On Calculating Power-Aware Connected Dominating Sets for Efficient Routing in Ad Hoc Wireless Networks

Jie Wu, Fei Dai, Ming Gao, and Ivan Stojmenovic

Abstract: **Efficient routing among a set of mobile hosts (also called nodes) is one of the most important functions in ad hoc wireless networks. Routing based on a connected dominating set is a promising approach, where the searching space for a route is reduced to nodes in the set. A set is dominating if all the nodes in the system are either in the set or neighbors of nodes in the set. Wu and Li [1] proposed a simple and efficient distributed algorithm for calculating connected dominating set in ad hoc wireless networks, where connections of nodes are determined by geographical distances of nodes. In general, nodes in the connected dominating set consume more energy in order to handle various bypass traffics than nodes outside the set. To prolong the life span of each node, and hence, the network by balancing the energy consumption in the network, nodes should be alternated in being chosen to form a connected dominating set. In this paper, we propose a method of calculating power-aware connected dominating set. Our simulation results show that the proposed approach outperforms several existing approaches in terms of life span of the network.**

Index Terms: **Ad hoc wireless networks, dominating sets, energy levels, mobile computing, routing, simulation.**

I. INTRODUCTION

An ad hoc wireless network is a special type of wireless networks in which a collection of mobile hosts with wireless network interfaces may form a temporary network, without the aid of any established infrastructure or centralized administration. If two hosts, located closely together within wireless transmission range of each other, are involved in the ad hoc wireless network, no real routing protocol or decision is necessary. However, if two hosts that want to communicate are outside their wireless transmission ranges, they could communicate only if other hosts between them in the ad hoc wireless network are willing to forward packets for them.

We can use a simple graph $G = (V, E)$ to represent an ad hoc wireless network, where V represents a set of wireless mobile hosts and E represents a set of edges. An edge between host pairs $\{v, u\}$ indicates that both hosts v and u are within their wireless transmission ranges. To simplify our discussion, we assume all mobile hosts are homogeneous, i.e., their wireless transmission ranges are the same. In other word, if there is an edge $e = \{v, u\}$ in E, it indicates that u is within v's range and v is within u's range. Thus the corresponding graph will be an undirected graph.

Routing in ad hoc wireless networks poses special challenges. Traditional routing protocols in wired networks, that generally use either *link state* [2], [3] or *distance vector* [4], [5], are no longer suitable for ad hoc wireless networks. In an environment with mobile hosts as routers, convergence to new, stable routes after dynamic changes in network topology may be slow and this process could be expensive due to low bandwidth. Routing information has to be localized to adapt quickly to changes such as host movements.

Dominating-set-based routing [1] is based on the concept of *dominating set* in graph theory [6]. A subset of the vertices of a graph is a dominating set if every vertex not in the subset is adjacent to at least one vertex in the subset. The main idea of this approach is to reduce the routing and searching process to a subgraph induced from the dominating set. Moreover, the dominating set should be connected for the ease of the routing process within the induced graph consisting of dominating nodes only. Vertices in a dominating set are called *gateway* hosts while vertices that are outside a dominating set are called *non-gateway* hosts. The main advantage of connected dominating-set-based routing is that it simplifies the routing process to that in a smaller subnetwork generated from the connected dominating set. This means that only gateway hosts need to keep routing information. As long as changes in network topology do not affect this subnetwork there is no need to re-calculate routing tables. Small connected dominating set also corresponds to a small forward node set in broadcasting [7] which minimize overall energy consumption per broadcast. In Fig. 1, v and w are gateway hosts which are connected, u, x, and y are non-gateway hosts. Each cycle in the figure corresponds to the wireless transmission range of a host. *Backbone-based routing* [8] and *spine-based routing* [9] use a similar approach, where a backbone (spine) consists of hosts similar to gateway hosts. *Cluster-based routing* [10] is another approach based on the notion of cluster. Hosts within vicinity (i.e., they are physically close to each other) form a cluster.

Clearly, the efficiency of this approach depends largely on the process of finding a connected dominating set and the size of the corresponding subnetwork. Unfortunately, finding a minimum connected dominating set is NP-complete for most graphs. Wu and Li [1] proposed a simple distributed *marking process* that can quickly determine a connected dominating set in a given

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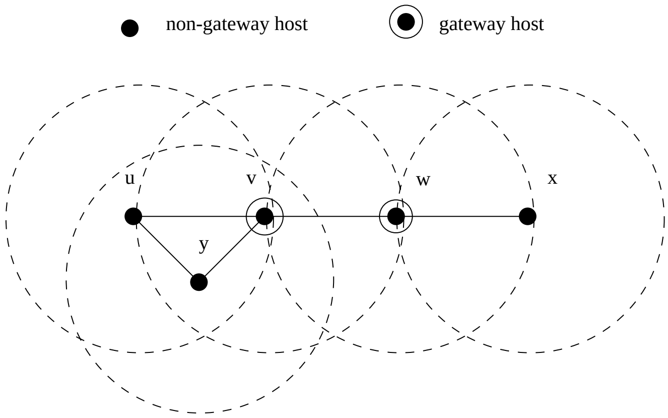


Fig. 1. A sample ad hoc wireless network.

connected graph, which represents an ad hoc wireless network. Basically, a node is marked gateway if two of its neighbors are not directly connected. Nodes that are marked gateway form a connected dominating set. It is shown that Wu and Li's approach outperforms several classical approaches in terms of finding a small dominating set and doing so quickly.

In ad hoc wireless networks, the limitation of power of each host poses a unique challenge for power-aware design [11]–[13]. There has been an increasing focus on low cost and reduced node power consumption in ad hoc wireless networks. Even in standard networks such as IEEE 802.11, requirements are included to sacrifice performance in favor of reduced power consumption [14]. In our approach, for certain cases we select non-shortest paths rather than shortest ones with low-energy nodes. In general, in order to prolong the life span of each node, and hence, the network, power consumption should be minimized as well as balanced among nodes. Unfortunately, nodes in the dominating set in general consume more energy in handling various bypass traffic than nodes outside the set. Therefore, a static selection of dominating nodes will result in a shorter life span for certain nodes, which in turn results in a shorter life span of the whole network. In this paper, we propose a method of calculating power-aware connected dominating set based on a dynamic selection process. Specifically, in the selection process of a gateway node, we give preference to a node with a higher energy level. Our simulation results show that the proposed selection process outperforms several existing ones in terms of longer life span of the network.

This paper is organized as follows: Section II summarizes related work in the field. Section III overviews the dominating-set-based routing and Wu and Li's decentralized formation of a connected dominating set. Section IV proposes two extensions to Wu and Li's approach: one is based on node degree and the other is based on energy level. An example is also included to illustrate different methods. Performance evaluation is done in Section V. Finally, in Section VI we conclude the paper.

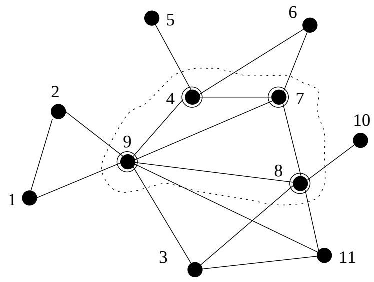
II. RELATED WORK

Toh [15] gave an excellent discussion on general issues related to power-aware (power-efficient) routing. It is argued that power conservation schemes should be applied to different network layers: physical layer ,data link layer, and network layer (where routing functions are located). At the network layer, power-efficient route can be selected based on either *minimum total transmission power routing* (MTPR) or *minimum battery cost routing* (MBCR) [16]. MTPR minimizes the total power needed to route packets on the network while MBCR maximizes the lifetime of all nodes. To achieve MTPR, Dijkstra's shortest path algorithm can be modified to obtain the minimum total power route [17]. MBCR and its variation [16] focuses directly on the lifetime of each host. *Conditional max-min battery capacity routing* (CMMBCR) [15] makes a better use of both MTPR and MBCR. Wieselthir *et al*., [18] discussed power-aware multicasting and broadcasting. A topology control using transmit power adjustment is proposed in [19], where the network generated with a "power-aware" topology can reduce the end-to-end packet delay and increase the robustness to node failure. Other surveys on power-aware routing can be found in [20] and [21].

