Power-Aware Broadcasting and Activity Scheduling in Ad Hoc Wireless Networks Using Connected Dominating Sets [1]

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Abstract

In ad hoc mobile wireless networks, due to host mobility, broadcasting is expected to be more frequently used to find a route to a particular host, to page a host, and to alarm all hosts. A straightforward broadcasting by flooding is usually very costly and results in substantial redundancy and more energy consumption. Power consumption is an important issue since most mobile hosts operate on battery. Broadcasting based on a connected dominating set is a promising approach, where only nodes in the dominating set need to relay the broadcast packet. 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 proposed a simple and efficient distributed algorithm for calculating connected dominating set in ad hoc wireless networks, where connections of nodes are determined by their geographical distances. In general, nodes in the connected dominating set consume more energy 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 system, nodes should be alternated in being chosen to form a connected dominating set. Activity scheduling deals with the way to rotate the role of each node among a set of given operation modes (dominating nodes versus dominated nodes in this paper). In this paper, we propose to apply power-aware connected dominating set notions to broadcasting and activity scheduling. The effectiveness of the proposed method in prolonging the life span of the network is confirmed through simulation.

Keywords: *Activity scheduling, ad hoc wireless networks, broadcasting, dominating sets, energy level, routing, simulation.*

1 Introduction

An ad hoc wireless network is a special type of wireless network 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. Examples of such networks are used in military, disaster rescue, wireless conferences, and monitoring in some kind of dangerous, remote or unaccessible environment.

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 each other's wireless transmitter ranges. To simplify our discussion, we assume all mobile hosts are homogeneous, that is, their wireless transmitter ranges are the same. In other word, if there is an edge $e = (v, u)$ in E, it indicates u is within v's range and v is within u's range. Thus the corresponding graph will be an undirected graph. In this case, a mobile host may not be able to communicate directly with other hosts in a single-hop fashion and a multi-hop scenario occurs, where the packets sent by the source host are relayed by several intermediate hosts before reaching the destination host.

Dominating-set-based broadcasting [21] is based on the concept of dominating set in graph theory. A subset of the vertices is a dominating set if every vertex not in the subset is adjacent to at least one vertex in the subset. In Figure 1, $\{v, w\}$ forms a dominating set in a graph with five vertices. The main idea of this approach is to limit the broadcast process to a subgraph induced from the dominating set. Moreover, the dominating set should be connected for the ease of the broadcast 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 broadcasting is that it simplifies the decision of retransmission to the one in a smaller subnetwork generated from the connected dominating set. This means that only gateway hosts need to relay the broadcast packet. Since non-gateway host is prevented from retransmitting, this mechanism will reduce power consumption, redundant retransmission and, hence, network contention.

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 [8]. Wu and Li [25] proposed a simple distributed algorithm, called *marking process*, that can quickly determine a connected dominating set in a given connected graph, which represents an ad hoc wireless network. Specifically, a host is marked as a gateway if it has two unconnected neighbors. This approach outperforms several classical approaches, such as the cluster approach [3, 12] and MCDS (minimum connected dominating set) [7, 19], in terms of finding a small connected dominating set and/or does so quickly [25]. Movement of one single node in clustering structure may trigger global structural updates, thus its maintenance is expensive. MCDS [19] is clustering type structure. Centralized algorithms such as [7] produce smaller sets but with unacceptable overhead even for static networks. Dominating sets have small overhead since movement of one node only affects the structure in its neighborhood.

In ad hoc wireless networks, the limitation of power of each host poses a unique challenge for power-aware design [16]. There has been an increasing focus on low cost and reduced node

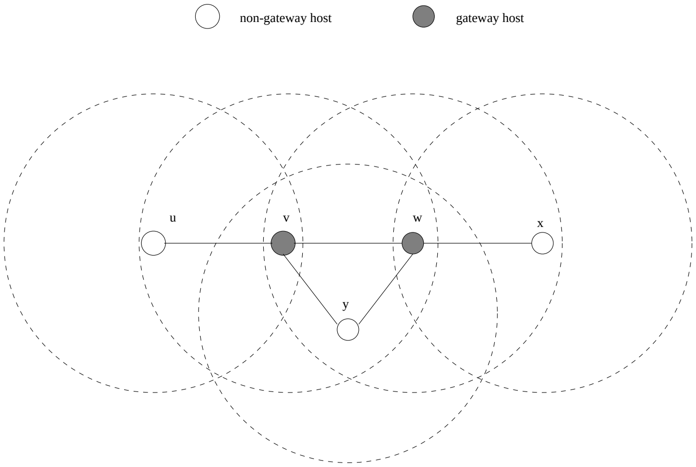


Figure 1: A sample ad hoc wireless network.

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 [4]. In order to prolong the life span of each node and, hence, the network, power consumption should be minimized and 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 result in a shorter life span of the whole network.

In this paper, we study dynamic selection of dominating nodes, also called *activity scheduling*. Activity scheduling deals with the way to rotate the role of each node among a set of given operation modes. For example, one set of operation modes is sending, receiving, idle, and sleeping. Different modes have different energy consumptions. Activity scheduling judiciously assigns a mode to each node to save overall energy consumptions in the networks and/or to prolong life span of each individual node. Note that saving overall energy consumptions does not necessarily prolong life span of a particular individual node.

We propose to save overall energy consumptions by allowing only dominating nodes (i.e., gateway nodes) to retransmit the broadcast packet. In addition, in order to maximize the lifetime of all nodes, an activity scheduling method is used that dynamically selects nodes to form a connected dominating set. Specifically, in the selection process of gateway nodes, we give preference to nodes with a higher energy level. We also give preference to nodes with less distance to their neighbors in the situation where nodes can adjust their transmission power. The effectiveness of the proposed method in prolonging the life span of the network is confirmed through simulation.

This paper is organized as follows: Section 2 reviews the related work, Wu and Li's decentralized formation of a connected dominating set, and two extensions to Wu and Li's approach: one is based on node degree and the other is based on energy level. Section 3 discusses the proposed power-aware broadcasting and activity scheduling. An example is also included to illustrate different activity scheduling methods. Performance evaluation is done in Section 4. In Section 5, we conclude the paper and discuss possible future work. Throughout the paper, we use terms node, host, and vertex interchangeable.

2 Literature Reviews

In this section, we first review related work, then Wu and Li's marking process for determining dominating nodes (gateway nodes) and, finally, Wu, Gao, and Stojmenovic's extended rules [24] that serve as the basis of our activity scheduling.

2.1 Related work

The broadcasting in literature has been studied mainly for the one-to-all model and we will use this term to refer to broadcasting schemes in which the same packet is retransmitted to all the nodes in the network. All-to-all broadcasting is less frequently used in ad hoc wireless networks. Flooding has been traditionally used for broadcasting where each host transmits (forwards) the broadcast packet once and only once. Flooding is also used for route discovery in source-initiated on-demand routing protocols such as DSR [10].

Broadcasting was sometimes studied in the context of the address serving in hierarchically clustered networks [11]. The address can be searched and updated by using a variety of algorithms, including flooding, multicast along a spanning tree, and sending a packet directly to each address server. A number of centralized (where each node is assumed to know the full graph topology) broadcast algorithms were proposed in literature. We are interested here only in distributed approaches.

Ni, Tseng, Chen, and Sheu [13] studied the *broadcast storm problem.* A straightforward broadcasting by flooding is usually very costly and results in serious redundancy, contention, and collisions. Several schemes, like probabilistic, counter-based, distance-based, location-based, and cluster-based scheme were proposed to reduce redundant rebroadcasts, and alleviate this storm problem.

In cluster-based broadcasting, nodes are divided into cluster with one of them serving as clusterhead in each cluster (the node with the smallest id in the neighborhood is selected as clusterhead). Each clusterhead has direct links to any of the hosts in its cluster. In the broadcast protocol, the source node forwards the broadcast packet to its clusterhead, which then initiates the construction of a virtual spanning tree of all clusterheads. Gerla and Tsai [6] described a modified version of algorithm in which the highest degree node in a neighborhood becomes the clusterhead.

Qayyum, Viennot and Laouiti [14] studied a multipoint relay method for efficient flooding in mobile wireless networks. Gerla, Kwon and Pei [5] proposed a combined clustering and broadcasting algorithm which has no communication overhead for either maintaining cluster structure or updating neighborhood information. The performance of the algorithm depends on two parameters whose best values are in accordance to network density and traffic load, which are generally information not available to hosts.

One simple way to prolong the lifetime of each host is to evenly distributed packet-relaying loads to each node to prevent nodes from being overused. This approach is used in LEACH [9], where a probabilistic approach to randomly select cluster heads in data gathering in sensor networks. Other metrics can be used together with the energy metric for certain routing applications. For example, power and cost can be combined into a single metric in order to choose power efficient paths among cost optimal ones. Various combinations have been studied by Stojmenovic and Lin [20] and Chang and Tassiulas [1].

Wu, Gao, and Stojmenovic [24] were the first to propose using energy metrics in dominating-set-based routing. The selection of a connected dominating set is through a marking process: a node is marked gateway if two of its neighbors are not directly connected. Recently, a modified marking process was proposed by a group at MIT [2]. A node is marked as 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 generates 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. In addition, the modified Wu's marking process costs more: $O(\Delta^3)$ with one-hop intermediate gateway (and $O(\Delta^4)$ with two-hop intermediate gateways) at each node vs. $O(\Delta^2)$ of Wu and Li's marking process, where 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. Also, this approach changes connected dominating set due to mobility only, not due to energy left at nodes.

