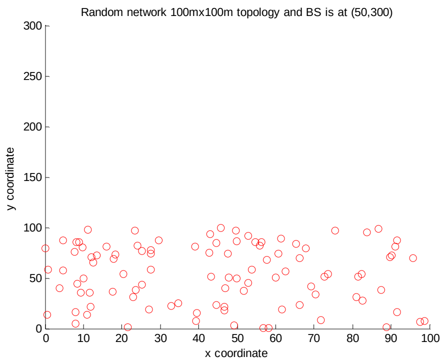

Fig. 1. Position of Sensors in Direct Transmission

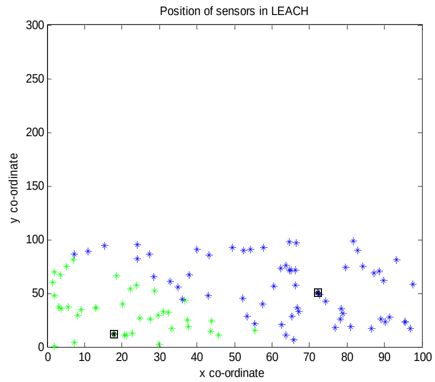

Fig.2. Position of Sensors in LEACH

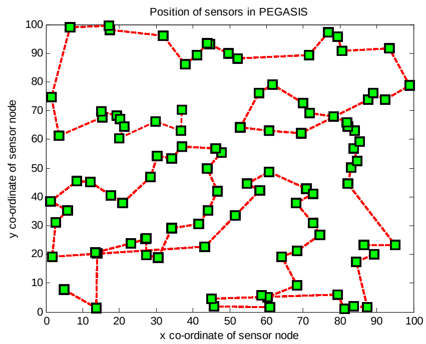

Fig. 3. Position of Sensors in PEGASIS

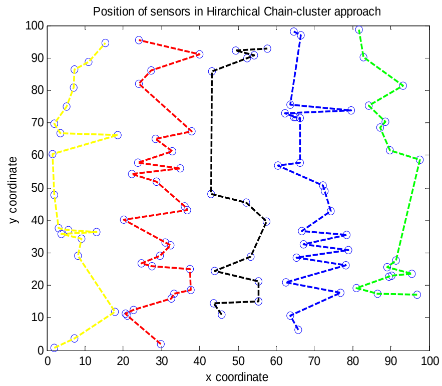

Fig.4. Position of Sensors in Hierarchical chain-cluster

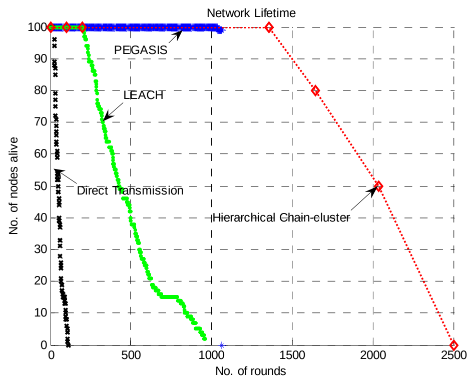

Fig. 5. Network Lifetime of various protocols

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Table II
LIFETIMES USING INITIAL ENERGY OF 0.5 J / NODE FOR THE SENSORS

Protocol	Round first node dies (FND)	Round last node dies (LND)
Direct	25	112
LEACH	214	997
PEGASIS	1102	1104
Hierarchical Chain-cluster	1524	2500

V. CONCLUSIONS

This study was carried out to investigate the performance of clustering algorithms like LEACH, PEGASIS etc. The advantages and disadvantages of these clustering based protocols were examined via simulation. Disseminating information in sensor networks with tight energy constraints is still an open problem. The study concludes that clustering the node keeps most of the communication inside the clusters and data aggregation reduces the messages volume travelling through the network, thus allowing energy saving. For continuous data delivery, the Hierarchical chain-cluster based data transmission protocol is seen to be the most energy efficient alternative.

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