

Latency and Lifetime-Aware Clustering and Routing in Wireless Sensor Networks

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Abstract—We investigate the latency and network lifetime-aware clustering problem for data collection in a WSN (Wireless Sensor Network) with one base station and propose a novel approach. Our approach consists of a polynomial-time heuristic for constructing clusters, a polynomial-time heuristic and an ILP (Integer Linear Programming) algorithm for constructing a routing tree for inter-cluster communication. We have performed extensive simulations on the network instances of 200, 400, 600, 800 and 1000 sensor nodes with uniform and random distributions, and compared our approach with two state-of-the-art approaches, namely MR-LEACH and DSBCV. Our simulation results show that the average network lifetime improvements of our approach using the ILP algorithm for constructing a routing tree over MR-LEACH and DSBCV are 35% and 62%, respectively, and the performance of the heuristic for constructing a routing tree is comparable to that of the ILP algorithm.

I. INTRODUCTION

A WSN consists of a set of autonomous sensor nodes. Each sensor node is typically battery powered, resulting in a limited lifetime. Clustering has been proposed to effectively increase the lifetime of a WSN. By clustering a WSN is partitioned into a set of disjoint clusters. Each cluster has a cluster head. The cluster head of each cluster collects the sensed data from each member, performs the data aggregation, and sends the aggregated data to the base station. Because of data aggregations, clustering reduces the overall data size and the number of communication sessions, effectively reducing the overall energy consumption of the entire sensor network. Furthermore, clustering improves the robustness of a WSN.

Many clustering algorithms have been proposed [2–4]. Among them is LEACH [3]. LEACH uses a probability scheme to select cluster heads. Each cluster head performs data aggregations and sends the aggregated data to the base station directly. Several clustering algorithms use multi-hop communication to prolong the network lifetime. Examples are MR-LEACH [2] and DSBCV [4]. A major problem with all the previous clustering algorithms is that they do not have a precise energy model for quantitatively representing the energy consumption of each sensor node when performing clustering and constructing a routing topology, resulting in unbalanced clusters and unbalanced energy consumption of cluster heads. For a comprehensive survey on the previous clustering approaches, the reader may refer to [1].

We investigate the following latency and network lifetime-aware clustering problem. Given a WSN with one base station and a natural number k , partition all the sensor nodes

into disjoint clusters and construct a routing tree for inter-cluster communication such that the lifetime of the WSN is maximized and the hop distance from any cluster to the base station does not exceed k . The network lifetime is defined as the number of time units until the first sensor node uses up its energy.

We propose a novel heuristic approach. Our approach consists of a polynomial-time heuristic for constructing clusters, a polynomial-time heuristic and an ILP algorithm for constructing a routing tree for inter-cluster communication. Unlike all the previous algorithms, our heuristic and the ILP algorithm construct a precise model for calculating the energy consumption of each sensor node by considering the cluster head rotations and the inter-cluster communication cost, making the routing tree more balanced in terms of energy consumption. We have performed extensive simulations on the network instances of 200, 400, 600, 800 and 1000 sensor nodes with uniform and random distributions. The simulation results show that our approach significantly improves two state-of-the-art approaches, namely MR-LEACH [2] and DSBCV [4] in terms of network lifetime.

II. NETWORK MODEL

The target WSN consists of a set V of N identical sensor nodes with the same initial energy, deployed on a 2D plane to continuously monitor the environment. The location of each sensor node is known. There is one base station. All the sensor nodes and the base station are static. In each unit time, each sensor node generates one packet of the sensed data, and sends the packet to its cluster head. After collecting the sensed data from all the members, the cluster head of each cluster performs data aggregation, and sends the resulting packet to its parent in the routing tree. We assume perfect data aggregations, that is, the output of each data aggregation performed by a cluster head has the same size as each packet received by the cluster head. The transmit power of each sensor node is adjustable, leading to a variable transmission range.

The energy for transmitting a packet of l bits over a distance d is defined as follows:

$$E_{Tx}(l, d) = lE_{elec} + l\epsilon d^\alpha = \begin{cases} lE_{elec} + l\epsilon_{fs}d^2, & d < d_0 \\ lE_{elec} + l\epsilon_{mp}d^4, & d > d_0 \end{cases} \quad (1)$$

The energy for receiving a packet of l bits is given as follows:

$$E_{Rx}(l) = lE_{elec} \quad (2)$$

The electronics energy E_{elec} , depends on factors such as the digital coding, modulation, and filtering. Whereas the amplifier energy $\epsilon_{fs}d^2$ or $\epsilon_{mp}d^4$, depends on the transmission distance and the acceptable bit-error rate. We assume that the energy for performing data aggregations is E_{DA} nJ per bit.

