A Clustering Topology Control Algorithms For Heterogeneous Wireless Network

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***Abstract*—One critical issue in designing sensor topology control algorithms is to minimize the energy consumption for longevity. Most existing algorithms on topology control assume homogeneous wireless nodes with uniform maximum transmission ranges, and cannot directly applied to heterogeneous wireless multi-hop networks in which the maximum transmission range of each node may be different. In this paper, we present a localized topology control algorithm for heterogeneous networks: Directed Relative Neighborhood Graph Based On Clustering (DRNGC). In this algorithm, each node in the same cluster selects a set of neighbors based on the locally collected information. Simulation results show that the DRNGC reduce average degree of cluster-heads by up to 75% and translate power of cluster-heads by up to 75%, implying that there is a significant amount of energy-saving in collecting sensed data and workload reducing of cluster head.**

I. Introduction

The rapid development in small, low-power, low-cost microelectronic and micro-electromechanical (MEMs) sensor technology [1] along with the advances in wireless technology have enabled wireless sensors to be deployed in large quantities to form wireless sensor networks for a wide variety of purposes, e.g., a high-density wireless sensor network can be deployed for specific information-gathering. In such a network, sensors need to route their sensed data to a base station, consuming highly-limited and unreplenishable energy resource which distinguish sensor networks form the traditional ad hoc networks [2]. Due to the sensors' limited energy retainment, energy efficiency and network capacity are among the most important issues in wireless networks [3, 4].

Topology control via per-node transmission power adjustment has been shown to be effective in extending network lifetime and increasing network capacity (due to better spatial reuse of spectrum). Instead of transmitting using the maximal power, nodes in a wireless multi-hop network collaboratively determine their transmission power and define the network topology by forming the proper neighbor relation under various topology control algorithms. By enabling wireless nodes to use adequate transmission power (which is usually much smaller than the maximal transmission power), topology control can not only save energy and prolong network lifetime, but also improve spatial reuse (and hence the network capacity). Several topology control algorithms [6-12] have been proposed to create power-efficient network topology in wireless multi-hop networks with limited mobility. However, most of them assume homogeneous wireless nodes with uniform maximum transmission ranges (except [6] and [13]).

In this paper, our research focuses on a two-layer sensor organization which with an additional overlay of fewer but more powerful sensors. Under such situations, we propose an algorithm (DRNGC) which is based on Directed Relative Neighborhood (DRNG) algorithm [13], but by considering cluster-construction we introduce new dimensions to the topology control problem. The proposed scheme partitions the network into clusters first, each with a cluster- head, forming a direct link between cluster-head and cluster-members. Note that the links can exist between cluster-heads or cluster-members which are in the same clusters, it also can exist between cluster-head and its cluster-members, but cluster-members in different clusters could not be connected. And then we use an improved DRNG [13] algorithm adjust per-node's transmission power to form a new topology of the wireless sensors networks.

The remainder of the paper is organized as follows. First we present the network model under consideration and related assumptions in Sec. II. Our distributed topology control algorithm is presented and analyzed in Sec. III. In Sec. IV, we show the correctness and effectiveness of our algorithm with simulation results. Finally we conclude the paper in Sec. V.

II. Network Model And Assumptions

In this section, we consider a wireless sensor network as shown in Figure 1. It is composed of two kinds of nodes, sensors and relays, which work as cluster-members and cluster-heads, respectively. Sensors can sense their environment and generate data packets. Relays are used for propagation. All nodes are arbitrarily deployed in a two-dimensional plane. Each node is equipped with an omni-