One simple way to prolong the lifetime of each host is to evenly distribute packet-relaying loads to each node to prevent nodes from being overused. This approach is used in LEACH [12], where a probabilistic approach to randomly select cluster heads in data gathering in sensor networks is used. Cluster heads in LEACH are not connected. Lin and Gerla [22] provided a general discussion on various clustering algorithms. A classical approach is the following: First, a distributed head selection process is applied. A node v is a *head* if it has the largest id (or maximum node degree) in its 1-hop neighborhood including v. A head and its neighbors form a cluster and these nodes are *covered*. The above process continues on all uncovered nodes. Once the head selection process completes, some non-cluster-head nodes called *repeaters* are selected that have two or more neighbors belong to different clusters. Repeaters nodes are used to connect clusters. Head nodes form a unconnected dominating set (in fact no heads are connected). Head nodes and repeaters nodes form a connected dominating set.

Other metrics can be used together with the energy metric for certain routing applications. For example, power and cost are combined into a single metric in order to choose power efficient paths among cost optimal ones. Various combinations are studied by Stojmenovic and Lin [23] and Chang and Tassiulas [24]. To our knowledge, no work has been done on selecting a dominating set using energy metrics.

Recently, a modified marking process was proposed by a group at MIT [25]. A node is marked gateway if two of its neighbors fail both of the following two conditions: (a) directly connected and (b) connected by one or two gateways. Compared with the marking process by Wu and Li, an additional condition (b) is added. This modified marking process will generate a smaller set of gateway nodes if nodes do not apply the marking process at the same time. If all nodes apply the marking process at the same time (initially all nodes are non-gateways), condition (b) cannot be used and this approach is reduced to the marking process discussed in this paper. In addition, the modified marking process costs more: $O(\Delta^4)$ with one-hop intermediate gateway (and $O(\Delta^5)$ with two-hop intermediate gateways) at each node vs. $O(\Delta^2)$ of Wu and Li's marking process, where



(a)

3
10
11

gateway domain member list

(b)

destination	member list	next hop	distance
9	(1,2,3,11)	9	1
4	(5,6)	7	2
7	(6)	7	1

gateway routing table

(c)

Fig. 2. A routing example.

Δ is the maximum number of neighbors for a node. In addition, each node in the modified marking process needs to know 3-hop neighborhood information while each node in the marking process only require 2-hop neighborhood information.

III. PRELIMINARIES

In this section, we review Wu and Li's dominating-set-based routing and a marking process that determines a connected dominating set from a given connected graph.

A. Dominating-Set-Based-Routing

Assume that a connected dominated set has been determined for a given ad hoc wireless network. The routing process in a dominating-set-based routing is divided into three steps:

1. If the source is not a gateway host, it forwards the packets to a *source gateway*, which is one of the adjacent gateway hosts.
2. This source gateway acts as a new source to route the packets in the *induced graph* generated from the connected dominating set.
3. Eventually, the packets reach a *destination gateway*, which is either the destination host itself or a gateway of the destination host. In the latter case, the destination gateway forwards the packets directly to the destination host.

Each gateway host keeps following information: *gateway domain membership list* and *gateway routing table*. Gateway domain membership list is a list of non-gateway hosts which are adjacent to gateway hosts. Gateway routing table includes one entry for each gateway host, together with its domain membership list. For example, given an ad hoc wireless network as shown in Fig. 2 (a), the corresponding routing information items at host 8 are shown as in Fig. 2. Fig. 2 (b) shows that host 8 has three members 3, 10, and 11 in its gateway domain membership list. Fig. 2 (c) shows the gateway routing table at host 8, which consists of a set of entries for each gateway together with its membership list. Other columns of this table, including distance and routing information, are not shown. The way that routing tables are constructed and updated in the subnetwork generated from the connected dominating set can follow either the link-state approach or the distance-vector approach. The dominating set can also be used in a *reactive approach* [26] where no routing tables are maintained and a route is obtained *on demand* through a search process within the dominating nodes only.

B. Formation of Connected Dominating Set

Wu and Li [1] proposed a simple decentralized algorithm for the formation of connected dominating set in a given ad hoc wireless network. This algorithm is based on a marking process that marks every vertex in a given connected and simple graph $G = (V, E)$. $m(v)$ is a marker for vertex $v \in V$, which is either T (marked) or F (unmarked). We assume that all vertices are unmarked initially. $N(v) = \{u|\{v, u\} \in E\}$ represents the *open neighbor set* of vertex v, i.e., $v \notin N(v)$. The marking process consists of the following three steps:

1. Initially assign marker F to every v in V.
2. Every v exchanges its open neighbor set $N(v)$ with all its neighbors.
3. Every v assigns its marker $m(v)$ to T if there exist two unconnected neighbors.

In the example of Fig. 1, $N(u) = \{v, y\}$, $N(v) = \{u, w, y\}$, $N(w) = \{v, x\}$, $N(y) = \{u, v\}$, and $N(x) = \{w\}$. After Step 2 of the marking process, vertex u has $N(v)$ and $N(y)$, v has $N(u)$, $N(w)$, and $N(y)$, w has $N(v)$ and $N(x)$, y has $N(u)$ and $N(v)$, and x has $N(w)$. Based on Step 3, only vertices v and w are marked T.

Assume that $V^{'}$ is the set of vertices that are marked T in V, i.e., $V^{'} = \{v|v \in V, m(v) = T\}$. The *induced graph* $G^{'}$ is the subgraph of G induced by $V^{'}$, i.e., $G^{'} = G[V^{'}]$. The following results [1] show several desirable properties of the induced graph.

Property 1: *Given a graph $G = (V, E)$ that is connected but not completely connected, the vertex subset $V^{'}$, derived from the marking process, forms a dominating set of G.*

Property 2: *The induced graph $G^{'} = G[V^{'}]$ is a connected graph.*

Property 3: *The shortest path between any two vertices does not include any non-gateway vertex as an intermediate vertex.*

Since the problem of determining a minimum connected dominating set of a given connected graph is NP-complete, the connected dominating set derived from the marking process is normally non-minimum. Wu and Li [1] also proposed two rules based on node ID to reduce the size of a connected dominating set generated from the marking process. First of all, a distinct ID, $id(v)$, is assigned to each vertex v in G. $N[v] = N(v) \cup \{v\}$ is the *closed neighbor set* of v, as oppose to the open one $N(v)$.

Rule 1: *Consider two vertices v and u in $G^{'}$. If $N[v] \subseteq N[u]$ in G and $id(v) < id(u)$, the marker of v is changed to F if vertex v is marked; that is, $G^{'}$ is changed to $G^{'} - \{v\}$.*

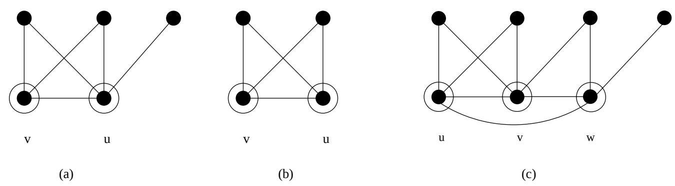


Fig. 3. Two examples for rule 1 and one for rule 2.