Xu, Heidemann, and Estrin [26] discussed the following sensor sleep node schedule. The given 2-D space is partitioned into a set of squares (called cells), such as any node within a square can directly communicate with any nodes in an adjacent square. Therefore, one representative node from each cell is sufficient. To prolong the life span of each node, nodes in the cell are rotated to be selected as a representative. The adjacent squares form a 2-D grid and the broadcast process becomes trivial. Note that the selected nodes in [26] make a dominating set, but the its size is far from optimal, and also it depends on the selected size of squares. On the other hand, the dominating set concept used here has smaller size and is chosen without using any parameter.

The notions of saving overall energy consumptions in the networks and/or to prolong life span of each individual node has been discussed in the context of unicasting. Toh [22] discussed 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 and wireless device, 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) [17]. MTPR minimizes the total power needed to route packets on the network while MBCR maximizes the lifetime of all nodes. Stojmenovic and Lin [20] described localized power and aware routing algorithms whose performance is close to the performance of non-localized shortest weight path algorithms.

2.2 Formation of connected dominating set

Wu and Li [25] 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.

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

Marking Process:

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.

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., $G' = G[V']$. It was shown in [25] that (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. (2) The induced graph $G' = G[V']$ is a connected graph. (3) The shortest path between any two nodes does not include any non-gateway node as an intermediate node.

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 [25] 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 in G' 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 node v is marked, i.e., G' is changed to $G' - \{v\}$.*

The above rule indicates that when the closed neighbor set of v is covered by the one of u, vertex v can be removed from G' if the ID of v is smaller than the one of u. Note that if v is marked and its closed neighbor set is covered by the one 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. The use of ID is to avoid the "simultaneous removal" problem where both marked nodes are removed.

In Figure 2 (a), since $N[v] \subset N[u]$, vertex v is removed from G' if $id(v) < id(u)$ and vertex u

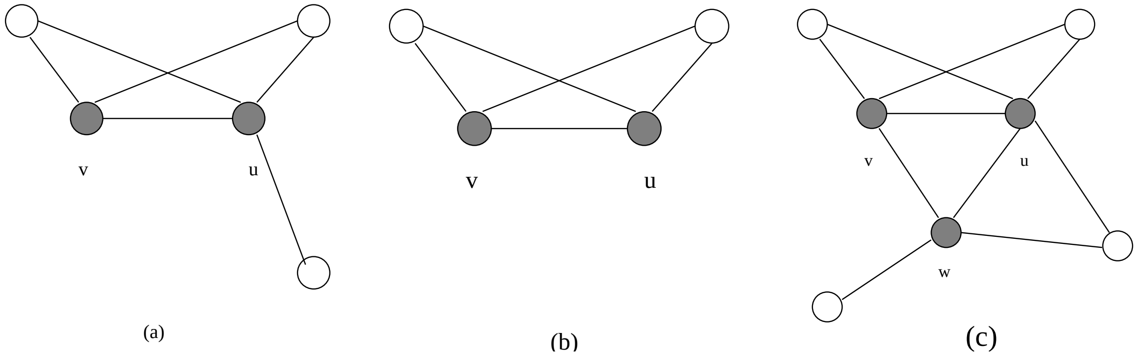


Figure 2: Three samples.

is the only dominating node in the graph. In Figure 2 (b), since $N[v] = N[u]$, either v or u can be removed from $G^{'}$. To make sure one and only one is removed, the one with a smaller ID is selected. We call the above process the *selective removal* based on node ID.

Rule 2: *Assume that* u *and* w *are two 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.

Note that u in Rules 1 and 2 and w are not necessarily marked. Therefore, there is no need of exchanging marking status before applying Rules 1 and 2. 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 Figure 2 (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 do 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). Therefore, to apply Rule 2, an additional step needs to be added in the marking process.

All the above examples represent just a global snapshot of the dynamic topology for a given ad hoc wireless network. Because the topology changes over time, the connected dominating set also needs to be updated. Wu and Li [25] showed the desirable locality feature of the marking process. More specifically, it is shown that only the neighbors of changing nodes need to update their gateway/non-gateway status. In both Rule 1 and Rule 2, the reference hosts (u and v in Rule 1 and u, v, and w in Rule 2) are neighbors. Wu [23] also gives an extended Rule 1 and Rule 2 where the reference hosts are not necessarily neighbors, but rather 2 hops away. Still, locality of update preserves.

2.3 Extended rules for activity scheduling

We review several extended rules proposed in [24] for selective removal of gateway nodes generated from the marking process. These rules will be served as the basis of our activity scheduling discussed in the next section. One rule 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 is to reduce the size of the connected dominating set while the energy-level-based approach is to reduce the size of the connected dominating set and to prolong the average life span of each node. We also introduced the distance aware rule and extended source-related and source-unrelated distance rules where nodes transmission power may be adjusted based on distance.

Node-degree-based rules. Rule 1a and Rule 2a are counterparts of Rule 1 and Rule 2, respectively. They are based on *node degree* (ND) [21] to reduce the size of a connected dominating set generated from the marking process. Again 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 $|N(u)|$.

In Rule 1a, when the closed neighbor set of v is covered by the one of u, node v can be removed from $G^{'}$ if the ND of v is smaller than the one of u. Node ID's are used to break a tie when the node degrees of two nodes are the same. In Rule 2a, the same coverage requirement used in Rule 2 is applied. ND is used to avoid simultaneous removal and ID is used to break a tie.

Energy-level-based rules. In Rule 1b and Rule 2b, *energy level* (EL) of each node is used [24]. These rules are used to prolong the average life span of a node, and at the same time, to reduce the size of a connected dominating set generated from the marking process. Again, we first assign a distinct ID, $id(v)$, and an initial EL, $el(v)$, to each vertex v in $G^{'}$. In Rule 1b, when the closed neighbor set of v is covered by the one of u, vertex v can be removed from $G^{'}$ if the EL of v is smaller than the one of u. ID is used to break a tie when $el(v) = el(u)$. Rule 2b is defined in the same way except neighbor set of v is covered by neighbor sets of two connected nodes u and w. A variation of energy-level-based rules, labelled as Rule 1b$^{'}$ and Rule 2b$^{'}$, uses ND when there is a tie in EL. ID is used only when there is a tie in ND.

Distance-Aware-based rules. In Rule 1c and Rule 2c, *maximum distance* (dis) of each node is used. Here the maximum distance is the distance from a node to all neighbors. In this mode we assume the energy consumption is changed according to distance. Since nodes can adjust their transmission power, these rules are used to reduce the average energy consumption of a node, and at the same time, to reduce the size of a connected dominating set generated from the marking process. Again, we first assign a distinct ID, $id(v)$, to each vertex v in $G^{'}$. In Rule 1c, when the closed neighbor set of v is covered by the one of u, vertex v can be removed from $G^{'}$ if the dis of v is larger than the one of u. ID is used to break a tie when $dis(v) = dis(u)$. Rule 2c is defined in the same way except neighbor set of v is covered by neighbor sets of two connected nodes u and w.

Extended distance-aware source-unrelated rules. A variation of distance-aware-based rules, labelled as Rule 1c$^{'}$ and Rule 2c$^{'}$. First apply distance-aware-based rules and get the CDS. Gateway nodes will not send the packet with maximum distance to all its neighbors but only to a subset of its neighbors. The $distance(v)$ is adjusted when a gateway relays a broadcast packet. Here, $distance(v)$ is defined as $\max\{d(v, u'|u'$: neighbor of v that is not a neighbor of w, where w is gateway and neighbor of v and $id(w) > id(v)$ $\}$. The algorithm of Rule 1c$^{'}$ and Rule 2c$^{'}$ is exactly the same as Rule 1c and Rule 2c.

Extended distance-aware source-related rules. A variation of distance-aware-based rules, labelled as Rule 1c$''$ and Rule 2c$''$. First apply distance-aware-based rules and get the CDS. A gateway nodes will not send the packet with maximum distance to all its neighbors but only to a subset of its neighbors. Here, $distance(v)$ is defined as $\max\{d(v, u'|u'$: a neighbor (but not upstream neighbor) of v that is not a neighbor of w, where w is gateway and neighbor of v and $id(w) > id(v)$ $\}$. The algorithm of Rule 1c$''$ and Rule 2c$''$ is exactly the same as Rule 1c and Rule 2c.

3 Power-Aware Broadcasting and Activity Scheduling

3.1 Broadcasting and activity scheduling

The general step of a power-aware broadcasting is based on the notions of gateways and non-gateways. Non-gateway hosts only *receive* the broadcast packet whereas gateway hosts *receive* and *send* the broadcast packet. Actually, each gateway host only sends (also called forwards) the broadcast packet once and only once. Therefore, the power-aware broadcasting based on connected dominating sets can be described as in **Power-Aware Broadcasting**.

Power-Aware Broadcasting

1. The source sends a broadcast packet to all its neighbors.
2. When a node receives the broadcast packet, it saves the packet the first time; otherwise, the packet is discarded.
3. When a gateway node receives the packet for the first time, it forwards the packet to its neighbors.

Figure 3 shows a graphic explanation of the power-aware broadcasting based on connected dominating sets. Note that the main purpose of using only gateways to forward the broadcast packet is to save the total power needed to broadcast packets.

