Centralized cluster based hierachical routing algorithm for Internet Connected Devices

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***Abstract*— In this section, we introduced a novel energy evaluation model for a centralized cluster based hierarchical network. Our model takes into account the energy consumption of various types of nodes involved during set-up and steady-state phases. Unlike the existing centralized cluster-based routing protocols, the underlying clustering technique of our proposed scheme eliminates the cluster head advertisement, i.e., cluster heads are no longer required to advertise themselves which further enhances the network lifetime. To reduce the overhead and transmission delay, the underlying clustering technique does not require simulated annealing for cluster head selection. Each node is either a normal node or a high energy node. The normal nodes are equipped with 2 joule while high energy nodes have 5 joule of residual energy. High energy nodes are only 5 percent of the normal nodes to balance network cost. They are uniformly distributed within the geographical region to enable energy-efficient access for normal nodes.**

In our scheme, high energy nodes perform multiple resource-intensive operations such as, assisting the base station in cluster head selection and relay back vital information to the base station. It is for this reason that high energy nodes refrain from participation in cluster head selection and only normal nodes are permitted to do so. In this section, first we explain the network operational model of our proposed scheme followed by a novel energy evaluation model which computes the energy consumption of sensor nodes during various phases.

Keywords—component; formatting; style; styling; insert (key words)

I. Introduction

In above section, we briefly explained our randomly distributed cluster-based hierarchical routing algorithm. Although, our proposed scheme is capable to enhance network lifetime and quality of data, however, it does not guarantee an optimal percentage of cluster heads in each round. It is a best-effort algorithm which tries to elect a near-optimal percentage of cluster heads in each round. In other words, the average percentage of cluster heads elected over a certain number of rounds remains optimal, but in each round, an optimal percentage is not guaranteed. This is because the threshold Equation (5) for cluster head selection is probabilistic in nature and depends on a random number generation as explained earlier. To guarantee an optimal percentage of cluster heads in each round, a centralized selection mechanism is required. A central entity such as a base station elects cluster heads for each round. Nodes are no longer required to generate random numbers and the probabilistic threshold value of Equation (5) has no further influence in the cluster head selection. Base station uses the residual energy and location information of each node to elect cluster heads. In the existing centralized cluster-based hierarchical routing protocols [1] [2] [3] [4], each node is required to transmit its location information and residual energy to a base station at the beginning of each round. Although, the existing protocols result in a near-optimal election of cluster heads but these protocols are not energy-efficient on part of each node. The transmission of residual energy and location information in each round is a burden on resource-starved sensor nodes. Furthermore, these protocols use simulated annealing algorithm [5] for solving NP-hard problem of finding *k*-optimal clusters [6]. However, they do not provide any detail on using simulated annealing algorithm for obtaining optimal clusters. These protocols incur high overhead in cluster head selection and advertisement, cluster formation and data transmission to a base station [7].

II. Network Operational Model

Our centralized cluster-based hierarchical routing algorithm operates in two phases, a setup phase and a steady-state phase. The set-up phase can be further subdivided into four sub-phases

- . Status
- Cluster Head Selection
- Cluster Formation

- Schedule Creation

During status sub-phase, each normal node transmits a status message to it's nearest high energy node before the start of each round. This message contains an 8-bit source ID, 8-bit destination ID and a variable-length residual energy field. The source ID is the identity of the transmitter node whereas destination ID is the identity of a nearest high energy node. The frame format of a status message is shown in Fig. 6

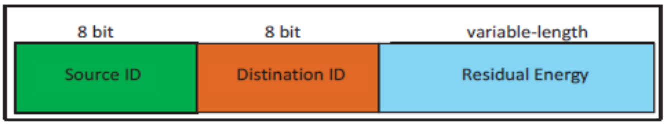


Fig 6: Frame Format of a Status Message

Each high energy node aggregates status messages from its neighboring normal nodes and transmits to a base station. Upon transmission to a base station, each high energy node goes to sleep mode until the beginning of next round. The base station retrieves the source ID and residual energy from each status message and stores locally within a queue. It then calculates the average residual energy (*Eavg*) using Equation (6)

$$E_{avg} = \sum_{i=1}^{i=n} \left(\frac{E_i}{n}\right) \qquad (6)$$

where, *Ei* is the residual energy of a normal node and *n* is the total number of such nodes. In our proposed scheme, *n* is equal to 100. During cluster head selection sub-phase, an optimal percentage of cluster heads are elected by the base station. The base station maintains a queue as shown in Fig. 7. Any node having *Ei* greater than *Eavg* is eligible for cluster head selection. In Fig. 3.7, the value of *Eavg* is equal to 1.5 joule for the current round. It is highly probable that there will be a large number of nodes for which *Ei* is greater than *Eavg* in each round. All such nodes are nominated as the possible candidates for cluster heads. If two or more candidates are located in the same geographical region, they are evaluated according to their residual energy values and their election as cluster heads in the past 1/ *kopt* rounds. In our network, the optimal percentage of cluster heads is 4% to 6% in each round for a network of *n* nodes. Among the candidates of Fig.7, nodes 2, 3 and 11 reside in one cluster whereas nodes 63 and 69 reside in another cluster as shown in Fig. 8.