The above rule states that when the closed neighbor set of v is covered by that of u, vertex v can be removed from G' if the ID of v is smaller than that of u. Note that if v is marked and its closed neighbor set is covered by that of u, it implies that vertex u is also marked. When v and u have the same closed neighbor set, the vertex with a smaller ID will be removed. It is easy to prove that $G' - \{v\}$ is still a connected dominating set of G. The condition $N[v] \subseteq N[u]$ implies that v and u are connected in G'. Note that Properties 1, 2, and 3 are still preserved after the application of Rule 1.

In Fig. 3 (a), since $N[v] \subset N[u]$, vertex v is removed from G' if $id(v) < id(u)$ and vertex u is the only dominating node in the graph. In Fig. 3 (b), since $N[v] = N[u]$, either v or u can be removed from G'. To ensure one and only one is removed, we pick the one with a smaller ID. We call the above process the *selective removal* based on node ID.

Rule 2: *Assume that u and w are two marked neighbors of marked vertex v in G'. If $N(v) \subseteq N(u) \cup N(w)$ in G and $id(v) = \min\{id(v), id(u), id(w)\}$, then the marker of v is changed to F.*

The above rule indicates that when the open neighbor set of v is covered by the open neighbor sets of two of its marked neighbors, u and w, if v has the minimum ID of the three, it can be removed from G' (see the example in Fig. 3 (c)). The condition $N(v) \subseteq N(u) \cup N(w)$ in Rule 2 implies that u and w are connected. The subtle difference between Rule 1 and Rule 2 is the use of open and close neighbor sets. Again, it is easy to prove that $G' - \{v\}$ is still a connected dominating set. Both u and w are marked, because the facts that v is marked and $N(v) \subseteq N(u) \cup N(w)$ in G imply that if $N(u) \not\subseteq N(w)$, u has two unconnected neighbors w and $x \in (N(u) - N(w))$ and shall be marked. Similarly, if $N(w) \not\subseteq N(u)$, w shall also be marked. Therefore, to apply Rule 2, no additional step needs to be added in the marking process. Note that Properties 1 and 2 are still preserved after the application of Rule 2, but not Property 3. That is, the hop count between two nodes may increase after Rule 2. In [1], it has been shown that the marking process, together with Rules 1 and 2, outperforms several classical approaches in terms of finding a small dominating set and doing so quickly.

All the above examples represent just global snapshot of the dynamic topology for a given ad hoc wireless network. Because the topology of the network changes over time, the connected dominating set also needs to be updated from time to time. Wu and Dai [27] show the desirable locality feature of the marking process. More specifically, it is shown that only the neighbors of changing hosts need to update their gateway/non-gateway status. Note that a simple way of maintaining the dominating set structure is also crucial in reducing overall energy consumption in the network. Feeney [28] shows that energy required to start up communication is relatively significant. Protocols using any kind of periodic hello messages, frequently used in ad hoc network literature, are extremely energy inefficient. Other features related to the marking process can be found in [1].

IV. EXTENDED RULES

In this paper, we consider several extended rules for selective removal. One is based on node degree and the other one is based on energy level associated with each node. The main goals of these two extensions are different: the node-degree-based approach aims at reducing the size of the connected dominating set while the energy-level-based approach tries to prolong the average life span of each node. The additional cost associated with extended rules is insignificant both in terms of communication and computation. Additional information that needs to be collected from neighbors are energy levels which can be piggybacked with the neighborhood information. In terms of computation, a few more cases need to be considered for each node to determine its status, but they will not increase the overall complexity. In the subsequent discussion, we use term node, host, and vertex interchangeably.

A. Node-Degree-Based Rules

In the following, we propose two rules based on *node degree* (ND) to reduce the size of a connected dominating set generated from the marking process. First of all, a distinct ID, $id(v)$, is assigned to each vertex v in G. In addition, $nd(u)$ represents the node degree of u in G, i.e., the cardinality of u's open neighbor set $N(u)$.

Rule 1a: *Consider two marked vertices v and u in G'. The marker of v is changed to F if one of the following conditions holds:*

1. *$N[v] \subseteq N[u]$ in G and $nd(v) < nd(u)$.*
2. *$N[v] \subseteq N[u]$ in G and $id(v) < id(u)$ when $nd(v) = nd(u)$.*

The above rule indicates that when the closed neighbor set of v is covered by that of u, node v can be removed from G' if the ND of v is smaller than that of u. Node ID's are used to break a tie when the node degrees of two nodes are the same. Note that $nd(v) < nd(u)$ implies that $N[u] \not\subseteq N[v]$, and if v is marked and its closed neighbor set is covered by that of u, it implies that node u is also marked. It is easy to prove that $G' - \{v\}$ is still a connected dominating set of G. The condition $N[v] \subseteq N[u]$ implies v and u are connected in G'.

Rule 2a: *Assume that u and w are two marked neighbors of marked vertex v in G'. The marker of v is changed to F if one of the following conditions holds:*

1. *$N(v) \subseteq N(u) \cup N(w)$, but $N(u) \not\subseteq N(v) \cup N(w)$ and $N(w) \not\subseteq N(u) \cup N(v)$ in G.*
2. *$N(v) \subseteq N(u) \cup N(w)$ and $N(u) \subseteq N(v) \cup N(w)$, but $N(w) \not\subseteq N(u) \cup N(v)$ in G; and one of the following conditions holds:*
   (a) $nd(v) < nd(u)$, or

   (b) $nd(v) = nd(u)$ *and* $id(v) < id(u)$.
3. $N(v) \subseteq N(u) \cup N(w)$, $N(u) \subseteq N(v) \cup N(w)$ *and* $N(w) \subseteq N(u) \cup N(v)$ *in G; and one of the following conditions holds:*
   (a) $nd(v) < nd(u)$ *and* $nd(v) < nd(w)$,
   (b) $nd(v) = nd(u) < nd(w)$ *and* $id(v) < id(u)$, *or*
   (c) $nd(v) = nd(u) = nd(w)$ *and* $id(v) = \min\{id(v), id(u), id(w)\}$.

The above rule indicates that when the open neighbor set of v is covered by the open neighbor sets of two of its marked neighbors, u and w (or simply v is covered by u and w); in case (1), if neither u nor w is covered by the other two among u, v, and w, node v can be removed from G'; in case (2), if nodes v, u are covered by u and w, v and w, respectively but w is not covered by u and v, node v can be removed from G' if the ND of v is smaller than that of u or the ID of v is smaller than that of u when their ND's are the same; in case (3), when each of u, v and w is covered by the other two among u, v and w, node v can be removed from G' if one of the following conditions holds: v has the minimum ND among u, v and w, the ND of v is the same as the ND of u but it is smaller than that of w and the ID of v is smaller than that of u, or the ND's of u, v, and w are the same and v has the minimum ID among u, v, and w. The condition $N(v) \subseteq N(u) \cup N(w)$ in Rule 2a implies that u and w are connected. Again, it is easy to prove that $G' - \{v\}$ is still a connected dominating set. Both u and w are marked, because the fact that v is marked and $N(v) \subseteq N(u) \cup N(w)$ in G does not imply that u and w are marked. Therefore, if one of u and w is not marked, v cannot be unmarked (change the marker to F).

B. Energy-Level-Based Rules

In the following, we propose two rules based on *energy level* (EL) to prolong the average life span of a host, and at the same time, to reduce the size of a connected dominating set generated from the marking process.

