Design and Analysis of Connected Dominating Set Formation for Topology Control in Wireless Ad Hoc Networks

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Abstract **– To efficiently manage ad hoc networks, this paper proposes a novel distributed algorithm for connected dominating set (CDS) formation in wireless ad hoc networks with time and message complexity *O*(*n*). This *Area* algorithm partitions the nodes into different areas and selectively connects two dominators that are two or three hops away. Compared with previous well-known algorithms, we confirm the effectiveness of this algorithm through analysis and comprehensive simulation study. The number of nodes in the CDS formed by this Area algorithm is up to around 55% less than that constructed by others.**

Keywords-wireless ad hoc networks; minimum connected dominating set; distributed algorithm; topology control

I. INTRODUCTION

In wireless ad hoc networks that are formed by autonomous mobile devices communicating by radio, topology control plays an important role in the performance of the protocols used in the network, such as routing, clustering and broadcasting. There are two approaches for topology control in ad hoc networks – transmission range control and hierarchical topology organization (clustering). The goal of this technique is to control the topology of the graph representing the communication links between network nodes, with the purpose of maintaining some global graph property while reducing energy consumption. Moreover, topology control has the positive effect of reducing contention when accessing wireless channels. In general, when the nodes' transmission ranges are relatively short, many nodes can transmit simultaneously without interfering with each other.

As mentioned above, transmission range control is a general approach to topology control in ad hoc networks. The construction of hierarchical topology (clustering) is another effective solution in topology control. Cluster-based constructions are commonly regarded as a variant of topology control in the sense that energy-consuming tasks can be shared among the members of a cluster.

Although wireless ad hoc networks have no physical infrastructure, it is natural to construct clusters through connected dominating set formation. In general, a *dominating set* (DS) of a graph $G = (V, E)$ is a subset $V' \subset V$ such that each node in $V-V'$ is adjacent to at least one node in V', and a *connected dominating set* is a dominating set whose induced sub-graph is connected. It has been pointed out that "*The most basic clustering that has been studied in the context of ad hoc networks is based on dominating sets*" [4]. Moreover, the CDS can also play an important role for message broadcasting in ad hoc networks [3]. Unfortunately, the dominating set and connected dominating set problems have been shown to be NP-Complete [5]. Even for a unit disk graph (UDG) [1], the problem of finding a minimum CDS (MCDS) is still NP-Complete [7].

This paper presents a novel distributed algorithm, named the *Area* algorithm, for CDS formation in wireless ad hoc networks. In this algorithm, we partition the nodes into different areas and *selectively* connect two dominators that are two or three hops away. Note that, the clusterheads in most clustering algorithms [17, 22] usually form a DS. Since they focused on clusterhead selection, the clusterheads and gateways (selected to connect two clusterheads) construct a CDS with relatively large size. The contribution of this paper mainly lies in that we introduce the *Area* concept to significantly reduce the number of connectors that connect two neighboring dominators, thus reduce the total size of final CDS.

The rest of the paper is organized as follows. Section 2 introduces the related work. Section 3 describes the network assumption and preliminaries used in this paper. In Section 4, we present our novel distributed CDS formation algorithm and give the performance analysis. Section 5 presents the simulation results. We point out future directions and summarize major results in Section 6.

II. RELATED WORK

In this section we discuss related work with respect to topology control in two categories: Transmission Range Control and Hierarchical Topology Organization (in the context of connected dominating set formation).

A. *Transmission Range Control*

Previous proposals for topology control took advantage of some original research topics in computational geometry, such as the minimum spanning tree [20], the Delaunay Triangulation [19], the Relative Neighborhood Graph [21], or the Gabriel Graph [8]. Most of these contributions mainly considered energy-efficiency of paths in the resulting topology. The CBTC algorithm [18] was the first construction to focus on several desired properties. A nice literature review of transmission range control can be found in [4].

