

Shortest Path Energy Efficient Hierarchical Clustering Protocol for Wireless Sensor Networks

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ABSTRACT

WSN lifetime depends on the energy consumptions of its sensor nodes. Hence, the major design issue which requires to be addressed, to prolong the lifespan of WSN, is energy efficiency. In contemporary hierarchical cluster-based routing protocols, communication within the network is less energy efficient which leads to the accelerated aging of these energy deficient networks. This work presents a hierarchical cluster based routing protocol named Shortest Path Energy Efficient Hierarchical Clustering (SPEECH) protocol that considers the unique characteristics of WSN. SPEECH aims at preserving the limited energy of sensor networks via optimal cluster formation and shortest path communications within the network. It is observed from a simulation that SPEECH is better in utilizing the limited energy of the network efficiently.

Keywords: Hierarchical clustering protocol, sensors, WSN, energy efficiency

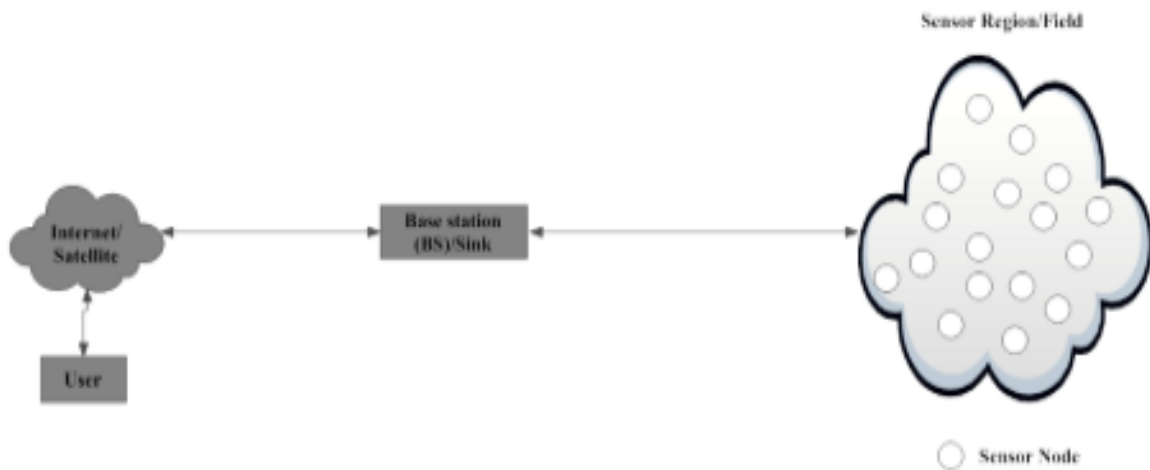
Introduction

Wireless sensor network (WSN) is composed of a large number of tiny devices called sensor nodes or motes, powered by a small battery. The sensor nodes are framed into a cooperative network and are capable of gathering and distributing data in places where other networks are inappropriate due to environmental and/or strategic reasons.¹ Along with sensor nodes, sink or base station (BS), the area of interest or sensor field, and control, room/User are the three main components of a WSN.² Figure 1 shows the WSN architecture. Sensor nodes are placed or installed in an area of interest in order to monitor different physical processes such as pressure, vibration, sound, temperature, heat, and moisture. They

are responsible for routing the sensed data to a remote station for further processing. The base station (BS) is a resource-rich node. It acts as a controller in WSN. Sensor field is the area which is to be monitored. This area is also called targeted area. The final destination of the sensed data by the WSN is the user or control room. Different sources may be used for sending data to this part. The two major categories of WSN applications according to to³ are monitoring and tracking. Health and wellness monitoring, structural and seismic monitoring, inventory monitoring, power monitoring, factory and process automation, indoor/outdoor monitoring and environmental monitoring are included in monitoring

applications. Tracking humans, animals, objects, and vehicles are some tracking applications of WSNs. This

This phase is carried out only once in SPEEHC. The setup phase selects cluster heads for around and uses the



classification can be further expanded with more categories like disaster relief, space exploration, and chemical processing.