In a dynamic system such as an ad hoc wireless network, network topology changes over time. The role of gateway and non-gateway can also be changed. An *update* is a role change (between gateway and non-gateway) of several nodes in the system. An *update interval* is the time between two adjacent updates in the network. To simplify the discussion, we assume that the update interval is uniform. A long interval is partitioned into small ones with uniform length (some adjacent intervals have no update). Assume that d and d' are energy consumption in a given interval for a gateway node and a non-gateway node, respectively. That is, each time after applying both Rule 1 and Rule 2 and their variations, EL of each gateway node will be decreased by d and EL of each non-gateway node will be decreased by d'. When the energy level of u, $el(u)$, reaches zero, it is assumed that node u ceases to function. In general, d and d' are variables which depend on the

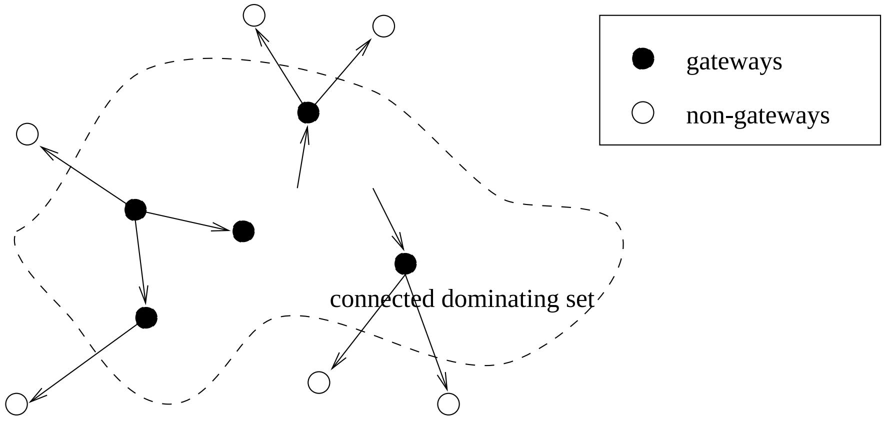


Figure 3: Power-aware broadcasting based on connected dominating set.

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.

In [15], 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 [9] and the energy loss model due to channel transmission [15]. Nodes status can also be classified as active and sleep mode and radio (associated with each node) can be in sending, receiving, idle, and sleeping modes. In this case, a more refined power consumption model [18] can be applied.

Saving the total power of each broadcast is not sufficient. A particular node may be depleted quickly if it is frequently selected as a gateway host by the marking process. Fortunately, for a given network configuration, there exists more than one dominating set that is connected. The activity schedule can then be applied to select gateways based on energy level of each node. This is done without violating the connectivity requirement and without generating too large a dominating set. In the latter case, a large dominating set will consume more total power for each broadcast. The proposed activity scheduling is to first construct a (large) connected dominating set using the Wu and Li's marking process and, then, without destroying the connectivity property, some nodes in the dominating set are withdrawn. The way of withdrawing is based on one of the rules discussed in the previous section. Clearly, the objective of activity scheduling is to prolong the life span of each individual node:

Note that Rule 1 and Rule 2 (and Rule 1a and Rule 2a) intend to reduce the size of dominating set only (i.e., overall energy consumption). Rule 1b and Rule 2b (and Rule 1b$^{'}$ and Rule 2b$^{'}$) intend to reduce both overall energy consumption and to prolong the life span of each individual node.

Activity scheduling

1. Use Wu and Li's marking process to construct a connected dominating set.
2. Withdraw some nodes in the set using (1) Rule 1 and Rule 2, (2) Rule 1a and Rule 2a, (3) Rule 1b and Rule 2b,(4) Rule 1c and Rule 2c and some of variants.

3.2 An example

Figures 4, 5, 6, and 7 show an example of using the proposed activity scheduling 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, i.e., information about its neighbors and the neighbors of all its neighbors.

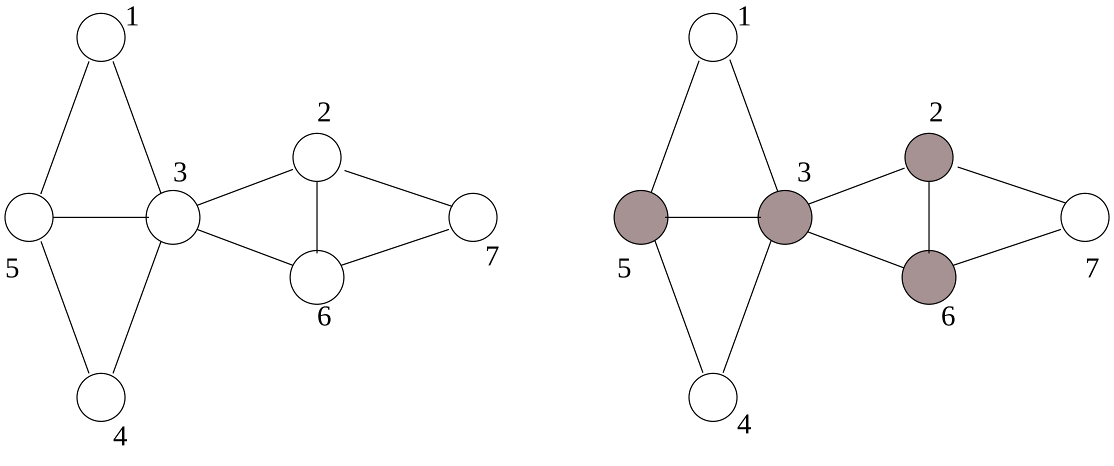
In Figure 4, node 1 will not mark itself as a gateway node because its only neighbors 3 and 5 are connected. Node 3 will mark itself as a gateway node because there is no connection between neighbors 1 and 2 (1 and 4, and so on). After node 3 marks itself, it sends its status to its neighbors 1, 2, 4, 5 and 6. This gateway status will be used to apply Rules 1 and 2 to unmark several gateway nodes to non-gateway nodes. Figure 4 (b) shows the gateway nodes (dark nodes) derived by the marking process without applying any rules.

By applying Rule 1, node 2 will be unmarked to the non-gateway status as shown in Figure 5 (c). The closed neighbor set of node 2 is $N[2] = \{2, 3, 6, 7\}$, and the closed neighbor set of node 6 is $N[6] = \{2, 3, 6, 7\}$. Apparently, $N[2] \subseteq N[6]$. Also the ID of node 2 is less than the ID of node 6, thus node 2 can unmark itself by applying Rule 1. Node 5 cannot be unmarked by apply rule 1 because its id 5 is larger than node $3'$s id.

By applying Rule 2, node 2 will be unmarked to the non-gateway status as shown in Figure 5 (d). Node 2 knows that its two neighbors 3 and 6 are all marked. This invokes node 2 to apply Rule 2 to check if condition $N(2) \subseteq N(3) \cup N(6)$ holds or not. The open neighbor set of node 2 is $N(2) = \{3, 6, 7\}$, the open neighbor set of node 3 is $N(3) = \{1, 2, 4, 5, 6\}$, the open neighbor set of node 6 is $N(6) = \{2, 3, 7\}$, and therefore, $N(3) \cup N(6) = \{1, 2, 3, 4, 5, 6, 7\}$. Apparently, $N(2) \subseteq N(3) \cup N(6)$. Node 2 has the min ID among nodes 2, 3, and 6. Thus node 2 can unmark itself by applying Rule 2.

In Rule 1a and Rule 2a, ND is used instead of ID to avoid simultaneous removal. Using Rule 1a, both nodes 2 and 5 will be unmarked to the non-gateway status as shown in Figure 5 (e). Using Rule 2a, node 2 will be unmarked to the non-gateway status as shown in Figure 5 (f).

By applying Rule 1b, node 6 will be unmarked to the non-gateway status as shown in Figure 6 (g), where the number inside each node corresponds to the energy level of that node. The closed neighbor set of node 6 is $N[6] = \{2, 3, 6, 7\}$, and the closed neighbor set of node 2 is $N[2] = \{2, 3, 6, 7\}$. Apparently, $N[6] \subseteq N[2]$, Also the energy level (EL) of node 6 is 7, which is less than the EL of node 2, thus node 6 can unmark itself by applying Rule 1b. Node 5 cannot unmark its



(a) (b)

Figure 4: (a) A sample graph. (b) Marked gateways without applying rules.

gateway status because its EL is equal to node $3'$s EL and its id is larger than node $3'$s id though $N[5] \subseteq N[3]$.

By applying Rule 2b, node 6 will be unmarked to the non-gateway status as shown in Figure 6 (h). Node 6 knows that its two neighbors 2 and 3 are all marked. This invokes node 6 to apply Rule 2b to check if condition $N(6) \subseteq N(2) \cup N(3)$ holds or not. The neighbor set of node 6 is $N(6) = \{2, 3, 7\}$, the open neighbor set of node 2 is $N(2) = \{3, 6, 7\}$, the neighbor set of node 3 is $N(3) = \{1, 2, 4, 5, 6\}$, and therefore, $N(2) \cup N(3) = \{1, 2, 3, 4, 5, 6, 7\}$. Apparently, $N(6) \subseteq N(2) \cup N(3)$, $N(2) \subseteq N(3) \cup N(6)$, but $N(3) \not\subseteq N(2) \cup N(6)$. The EL of node 6 is less than the EL of node 2. Thus node 6 can unmark itself by applying Rule 2b.

Using the other version of the energy-level model, both nodes 5 and 6 will be unmarked to the non-gateway status based on Rule $1b'$ as shown in Figure 6 (i). By applying Rule $2b'$, node 6 will be unmarked to the non-gateway status as shown in Figure 6 (j).

By applying Rule 1c, node 2 will be unmarked to the non-gateway status as shown in Figure 7 (k), where the number beside each edge is the distance between the pair of vertex. The closed neighbor set of node 6 is $N[6] = \{2, 3, 6, 7\}$, and the closed neighbor set of node 2 is $N[2] = \{2, 3, 6, 7\}$. Apparently, $N[2] \subseteq N[6]$, Also the maximum distance to all neighbors (DS) of node 2 is 8. The maximum distance to all neighbors (DS) of node 6 is 5, which is smaller than the DS of node 2. Nodes with the larger maximum distance will be unmarked. Thus node 2 can unmark itself by applying Rule 1c. Node 5 also unmark its gateway status because its DS($= 9$) is larger than node $3'$s DS($= 8$), and here we do not need node id in this case. Here The value inside the circle indicate the distance with which the gateway nodes will send the packet out. It is equal to the maximum distance to all its neighbors. For example, gateway node 3 will send packet out with distance 8 and gateway node 6 will use distance 5.