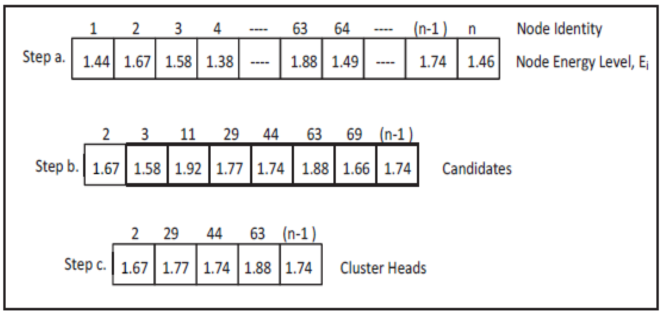


Fig 7: Candidate Nodes and Cluster heads

Only one candidate in each cluster is allowed to be elected as cluster head. Among nodes 2, 3 and 11, node 11 has the highest *Ei*, however, this node has previously been elected as cluster head in the past $1/K_{opt}$ rounds which makes it ineligible for the current round. The elimination of node 11 from cluster head selection paves the way for node 2 and 3 as the possible nominees for cluster head in the current round. Node 2 takes preference over node 3 for cluster head selection because the former has higher E_i and has not been elected as cluster head in the past $1/k_{opt}$ rounds. In the second cluster, the election procedure is rather straightforward. Node 63 has a higher E_i than node 69. Furthermore, it has not been elected previously over the past 1/ k_{opt} rounds. We used the term *cluster* while referring to Fig. 7 and Fig. 8 for clarity and simplification purposes.

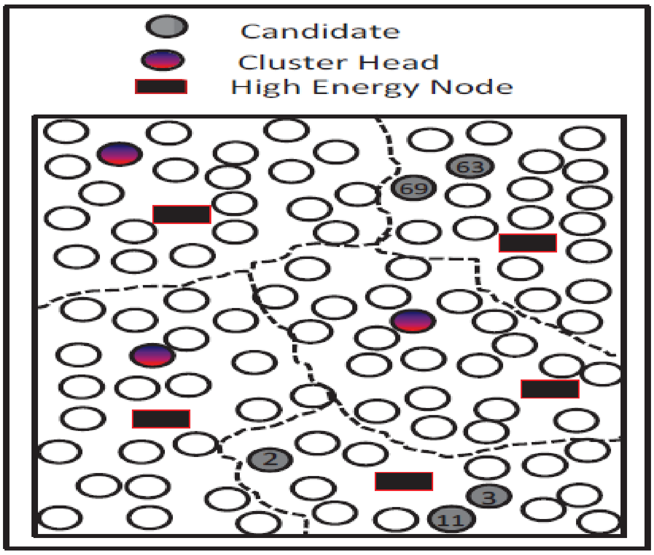


Fig 8: Cluster Head Selection

In reality, there is no such thing like cluster at the time of evaluating *Ei* by the base station. Once a base station evaluates the residual energy of each node, only then the cluster heads are selected and clusters are formed. In the beginning, all normal nodes reside within a *region* inside a sensor field.

The cluster head selection sub-phase is a complex resource-intensive task which incurs high processing overhead and network delay. During this phase, the normal nodes and high energy nodes remain in sleep mode to conserve their battery powers. Once an optimal percentage of cluster heads are selected for the current round, the base station transmits a message to each normal node. This message contains ID of each normal node and ID of its respective cluster head. At this point of time, there are two types of normal nodes within the network: non-cluster head nodes and cluster head nodes. Non-cluster head nodes are those normal nodes that participated in cluster head selection but were unable to satisfy the criteria for selection. The base station assigns a cluster head to each non-cluster head in order to form a cluster. The non-cluster heads become member nodes of a cluster head within each cluster. The formation of a cluster around each cluster head signals the end of cluster formation sub-phase. The direct association of a member node with its respective cluster head enhances network lifetime because a cluster head is no longer required to advertise itself. Furthermore, each member node avoids the transmission of join-request messages to its cluster head. The completion of cluster formation sub-phase is initiated by schedule creation sub phase. During this sub-phase, each cluster head assigns TDMA slots to its member nodes which allow them to transmit their data using these slots. Furthermore, the creation of schedule allows the nodes to remain in sleep mode and wake up only on their allocated time slots.