Figure 1. WSN Architecture

Routing is the main consumer of energy in WSN. Hierarchical cluster based routing uses high-energy nodes for data transmission and computation whereas uses low energy nodes for carrying out the sensing task in the targeted area. This approach was first tested in wired networks.⁴ the most accepted routing schemes in WSN are the hierarchical or cluster based routing schemes due to their flexibility, scalability, effectiveness and most of all, the optimum utilization of the limited battery of a sensor node.

Hierarchical routing protocols decrease the rapid aging of WSN due to energy-aware communication within the network. In such protocols, a set of special nodes known as cluster heads makes a wireless backbone to the BS. These cluster heads are either selected randomly or on the basis of maximum energy remained at a node in the network. Each cluster head is responsible for data collection from its members in the cluster and transmitting it to the BS. This communication needs to be more energy efficient for increasing the lifetime of WSN. For this purpose, we propose Shortest Path Energy Efficient Hierarchical Clustering (SPEEHC) protocol. SPEEHC forms optimal clusters using a greedy approach and applies DIJKSTRA's based shortest path algorithm for communication between BS and cluster heads. We divided the operation of SPEEHC into three phases. The optimal cluster formation phase divides the network into energy efficient optimal clusters via a greedy approach.

first part of Minimum Multi-Hop Path (MMHP-I) algorithm for calculating shortest paths from all cluster heads to BS. In the steady state phase, the actual transmission of data occurs from each cluster head to BS. In this phase, cluster heads use the second part of Minimum Multi-Hop Path (MMHP-II) algorithm in order to reach to BS. The paper organization is as follows: section II discusses the related work, proposed work is described in section III and section IV presents the simulation results and finally section V concludes SPEECH with some remarks on future directions.

Low Energy Adaptive Clustering Hierarchy (LEAH)⁵ follows the principle of clustering for distributing power dissipation over the entire network. This approach divides the network into clusters on the basis of data collection and selects the cluster heads randomly. The members of a cluster transmit the sensed data to their cluster head which first aggregates the data and then forwards it to the BS. The first problem with LEACH is its non-optimal cluster formation and no cluster head selection for some rounds. Similarly, cluster heads directly transmit their data to BS in LEACH and such communication over longer distances consumes more energy of the network. Similarly, for overcoming the problem of non-uniform distribution of cluster heads,⁶ proposed Energy Aware Uniform Cluster Head Distribution (EAUCD) protocol. In this technique, representative nodes (RN) are selected uniformly from all parts of the network on the basis of maximum residual energy. EAUCD consists of three phases. The first phase is called the initialization phase in which the sensor network is broken down into parts via a greedy approach. The second phase is the setup phase

where from each part of the sensor field a single node is chosen as an RN. The final phase is called the steady state phase, here the actual data transmission is carried out from RN to the BS for onward processing. EAUCD can only be applied to square regions which are a flaw in this approach. Another hierarchical protocol proposed in⁷ is Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN). Hard Threshold and Soft Threshold are the two attributes communicated by cluster heads to its member in this approach. These attributes are the sensed parameter values using which a cluster member decides what to do next. The sensed parameter absolute value beyond which a cluster member must have to transmit the value to the cluster head was the Hard Threshold. Soft Threshold was that value of collected data beyond which the sensor node must have to turn on its transmitter. In the same authors proposed Adaptive Periodic Threshold Sensitive Energy Efficient Sensor Network (APTEEN).⁸ The threshold values as well as the maximum time interval between two packets are included in the extra attribute. The protocol becomes more useful even for time driven networks with this modification. Information such as a node is dead or failed to transmit data can be easily known to the BS due to the periodic transmission of data. About 100-300% improvement is achieved by Power-Efficient Gathering in Sensor Information Systems (PEGASIS).⁹ over LEACH. In this approach sensor nodes exchange data by constructing a chain. Nodes in the network transmit to and receive from only one node and only one node in the chain is responsible for sending data to the BS. Data is aggregated by each node along with its own data and then transmit it onward in the chain. BS finally receives the aggregated data from one node selected from the chain. The greedy method is used for constructing the chain. HEED (Hybrid Energy Efficient Distributed) is another clustering approach proposed in¹⁰ although LEACH is much more efficient in terms of energy, random selection of cluster heads is the main problem with this approach. The random selection sometimes results in a non-uniform distribution of cluster heads which wastes energy instead of saving it. This problem also affects the data collection process. HEED avoid the random selection of cluster heads by using the communication cost and residual energy level for electing cluster heads.