By applying Rule 2c, node 2 will be unmarked to the non-gateway status as shown in Figure

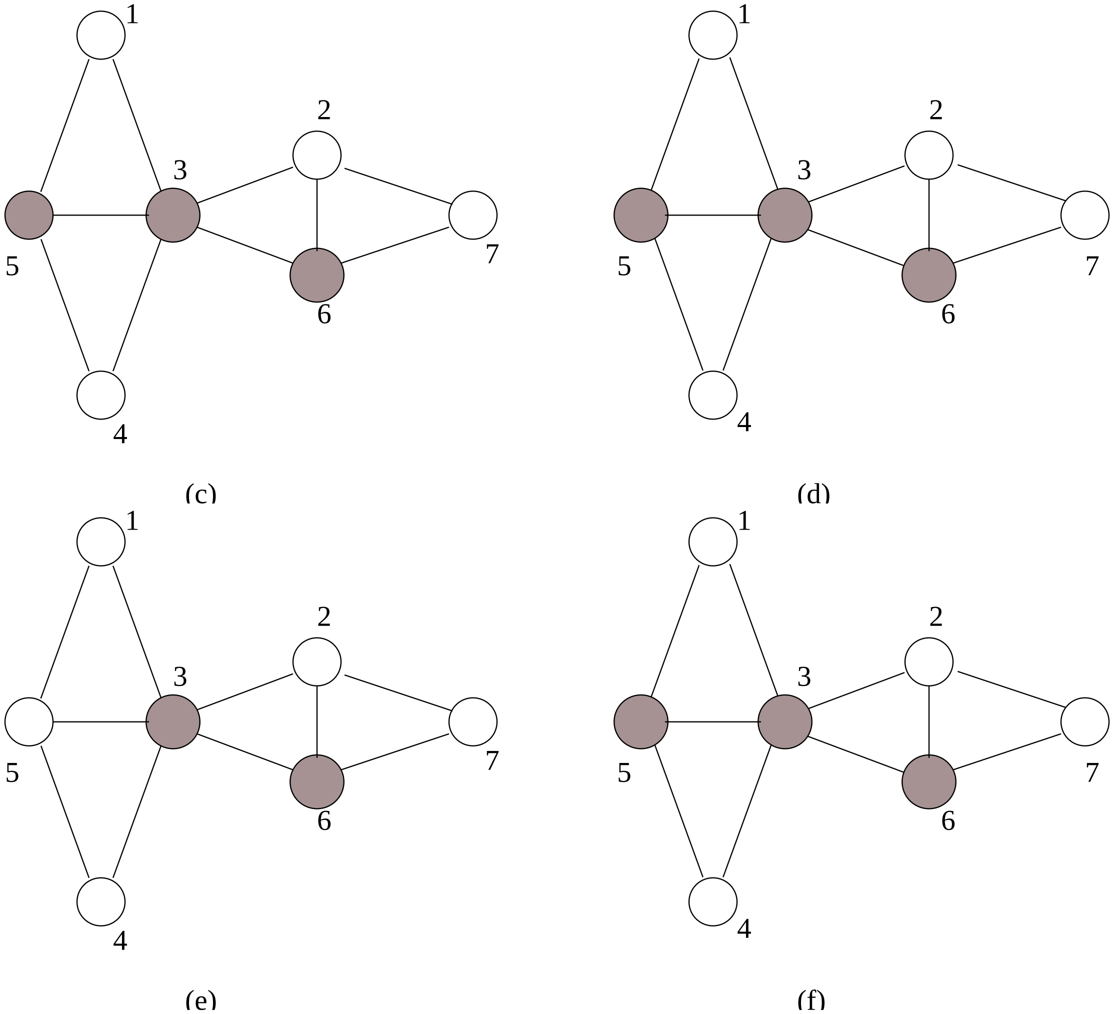


Figure 5: Marked gateways by applying (c) Rule 1, (d) Rule 2, (e) Rule 1a, and (f) Rule 2a.

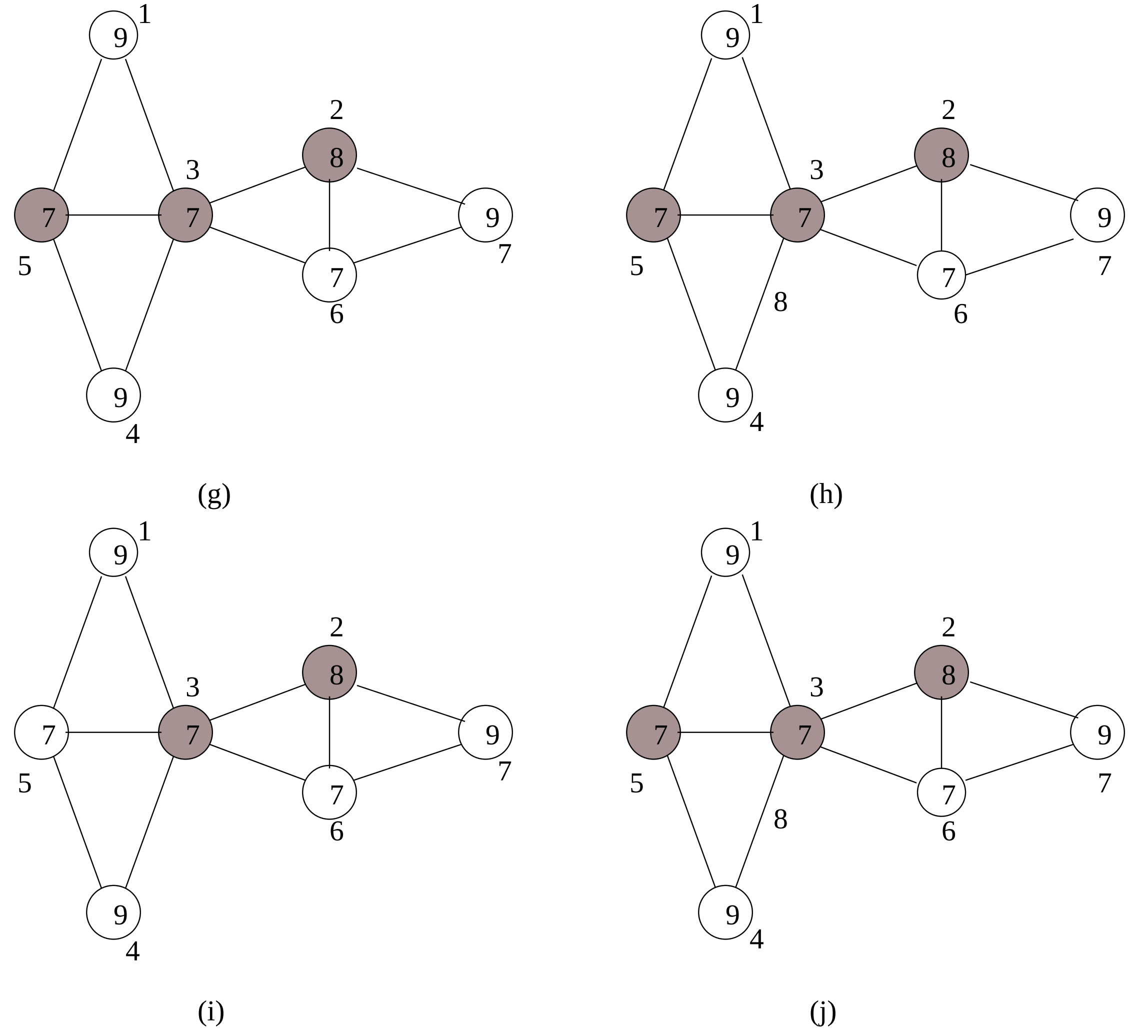
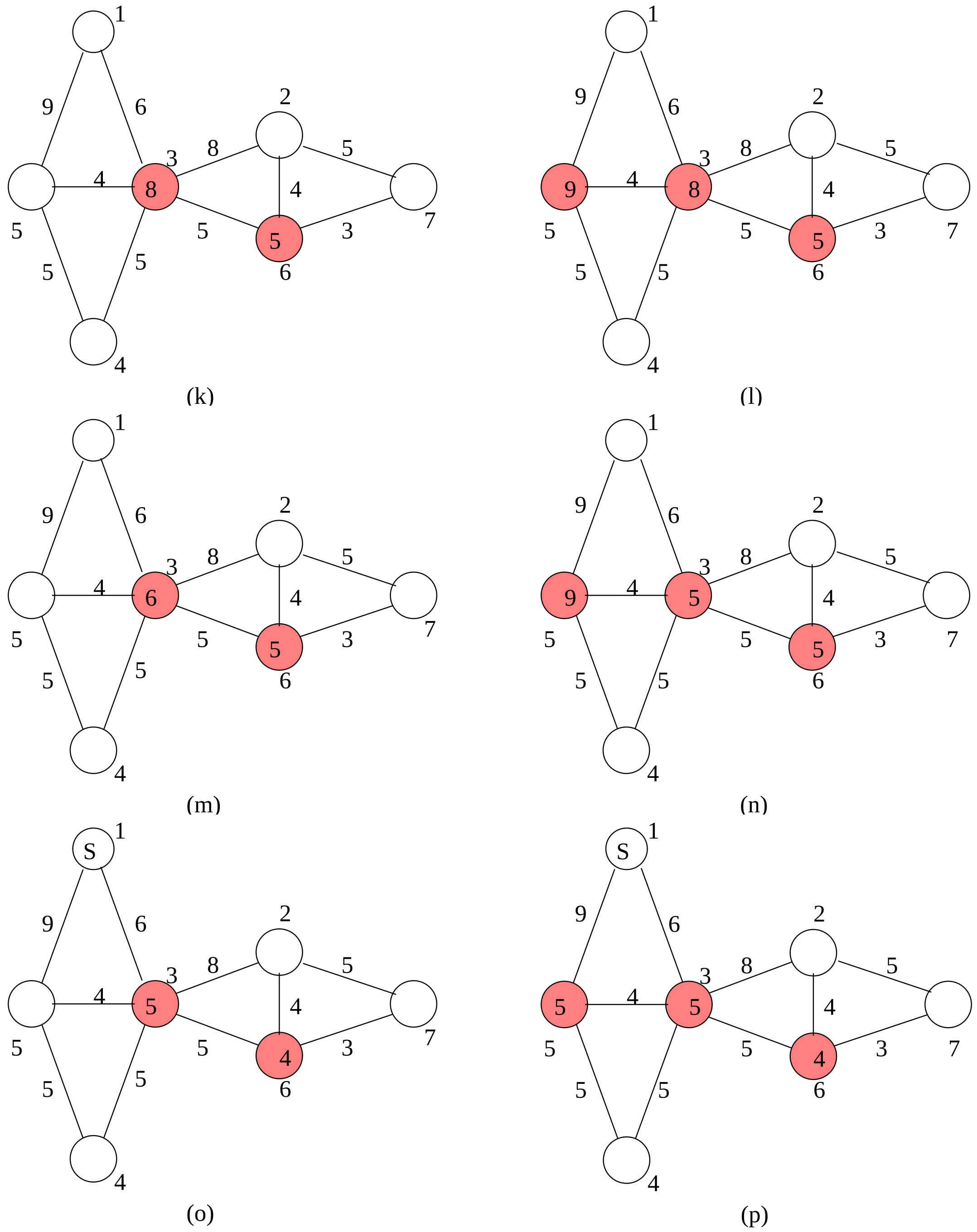