The completion of status, cluster head selection, cluster formation and schedule creation sub-phases signal the end of set-up phase and initiation of a steady-state phase. During steady-state phase, each member node collects data according to a predefined condition and transmits to its cluster head using the allocated TDMA slots. When all the member nodes within each cluster have transmitted their data, the cluster heads perform necessary signal processing to eliminate redundant data packets. Because multiple cluster heads are involved during this process, it would be a resource consuming task if all these nodes transmit their aggregated data directly to a base station. To reduce their energy consumption, one of the cluster head is elected as a leader node which collects data from other cluster heads as shown in Fig. 9.

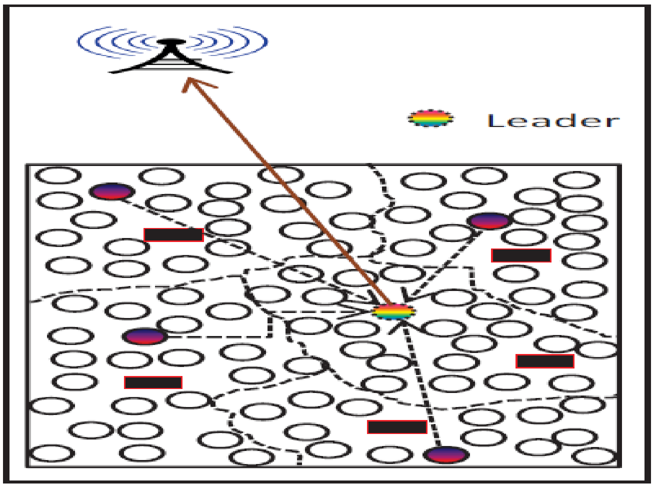


Fig 9: Data Transmission to a Base Station

The leader node further aggregates the incoming data from the remaining cluster heads and transmits to a base station. The task performed by a leader node is resource-consuming and as a result the cluster heads take turn to become a leader node in each round. Among the cluster heads, the one having the largest residual energy in a particular round is elected as a leader node. The completion of set-up phase and steady-state phase is coined as one complete round as previously discussed. After the completion of steady-state phase, status messages are transmitted again and a new round starts. The complete set of operations performed during each round is shown in the flowchart of Fig. 10.

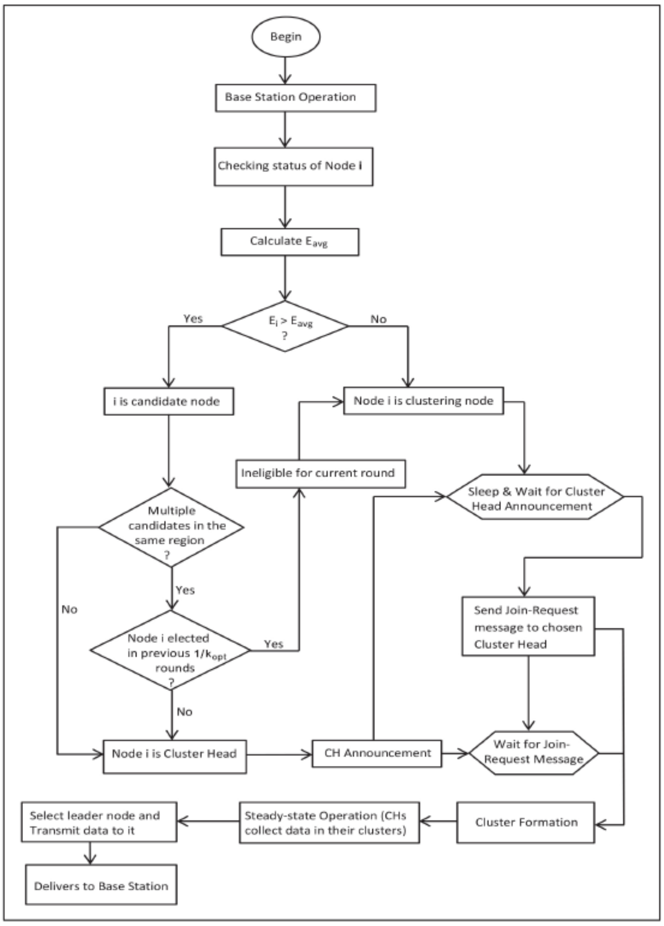


Fig 10: Flowchart of Set up and steady -state Phases

III. Energy Evaluation Model

During set-up phase and steady-state phase, a series of operations are performed and each one consumes a considerable amount of energy. The energy consumption of a node depends on the operation it performs at a particular time. A single node may perform one or more operations in each round. The type of operation along with the distance metric determine the energy consumption of a node.