Base Station Controlled Dynamic Clustering Protocol (BCDCP) presented in¹¹ uses the concept of hierarchical clustering protocols. Energy-rich BS is used in this protocol for cluster and routing paths set up, rotate the

cluster heads randomly, and perform other power-efficient functions. Some of the advantages of this approach are balanced clusters formation where the approximately same number of member nodes are served by each cluster head in order to minimize the cluster head load, placing cluster heads uniformly over the entire sensor network and multi-hop communication among cluster heads for forwarding data to cluster heads. BCDCP extends network lifetime through better energy savings.

Proposed Model

The three phases of SPEECH in which it operates are the optimal cluster formation phase, setup phase, and steady state phase. The remaining parts of this section elaborate these phases.

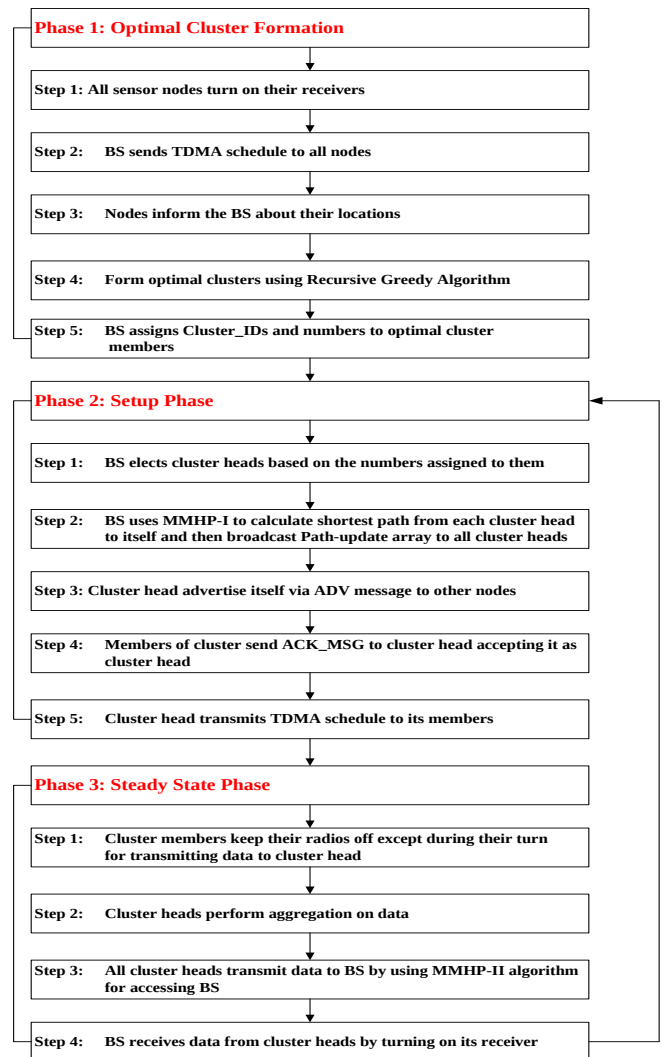


Figure 2. SPEECH Protocol Overview using an Algorithmic Chart

Optimal Cluster Formation Phase

This phase is carried out only once during the lifetime of the sensor network. In order to avoid the inefficient clusters formed in LEACH, the SPEEHC protocol uses a greedy approach for dividing the sensor network into optimal clusters. These optimal clusters utilize the scarce power sources of sensor networks efficiently and hence extend the WSN lifetime.