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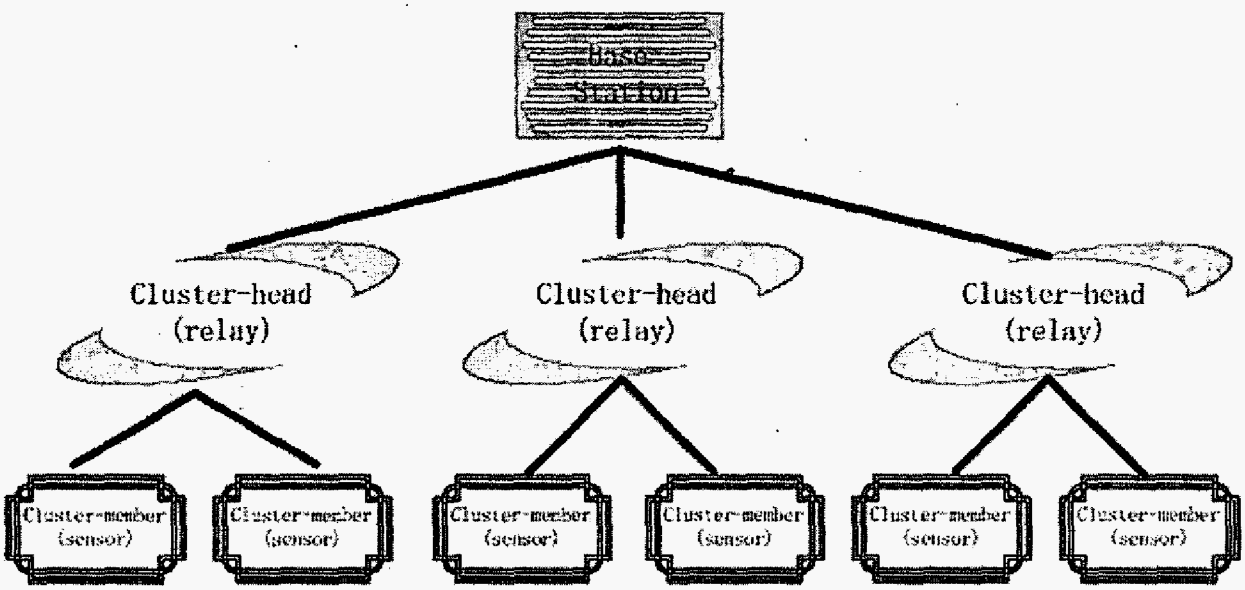

Figure 1. Construction of wireless sensor network

directional antenna with adjustable transmission power. Since nodes are heterogeneous, they have different maximum transmission powers and radio ranges. All data collected by the sensors is to be sent to a single or multiple base stations located outside the sensing field whose location is assumed to be fixed. And direct communications between the cluster-heads or in the interior clusters comprise wireless links. Such a scenario is motivated by applications in which data is desired from a hostile environment, such as a volcano or a swamp, where sensors are likely to be deployed in an unmanned manner.

We define this WSN as a directed graph $G=(V(G),E(G))$ where $V(G)=\{v_1,v_2,...,v_n\}$ is the set of randomly distributed nodes (sensors and relays) in the network and $E(G)$ is the set of links (edges). Each $v_i \in V$ has its maximum communication radio range with radius R_{v_i} that v_i can cover using its maximal transmission Power. In a heterogeneous network, the transmission ranges of nodes may not be the same. The distance between a sender v_i and receiver v_j is denoted by $d(v_i,v_j)$. An edge, denoted by $(v_i,v_j) \in E$, exist between v_i and v_j if $d(v_i,v_j) \le R_{v_i}$. Note that (v_i,v_j) is an ordered pair representing an edge from node v_i to node v_j, i.e., (v_i,v_j) and (v_j,v_i) are two different edges. A unique id (such as an IP/MAC address) is assigned to each node. Here we let $id(v_i)=i$ for simplicity; v_i working as a cluster-head (relays) is denoted by c_i. A set $C \in V$ is defined as a set of cluster-heads. Each sensor $v_j \in \{V-C\}$ is belongs to c_i if and only if $d(c_i,v_j)$ is minimum among all the cluster-head in C. The set of cluster-members of c_i will be denoted by M_{c_i} such that $\bigcup_{\forall c_i \in C} M_{c_i} = V-C$.

The information needed by the proposed algorithms is the knowledge of all existing edges in G. An edge that was not formed in the network, whether because the two end-nodes of the edge are too far away to communicate, or because there is an obstacle in between, does not have any impact on the results. As long as the original topology (which has taken into account of the obstacles in the network) is strongly connected, our algorithms can be applied to preserve the connectivity. This implies whether or not obstacles exist in the deployment area does not affect the correctness of the proposed algorithms. Now, let us introduce the following definitions.

***Definition 1** (Weight Function):* Given two edges (u_1,v_1), $(u_2,v_2) \in E$ and the Euclidean distance function $d(*,*)$, the weight function $w: E \rightarrow R$ satisfies:

$$
\begin{aligned}
& w(u_1,v_1) > w(u_2,v_2) \\
& \Leftrightarrow \ d(u_1,v_1) > d(u_2,v_2) \\
& or \ (d(u_1,v_1) = d(u_2,v_2) \,\&\&\, \max\{id(u_2),id(v_2)\}) \\
& or \ (d(u_1,v_1) = d(u_2,v_2) \\
& \qquad \&\& \max\{id(u_1),id(v_1)\} = \max\{id(u_2),id(v_2)\} \\
& \qquad \&\& \min\{id(u_1),id(v_1)\} > \min\{id(u_2),id(v_2)\})
\end{aligned}
$$