Figure 6: Marked gateways by applying (g) Rule 1b, (h) Rule 2b, (i) Rule 1b$'$, and (j) Rule 2b$'$.



(k) (l) (m) (n) (o) (p)

Figure 7: Marked gateways by applying (k) Rule 1c, (l) Rule 2c, (m) Rule 1c$'$, and (n) Rule 2c$'$, (o) Rule 1c$''$, and (p) Rule 2c$''$.

7 (l). Node 2 knows that its two neighbors 3 and 6 are all marked. This invokes node 2 to apply Rule 2c to check if condition $N(2) \subseteq N(6) \cup N(3)$ holds or not. The neighbor set of node 6 is $N(6) = \{2, 3, 7\}$, the open neighbor set of node 2 is $N(2) = \{3, 6, 7\}$, the neighbor set of node 3 is $N(3) = \{1, 2, 4, 5, 6\}$, and therefore, $N(6) \cup N(3) = \{1, 2, 3, 4, 5, 6, 7\}$. Apparently, $N(2) \subseteq N(6) \cup N(3)$, $N(6) \subseteq N(3) \cup N(2)$, but $N(3) \not\subseteq N(2) \cup N(6)$. The DS of node 2 is larger than the DS of node 6. Thus node 2 can unmark itself by applying Rule 2c. The value inside the circle of gateway node is defined as rule 1c.

Using the extended distance-aware model without source considered, both nodes 5 and 2 will be unmarked to the non-gateway status based on Rule 1c as shown in Figure 7 (m). But note when sending packet gateway hosts calculate maximum distance using different strategy as described early. In order to find maximum distance, node 3 will search this neighbor set $\{1, 4, 5, 6\}$ and find the maximum distance is 6. Node 3 does not check neighbor node 2 since node 2 connects to node 6 and node 6 is a neighbor 3. Node $6'{s}$ id > node 3. By applying Rule 2c, node 2 will be unmarked to the non-gateway status as shown in Figure 7 (n). Here the value inside the circle is 9, 5, 5 for node 5, node 3 and node 6 respectively.

Using the extended distance-aware model with source considered, both nodes 5 and 2 will be unmarked to the non-gateway status based on Rule 1c as shown in Figure 7 (o). But here value inside circle is different from last two distance rules. In order to find maximum distance, node 3 will search this neighbor set $\{4, 6\}$ and find the maximum distance is 5. Node 3 does not check neighbor node 1, node 2 and node 5. The reason is node 1 is the source, node 5 is covered by source and node 2 is covered by gateway node 6. By applying Rule 2c, node 2 will be unmarked to the non-gateway status as shown in Figure 7 (p). Here the value inside the circle is 5, 5, 4 for node 5, node 3 and node 6 respectively. Since node 5 only search node 4 and distance is 5, node 3 search node 6 and the distance is 5, node 6 search node 2 and 7 and distance is 4.

4 Performance Evaluation

In this section, we compare different approaches for determining a connected dominating set in a mobile ad hoc wireless network with and without applying two rules and their variations. 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 and their variations. In addition, the average life spans of the network under different rules are also simulated. The simulation is conducted in a 100 × 100 2-D free-space by randomly allocating a given number of hosts ranging from 10 to 100. The energy level of each host is initialized to 100. ρ represents the probability of movement for each host (ρ is 0.5 in our simulation). For each host in an update interval, $rand(0, 1)$, a random number in [0...1], is associated with each node. If the number is less than ρ, it represents that the corresponding host remains stable in the corresponding interval. If the number is great than or equal to ρ, the corresponding host moves within the range of l units (l is 5 in our simulation) in any direction. Since host has the same transmission radius, the generated graph is an undirected one.

The network is randomly generated based on two different methods. The first one is based on a *fixed transmitter range* and the second one is based on a *fixed node degree*. The relationship between these two parameters are the following: When $r \ll m$, the average node degree can be approximated as $d = (\frac{\pi r^2}{m^2})n$, where r is the transmitter range and m is the length of each side of the confined broadcast space, n is total number of nodes. For example, when the fixed transmitter range is 25 in a 100×100 network with 50 nodes, the corresponding node degree is about 9. The simulation is conducted using the following procedure:

1. An undirected graph is randomly generated.
2. Start a new updated interval by applying the marking process to generate gateway nodes, then applying four sets of rules: based on ID rules, based on ND rules (1a and 2a), based on EL rules (1b, 2b, $1b^{'}$ and $2b^{'}$), based on Distance rules and its variants(1c, 2c, $1c^{'}$, $2c^{'}$, $1c^{''}$ and $2c^{''}$). Record the number of gateway nodes generated in the current interval.
3. Energy level of each node is reduced by d and $d^{'}$ depending on its status (gateway/non-gateway). If the energy level of one node becomes zero, the simulation stops and records the number of update intervals and total remaining energy. Otherwise, each node roams around the given 2-D space based on the given probability model and a new graph is generated, and then, goto step 2.

We design two types of simulations experiment. First one called $Type$ I experiment and second one called $Type$ II experiment. The initial energy level is 100 units for $Type$ I simulation and $1J$ for $Type$ II simulation. In $Type$ I experiment, to simplify our simulation, we assume that update intervals are homogeneous, i.e, d and $d^{'}$ are the same for all intervals. Here we select two sets of d and $d^{'}$: $d = 1.0$ and $d^{'} = 0.1$ for set-1; $d = 2.0$ and $d^{'} = 1.0$ for set-2. In each simulations, two results are presented in two charts in one row. The left chart corresponds to the fixed transmitter range of 25 or 50 and the right one corresponds to the fixed node degree of 9 or 18.

Then in $Type$ II experiment, we assume node can adjust transmission power and the power consumption is related the distance between neighbor. We differ the the power consumption in different operation like packet reception and packet sending. The energy consumption model we use here is:

1. *Send operation:* $u(d) = a + \beta d^k$
2. *Receive operation:* $u(d) = a$

Here, d is the geometrical distance between the sender and receiver, $a = 50nJ/bit$, $\beta = 100pJ/bit/m^2$ and $k = 2$ in our experiment. So for a gateway node it need consume power $2a + \beta d^k$ when it relay each packet(1 bit) to its neighbor. but when the gateway is the source node it only consume $a + \beta d^k$ for each packet(1 bit). For the non-gateway node, it consume power a if it is not the source node. Otherwise it will also need power $a + \beta d^k$ for each packet(1 bit). In our simulation we assume the packet size is 2000 bit long. The distance is the maximum distance to all its neighbors. So energy consumption is different for different nodes and may be changed. we also select two sets of p(p is the die rate): $p = 1st$ for set-1; $p = 10\%$ for set-2. In each simulations,

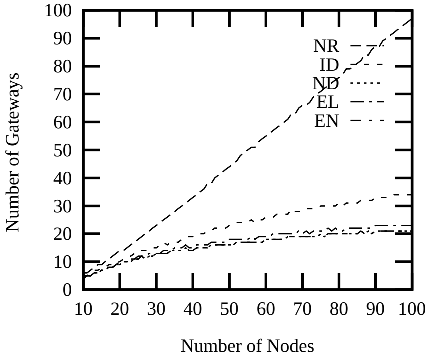


Figure 8: The average numbers of gateway nodes for different schemes in a static network with a fixed transmitter range of 25.