There are five steps involved in the cluster formation phase. In step 1 of this phase as shown in Figure 2, all the deployed sensor nodes turn on their receivers. BS sends a TDMA schedule to all the nodes in step 2. In the next step i.e. step 3 every sensor node in the field sends information to BS about its location which contains n_ID and n_LOC . The BS now knows the locations of all sensors and uses algorithm presented in next section for the formation of optimal clusters in step 4 of this phase. In the final step, BS distributes Cluster_IDs and numbers to all nodes which are physically close to each other. That is, they are a member of optimal clusters obtained as a result of the recursive greedy algorithm. The nodes sharing same Cluster_IDs belong to the same cluster.

Greedy Algorithm for Network Division into Optimal Clusters

Suppose that $\text{const} \geq 1$ are any real number. A (const, k) -way clusters of a Sensor network SN is a breakdown of SN into $SN_1, \dots, SN_k$ such that $SN_i \leq \text{const} * SN/k$, for all $1 \leq i \leq k$. Thus, the k -way division is a $(2, k)$ -way network partition. The cost of a (const, k) -way division is the number of connections of SN whose two endpoints are not in the same subnetwork.

Bring to mind that a γ -bisection, $1/2 < \gamma < 1$, is the clustering of a sensor network SN into two sub-networks SN_1 and SN_2 such that both $SN_1 \leq \gamma * SN$ and $SN_2 \leq \gamma * SN$. The cost of a γ -bisection is the number of connections between SN_1 and SN_2 .

We first show that the following standard recursive clustering scheme finds a $(2, k)$ -way clusters with the cost at most $O(\log k)$ times the cost of the optimal k -way clustering.

Algorithm(Recursive Greedy Algorithm)

Input: (Sensor network SN of n Nodes and an integer k).

Output: (a $(2, k)$ -way clusters of SN).

Step 1. Let $i = n/k$;

Step 2. Let $SN_1, \dots, SN_h$ be the S subnetworks obtained from calling the sub procedure Recursive Clustering (SN, i) below;

Step 3. If $S \leq k$, then return $(SN_1, \dots, SN_h)$ else repeatedly merge the smallest two

Sub-networks until k sub-networks remain.

Sub procedure (Recursive Clustering (SN, i))

RC-1 Let $s = SN/i$;

RC-2 Find an optimal $(1/2 + 1/s)$ -bisection SN' and SN'' of SN;

RC-3 If $SN' > 2i$ then Recursive Clustering (SN' , i);

RC-4 If $SN'' > 2i$ then Recursive Clustering (SN'' , i);

The recursive clustering algorithm will divide the network into optimal k clusters. It is based on the two-way graph partitioning which is called bisection. The bisection is performed recursively until the network is divided equally into k sub-networks. The optimal bisection keeps minimum interaction between sensor nodes of different clusters. The algorithm produces optimal clusters which reduce energy consumption and hence plays a key role in extending network lifetime.

Setup Phase

This phase has five steps. After the optimal cluster creation, BS selects a node having number 1 as cluster head from a group of nodes sharing the same Cluster_IDs. In round 2, the node with number 2 will be cluster head for the optimal cluster and so on. This is performed in step 1 of this phase. Similar to [5], SPEEHC also assumes that the number of cluster heads is predefined for the network.

MMHP-I

In step 2, BS uses the first part of Minimum Multi-Hop Path (MMHP) algorithm given below for calculating shortest path from each cluster head to itself.

Algorithm Initialization

Step 1: The BS is assigned the value 0 as its distance; the algorithm starts its operations from this node

Step2: All other nodes i.e., cluster head in the network are assigned the value ∞

Step 3: BS is designated as start of the network

MMHP-I Algorithm

Value [BS] $\leftarrow 0$ // BS is the base station

for each Node $\in N - \{BS\}$ // N is the total number of nodes (These are actually cluster heads)

do value [Node] $\leftarrow \infty$ // initially each cluster head is assigned ∞

Priority-Queue $\leftarrow BS + N$ // BS plus total Nodes

While Priority-Queue $\neq \emptyset$

do

Optimal-Node $\leftarrow \text{EXTRACT-MIN}(\text{Priority-Queue})$

For each

Node $\in \text{Adjacent}[\text{Optimal-Node}]$

```

do if Value[Node] > value[optimal-Node] + distance
(optimal-Node, Node)
then
Path-update [Node] ← Optimal-Node
Value [Node] ← Value[optimal-Node] + distance
(optimal-Node, Node)

```

BS then saves the Path-update array on each node (cluster head). This array is then used by every cluster head for accessing the BS.