During status sub-phase, each normal node transmits its location information and residual energy to a nearest high energy node. The amount of energy consumed by a normal node (*Estatus*) during this sub-phase is calculated using Equation (7).

$$E_{status}(m,d) = mE_{elec} + m \in f_s d_{HEN}^2, d_{HEN} < d_c \qquad (7)$$

Here, *m* is the size of message and *dHEN* is the distance between a normal node and the nearest high energy node. Because, our network model uses a (100 × 100) square meter area, it is most likely that a normal node is within the free-space range of a high energy node.

Each high energy node receives status messages from multiple neighboring normal nodes and transmits to a base station. The amount of energy consumed by a high energy node (E_{HEN}) during status sub-phase is calculated using Equation (8)

$$E_{HEN}(m,d) = \begin{cases} mE_{elec}x + mc_{fs}\, d_{BS}^2, & d_{BS} < d_c, \\ mE_{elec}x + m€_{mp}\, d_{BS}^4, & d_{BS} \ge d_c \end{cases} \qquad (8)$$

Here, *x* is a subset of normal nodes communicating with a particular high energy node, $\forall x \in n \wedge x < n$ and d_{BS} is the distance between a high energy node and the base station. If the base station is located at a distance less than *dc*, free-space propagation model is used, otherwise, multipath ground propagation model is used.

When the base station selects an optimal percentage of cluster heads, it advertises them to all the normal nodes. Each cluster head collects data within its cluster and transmits to the base station using a two-hop communication link. The energy consumed by a cluster head (E^{CH}) is calculated using Equation (9).

$$E_{HEN}(m,d) = \begin{cases} mE_{elec}\left(\frac{m}{k_{opt}}\right) + mE_{DA}\left(\frac{m}{k_{opt}}\right), & d_{LN} < d_c, \\ mE_{elec}x + m€_{mp}\, d_{BS}^4, & d_{LN} \ge d_c \end{cases} \qquad (9)$$

Here, k_{opt} is the optimal number of clusters which is always equal to the number of cluster heads because, there is one cluster head per cluster and d_{LN} is the distance between a cluster head and a leader node.

We used balanced-clustering technique [8] to establish nearly equal-sized clusters. The base station knows the location of each node and always tries to select cluster heads which are easily accessible to member nodes provided that such cluster heads satisfy the selection criteria. The base station tries its best to distribute equal load in each cluster, i.e., 20 nodes per cluster for a network of 100 nodes. Using these calculations, the value of k_{opt} is 5 for a network of 100 nodes. The use of balanced-clustering technique enables our proposed algorithm to elect an optimal number of clusters and cluster heads in most of the round over the span of network lifetime. Each cluster head consumes energy in data processing (E_{elec}), data aggregation within its cluster (E_{DA}) and transmission to a leader node (d_{LN}). In Equation (9), the cluster heads only perform data processing, data aggregation and transmission to a leader node. They were not assumed to sense data within their respective clusters, a role similar to the member nodes. However in case, if the cluster heads sense the data as well, their energy consumption is much higher. This is due to the fact that each cluster head not only collects and transmits data from member nodes but also senses its neighborhood for data collection. Furthermore, each cluster head aggregates its own data with the data of member nodes. The energy consumption of each sensing cluster head is computed using Equation (10).

$$E_{sensing-CH}(m.d) = \begin{cases} \alpha I + mE_{elec}\left(\frac{n}{K_{opt}}\right) + mE_{DA}\left(\frac{n}{K_{opt}}\right) + m\epsilon_{f_s d^2 LN} & , d_{LN} < d_c \\ \alpha I + mE_{elec}\left(\frac{n}{K_{opt}}\right) + mE_{DA}\left(\frac{n}{K_{opt}}\right) + m\epsilon_{f_s d^4 LN} & , d_{LN} \geq d_c \end{cases} \quad (10)$$

Where, α is the amount of energy consumed, by a cluster head in sensing a single bit and I is the total number of bits in the sensed message.
The amount of energy consumed by a member node (E_{member}) within its cluster is computed using Equation (11).

$$E_{member} = \alpha I + mE_{elec} + m\epsilon_{f_s} d_{CH}^2 \qquad d_{CH} < d_c, \quad (11)$$