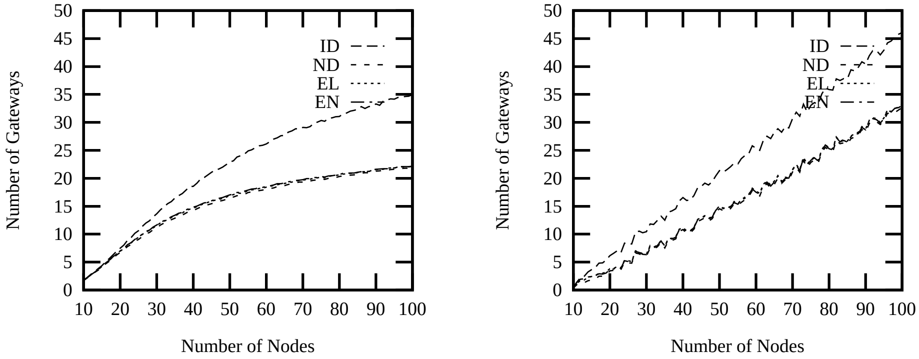


Figure 9: The average numbers of gateway nodes for different schemes when $d = 1.0$ and $d' = 0.1$. The left chart has a fixed transmitter range of 25 and the right chart has a fixed node degree of 9.

two results are presented in two charts in one row. The left one corresponds to the die rate $p = 1st$ and the right one corresponds to the die rate $p = 10\%$.

Four sets of simulation have been conducted. In the first one, we record the average number of gateway nodes in a static ad hoc network (without mobile hosts) and in a regular ad hoc network (with mobile hosts). The average number is derived from 400 samples. In the second one, we calculate the total remaining energy of all nodes when the first host runs out of battery. In the third one, we record the average number of update intervals before the first host runs out of battery. In the forth one,we calculate the average and maximum distance among all nodes. Note that the distance here means hop count.

Figures 8, 9, and 10 show results of the first simulation in $Type$ I experiment. In these figures, NR, ID, ND, EL, and EN 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 EN), respectively. Figure 8 shows results for static ad hoc networks (without mobile hosts). 400 samples are used with one result for each sample. Figures 9 and 10

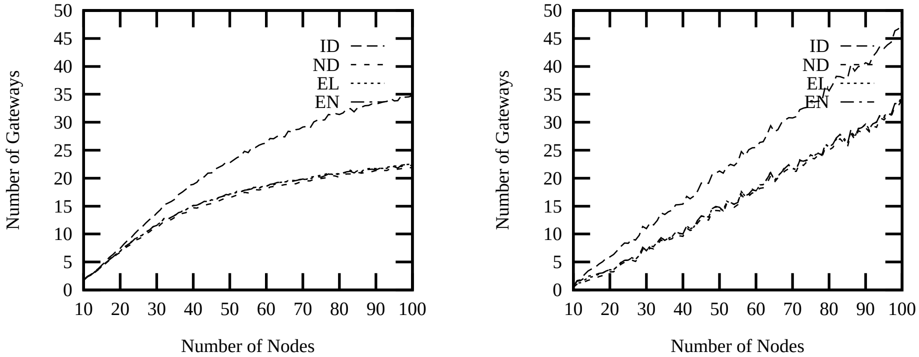


Figure 10: The average numbers of gateway nodes for different schemes when $d = 2.0$ and $d' = 1.0$.

are results for regular ad hoc wireless networks (with mobile hosts). The result for each sample is derived by averaging the number of gateways at each interval until the first host is depleted. Simulation results show that the marking process without rules fares poorly in terms of the number of gateway generated. The number of gateways under ND, EL, and EN stay very close. The one for ID is about 1/3 more than one for ND, EL, and EN. Also, the number of gateways is relatively insensitive to the type of networks (static or dynamic) and the selection of d and $d^{'}$. The number of gateways is directly affected by the node degree since it is linearly proportional to the node degree.

Figures 11 and 12 show results for the second simulation in Type I experiment. It is based on different selections of d and d'. These results show the total energy left among all nodes after the first depleted host. The (increasing) order of leftover energy is the reverse order of the one for the life span of the first depleted node. The simulation confirms the absence of any abnormal situation (e.g., a network with shorter life span of the first depleted node has more leftover energy). Note that when flooding is used, we assume that each node has the same amount of energy (d) and there will be no left-over energy. Again, parameter "node degree" has direct impact on the left-over energy than parameter "transmitter range" has. The rate that the left-over energy decreases when the number of nodes increases is relatively insensitive to the selection of parameters d and $d^{'}$.

Figures 13 and 14 show results of the third simulation in Type I experiment. The (increasing) order of life span of the first depleted host is: ID, ND, EL, and EN. The life span under ID is shortest. This result is expected since the number of gateways under ID is the largest and gateway hosts consume more energy than non-gateway hosts. EN and EL stay close, with ND a distance third. Note that using flooding, each host is a gateway and forwards the broadcast packet once. Therefore, the life span of all nodes is 100 for set-1 simulation and 50 for set-2 simulation. That is, the life span of the first depleted node is extended by about 100% under ND, EL, and EL for set-1 simulation (see Figure 13) and by about 30%-40% under ND, EL, and EN for set-2 simulation (see Figure 14).

Figures 15 shows the number of gateways when transmission range r=50 and average node degree d=18. The number of gateways under ND, EL, and EN stay very close and are less than 5. The reason is that transmission range is 50. So the graph is a dense graph, where nodes are close to each other. The number of gateway when degree is 18 is also much less than when degree is 9.

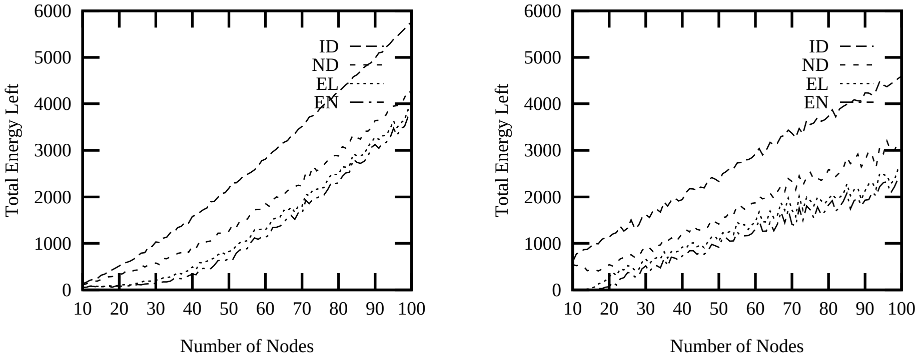


Figure 11: Comparison of left-over energy when $d = 1.0$ and $d' = 0.1$.

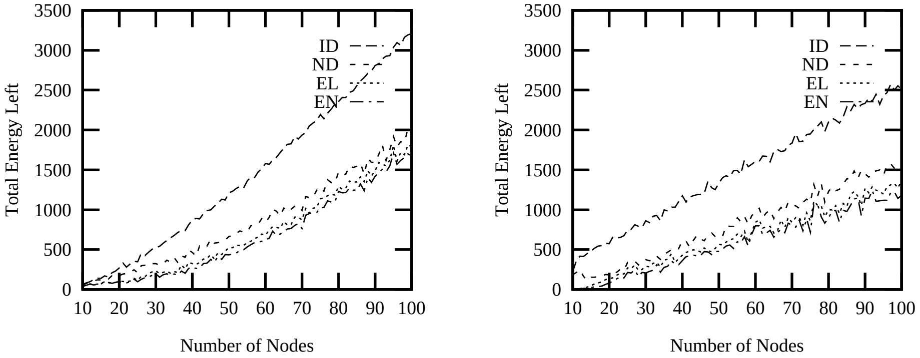


Figure 12: Comparison of left-over energy when $d = 2.0$ and $d' = 1.0$.

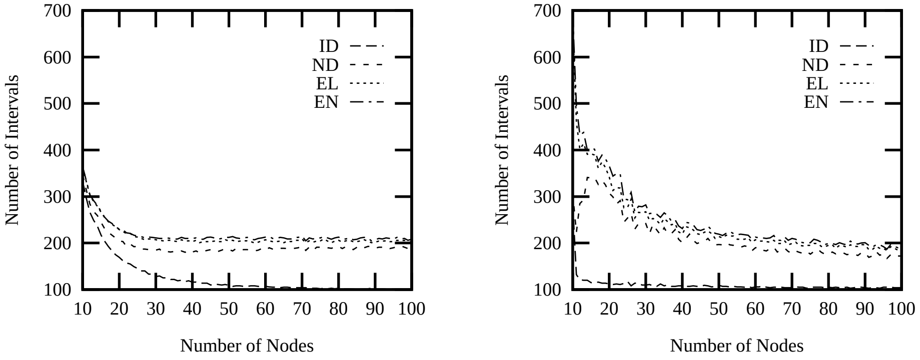


Figure 13: Comparison of total intervals before a node dies when $d = 1.0$ and $d' = 0.1$.

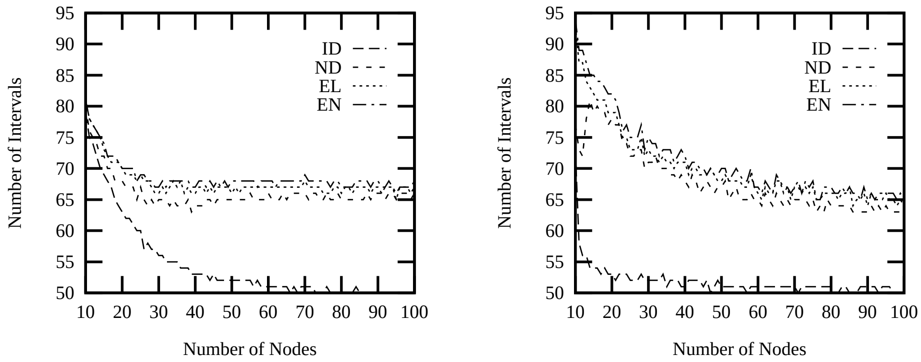


Figure 14: Comparison of total intervals before a node dies when $d = 2.0$ and $d' = 1.0$.