III. CLUSTER CONSTRUCTION

In order to meet the latency requirement, our clustering heuristic first partitions the target WSN into k disjoint layers. All the sensor nodes in each layer form a group $G_i (i = 1, 2, \dots, k)$. For the details of our group construction algorithm, the reader may refer to [1]. Figure 1 shows the groups of a WSN with $k = 3$.

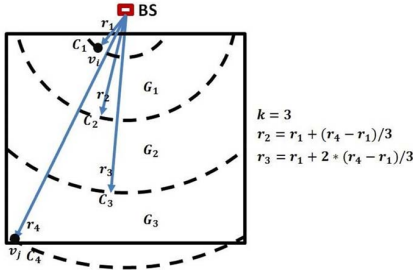


Fig. 1. The groups of a WSN

Next, our clustering heuristic partitions all the sensor nodes of each group into disjoint clusters. In the cluster construction phase, we ignore the energy consumption of inter-cluster communication and aim at constructing clusters such that each sensor node consumes the same amount of energy. The energy consumed for inter-cluster routing will be considered when constructing a spanning tree for inter-cluster routing. Our heuristic for constructing clusters works as follows:

For each group $G_i (i = 1, 2, \dots, k)$, do the following:

- 1) Establish a polar coordinate system with the base station as the pole and the vector from the base station to the left most sensor node on the boundary of the WSN as the polar axis.
- 2) Create a queue Q_i of all the sensor nodes in G_i sorted in a non-decreasing order of their angular coordinates.
- 3) Repeat the following steps to construct clusters $c_s \in G_i$ until Q_i is empty:
 - a) Create an empty cluster $c_s (s = 1, 2, \dots)$.
 - b) Keep removing a sensor node from Q_i and add it to c_s until the minimum average energy consumption of all the sensor nodes in c_s exceeds a threshold $\overline{LA}$.

The minimum average energy consumption of all the sensor nodes in a cluster is calculated by assigning an optimal time period t_i to each sensor node v_i running as the cluster head and making all the sensor nodes consume the same amount of energy during each round. The threshold $\overline{LA}$ is the average energy consumption of a set of tentative clusters. For the details of computing the minimum average energy

consumption of a cluster and the threshold $\overline{LA}$, the reader may refer to [1].

IV. ROUTING TREE CONSTRUCTION

In this section, we propose a polynomial-time heuristic and an ILP algorithm for constructing a routing tree.

A. Candidate Graph Construction

Both our heuristic and ILP algorithm construct an undirected graph, namely candidate graph. In the candidate graph $G = (V \cup \{BS\}, E)$, the set of vertices consists of all the clusters and the base station (BS). The set E of edges is constructed as follows:

- 1) For each cluster $c_i \in V$, compute its centroid.
- 2) For each cluster c_i in group G_1 , the edge (c_i, BS) is in E .
- 3) For each cluster c_i in group $G_j (j = k, k-1, \dots, 2)$, all the edges between c_i and clusters in group G_{j-1} are constructed as follows:
 - a) Let c_s be a cluster in G_{j-1} such that the centroids of c_i and c_s has the shortest Euclidean distance, $h_{i,s}$ the Euclidean distance between the centroids of c_i and c_s , and P_i a set of clusters in group G_{j-1} such that the Euclidean distance between the centroids of c_i and each cluster in P_i is at most $\lambda h_{i,s}$, where λ is a pre-defined constant.
 - b) For any cluster $c_t \in P_i$, the edge (c_t, c_i) is in E .

Figure 2 shows a candidate graph, where λ is set to 2. The value of λ affects the performance of the inter-cluster routing tree. Typically, a small value for λ will suffice.

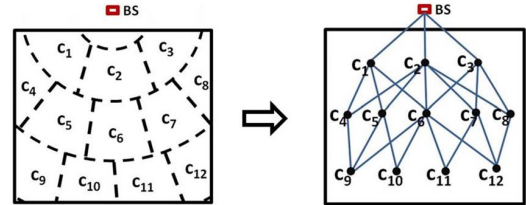


Fig. 2. Constructing the candidate graph

B. Computing Transmit Energy Consumption Between Adjacent Clusters

When considering a cluster c_j as the parent of a cluster c_i , we need to know the additional energy consumption incurred to both c_i and c_j due to inter-cluster communication. The cluster head rotation complicates the calculation of the additional energy consumption. Next, we describe how to calculate the additional energy consumption brought to each cluster.

For each cluster c_i , we specify a particular order for each sensor node in c_i to be the cluster head as follows:

- All the sensor nodes in c_i take turns to be the cluster head in a non-decreasing order of their Euclidean distances to the base station.

Given two clusters c_i and c_j , let $U_{i(x),j}$ be the transmit energy consumption of a sensor node x when running as the cluster head in cluster c_i and sending packets to cluster c_j in one round, and $Q_{i(x),j}$ the energy consumption of a sensor node x when running as the cluster head in cluster c_i and receiving packets from cluster c_j in one round.