In step 3, cluster head informs via an ADV message other nodes in the cluster that the role of cluster head is assigned to it for the current round. ADV is an advertisement message that contains node ID and header that differentiate it from other messages. All the nodes in a cluster send an ACK_MSG to the node elected as a cluster head in step 4. This step completes the cluster setup for the current round. Cluster heads in SPEEHC are responsible for synchronizing data transmission within their clusters. In step 4 of this phase, cluster head of a cluster creates a TDMA schedule and sends it to all its members. This schedule informs the cluster members that when can they transmit their data to cluster head i.e., every node of the cluster has an allotted time slot in the schedule during which the node sends its data to the cluster head. It allows the cluster members to turn off their radio components except when they have to transmit data during their allocated time slots. The advantages of the TDMA schedule include collision avoidance and minimum energy usage.

Steady State Phase

This is the phase where all cluster heads transmit their data to BS via shortest paths calculated using MMHP-I algorithm. In step 1 of this phase, all members transmit their data to BS according to the TDMA schedule. Cluster head aggregates the data it received from its members in step 2. All cluster heads use the Path update array sent by BS to them for accessing the BS in step 3 of this phase by using the algorithm explained below.

MMHP-II

Communication between BS and clusters heads in other hierarchical protocols is direct which cause more energy dissipation from cluster heads because of long-haul communication. We used the first part of MMHP algorithm for calculating paths from all cluster heads to BS which are more energy economical than the direct transmission in LEACH and EAUCD. The algorithm MMHP-II given below is used by each cluster head in order to reach to BS which is an energy efficient path.

MMHP-II Algorithm

```

i=0
root = Path-update[ID]
While root ≠ 0
    route[i] = root
    temp = root
    root = Path-update[root]
    if root == 0
        route[i+1] = path-update[temp]
    i++

```

After aggregating the data all cluster heads start transmitting their data to BS via the energy efficient paths using the above algorithm. Finally in step 4 BS turns on its receiver for collecting data from all cluster heads. With this, the first round of the protocol is completed. For the next round, the setup phase is immediately started again after the end of steady state phase of the previous round. All the subsequent rounds follow the same procedure.

Cluster Head Selection Process

BS is responsible for the selection of cluster heads in SPEEHC. The protocol does not consume more energy of sensor nodes by distributing the load of being cluster head among all the nodes in the network. As all the data in a cluster is forwarded to cluster head, so more energy of cluster head is consumed as compared to ordinary nodes. Each and every sensor node in WSN takes its turn to be a cluster head in order to distribute equally the energy-hungry duties of the cluster head. Thus it is necessary for the cluster formation algorithm to make every node cluster head for an equal number of times.

In SPEEHC, BS assigns numbers in ascending order to all the nodes which have similar Cluster_IDs. In each round cluster heads are selected in sequence by BS based on the numbers assigned to them i.e., in round 1 node with number 1 will be cluster head, node numbered 2 will be cluster head in the second round and so on. Suppose there are 20 nodes in a cluster then after 20th round node with number 1 will become cluster head again. Along with node numbers, in SPEEHC BS also checks the energy level of the node as BS saves energy level of each cluster head at the end of each round. For example, in round number 21, the node with number 1 is to be selected as cluster head again but if its energy level is below a specified level, then instead of it, BS checks node with number 2 whether or not it can become cluster head. Similarly, if node 2 is deficient in energy too, then node 3 is selected as a cluster head and so on. This process of electing cluster head is more simple and

energy efficient in SPEEHC than other hierarchical protocols like LEACH.

Though cluster head selection process has some overhead but if the role of cluster head is not rotated then soon a node acting as cluster head will pass away because of being busy all the time. As a result, the network will be unable to collect data from that part of sensor field monitored by the cluster represented by the cluster head which has been died.