B. *Connected Dominating Set*

Das et al proposed a MCDS based routing algorithm for wireless ad hoc networks [2]. This algorithm is a distributed version of Guha and Khuller's centralized algorithm to calculate connected dominating set [10]. The algorithm proposed by Wu and Li first finds a connected dominating set and then prunes certain redundant nodes from the CDS [11]. Their algorithm is fully localized, but does not guarantee a good approximation ratio. Hereafter, this algorithm [11] is referred to as Rule 1&2 (so named for the two pruning rules). Stojmenovic et al also presented a distributed construction of CDS in the context of clustering and broadcasting [12]. The solution proposed in [23] relies on all nodes having a common clock and requires two-hop neighbor information. In CEDAR [13], a virtual infrastructure called the *core* is constructed to approximate a *minimum dominating set* (not connected) of the underlying network.

For distributed clustering algorithm, it is undesirable to have neighboring cluster-heads [17]. It is also undesirable to have one-hop away neighboring dominators in dominating set formation. This leads to the well-known concept of *maximal independent set* (MIS). An independent set of graph $G = (V, E)$ is a subset $S \subset V$ such that for any pair of vertices in S, there is no edge between them. Obviously, a MIS S is also an independent DS. The two heuristic algorithms proposed by Alzoubi et al [14] take advantage of the property of MIS, thus may guarantee a constant approximation ratio of 8 and 12 respectively. Although these two algorithms are distributed, they are not localized. To address the problem of non-localized computation, Alzoubi et al also proposed a message-optimal localized algorithm with linear time and message complexity [15]. The approximation ratio of this algorithm is bounded by 192. Recently, Wang et al proposed an efficient distributed method to construct a low-cost weighted minimum connected dominating set [24].

III. Network Assumptions and Preliminaries

In this paper, we assume that an ad hoc network comprises a group of nodes communicating with the same transmission range. Scheduling of transmission is the responsibility of MAC layer. Each node has a unique ID and each node knows the ID and degree of its neighbors, which can be achieved through periodically broadcasting "HELLO" messages by each node. Since the emphasis of this paper is on the CDS formation, we do not consider the node mobility. Dynamic topology change can be handled by the mechanisms proposed in [11, 15]. We call the nodes in the dominating set *dominators*, the nodes not in the dominating set *dominatees*, and the nodes that connect two or three hops away dominators *connectors*. Especially, we call the connector that connects dominators two and three hops away as *one-hop connector* and *two-hop connector*, respectively. Next, we give some well-known preliminaries.

Preliminary 1: *By building a dominating set through MIS construction, for every node u, the number of dominators inside the disk centered at u with radius k-unit is bounded by a constant* l_k.

Proof: Alzoubi et al gave a proof through calculation of $l_k < (2k + 1)^2 - 1$ [15]. When $k = 2, 3$, we have $l_k = 23, 47$. Recently, Li et al have proved that $l_3 = 42$ [16].

Preliminary 2: *Let G be a UDG and opt be the size of a minimum CDS for G, then the size of any MIS for G is at most* $3.8 \times opt + 1.2$.

The proof of this preliminary bounds the size of any MIS in G and can be found in [9].

Preliminary 3: *In a DS, the maximum distance to another closest dominator from any dominator is* 3.

Proof: By contradiction. Assume that the maximum distance from a dominator u to the closest dominator v is 4, and the shortest path between u and v is $\{u, x, y, z, v\}$. According to the definition of dominating set, node y must have a dominator, say w, which is one hop closer (three hops) to u than v. This contradicts the assumption that v is the closest dominator to u.

IV. Area Based CDS Formation Algorithm

A. Overview

A well-known method for building connected dominating set is to construct a MIS first, which is also a dominating set, then add some connectors to guarantee the connectivity. This method was utilized by Alzoubi et al [14, 15]. The algorithms in [14] were implemented by first electing a leader r among the nodes, which was going to be the root of a spanning tree T. The approximation ratios of these algorithms are attractive, however, the message complexity $O(n\log n)$ which is bounded by the distributed leader election, is quite high in real practice [6]. Moreover, they are not localized algorithms. The algorithm presented in [15] has an optimal message complexity $O(n)$, but it connects any pair of dominators (at most three hops away) by adding one or two connectors. Consequently, the resultant CDS has a relative large size with some redundant connectors.

Our main objective of this Area algorithm is to reduce the size of CDS. We use the *most-valued-nodes* as the metric to select the nodes among all nodes in the graph for the CDS. The *value* of a node is a performance-related characteristic such as node ID, node degree, or remaining battery life. In this paper, we define two kinds of *most-valued-nodes*, one is the node with the minimum ID among all the candidates of dominators or connectors (the resulting Area algorithm is called Min ID), and the other is the node with the maximum degree among all the candidates (hence, called Max Degree). In the following description of Area algorithm, we will use node degree as the selection metric.