Based on Equation 2, in a unit time, the energy consumption of x in c_i when receiving a packet from c_j is equal to $E_{Rx}(l)$. The duration of x to be the cluster head in each round is t_x . When x runs as the cluster head, it needs to not only receive a packet from each member, but also perform the data aggregation. Therefore, $Q_{i(x),j}$ is calculated as follows:

$$Q_{i(x),j} = (E_{Rx}(l) + l * E_{DA}) * t_x \quad (3)$$

In order to compute $U_{i(x),j}$, we need to construct cluster head schedules for c_i and c_j . A cluster head schedule specifies the time period of each member acting as the cluster head. Figure 3 shows the cluster head schedules of two cluster c_i and c_j in one round, where c_i and c_j have m nodes and n nodes, respectively.

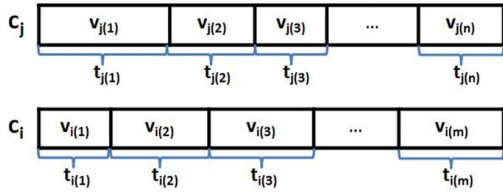


Fig. 3. An example of cluster head schedules

Note that the sum of the time periods of all the sensor nodes in c_i is equal to T , the duration of one round. All the time periods t_i are computed by using the approach described in [1]. For each sensor node x in cluster c_i , we need to partition its time period t_x when acting as the cluster head into multiple sub-periods. Each sub-period represents that a different sensor node in c_j is the cluster head of c_j during the sub-period. Figure 4 shows the sub-periods of each sensor node in c_i .

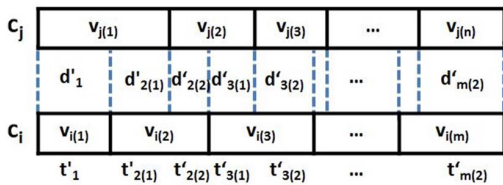


Fig. 4. A cluster head schedule for c_i with sub-periods

Given the time period t_x of a sensor node x in c_i and a sub-period $t'_s \in t_x$, let d'_s be the Euclidean distance between x and the cluster head of c_j during the sub-period t'_s . The transmit energy consumption $U_{i(x),j}$ of the sensor node x running as the cluster head of c_i is calculated as follows:

$$U_{i(x),j} = \sum_{t'_s \in t_x} E_{Tx}(l, d'_s) * t'_s \quad (4)$$

C. Heuristic

For ease of description, we introduce the following notations:

- W_i : the weight of cluster c_i , denoting the energy consumption of c_i . The initial value of W_i is set to LA_i as defined in [1]. W_i will be updated whenever a cluster selects c_i as its parent or c_i is assigned a parent cluster.
- $EW_{i,j}$: the edge weight between clusters c_i and c_j . $EW_{i,j}$ is equal to the maximum energy consumption of c_i and c_j based on the current partial routing tree.

Our heuristic constructs a routing tree in a bottom-up way, starting with the clusters in group G_k . At each step, for each cluster c_i in group G_j ($j = k, k-1, \dots, 2$), it selects a cluster among all the immediate ancestors in the candidate graph as its parent such that the maximum energy consumption of c_i and its parent cluster is minimized.

Consider that our heuristic selects a parent for each cluster c_i in a specific group G_j . We define a priority of each cluster c_i in G_j to be the number of immediate ancestors of c_i in the candidate graph, where a smaller number implies a higher priority. Our heuristic works for all the clusters in G_j as follows:

- 1) Compute the priority of each cluster in G_j .
- 2) Repeat the following until each cluster in G_j is assigned a parent:
 - a) Select a cluster c_i which has the highest priority among all the clusters in G_j without a parent.
 - b) Compute the edge weight of each edge between c_i and its immediate ancestors in the candidate graph. The edge weight between c_i and each immediate ancestor c_p is computed as follows:
 - i) Find the largest transmit energy $U_{i(max),p}$ of all the sensor nodes in cluster c_i .
 - ii) Find the largest receive energy $Q_{p(max),i}$ of all the sensor nodes in cluster c_p .
 - iii) The edge weight between cluster c_i and c_p is $EW_{i,p} = \max \{W_i + U_{i(max),p}, W_p + Q_{p(max),i}\}$.
 - c) Select a cluster c_s in G_{j-1} as the parent of c_i satisfying that c_s is an immediate ancestor in the candidate graph and the edge weight between c_i and c_s is the smallest among the weights of the edges between c_i and all its immediate ancestors in the candidate graph.
 - d) Update the weights of clusters c_i and c_s by $W_i = W_i + U_{i(max),s}$, $W_s = W_s + Q_{s(max),i}$.