***Definition 2** (Neighbor Set):* Node v is an *out-neighbor* of node u (and u is an *in-neighbor* of v) under an algorithm A, denoted $u \xrightarrow{A} v$, if and only if there exists an edge (u,v) in the topology generated by the algorithm. In particular, we use $u \longrightarrow v$ to denote the neighbor relation in G. $u \xleftrightarrow{A} v$ if and only if $u \xrightarrow{A} v$ and $v \xrightarrow{A} u$. The *Out-Neighbor Set* of node u is $N_A^{out}(u) = \{v \in V(G) : u \xrightarrow{A} v\}$, and the *In-Neighbor Set* of u is $N_A^{in}(u) = \{v \in V(G) : v \xrightarrow{A} u\}$

***Definition 3** (Topology):* The topology generated by an algorithm A is a directed graph $G_A = (E(G_A), V(G_A))$, where $V(G_A) = V(G)$, $E(G_A) = \{(u,v) \in E(G) : u \xrightarrow{A} v\}$.

***Definition 4** (Radius):* The radius, R_u of node u is defined as the distance between node u and its farthest out-neighbor (in terms of Euclidean distance), i.e. $R_u = \max_{v \in N_A^{out}(u)} \{d(u,v)\}$

We make the following assumptions in this work:

- Heterogeneous sensors are uniformly distributed over a geographical area and they are capable of adjusting transmission power depending on the distance to the receiver.
- Each sensor is aware of its location in the network with the help of GPS or other means as in [14, 15].
- A sensed result collected by a cluster head has to be delivered to the base station over a multi-hop routing path if the base station is not within the radio range.

III. ALGORITHM

In this section, we propose our localized topology control algorithm in the following phases:

A. Cluster Formation

In phase 1, the network is partitioned into clusters as follows. Each cluster-head (relay) broadcast a message, referred to as the *welcome request* (WRQ) in the flood-broad way. The information contained in a WRQ should at least include the node id and the position of the node. These messages can be sent either in the date channel or in a separate control channel. Without loss of generality, for arbitrary node, v_i, upon receiving the overall WRQ messages of cluster-heads, every $d(v_i, c_j)$ which $\forall c_i \in C$ is know. It is easy for v_i to choose the nearest one as its cluster-head and reply a *join request (JRQ)* with its id and location.

Having the JRQ of its cluster-members, cluster-heads broadcast the list of its cluster-members and the clusters formed.

B. Establishing the vicinity topology

In the stage of establishing the vicinity topology, every node collects the information of its neighborhood. In particular, each node needs to know all the edges in its neighborhood. In [12], the *Reachable Neighborhood* was used for the local topology construction. We modify the definition for heterogeneous clustering networks as follows:

***Definition 5** (Reachable Neighborhood):* The reachable neighborhood N_u^R is the set of nodes that node u can reach using its maximal transmission power, and in the same cluster with u, or both u and N_u^R are cluster-heads. For each node $u \in V(G)$, let $G_u^R = (V(G_u^R), E(G_u^R))$ be an induced subgraph of G such that $V(G_u^R) = N_u^R$.

The skeleton is described as follows. Node v_i broadcasts a message, referred to as the *initialization request* (IRQ) message, using its maximum transmission power P_i^{max}, to other cluster-members in its cluster. If v_i is a cluster-head, it also broadcasts the message to other cluster-heads. The set of nodes that receive the IRQ message are referred to as the *vicinity nodes* of node v_i. The IRQ message includes the location and id of v_i, (x_i, y_i), as well as P_i^{max}. Upon receiving such an IRQ message, each node v_j in $N_{v_i}^R$ replies to node v_i with an *initialization reply* (IRP) message, with its location (x_j, y_j) and P_j^{max}.

In order for nodes in $N_{v_i}^R$ to decide the transmission powers for sending the IRP messages, we discuss the following two cases.

(1) For a node $v_j \in N_{v_i}^R$, if $P_j^{max} \geq d(i,j)$, v_j can reach node v_i via the single-hop link.

(2) If $P_j^{max} \leq d(i,j)$, v_j must find a multi-hop path to reach v_i. There are at least three solutions. (a) v_j Uses P_j^{max} to broadcast its IRP message with a special bit toggled to signal that the IRP may need to be relayed. When any other nodes receive such an IRP not addressed to them, they assist with relaying the message by re-broadcasting with their maximum transmission power. (b) v_j can send the IRP message via network layer packet routing protocols to v_i. A better approach in this case is to have v_j piggy-back the IRP message to v_i when it sends data packets to node v_i. (c) Node v_j takes advantage of the services provided by the sub-routing layer [16] to pass the IRP message back to v_i.