In all the rounds of SPEEHC, same optimal clusters are used constructed in phase 1 until the network pass away. Cluster heads are selected on the basis of numbering assigned by BS and energy levels of nodes. The numbering of nodes rotates the role of cluster head for the uniform energy load distribution among all the cluster members. Cluster head compresses data that they collect from cluster's member nodes and then forward the aggregated data to BS. This compression saves energy as cluster head need to transmit only a small amount of data to BS. Similarly like EAUCD⁶, in order to avoid and inter and intra-cluster collisions SPEEHC uses TDMA/CDMA MAC. However, a collection of data is periodic and centralized.

According to simulation results, SPEEHC protocol dissipates less energy than LEACH⁵ and EAUCD⁶ because of its energy efficient communication within the network.

Simulation

The layout of the sensor network is shown in Figure 3 for simulation. The network is a collection of 90 static nodes and a BS. More precisely, nodes within the sensor field are supposed to be deployed arbitrarily. The sensor field is a square area with one side $L=90$ m. BS position is away from the closest point of the sensor area at a distance D . During the simulation tests, D 's values vary between 100m-1000m. All nodes forward their sensed data during their time frames.

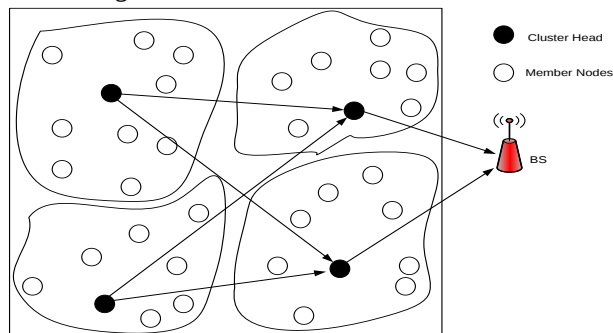


Figure 3. WSN Layout for Simulation

It is also supposed that all cluster heads send their remaining energy to BS directly during the start of each round. Finally, a free space communication model is assumed where no obstacles interrupt the communication. Therefore, a message retransmission is not needed. Table 1 summarizes the parameters used in the simulation similar to.¹² In our simulation, we assume a simple radio model like¹¹ where k -bit data transfer between two nodes separated by r meters requires the energy for transmission and reception.

Table 1: Summary of Simulation Parameters

Parameter	Value
Network Size	900x900m
Number of sensors	90
Distance between BS and targeted area	100/200/300
Initial Energy of Node	0.5J
Transmitter/Receiver Circuitry Dissipation	50nJ/bit
$E_{Tx}=E_{Rx}$	
Amplifier Energy Cost E_{amp}	0.0013 pJ/b/m ²
Data packet size	4000 bits

We perform more than 15 simulation experiments in order to compare SPEEHC with LEACH and EAUCD in terms of energy dissipation, net data sent to BS, and overall lifetime of the sensor network. In these experiments, the number of nodes remained alive over time was tested for all the three protocols in cases when BS is either outside the network or within the network. The experiments show better performance of SPEEHC than its competitors.

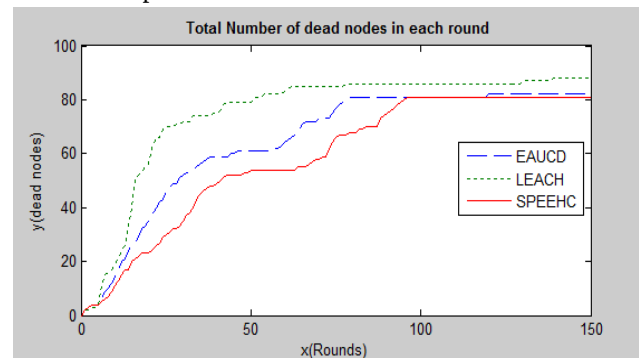


Figure 4. Comparison of SPEEHC to LEACH & EAUCD with respect to number of dead nodes in each round