We first assign a distinct ID, $id(v)$, and an initial EL, $el(v)$, to each vertex v in G'. In a dynamic system such as an ad hoc wireless network, network topology changes over time. Therefore, the connected dominating set also needs to change. Wu and Li [1] showed that the connected dominating set only needs to be updated in a localized manner, i.e., only neighbors of changing hosts need to update their gateway/non-gateway status. An *update interval* is the time between two consecutive updates in the network. Assume that d' and d are energy consumption in a given interval for a gateway host and a non-gateway host, respectively. That is, each time after applying both Rule 1b and Rule 2b (discussed below), EL of each gateway host will be decreased by d' and EL of each non-gateway host will be decreased by d. When the energy level of u, $el(u)$, reaches zero, it is assumed that host u ceases to function. In general, $d' > d$ and d' and d are variables dependent on the length of update interval and bypass traffic. Given an initial energy level of each host and values for d' and d, the energy level associated with each host has multiple discrete levels.

Rule 1b: *Consider two marked vertices v and u in G'. The marker of v is changed to F if one of the following conditions holds:*

1. $N[v] \subseteq N[u]$ *in G and* $el(v) < el(u)$.
2. $N[v] \subseteq N[u]$ *in G and* $id(v) < id(u)$ *when* $el(v) = el(u)$.

The above rule indicates that when the closed neighbor set of v is covered by that of u, vertex v can be removed from G' if the EL of v is smaller than that of u. ID is used to break a tie when $el(v) = el(u)$.

In Fig. 3 (a), since $N[v] \subset N[u]$, node v is removed from G' if $el(v) < el(u)$ and node u is the only dominating node in the graph. In Fig. 3 (b), since $N[v] = N[u]$, either v or u can be removed. To ensure that one and only one is removed, we pick that with a smaller EL.

Rule 2b: *Assume that u and w are two marked neighbors of marked vertex v in G'. The marker of v is changed to F if one of the following conditions holds:*

1. $N(v) \subseteq N(u) \cup N(w)$, *but* $N(u) \not\subseteq N(v) \cup N(w)$ *and* $N(w) \not\subseteq N(u) \cup N(v)$ *in G.*
2. $N(v) \subseteq N(u) \cup N(w)$ *and* $N(u) \subseteq N(v) \cup N(w)$, *but* $N(w) \not\subseteq N(u) \cup N(v)$ *in G; and one of the following conditions holds:*
   (a) $el(v) < el(u)$, *or*
   (b) $el(v) = el(u)$ *and* $id(v) < id(u)$.
3. $N(v) \subseteq N(u) \cup N(w)$, $N(u) \subseteq N(v) \cup N(w)$ *and* $N(w) \subseteq N(u) \cup N(v)$ *in G; and one of the following conditions holds:*
   (a) $el(v) < el(u)$ *and* $el(v) < el(w)$,
   (b) $el(v) = el(u) < el(w)$ *and* $id(v) < id(u)$, *or*
   (c) $el(v) = el(u) = el(w)$ *and* $id(v) = \min\{id(v), id(u), id(w)\}$.

The above rule indicates that when v is covered by u and w; in case (1), if neither u nor w is covered by the other two among u, v, and w, node v can be removed from G'; in case (2), if nodes v, u are covered by u and v, v and w, respectively, but w is not covered by u and v, node v can be removed from G' if the EL of v is smaller than that of u or the ID of v is smaller than that of u when their ND's are the same; in case (3), when each of u, v and w is covered by the other two among u, v and w, node v can be removed from G' if one of the following conditions holds: v has the minimum EL among u, v, and w, the EL of v is the same as the EL of u but it is smaller than that of w and the ID of v is smaller than that of u, or the EL's of u, v, and w are the same and v has the minimum ID among u, v, and w.

In the following, we propose another two rules based on EL to prolong the life span of each node to reduce the size of a connected dominating set. Unlike Rule 1b and Rule 2b where ID is used when there is a tie in EL, in Rule $1b'$ and $2b'$, ND is used when there is a tie in EL and ID is used only when there is a tie in ND.

Rule 1b$'$: *Consider two vertices v and u in G'. The marker of v is changed to F if one of the following conditions holds:*

1. $N[v] \subseteq N[u]$ *in G and* $el(v) < el(u)$.
2. $N[v] \subseteq N[u]$ *in G and* $nd(v) < nd(u)$ *when* $el(v) = el(u)$.
3. $N[v] \subseteq N[u]$ *in G and* $id(v) < id(u)$ *when* $el(v) = el(u)$ *and* $nd(v) = nd(u)$.

The above rule indicates that when the closed neighbor set of v is covered by that of u, node v can be removed from G' if the EL of v is smaller than that of u. When there is a tie in EL, v can be removed if the ND of v is smaller than the one of u, and when there is a tie ND, v can be removed if the ID of v is smaller than that of u.

Rule 2b$'$: *Assume that u and w are two marked neighbors of marked vertex v in G'. The marker of v is changed to F if one of the following conditions holds:*

1. *$N(v) \subseteq N(u) \cup N(w)$, but $N(u) \not\subseteq N(v) \cup N(w)$ and $N(w) \not\subseteq N(u) \cup N(v)$ in G.*
2. *$N(v) \subseteq N(u) \cup N(w)$ and $N(u) \subseteq N(v) \cup N(w)$, but $N(w) \not\subseteq N(u) \cup N(v)$ in G; and one of the following conditions holds:*
   (a) $el(v) < el(u)$, or
   (b) $el(v) = el(u)$; and $nd(v) < nd(u)$, or, $id(v) < id(u)$ when $nd(v) = nd(u)$.
3. *$N(v) \subseteq N(u) \cup N(w)$, $N(u) \subseteq N(v) \cup N(w)$ and $N(w) \subseteq N(u) \cup N(v)$ in G; and one of the following conditions holds:*
   (a) $el(v) < el(u)$ and $el(v) < el(w)$,
   (b) $el(v) = el(u) < el(w)$; and $nd(v) < nd(u)$, or, $id(v) < id(u)$ when $nd(v) = nd(u)$, or
   (c) $el(v) = el(u) = el(w)$ and v satisfies Step 3 of Rule 2a.

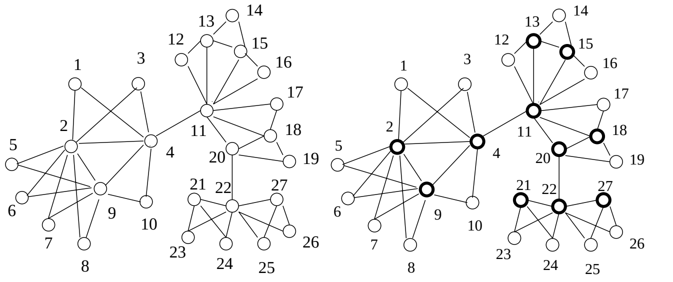
The above rule indicates that when v is covered by u and w; in case (1), if neither u nor w is covered by the other two among u, v, and w, node v can be removed from G'; in case (2), if nodes v, u are covered by u and v, v and w, respectively, but w is not covered by u and v, node v can be removed if the EL of v is smaller than that of u, or the EL of v is the same as that of u. In the latter case, either the ND of v is smaller than that of u or the ID of v is smaller than that of u when their ND's are the same; in case (3), when each of u, v, and w is covered by the other two among u, v, and w, node v can be removed if one of the following conditions holds: the EL of v has the minimum EL among u, v, and w, the EL of v is the same as the EL of u but it is smaller than that of w and the ND of v is smaller than that of u or the ID of v is smaller than that of u when the ND of v is the same as that of u, or the EL of u, v, and w are the same when it satisfies Step 3 of Rule 2a.