B. Max Degree Algorithm

Define the rank of node u to be an ordered pair of (δ_u, id_u) where δ_u is the node degree and id_u is the node ID of u. We say that a node u with rank (δ_u, id_u) has a higher order than a node v with rank (δ_v, id_v) if $\delta_u > \delta_v$, or $\delta_u = \delta_v$ and $id_u < id_v$. Each node is in one of the four states: *unmarked*, *dominatee*, *dominator* and *connector*. Each node is initially in an unmarked state and subsequently enters either the dominatee or dominator state. The connector state can only be entered from the dominatee state. In this Area algorithm, we partition the nodes into different areas and each area is supposed to have a unique area ID. Thus, each node is also assigned an area ID to indicate which area it belongs to. For simplicity of description, we first give some definitions below:

Definition 1: *Seed Dominator* – A dominator that has the highest rank among its one-hop neighbors.

Definition 2: *Non-seed dominator* – A dominator that has at least one one-hop neighbor with higher rank.

Definition 3: *Border Dominator* – A dominator that has two or three hops away neighboring dominators with different area ID.

1) Area Formation: First, an unmarked node *u* with the highest rank among its unmarked one-hop neighbors becomes a dominator and broadcasts a DOMINATOR message to its neighbors. Note that such node does exist in the beginning. After receiving a DOMINATOR message, a node, say *v*, changes its state to be the dominatee if its current state is unmarked. If it is the first time that *v* receives a DOMINATOR message, *v* also broadcasts a DOMINATEE message to its neighbors. The same procedure is repeated until each node becomes either a dominator or a dominatee.

In fact, seed dominators are the starting points of the process of these MIS based algorithms and they are the cores of the areas. The ID of a seed dominator automatically becomes the ID of the corresponding area. During the area formation, we add an item, *Area ID*, into the DOMINATOR message to indicate the area that the dominator belongs to. When an unmarked node receives the first DOMINATOR message, it becomes a dominatee of the area indicated in this message. Each dominatee also inserts its area ID into the DOMINATEE message that it broadcasts to its neighbors. Then every non-seed dominator can know the area it belongs to from its neighboring dominatees. If neighboring dominatees have different area IDs, the non-seed dominator can arbitrarily select one area to join. The nodes with the same area ID form an area eventually.

2) Area Connection: After the nodes are partitioned into different areas, the following steps are executed by the related nodes:

1. Each dominatee broadcasts a ONE-HOP-DOMINATOR message which contains all node IDs and area IDs of its one-hop away dominators.
2. After receiving a ONE-HOP-DOMINATOR message, each node knows its two-hop away dominators and the corresponding neighbors to connect these dominators. The neighbor with higher rank has the priority to be chosen as a connector (maybe NOT the connector in the final CDS).
3. Upon reception of the ONE-HOP-DOMINATOR message from all its neighboring dominatees, a dominatee broadcasts a TWO-HOP-DOMINATOR message which contains all node IDs and area IDs of its two-hop away dominators.
4. After receiving a TWO-HOP-DOMINATOR message, each dominator knows its three-hop away neighboring dominators and the relevant neighbors to connect these dominators. Also, the neighbor with higher rank has the priority to become a connector.

After having the knowledge of all the two-hop and three-hop away neighboring dominators, each dominator can know whether it is a border dominator. Dominators inside an area only try to connect their two-hop away neighboring dominators with larger IDs by selecting one connector. Border dominators only connect one two-hop or three-hop away neighboring dominator with larger IDs in an adjacent area by selecting one or two connectors. That is, if a border dominator has connected to a two-hop away neighboring dominator in an adjacent area, it will not try to connect the three-hop away neighboring dominator in the same adjacent area. Then the dominating set is constructed through a sweep of the network spreading outwards from the seed dominators. To illustrate the algorithm, Figure 1 gives an example of the CDS formation using Max Degree algorithm.