D. ILP Algorithm

The objective of our ILP algorithm is to construct a shortest path spanning tree rooted at the base station such that the network lifetime is maximized. For each cluster c_i in the

candidate graph G , we introduce the following additional notations:

- PS_i : a set of the immediate ancestors of a cluster c_i in the candidate graph. Each cluster in PS_i is a candidate parent of c_i .
- CS_i : a set of the immediate successors of a cluster c_i in the candidate graph. Each cluster in CS_i is a candidate child of c_i .

In order to represent each edge uniquely, we stipulate that an edge $E_{i,j}$ denotes the edge between cluster c_i in group G_{s+1} and cluster c_j in group G_s .

For each edge $E_{i,j}$, we introduce a binary decision variable $X_{i,j}$ as follow:

$$X_{i,j} = \begin{cases} 1 & c_j \text{ is selected as the parent of } c_i \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Therefore, for each cluster c_i , we have the following parent selection constraint:

$$\sum_{c_j \in PS_i} X_{i,j} = 1 \quad (6)$$

The above constraint implies that among all the candidate parents of c_i , only one cluster can be selected as the parent of c_i .

Next, we derive the energy constraint for each sensor node. For each sensor node in cluster c_i , its intra-cluster energy consumption is LA_i defined in [1]. The energy consumption of a sensor node x in c_i when acting as the cluster head and sending packets to its parents is $\sum_{c_s \in PS_i} (X_{i,s} * U_{i(x),s})$, and the energy consumption of a sensor node x when acting as the cluster head of c_i and receiving packets from children nodes is $\sum_{c_t \in CS_i} (X_{t,i} * Q_{i(x),t})$. Therefore, the total energy consumption W_x of a sensor node x satisfies the following constraint:

$$W_x = LA_i + \sum_{c_s \in PS_i} (X_{i,s} * U_{i(x),s}) + \sum_{c_t \in CS_i} (X_{t,i} * Q_{i(x),t}) \quad (7)$$

The maximum total energy consumption W_{max} of all the sensor nodes in V is calculated as follows:

$$W_{max} = \max_{x \in V} \{W_x\} \quad (8)$$

Our optimization objective function is shown as follow:

$$\min W_{max} \quad (9)$$

V. SIMULATION RESULTS

In order to evaluate the performance of our approach, we have implemented our approach, and the two state-of-the-art approaches MR-LEACH [2] and DSBCV [4] that consider the same aggregation model as ours. We generate network instances of 200, 400, 600, 800, and 1000 sensor nodes deployed in a $200m * 200m$ square area, with uniform and random distributions. For each network instance, we choose 10, 15 and 20 for k , respectively. Each sensor node generates

one packet of data in each time unit. The initial energy of each sensor node is $1 J$ and the data packet size is 4000 bits . The other parameters are $E_{elec} = 50 \text{ nJ/bit}$, $\epsilon_{fs} = 10 \text{ pJ/bit/m}^2$, $\epsilon_{mp} = 0.0013 \text{ pJ/bit/m}^4$, $d_0 = 87 \text{ m}$, and $E_{DA} = 5 \text{ nJ/bit}$.

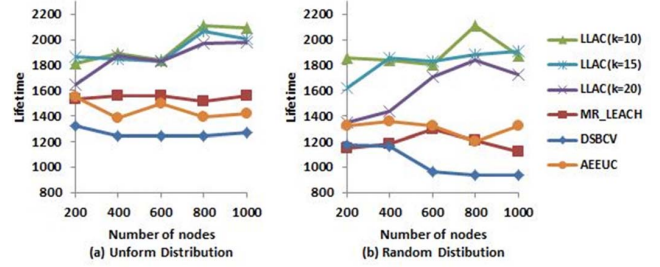


Fig. 5. Comparison of network lifetimes

Figure 5 shows the network lifetimes achieved by MR-LEACH, DSBCV, and our approach using the ILP algorithm for constructing a routing tree, where LLAC (Latency and Lifetime-Aware Clustering algorithm) denotes our approach. We can see that our approach LLAC achieves much better performance than MR-LEACH and DSBCV. Compared to DSBCV, the maximum improvement, the minimum improvement, and the average improvement of our approach are 126%, 6%, and 62%, respectively. Compared to MR-LEACH, the three improvements are 74%, 8%, and 35%, respectively.

We have compared the performance of our heuristic and the performance of our ILP algorithm for constructing a routing tree. The simulation results show that the average ratio between the network lifetime achieved by our approach using the heuristic and the network lifetime achieved by our approach using the ILP algorithm is 93% for uniform distribution, and 90% for random distribution. We also evaluated the impact of k on the network lifetime. For the details of our simulation results and analysis, the reader may refer to [1].

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