C. An Example

Figs. 4, 5, and 6 show an example of using the proposed marking process and its extensions to identify a set of connected dominating nodes. Each node keeps a list of its neighbors and sends this list to all its neighbors. By doing so each node has distance-2 neighborhood information.

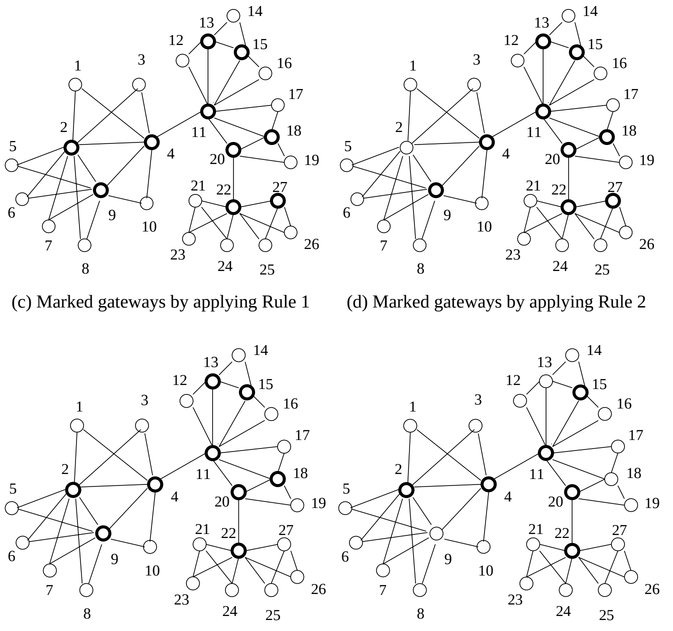
In Fig. 4 (a), node 1 will not mark itself as a gateway node because its only neighbors 2 and 4 are connected. Node 4 will mark itself as a gateway node because there is no connection between neighbors 3 and 9 (3 and 11). Fig. 4 (b) shows the gateway nodes (nodes with cycles) derived by the marking process without applying any rules.

After applying Rule 1, node 21 will be unmarked to the non-gateway status as shown in Fig. 5 (c). The closed neighbor set



(a) Example graph (b) Marked gateways without applying rules.

Fig. 4. An example of marking process.



(c) Marked gateways by applying Rule 1 (d) Marked gateways by applying Rule 2

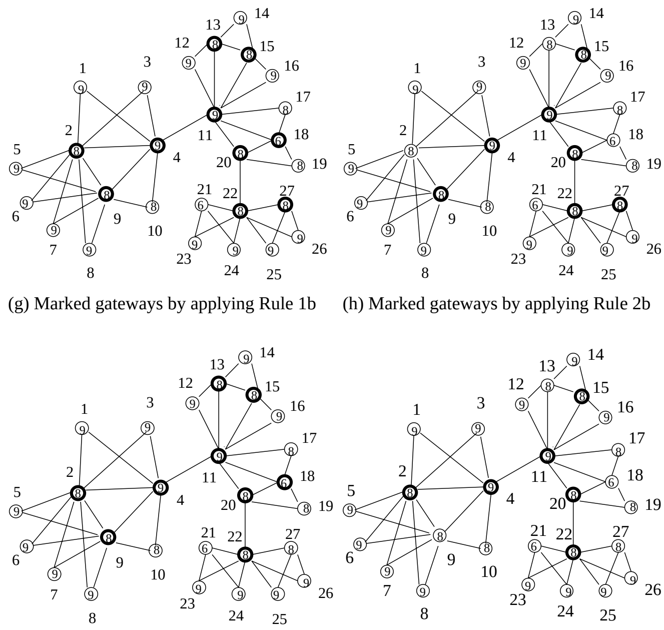
(e) Marked gateways by applying Rule 1a (f) Marked gateways by applying Rule 2a

Fig. 5. Examples for rules 1, 2, 1a, and 2a.

of node 21 is $N[21] = \{21, 22, 23, 24\}$, and the closed neighbor set of node 22 is $N[22] = \{20, 21, 22, 23, 24, 25, 26, 27\}$. Apparently, $N[21] \subseteq N[22]$. Also the ID of node 21 is less than the ID of node 22, thus node 21 can unmark itself by applying Rule 1. Also, $N(2) \subseteq N(4) \cup N(9)$. Node 2 has the minimum ID among nodes 2, 4, and 9. Thus node 2 can unmark itself by applying Rule 2 (see Fig. 5 (d)).

Apparently $N[21] \subseteq N[22]$ and $N[27] \subseteq N[24]$. In addition, node 21 has the minimum ND among nodes 21, 22 and 27, thus both nodes 21 and 27 can unmark themselves by applying Rule 1a (see Fig. 5 (e)). Also, $N(9) \subseteq N(2) \cup N(4)$, $N(2) \subseteq N(4) \cup N(9)$, but $N(4) \not\subseteq N(2) \cup N(9)$. For node 13, $N(13) \subseteq N(11) \cup N(15)$, $N(15) \subseteq N(11) \cup N(13)$, but $N(11) \not\subseteq N(13) \cup N(15)$. For node 18, $N(18) \subseteq N(11) \cup N(20)$, $N(11) \not\subseteq N(18) \cup N(20)$, and $N(20) \not\subseteq N(11) \cup N(18)$. Thus nodes 9, 13, and 18 can unmark themselves by applying Rule 2a (see Fig. 5 (f)).

After applying Rule 1b, node 21 will be unmarked to the non-gateway status as shown in Fig. 6 (g), where the number inside each node corresponds to the energy level of that node. The energy level assigned to each node is a random



(g) Marked gateways by applying Rule 1b (h) Marked gateways by applying Rule 2b

(i) Marked gateways by applying Rule 1b' (j) Marked gateways by applying Rule 2b'

Fig. 6. Examples for rules 1b, 2b, 1b$'$, and 2b$'$.

number in this figure. The closed neighbor set of node 21 is $N[21] = \{21, 22, 23, 24\}$, and the closed neighbor set of node 22 is $N[22] = \{20, 21, 22, 23, 24, 25, 26, 27\}$. Apparently, $N[21] \subseteq N[22]$, also the EL of node 21 is less than the EL of node 22, thus node 21 can unmark itself by applying Rule 1b. Also, $N(2) \subseteq N(4) \cup N(9)$. The EL of node 2 is as same as the EL of node 9 and the ID of node 2 is smaller than that of node 9. For node 13, $N(13) \subseteq N(11) \cup N(15)$, $N(15) \subseteq N(11) \cup N(13)$, but $N(11) \not\subseteq N(13) \cup N(15)$ and the EL of node 13 is as same as that of node 15 and node ID of node 13 is smaller than that of node 15. For node 18, $N(18) \subseteq N(11) \cup N(20)$, and $N(20) \not\subseteq N(11) \cup N(18)$, and node has the minimum EL among nodes 11, 18 and 20. Thus nodes 2, 13 and 18 can unmark themselves by applying Rule 2b.

Following the similar argument, after applying Rule 1b$'$, both nodes 21 and 27 will be unmarked to the non-gateway status as shown in Fig. 6 (i); after applying Rule 2b$'$, nodes 9, 13 and 18 will be unmarked to the non-gateway status as shown in Fig. 6 (j).