3) Example: In Figure 1, the IDs of nodes are labeled beside the nodes. Black nodes represent the dominators, black nodes with outer circle represent the seed dominators and gray nodes represent the connectors. A possible execution scenario is shown in Figure 1(b - d), as explained below:

1. Initially all nodes are unmarked (Figure 1(a)).

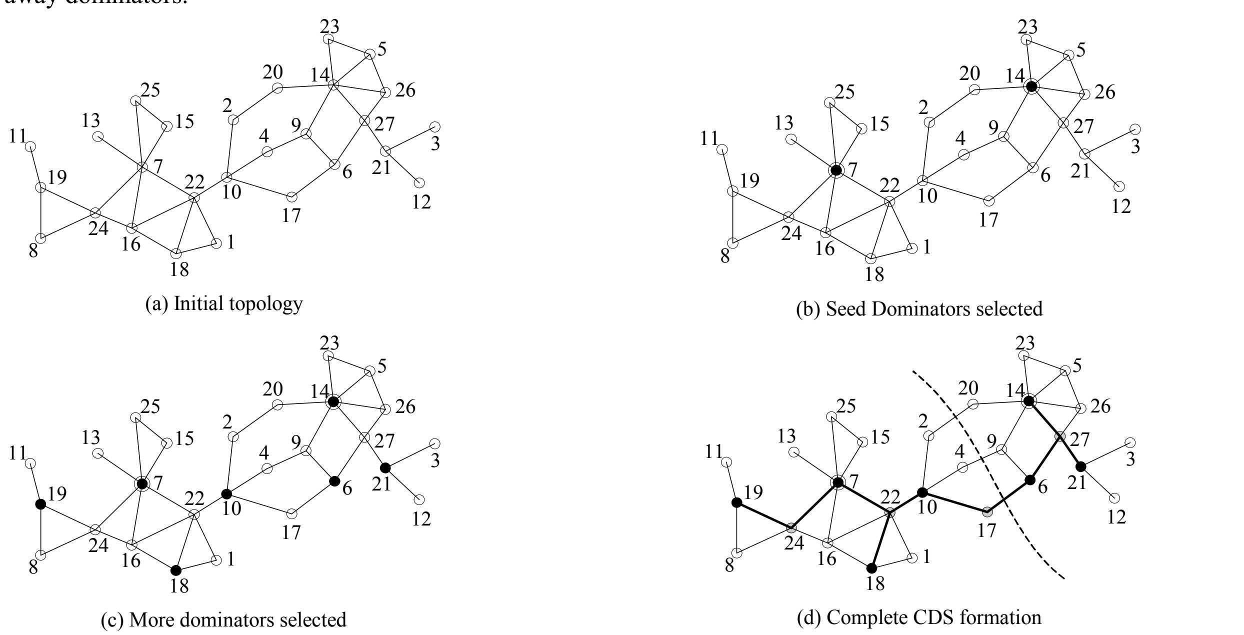

(a) Initial topology
(b) Seed Dominators selected
(c) More dominators selected
(d) Complete CDS formation

Figure 1. CDS Construction by Max Degree Algorithm

2. Nodes 7 and 14 declare themselves as dominators, since they have the highest ranks among their unmarked one-hop neighbors. These two dominators are also seed dominators. After receiving a DOMINATOR message, nodes 5, 9, 13, 15, 16, 20, 22, 23, 24, 25, 26 and 27 declare themselves as the dominatees and broadcast DOMINATEE messages (Figure 1(b)).
3. After receiving DOMINATEE messages from their neighbors, nodes 6, 10, 18, 19 and 21 declare themselves as dominators and broadcast DOMINATOR messages. The reason is that all their neighbors with higher ranks became dominatees, thus their ranks become the highest among their unmarked neighbors. At this time, all the dominators form a MIS and there are two areas centered at dominators 7 and 14 respectively. Suppose dominators 10 and 6 choose to join the areas with ID 7 and 14, respectively. (Figure 1(c)).
4. After each dominatee broadcasts ONE-HOP-DOMINATOR and TWO-HOP-DOMINATOR messages, every dominator knows its two-hop and three-hop away neighboring dominators. According to the definition, dominators 6, 10 and 14 know that they are border dominators. Finally, dominatees 22 and 24 are selected to become connectors by dominator 7 to connect dominators 10, 18 and 19; dominatee 27 is selected as connector by dominator 6 to connect dominator 14. Dominatee 17 is selected by dominator 6 to connect the two adjacent areas. Obviously, all the black and gray nodes form a connected dominating set of the graph and the induced sub-graph is indicated by the thick black lines (Figure 1(d)).