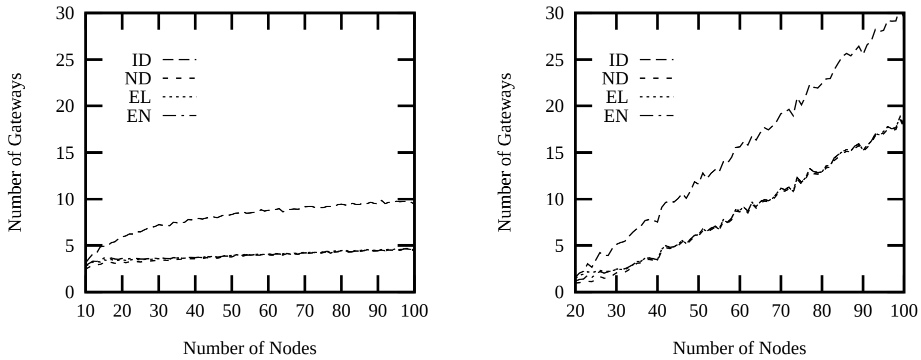


Figure 15: The average numbers of gateway nodes for different schemes when $d = 1.0$ and $d' = 0.1$. (Left chart) fixed transmitter range of 50 and (right chart) fixed node degree of 18.

when number of node is 50, average number of gateway is about 3.8 ($r = 50$) and 6.1 (degree= 18) for ND, EL and EN rule. But for ID rule it is 8.3 ($r = 50$) and 11.6 (degree= 18). Still the number of gateways is directly affected by the node degree since it is linearly proportional to the node degree.

Figures 16 show results for total energy leftover among all nodes after the first depleted host. We can see that this figure is quite similar to the one of last pair ($r = 25$ and degree = 9). It just has a little larger energy leftover then last pair. The interesting thing is even though there are more energy leftover but the intervals is longer than last pairs. The reason is that the set of gateway is much smaller that last ones.

Figures 17 shows average number of intervals before the first node depleted. The (increasing) order of life span of the first depleted host is still as: ID, ND, EL, and EN. The life span under ID is shortest and EN is the longest. As the number of nodes increase the intervals increase when r=50. But for degree = 18 the curve going down. The reason is when transmission is very large, the graph is a dense graph. Each node has many neighbors. That means the more nodes each node

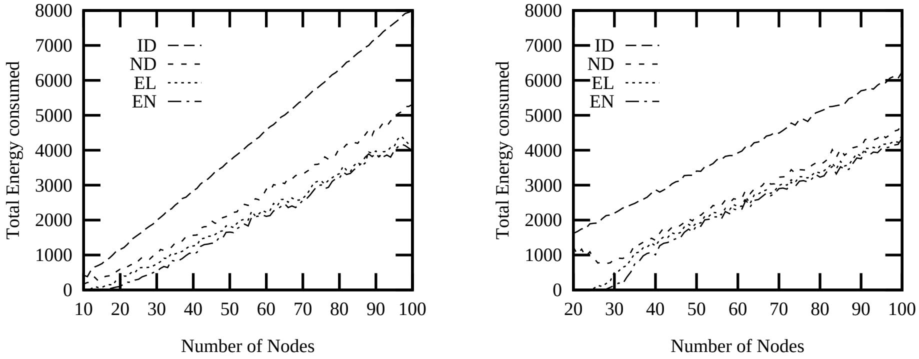


Figure 16: Comparison of leftover energy when $d = 1.0$ and $d' = 0.1$.

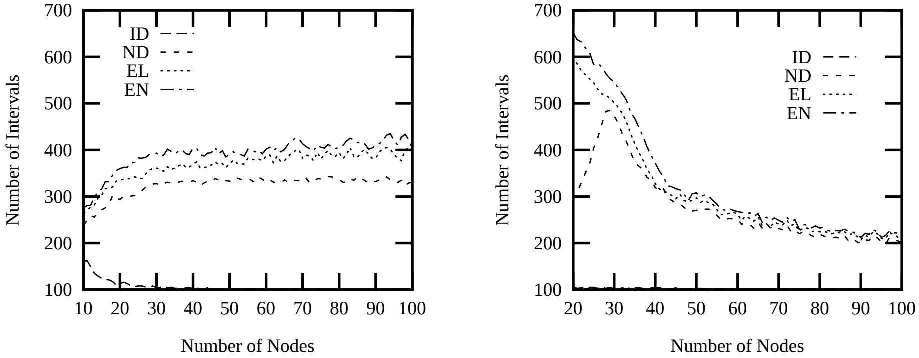


Figure 17: Comparison of total intervals before a node dies when $d = 1.0$ and $d' = 0.1$.

has more neighbors. But with fixed node degree each node has relative fixed number of neighbors. And we also see the result is quite different when node has big transmission range.

Figures 18 show results of the first simulation in the Type II experiment. Note here *FL* notation means no rule is applied, just flooding. *ID* means node id is a key used to unmark a node gateway status. *DS* means maximum distance is the primary key to unmark a node gateway status. *EL* uses node remaining power and *ED1* uses maximum distance as primary key to change node status from gateway to non-gateway exactly as DS does. But under ED1 rule the gateway will send out packet with extended distance, which is different from DS rule. Here the ED1 rule is not source-related. *ED2* is similar to ED1 rule except ED2 is source-related. The result for each sample is derived by averaging the number of gateways at each interval until the first host, 10 % and 100 % node(s) is depleted. By flooding the number of gateway is equal to the number of nodes. So, It is not necessary to show FL in the table or figure of number of gateways. The number of gateways under DS and EL stay very close. Actually the number of gateways under DS rule should equal to ones under ED1 and ED2 rules because all of them use maximum distance as primary key to change node status. The difference in the table is because of intermediate calculation rounding. The one for ID is about 1/3 more than one for DS and EL like in type I experiment. Also, the number of

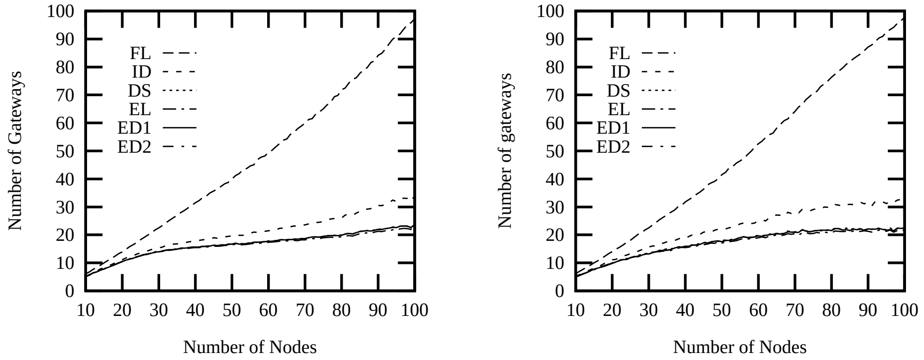


Figure 18: The average number of gateway nodes for different schemes when $p = 1st$ and $p = 10\%$

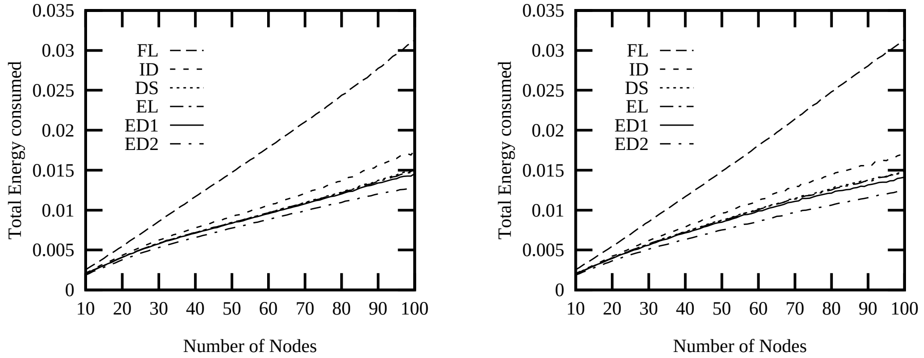


Figure 19: Comparison of total power consumption per packet when $p = 1st$ and $p = 10\%$

gateways is relatively insensitive to p, which is the percentage of nodes die.

Figures 19 shows results for the second simulation in the Type II experiment based on different die rate p. These results show the total power consumption by all nodes every broadcasting. The (increasing) order of energy consumption is the reverse order of the one for the life span of the first depleted node. Since our power unit used is very small, our $a = 50nJ/bit$, $\beta = 100pJ/bit/m^2$ and $k = 2$, and packet size is 2000 bit. So even a little bit difference of total power consumption will affect the number of intervals. Unfortunately the figures can not show that small unit. It's better to look at the values in the table. ED2 always consumes the least energy for every packet broadcasting. ED1 is a little more than ED2 but less than others. DS need more energy than EL when number of nodes increase because each time DS has relatively more gateways than EL and gateway send packet out using maximum distance. So overall power consumption is much more than EL, ED1 and ED2 rules. When number of nodes is small DS has less total energy consumption than EL.