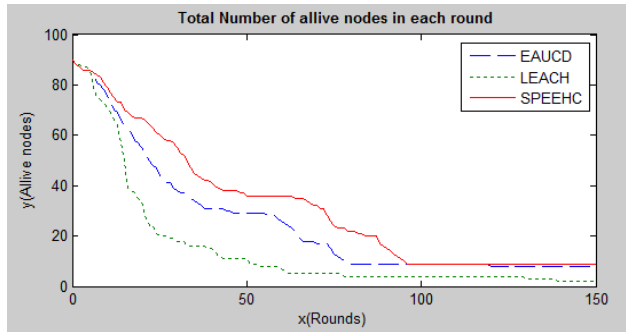


Figure 5. Comparison of SPEEHC with LEACH and EAUCD in terms of the nodes remaining alive after each round in a network of 90 nodes deployed randomly in a square area of 900mx 900m

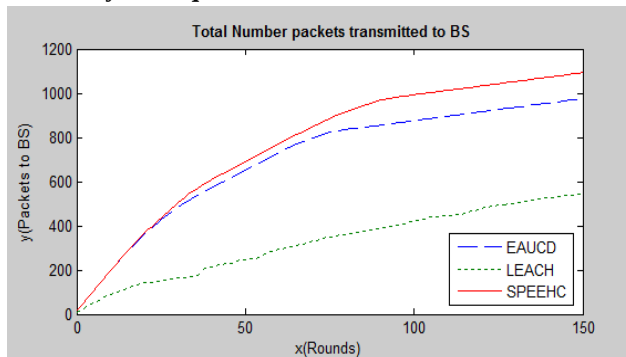


Figure 6. Total number of data packets that each protocol transmits to BS at the end of each round

The SPEEHC is simulated having cluster heads of 10% of the total network via MATLAB. The network nodes are deployed randomly. The Figure 4, 5, and 6 show the comparison of these protocols using Select = 50 nJ/bit. The ratio of dead nodes after each round of SPEEHC is quite low due to less energy consumption as compared to LEACH and EAUCD where more energy dissipation leads to the death of more nodes. Figure 4 depicts this result clearly. In a similar way, Figure 5 shows that SPEEHC leads in a number of nodes alive after each round and due to the maximum number of alive nodes, the network is able to transmit more data packets from the sensor area to the end user. It is obvious from the line of SPEEHC in Figure 6 that this protocol transmits a large number of messages to BS than LEACH and EAUCD. The experiments clearly signify that SPEEHC achieves more energy savings and thus able to extend the lifetime of WSN.

Conclusion

We addressed two issues in this work for the longevity of the network life. Optimal cluster formation is the first contribution of the work where we divided WSN into

optimal clusters which lead to more energy conservation. An algorithm is presented which bisect the network in a greedy way into optimal clusters. This division helps in avoiding non-optimal clusters which may be formed in hierarchical protocols such as LEACH. The mentioned protocol sometimes creates a situation where no cluster heads are selected for some round due to non-optimal cluster formation or sometimes selects more cluster heads from a single region. This causes more energy consumption even than traditional protocols. Our algorithm overcomes these problems by dividing WSN via greedy approach. The algorithm also distributes the responsibility of cluster heads uniformly in all the clusters.

The second issue we resolved in this work is the direct transmissions of cluster heads to BS in prior protocols like EAUCD and LEACH. This type of transmission dissipates more energy from the network which is deficient in the resource. We presented an algorithm called MMPH for calculating shortest path from each cluster heads to BS. This saves significant energy due to communication over shortest distances instead of the long haul communication of cluster heads with the base station in other protocols. The algorithm is based on the popular DIJKSTRA shortest path algorithm where BS is the root node. In this work, the network performance is not investigated for lower or higher head count which is needed to be done in future.

Similarly, we only compare the protocol's performance with standard LEACH and EAUCD only. The performance of various other hierarchical clustering algorithms like HEED, PEGASIS, TEEN etc. haven't been taken into consideration. Moreover, simulation has been done in MATLAB but the work can be simulated in network simulators such as NS2, QualNet, EXata, OPNET and TinyOS via MICA motes for getting more realistic network performance.

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