Note that compared with dominatee 9 with rank (3, 9), dominatee 27 has a higher rank (4, 27), so it is selected by dominator 6 to connect dominator 14. Dominatee 27 is also the only node that connects dominators 14 and 21. Since dominator 10 has a two-hop away neighboring dominator (node 6) in the adjacent area, it will not try to connect its three-hop away neighboring dominator, node 14, in the same area. From the above example, we can see that the benefit of using the area concept is that dominators can selectively connect to their two or three hops away neighboring dominators, thus, reduce the size of the final CDS.

C. Performance Analysis

In this subsection, we show the correctness, analyze the time and message complexity of the Area algorithm, and give the approximation ratio of this algorithm.

Theorem 1. *The dominators and connectors selected by the Area algorithm form a CDS.*

Proof: In this Area algorithm, it can be easily proved that each dominator has at least one two-hop away neighboring dominator in the area it belongs to if there is any other dominator existing in the same area. To connect each pair of two-hop away dominators, we can guarantee the connectivity inside these areas. Note that we also connect two adjacent areas using at least one path, thus, this theorem is proved.

Theorem 2. *The Area algorithm has both time and message complexity of* $O(n)$.

Proof: The time complexity of this algorithm is bounded by MIS construction which has the worst time complexity $O(n)$. The worst case occurs when all nodes are distributed in a line and in either ascending or descending order of their ranks. The rest of the process have time complexity at most $O(n)$. Since each node sends a constant number of messages, the total number of messages is also $O(n)$.

Theorem 3. *Let G be a unit disk graph and opt be the size of a minimum CDS for G, then the size of CDS constructed by this Area algorithm is within a constant approximation ratio of opt.*

Proof: From Preliminary 2, we know that the size of MIS is at most $3.8\times opt + 1.2$. Since each pair of nodes in MIS introduces at most two nodes to CDS, from Preliminary 1, the number of nodes in the CDS is at most $(42\times 2/2 + 1)\times(3.8\times opt + 1.2) = 163.4\times opt + 51.6$.

The density μ of graph can be calculated as

$$\mu(r) = (n\pi r^2)/A \quad (1)$$

where n is the number of nodes in the graph, A is the area of the graph and r is the transmission range.

Let D be the maximum density of packing of n equal circles in a circle. The upper bound of D is given in [25]:

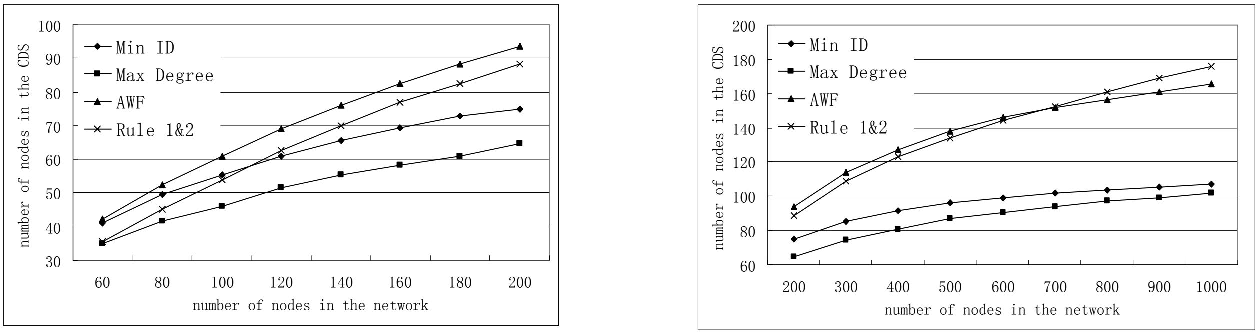
$$D \le \frac{n}{\left[1-\frac{\sqrt{3}}{2}+\sqrt{\frac{3}{4}+\frac{2\sqrt{3}}{\pi}(n-1)}\right]^2} \quad (2)$$

From (1) and (2), we can further refine l_2 in Preliminary 1 to be 21. Remember that, in this Area algorithm, the dominators and one-hop connectors form a CDS in the induced sub-graph of each area. Let *opt′* be the size of a minimum CDS for the induced sub-graph of an area. Through the similar analysis of Theorem 3, the size of CDS for an area is at most $(21/2 + 1)\times(3.8\times opt' + 1.2) < 44\times opt' + 14$.