V. PERFORMANCE EVALUATION

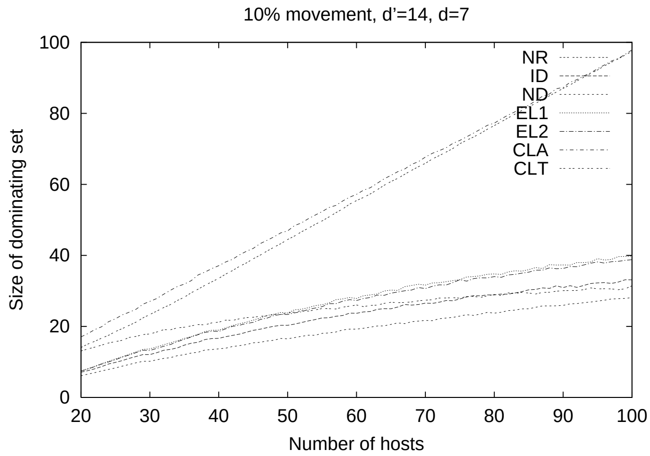
In this section, we compare different approaches for determining a connected dominating set in an ad hoc wireless network with and without applying two rules and their variations. Specifically, we measure the size of the connected dominating set generated from the marking process and compare it with the size of the connected dominating set after applying different rules, which include the rules based on ID, the rules based on ND, and the rules based on EL. In addition, the average life spans of the network under different rules are also simulated. To perform a fair comparison with other methods, an energy-aware cluster-based approach is adopted: cluster heads are decided based on their energy levels. Node id is used to break a tie in energy levels. There are two extreme ways to select repeaters to connect adjacent cluster heads: the "normal" one includes all repeaters that meet the condition (i.e., nodes with two or more neighbors in different clusters) and the 'optimized' one uses a variation of Kruskal's algorithm (for constructing a minimum spanning tree) that sequentially merges two fragments (initially each cluster is a fragment). The "normal" is labeled as CLA and "optimized" on is called CLT. Again, d' (d) is amount of energy consumed at each update interval for a repeater and a cluster head (non-cluster-head and non-repeater node). To unify the notation, repeaters and cluster heads are called gateways. Other nodes are called non-gateways.

The simulation is conducted in a 100 × 100 2-D free-space by randomly allocating a given number of hosts ranging from 20 to 100. The radius of transmitter range is assumed to be 25, and the energy level of each host is initialized to 1000. The number c represents the percentage of moving host. In our simulation c is 10% for networks with low mobility and 50% for networks with high mobility. In each update interval, $c\%$ of the total hosts are randomly picked as moving hosts. Each moving host moves l units towards a random selected destination, where l is a random number in [1...25]. If the destination is too close to its original position (i.e., the distance between them is smaller than l), another random destination is selected and this process continues until the host moves l units. In this paper, like many existing approaches, we do not deal with the issue on how messages use a shared channel to avoid contention and collision. It is assumed that this issue is taken care of at the MAC layer.

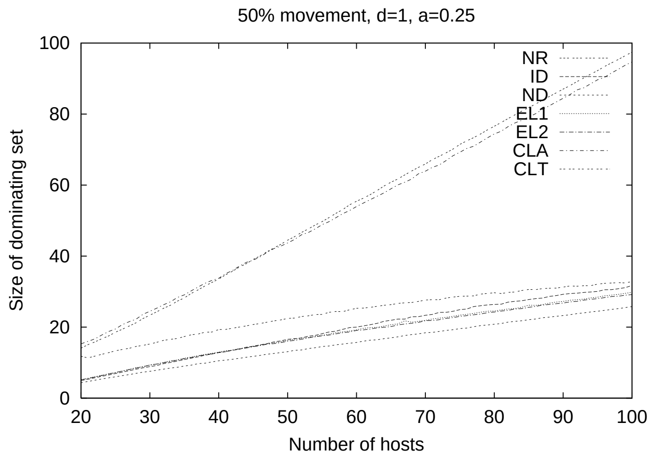
The simulation is conducted using the following procedure:

1. An undirected graph is randomly generated with each host assigned a uniform energy level.
2. Start a new update interval by applying the marking process to generate gateway hosts, then applying four sets of rules: rules based on ID, rules based on ND (1a and 2a), and rules based on EL (1b, 2b, 1b$'$ and 2b$'$). Similarly, apply CLT and CLA for the cluster-based approach. Record the number of gateway hosts generated in the current interval.
3. The energy level of each host is reduced by d' and d depending on its status (gateway/non-gateway). If the energy level of one host becomes zero, the simulation stops and records the number of update intervals. Otherwise, each host roams around the given 2-D space based on the given model and a new graph is generated, and then, go to step (2).

In [29], an energy cost model is given for transmitting and receiving operations. Specifically, receiving cost includes electronics part while transmitting cost includes electronics part and amplifier part. Therefore, a transmitting operation costs more than a receiving operation. In dominating-set-based routing, gateway nodes perform both transmitting and receiving operations while non-gateway nodes perform receiving operations only (except when they are the source of a routing process). Clearly, $d' > d$. The actual ratio of d'/d depends on many factors such as network topology and traffic patterns. d' and d can be modeled more precisely using the first order radio model [12] and the energy loss model due to channel transmission [29].



(a)



(b)

Fig. 7. The numbers of gateway nodes under different rules: (a) when (a) $c = 10\%$, $d^{'} = 14$, $d = 7$; (b) $c = 50\%$, $d = 1$, $\alpha = 0.25$.

Nodes status can also be classified as active and sleep mode and radio (associated with each node) can be in transit, receive, standby or off mode. In this case, a more refined power consumption model can be applied [30].

To simplify our simulation, we assume that update intervals are homogeneous, i.e., once defined $d^{'}$ and d remain the same for all intervals. The ratio between $d^{'}$ and d can be a constant or a variable. For constant ratio, we use two models to simulate two different networks with relatively "idle" and "busy" gateway hosts, respectively. For variable ratio, we use a novel model to simulate the routing and packet relaying behavior of gateway hosts. In all three models, $d^{'}$ is selected in such a way that $d^{'} > d$.

1. $d^{'} = 14$ and $d = 7$, i.e., $d^{'}$ is twice of d.
2. $d^{'} = 20$ and $d = 1$, i.e., $d^{'}$ is twenty times of d.
3. $d^{'} = 1 + \alpha|G| + \beta\frac{|G|}{|G^{'}|}$ and $d = 1$, where $\alpha|G|$ is the cost related to routing information gathering and updating and $\beta\frac{|G|}{|G^{'}|}$ is the cost associated with packet relay.

Model 3 is probably more realistic since the bypass traffic depends on the total number of hosts ($|G|$) which is distributed to gateway hosts ($G^{'}$). Also, routing information gathering and updating depends on the size of the network ($|G|$). The detailed derivation process is the following: We denote the energy cost for each receive operation as E_{recv} and send operation as $E_{send} = kE_{recv}$, $k \geq 1$. Suppose the communication flow is evenly distributed; that is, during each updating interval, each host is the source and destination of n packets. Totally $n|G|$ packets are transferred by the network. Non-gateway hosts only send (receive) a packet that they are the source (destination). Therefore, their energy consumption during each interval is:

$$d = n(E_{send} + E_{recv}) = n(k+1)E_{recv}. \quad (1)$$

Gateway hosts consume more energy because they have two extra tasks: (a) routing information gathering and updating and (b) packet relay. Suppose a path needs updating for every m packets, and each updating process includes a flooding among all gateway hosts, the corresponding energy consumption for each gateway host is:

$$E_{routing} = \frac{n|G|}{m}(E_{send}+\delta^{'}E_{recv}) = \frac{|G|}{m}n(k+\delta^{'})E_{recv}, \quad (2)$$

where $\delta^{'}$ is the average node degree in $G^{'}$. Suppose the task of relaying packets is evenly distributed among all gateway hosts, the corresponding energy consumption for each gateway host is:

$$E_{relay} = \frac{(l-1)\cdot n|G|}{|G^{'}|}(E_{send} + E_{recv}) = (l-1)\frac{|G|}{|G^{'}|}n(k+1)E_{recv}, \quad (3)$$

where l is the average length (in hops) of each path. From equations (1), (2), and (3), the energy consumption of gateway hosts during each interval is at the bottom of this page:

where $\alpha = \frac{k+\delta^{'}}{m(k+1)}$ is the routing overhead coefficient and $\beta = (l-1)$ is average number of relays for each packet. In our simulation, α is 0.02 or 0.05 for networks with low mobility and 0.1 or 0.25 for networks with high mobility; that is, the routing overhead is proportional to the frequency of topology changes. The value of β is computed based on the average length of the shortest paths with gateway hosts as the intermediate hosts, and

$$\begin{aligned} d' &= d + E_{routing} + E_{relay} \\ &= n(k+1)E_{recv} + \frac{|G|}{m}n(k+\delta^{'})E_{recv} + (l-1)\frac{|G|}{|G^{'}|}n(k+1)E_{recv} \\ &= (1+\alpha|G| + \beta\frac{|G|}{|G^{'}|})d \end{aligned} \quad (4)$$

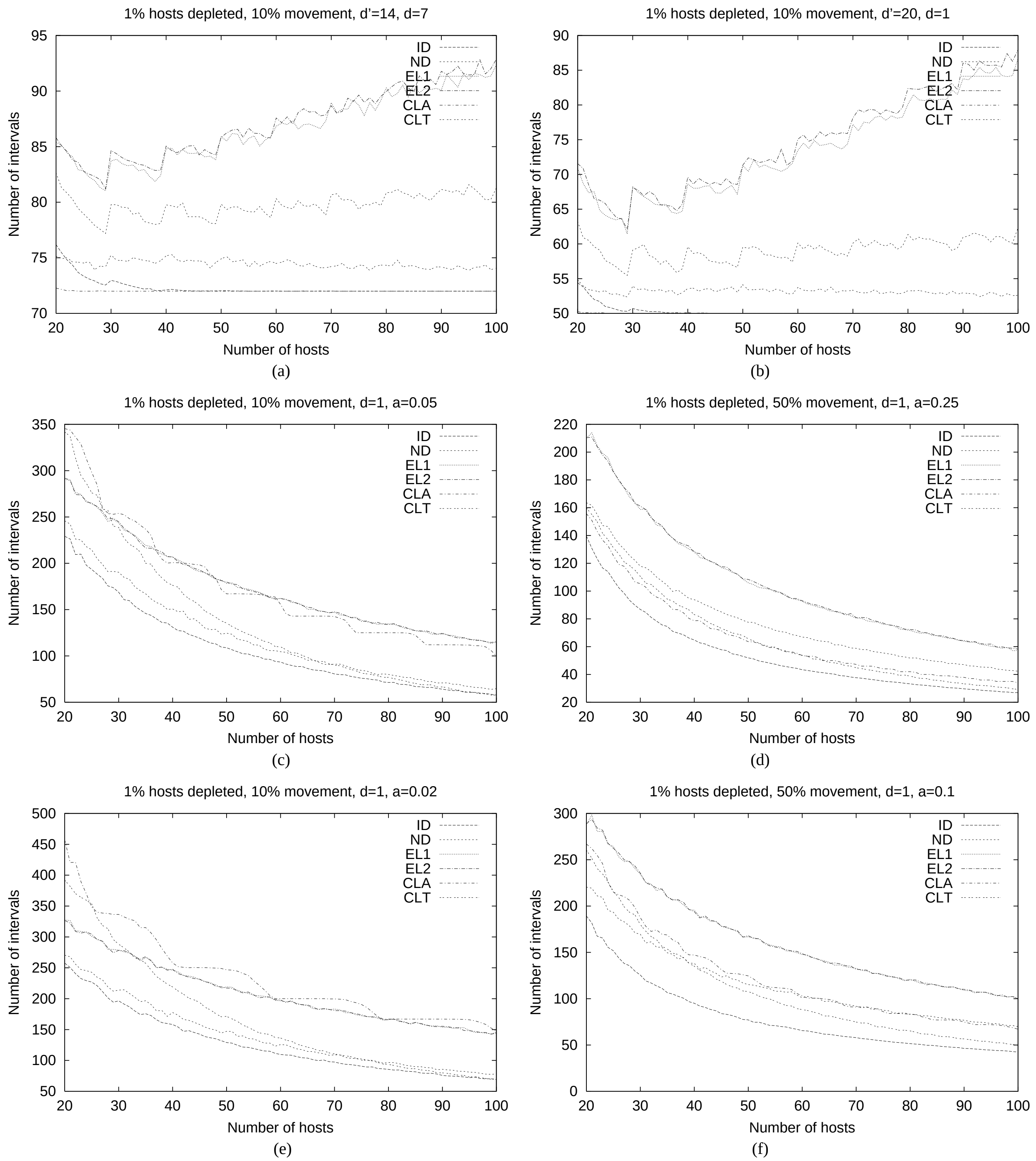


Fig. 8. Average number of intervals before 1% of nodes is depleted when (a) $c = 10\%$, $d^{'} = 14$, $d = 7$; (b) $c = 10\%$, $d^{'} = 20$, $d = 1$; (c) $c = 10\%$, $d = 1$, $\alpha = 0.05$; (d) $c = 50\%$, $d = 1$, $\alpha = 0.25$; (e) $c = 10\%$, $d = 1$, $\alpha = 0.02$; and (f) $c = 50\%$, $d = 1$, $\alpha = 0.1$.

is proportional to the network diameter. Note that when a gateway host relays a control or data packet, its non-gateways neighbors also "hear" the packet and consume energy in receiving the packet. However, by assuming that non-gateway hosts can enter a reduced energy consumption mode when data is being transmitted if they are not the destination of the packet [28], we can omit this part of energy consumption. The energy consumption in maintaining a connected dominating set is uniform across the network (for both gateways and non-gateways), and we assume that it is included in d and the d component of $d^{'}$.