Having the knowledge of the locations and maximum transmission powers for itself and all its vicinity nodes, and

TABLE I. THE AVERAGE DEGREE OF CLUSTER-HEADS DERIVED USING NONE AND DRNGC

Id of cluster-head		1	2	3	4	5	6	7	8	9	10
Out-degree	NONE	17.32	22.35	12.21	18.17	16.61	13.42	11.25	35.27	12.33	19.21
	DRNGC	3.76	11.43	3.32	8.44	6.51	6.14	4.14	12.51	2.11	8.71
In-degree	NONE	12.51	13.75	11.28	13.31	12.93	11.42	10.31	18.72	10.93	14.51
	DRNGC	2.37	7.51	5.34	6.76	5.75	3.24	2.12	8.54	1.66	4.78

TABLE II. THE AVERAGE TRANSLATE RADIUS R_c OF CLUSTER-HEADS DERIVED USING NONE AND DRNGC

Id of cluster-head		1	2	3	4	5	6	7	8	9	10
R_c	NONE	102.91	129.38	120.81	109.32	103.2	103.74	115.5	147.2	149.04	127.76
	DRNGC	36.754	28.371	44.262	63.688	34.109	57.037	26.995	21.904	63.688	28.371

under the assumption that the path loss models of all vicinity nodes are coherent, node v_i may derive the existence of the *vicinity edge*. Consequently, node v_i constructs its local *vicinity topology* that includes all its vicinity nodes, itself and the discovered *vicinity edges*.

C. Topology Construction

After obtaining $E(G^R)$, the neighbor relation in DRNGC can be defined.

***Definition** 6 (Neighbor Relation in DRNGC):* For *Directed Relative Neighborhood Graph based on clustering* (DRNGC), $v \xrightarrow{DRNGC} u$ if and only if $v \in N_u^R$ and there does not exist a third node $q \in N_u^R$ such that $w(u,q) < w(u,v)$ and $w(q,v) < w(u,v)$; $d(q,v) \le R_q$.

Each node broadcasts its own maximal transmission power in the *Hello* or *Hi* message. By measuring the receiving power of the messages, each node *u* can determine the specific power level required to reach each of its out-neighbor [12]. Node *u* then uses the power level that can reach its farthest neighbor as its transmission power. This approach can be applied without knowing the actual propagation model.

IV. NUMBERICAL RESULTS

In order to show the correctness and effectiveness of our algorithm, we carry out experiments to measure the power efficiency of the final topology. Each data point reported below is an average of 100 simulation runs. We consider networks with 100 nodes uniformly distributed in a 100m× 100m region. 10 of them are relays (cluster-heads) whose transmission ranges are uniformly distributed in [100m, 150m], others are sensors (cluster-members) whose transmission ranges are uniformly distributed in [5m, 10m].First we define the *out-degree* and *in-degree* as follows:

Definition 7 (Degree): The out-degree of a node u under an algorithm A, denoted $\deg_A^{out}(u)$, is the number of out-neighbors of u, i.e., $\deg_A^{out}(u) = |N_A^{out}(u)|$. Similarly, the in-degree of a node u, denoted $\deg_A^{in}(u)$, is the number of in-neighbors, i.e., $\deg_A^{in}(u) = |N_A^{in}(u)|$.

We contrast the average degree (which is proportional to workload of cluster-heads) and translation radius (which is proportional to translate power of cluster-heads) derived using the maximal transmission power (labeled as NONE) with DRNGC in Table I and II. As shown in Table I and II, DRNGC significantly reduces the average degree of cluster-heads and translation power, i.e., both the workload of cluster-heads and the energy consumption of network are significantly reduced.

V. CONCLUDING

In this paper, we have proposed a localized topology control algorithm for heterogeneous networks: Directed Relative Neighborhood Graph Based on Clustering (DRNGC). Through analysis and simulation, we show that our algorithm provides a solution to the topology control problem in a network of heterogeneous wireless devices with different maximum transmission ranges. The result topology is shown to have a significant amount of energy-saving in collecting sensed data and workload reducing of cluster head for the average degree of cluster head reduces by up to 75% and average translate power by up to 75%.

As part of our future research, we will consider the connectivity of the networks which may render disconnected network topologies for their different maximal transmission ranges.

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