Next section gives extensive simulation study to verify the efficiency of this Area algorithm in terms of the size of CDS.

V. Experimental Simulation

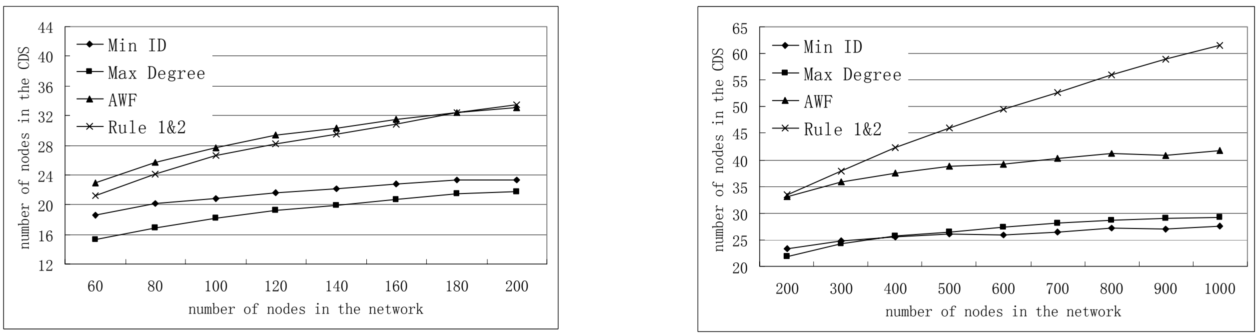
We compare the proposed two Area algorithms, Min ID and Max Degree, with Rule 1&2 [11] and Alzoubi's algorithm [15] in this section. For simplicity, we call Alzoubi's algorithm as AWF in the following. As mentioned above, Rule 1&2 first finds a CDS and then prunes some redundant nodes from the CDS using two rules (Rule 1 and Rule 2). In the first phase, each node is marked true (dominator) if it has two unconnected neighbors. According to Rule 1, a marked node can unmark itself if its neighbor set is covered by another neighboring marked node. According to Rule 2, a marked node can unmark itself if its neighborhood is covered by two other neighboring directly connected marked nodes. The combination of Rules 1 and 2 is fairly efficient to reduce the size of CDS. AWF can also be briefly described as two phases. In the first phase, a MIS is constructed. Note that, this MIS is also a DS. In the second phase, each dominatee identifies the dominators that are at most two hops away from itself and broadcasts this information. Using such information from all neighbors, each dominator identifies a path of at most three hops to each dominator that is at most three hops away from itself, and informs all nodes in this path to become the connectors and join the final CDS.



(a) # of nodes in CDS ($n \in [60, 200]$)

(b) # of nodes in CDS ($n \in [200, 1000]$)

Figure 2. The number of nodes in CDS when r is 15 units



(a) n ranges from 60 to 200

(b) n ranges from 200 to 1000

Figure 3. The number of nodes in CDS when r is 30 units

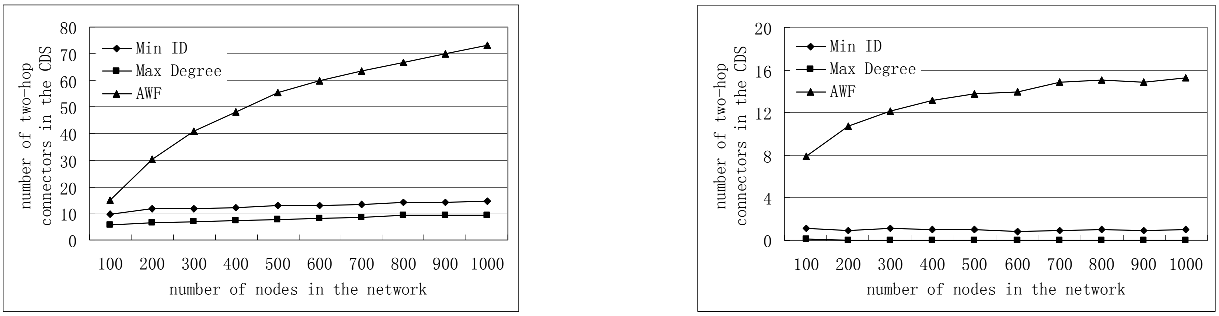
In the simulation scenario, a given number of nodes (ranging from 60 to 200 with increment step of 20 and from 200 to 1000 with increment step of 100, respectively) were randomly and uniformly distributed in a square simulation area of size 100 by 100 units. Each node has a fixed transmission range r (r = 15, 30 units, respectively). All the simulation results presented here were obtained by running these algorithms on 300 connected graphs. This allows us to test these algorithms on increasing density of network from n = 60, r = 15, and $\mu(r)$ = 4 (sparse network) to n = 1000, r = 30, and $\mu(r)$ = 283 (very dense network).