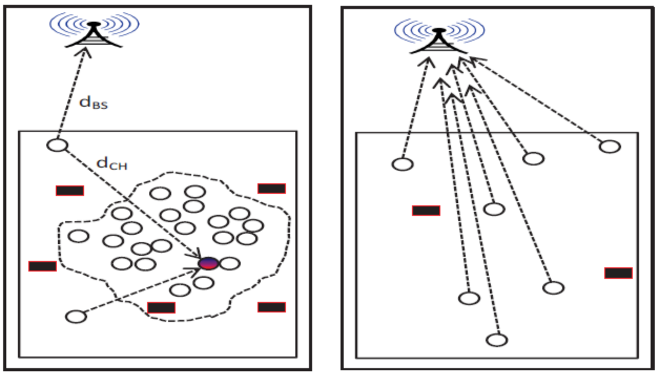
Here, d_{CH} is the distance between a member node and its cluster head. The member node is in close neighborhood of a cluster head, therefore, free-space propagation model is an obvious choice. Once each cluster head collects data from its member nodes, a leader node is elected by them to transmit their data to a base station. The amount of energy consumed by a leader node (E_{LN}) is computed using Equation (12).

$$E_{LN}(m,d) = \begin{cases} mE_{elec}\left(\frac{n}{k_{opt}}\right) + mE_{DA}\left(\frac{n}{k_{opt}}\right) + mE_{DA}\left(\sum_{i=1}^{k_{opt}-1} CH_i\right) + m\epsilon f_s d_{BS,}^2 & d_{BS<d_c} \\ mE_{elec}\left(\frac{n}{k_{opt}}\right) + mE_{DA}\left(\frac{n}{k_{opt}}\right) + mE_{DA}\left(\sum_{i=1}^{k_{opt}-1} CH_i\right) + m\epsilon_{mp} d_{BS,}^4 & \geq d_c \end{cases} \quad (12)$$

Here, d_{BS} is the distance between a leader node and the base station. Each leader node consumes energy in data processing and data aggregation within its cluster. Furthermore, it consumes energy in aggregating data from other cluster heads (C_{Hi}) and in data transmission to the base station.
During a particular round, one or more normal nodes may be far away from their nearest cluster heads and may refrain themselves of joining them. Instead, it may be more energy efficient if such nodes transmit their data directly to the base station as shown in Fig. 11(a). We call such nodes as isolated nodes and the amount of energy consumed by an isolated node ($E_{isolated}$) is calculated using Equation (13).

$$E_{isolated}(m,d) = \begin{cases} mE_{dec} + m\epsilon_{fs} d_{BS,}^2 d_{BS} < d_c < d_{CH}, \\ mE_{dec} + m\epsilon_{mp} d_{BS}^4, d_{BS} < d_c < d_{BS} \end{cases} \quad (13)$$

Here, d_{BS} is the distance between an isolated node and the base station and d_{CH} is the distance between an isolated node and the nearest cluster head. For an isolated node to transmit its data directly to a base station, d_{BS} must always be less than d_{CH}.



(a) Isolated Nodes (b) Insufficient Nodes To Form Clusters

Fig 11: Energy Consumption in Different Scenarios

In WSNs, there are not sufficient nodes toward the end of network lifetime. Therefore, it may not be possible to form one or more clusters. In that case, each normal node transmits its data directly to the base station as shown in Fig. 11(b). The amount of energy consumed by each node (E_{end}) is calculated using Equation (14).

$$E_{end}(m,d) = \begin{cases} mE_{elec} + m\epsilon_{f_s} d_{BS,}^2 \; d_{BS} < d_{c,} \\ mE_{elec} + m\epsilon_{mp} d_{BS,}^4 \; d_{BS} < d_{c,} \end{cases} \quad (14)$$

The amount of energy consumed in any particular round (E_{round}) is calculated using Equation (15)

$$E_{round} = E_{status} + E_{HEN} + E_{CH} + E_{member} + E_{LN} + E_{isolated} \quad (15)$$

Finally, the total amount of energy (E_{Total}) consumed over the span of network lifetime is computed using Equation (16).

$$E_{Total} = \sum_{i=1}^{i=r} E_{round} + \sum_{i=1}^{i=r} E_{end} \quad (16)$$

Here, r is the total number of rounds over which a network operates. When there are one or more clusters within a network, E_{round} is the end product. However, towards the end of network lifetime, there are not sufficient nodes to form one or more clusters in any round and the end result is $E_{end.}$ The sum of E_{round} and E_{end} result in the total amount of energy consumed over the span of network lifetime.

IV. Conclusion

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