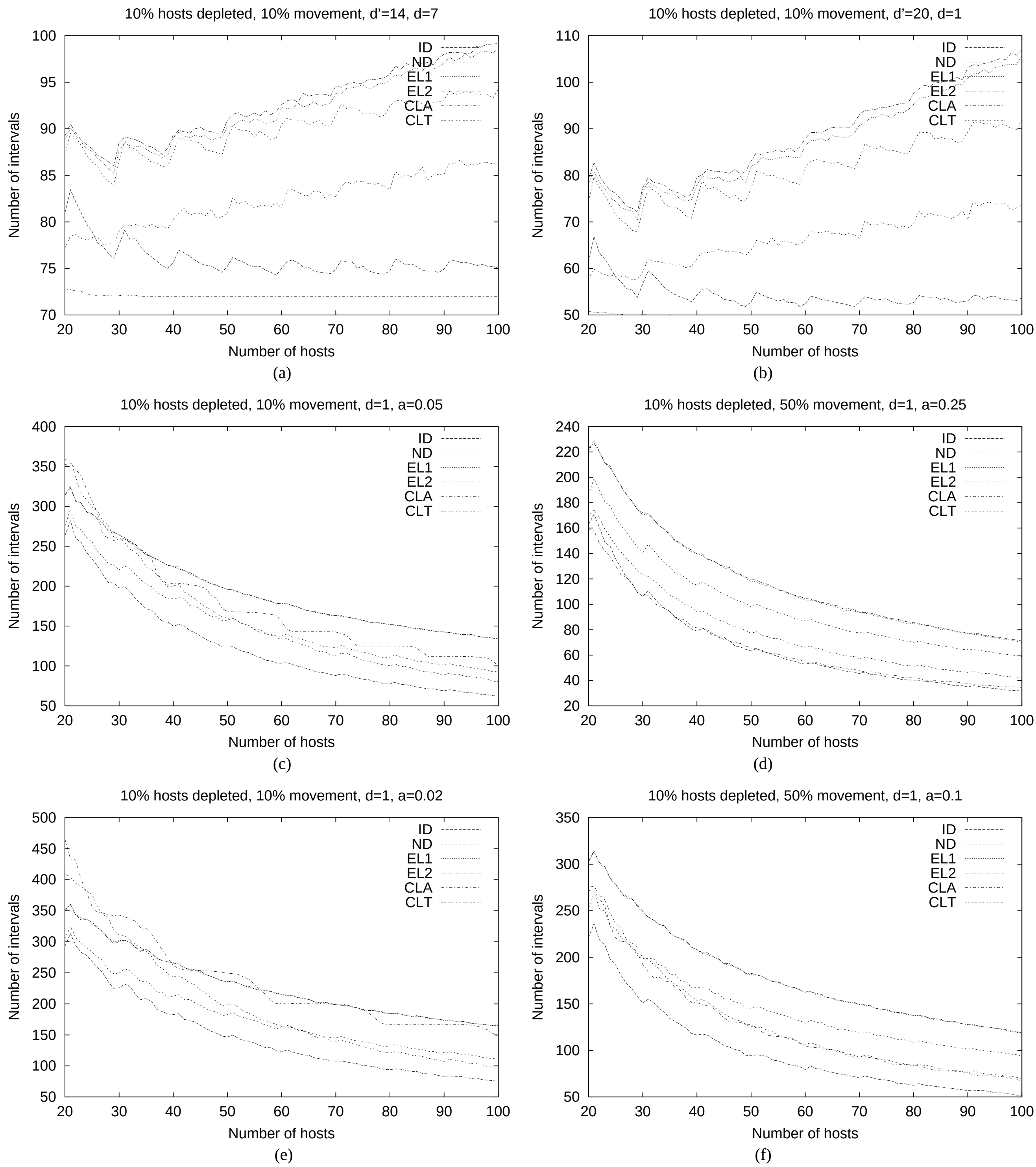


Fig. 9. Average number of intervals before 10% of nodes is depleted when (a) $c = 10\%$, $d' = 14$, $d = 7$; (b) $c = 10\%$, $d' = 20$, $d = 1$; (c) $c = 10\%$, $d = 1$, $\alpha = 0.05$; (d) $c = 50\%$, $d = 1$, $\alpha = 0.25$; (e) $c = 10\%$, $d = 1$, $\alpha = 0.02$; and (f) $c = 50\%$, $d = 1$, $\alpha = 0.1$.

Two termination conditions are used: the simulation terminates (a) when 1% of nodes are depleted (i.e., the first node when the number of nodes is no more than 100) and (b) when 10% of nodes are depleted. Two sets of simulation studies have been conducted. In the first one, we record the average number of gateway hosts. In the second one, we record the average number of update intervals when the first 1% (and 10%) of hosts run out of battery. The simulation is repeated until we achieve a precision of 1% with confidence level of 90%.

Fig. 7 shows results of the first simulation. In this figure, NR, ID, ND, EL1, and EL2 represent marking process without applying rules (no rule), Rule 1 and Rule 2 (based on ID), Rule 1a and Rule 2a (based on ND), Rule 1b and Rule 2b (based on EL), and Rule 1b$'$ and Rule 2b$'$ (based on EL), respectively. The average numbers of gateway hosts for NR, ID, and ND are calculated by averaging the results from randomly generated graphs. The average numbers for EL1 and EL2, however, depend on the energy level of each host (which is initialized to the same value) and the energy consumption function (one for gateway and one for non-gateway). Two energy consumption functions and corresponding network mobility models are used: one with $c = 10\%$, $d' = 14$ and $d = 7$ and the other with $c = 50\%$, $d' = 1 + 0.25|G| + \beta \frac{|G|}{|G'|}$ and $d = 1$. Each host roams around following the same model described early from one interval to another. The number of gateways is recorded at each interval. Results in Fig. 7 show that the average numbers of gateway hosts for CLT, ID, ND, EL1, and EL2 are relatively close. CLA and NR are by far the worst (almost every host is gateway). ND is always the best in both situations. When the network mobility is low ($c = 10\%$), EL1 and EL2 stay very close and are worse than ID and CLT. The order from the best to the worst is CLA, NR, EL1, EL2, ID, CLT, and ND. When the network mobility is high ($c = 50\%$), EL1, EL2, and ID stay very close and are better than CLT. The order from the best to the worst is NR, CLA, CLT, ID, EL1, EL2, and ND.

Fig. 8 shows six results of the second simulation based on different selections of d and d' under the first termination condition (i.e., the 1% of nodes is depleted). Fig. 9 shows four results of the second simulation based on different selections of d and d' under the second termination condition (i.e., the 10% of nodes is depleted). Results show that results for 1% is comparable to ones for 10% in terms of relative rankings of different methods under different energy consumption functions. When the energy consumption functions are constant for both d and d' ($d = 7$ and $d' = 14$ in one simulation and $d = 1$ and $d' = 20$ in another simulation), EL1 and EL2 have the best performance (in terms of longer life span) with EL2 slightly edging EL1. ID performs poorly since hosts with small id's tend to be frequently selected and these hosts die quickly. So does CLA because almost every host is continuously designated as gateway. When the energy consumption function for d' is $1 + \alpha|G| + \beta|G|/|G'|$, EL1 and EL2 are still the best except in Fig. 9 (e) and ID is still the worst. Unlike the other two energy consumption functions with constant selections of d and d', the life span of larger networks is shorter because of the higher routing and relaying overhead. When the network is relatively stable ($c = 10\%$) and the routing overhead is relatively low ($\alpha = 0.05$), the performance for CLA improves significantly to almost as good as EL1 and EL2. This is not surprising, since the denominator $|G'|$ in the energy consumption function for CLA is significantly larger than that for others. That is, the d' value for CLA is smaller than that for others. Therefore, hosts tend to live longer. When the routing overhead is very low ($c = 10\%$ and $\alpha = 0.02$), CLA even slightly outperforms EL1 and CL2. Clearly, trade offs are possible by increasing the size of the connected dominating set for a longer life span of the network. However, when the network is highly mobile ($c = 50\%$) and the routing information is updated frequently ($\alpha = 0.25$ or $\alpha = 0.1$), CLA is worse than ND, which has the smallest $|G'|$, because the benefit of lower forwarding overhead is balanced by the higher routing overhead.

VI. CONCLUSIONS

In this paper, we have extended Wu and Li's distributed algorithm for calculating a connected dominating set in a given ad hoc wireless network. The connected dominating set is selected based on the node degree and the energy level of each host. The objective is to provide a selection scheme so that the overall energy consumption is balanced in network, and at the same time, a relatively small connected dominating set is generated. A simulation study has been conducted to compare the life span of the network under different selection policies. The results have shown that the proposed approach based on energy level is clearly the best in terms of the longer life span of the network. Our future work will focus on more in-depth simulation under different settings.

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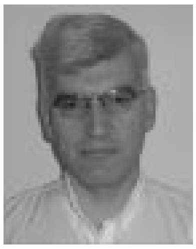

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