When the CDS is used for routing in ad hoc networks, the number of nodes responsible for routing can be reduced to the number of nodes in the CDS. Thus, we prefer smaller size of CDS. Figures 2(a) and 2(b) show the simulation results when the node's transmission range is 15 units. Figure 2(a) shows the trend when the number of nodes in the network ranges from 60 to 200 (the corresponding graph is sparse), whereas Figure 2(b) shows the trend when the number of nodes in the network ranges from 200 to 1000 (the corresponding graph is dense). The number of nodes in the CDS increases when more nodes join the network, because the number of dominators increases and more nodes may be selected as the connectors, thus the size of CDS increases. From the two figures, we also notice that the size of CDS is more sensitive to the number of nodes in the range from 60 to 200 (sparse network) than to that in the range from 200 to 1000 (dense network). As the number of nodes increases, the gap between the two Area algorithms and the other two becomes significant. And among these four algorithms, the performance of Max Degree is the best. When the number of nodes in the network reaches 1000, the number of nodes in the CDS constructed by Max Degree is only about 60% of that constructed by Rule 1&2 or AWF.

Figures 3(a) and 3(b) show the results when the node's transmission range is set as 30 units and the number of nodes in the networks ranges from 60 to 200 and from 200 to 1000, respectively. When the transmission range increases, as more nodes may be connected, the network becomes denser if the number of nodes is fixed. In this case, the size of CDS only increases slightly as the size of the network increases. Based on our simulation results, we find that among these four algorithms, Min ID outperforms the other three, followed by Max Degree, in very dense networks. Comparing Figures 2(a) and 2(b) with Figures 3(a) and 3(b), we find that increasing the node's transmission range can increase the coverage area of each node and, therefore, increase the density of the network, which leads to a smaller size of the CDS. When the number of nodes in the network reaches 1000, the number of nodes in the CDS constructed by Min ID is only about 45% of that constructed by Rule 1&2. We also compared the number of two-hop connectors in the CDS constructed by Min ID, Max Degree and AWF and the simulation results are given in Figures 4(a) and 4(b) respectively. We can see that both Min ID and Max Degree select much less two-hop connectors than AWF. In very dense networks, the number of two-hop connectors in the CDS constructed by Min ID and Max Degree approximates to zero.

VI. Conclusion and Future Work

In this paper, we proposed a novel distributed algorithm for connected dominating set formation in wireless ad hoc networks. In this *Area* algorithm, we partition the nodes into



(a) transmission range r = 15 units (b) transmission range r = 30 units

Figure 4. The number of two-hop connectors in CDS when n is from 100 to 1000

different areas and selectively connect dominators that are two or three hops away. The time complexity and message complexity of this algorithm are both $O(n)$. Moreover, this algorithm is localized, in which simple local node behavior achieves a desired global objective. From the simulation study, we have observed that this *Area* algorithm always outperforms Rule 1&2 [11] and AWF [15] regardless of the size and density of the networks in terms of the size of CDS.

In this Area algorithm, each node only requires the knowledge of its one-hop neighbors and a constant number of two-hop and three-hop neighbors, thus, the communication overhead is expected to be low. For the limited space, we will not present the related results here and refer the interested reader to [26]. For simplicity, we did not consider the issues of node energy and mobility. Our current work focuses on using the integration of residue energy and node mobility as the selection criteria instead of node ID and node degree.

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