Figures 20 shows results of the third simulation in the Type II experiment. The (increasing) order of life span of the first depleted host is: FL, ID, DS, ED1, EL and ED2. The life span under FL is shortest. This is obvious since the number of gateways under flooding is equal to the number

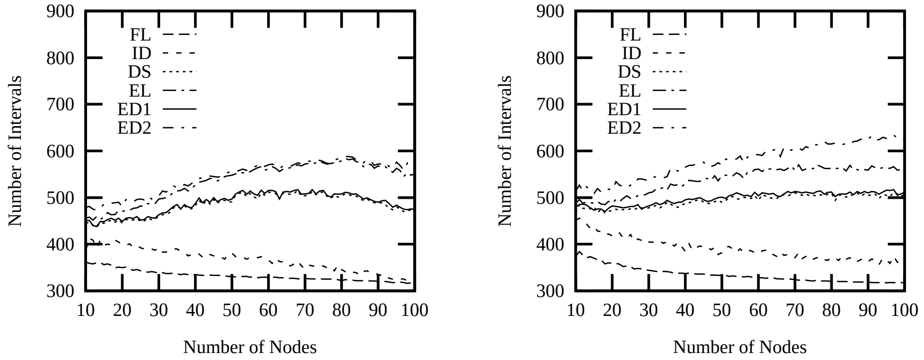


Figure 20: Comparison of number of intervals when $p = 1st$, $p = 10\%$

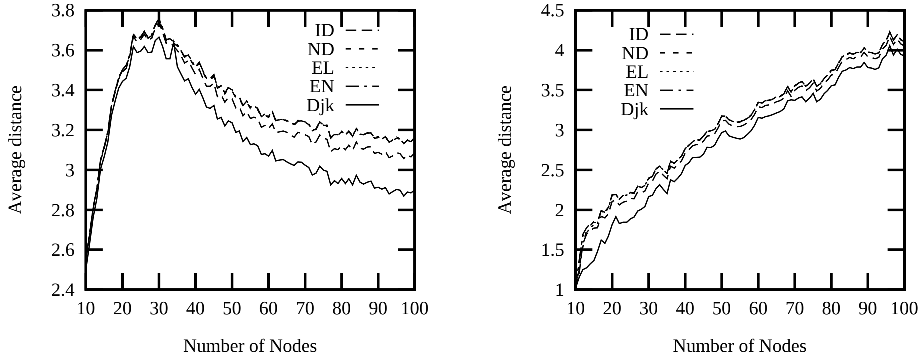


Figure 21: Comparison of average distance when $d = 1.0$ and $d' = 0.1$.

of nodes, which is the largest and gateway hosts consume more energy than non-gateway hosts. DS and ED1 stay very close. ED2 always has the longest lifespan. Lifespan under EL rule before first node deplete is the second longest because it balance the energy consumption in nodes, which has more energy left. Note that using flooding, each host is a gateway and forwards the broadcast packet once. The update interval until the first node depleted is extended by about $45\% - 70\%$ under DS, EL, ED1 and ED2 rule, and increased by about $47\% - 75\%$ when 10% node die. It increase about $52\% - 98\%$ when 50% node die. So, based on different rules can dramatically increase the node lifetime. Rule DS, EL and ED1 and ED2 can delay the first node death (power comes to zero) much longer than ID rule. ED2 extend longest lifespan. When percentage of die node increases interval under EL rule is less than other rules. The reason is gateway node us maximum distance to all its neighbors as ID rule. So it consumes more overall energy than rule like DS, ED1 and ED2. EL has more interval than rule DS and ED1 in the case of first node deplete just because it balances well energy consumption and tries to avoid using node with less power as gateway node. But this strategy can not avoid that its overall more energy consumption. So it has shorter lifespan than DS, ED1 and ED2 in the case of more nodes deplete.

Figures 21, 22, 23, and 24 show results for the forth simulation in the Type I experiment. These

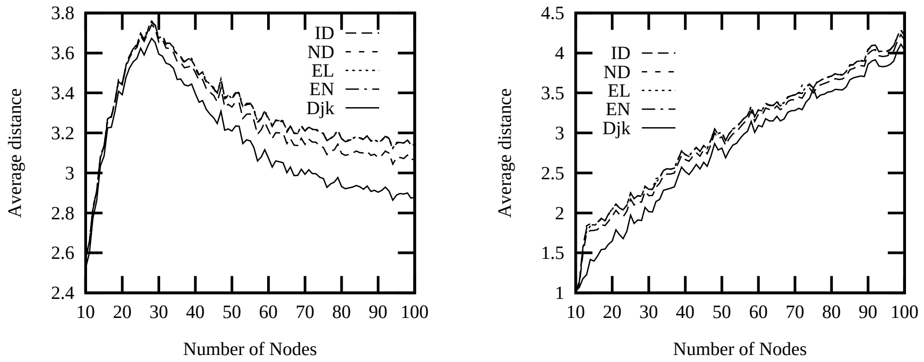


Figure 22: Comparison of average distance when $d = 2.0$ and $d' = 1.0$.

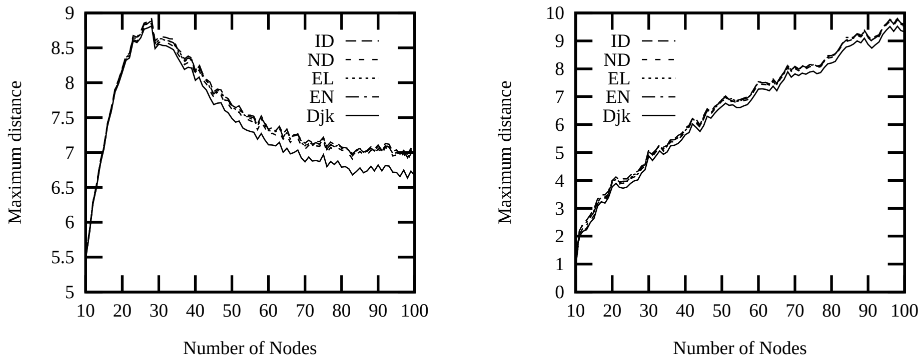


Figure 23: Comparison of maximum distance when $d = 1.0$ and $d' = 0.1$.

results show the average and maximum distance among all nodes before the first depleted host. Average distance (shown in Figures 21 and 22) is almost equal for NR and Djk (the curve for NR is not shown). Their overall average is about 3.15 (r=25) and 2.84 (d=9) when d=1.0 and $d^{'}$=0.1 (set-1 simulation). This is reasonable because NR has much more gateways than other mark rules. Djk corresponds to the shortest path derived by applying the Dijkstra's shortest path algorithm. Results of ND, EL, and EN are very close to each other with an overall average of 3.32 (r=25) and 3.07 (d=9) for set-1 simulation. ID is between the above two groups with an overall average distance of 3.27 (r=25) and 3.01 (d=9) for set-1 simulation. The average distance for set-2 simulation (d=2.0 and $d^{'}$=1.0) is very close to the result of set-1 simulation. When the node transmission range is fixed (here r=25) the average distance increases very fast as the number of nodes increases from 10 to about 30, then the curve goes down as the number of nodes increases. The reason is that for a fixed transmitter range, the connectivity requirement forces the increase of the average distance until the network reaches a certain degree of density (about 30 nodes when $r = 25$), then the average distance decreases as the network becomes dense. Without the connectivity requirement, the average distance would be decreasing as the the number of nodes increases. When the node degree is fixed, the average distance always increases as the the number of nodes increases.

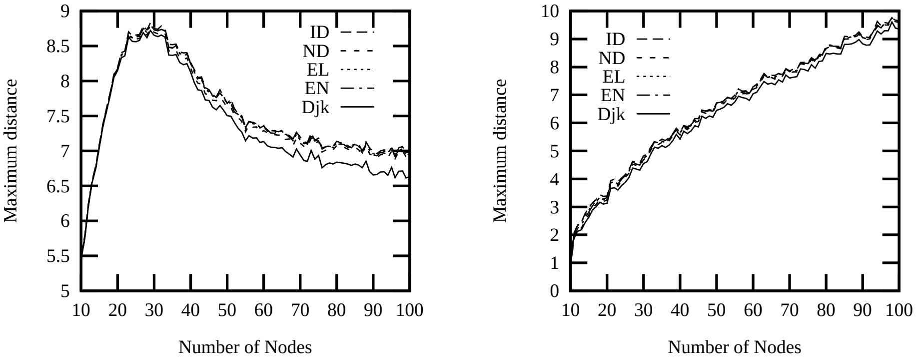


Figure 24: Comparison of maximum distance when $d = 2.0$ and $d' = 1.0$.

Figures 23 and 24 show results for the maximum distance among all nodes before the first depleted host in the Type I experiment. The maximum distance is almost equal for NR and Djk like the average distance case (again the curve for NR is not shown). Their overall average is about 7.36 (r=25) and 6.42 (d=9) for set-1 simulation. Djk is always the smallest. Results of ND and EN are also very close to each other with an overall average of 7.55 (r=25) and 6.64 (d=9) for set-1 simulation. For ID and EL, their maximum distance stays close with about 7.53 (r=25) and 6.62 (d=9) for set-1 simulation. Again, results of set-2 simulation are similar to the ones of set-1 simulation for the maximum distance. Overall, the curves for the maximum distance are very close to the ones for the average distance under all cases.

5 Conclusions

In this paper, we have applied Wu and Li's distributed algorithm for broadcasting in 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. We also introduce the distance rule and two extended distance rules in order to further reduce network broadcasting energy consumption where node can adjust transmission power. In the broadcasting process, only dominating hosts are responsible for retransmitting the broadcast packet. The objective is to devise a selection scheme (for dominating hosts) so that the overall energy consumption is balanced in the 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 for the fixed energy consumption d and d' the energy rule is a winner as of longer network lifespan before first node depleted. For the variable energy consumption model where nodes can adjust their transmission power. The extended distance rule is a winner as of longer network life time. Our future work will perform more in depth simulation under different settings. Experiments also show that all extended rules do not introduce much transmission latency according to overall average and maximum number of hops.

Although host mobility gives sufficient flexibility in choosing gateway nodes based on their energy levels, such flexibility is very limited in an ad hoc wireless networks with static hosts (such as sensor networks). That is, the selection of nodes to form a connected dominating set is limited to a special subset of nodes. Clearly, these nodes tend to be depleted sooner than the other nodes. Ways to handle this situation will be part of our future work.

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