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Energy Efficient Dominating Set Based Topology Maintenance in Ad Hoc Wireless Networks

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To my teachers and parents

Abstract

In a multi-hop wireless network, each node is able to send a message to all of its neighbors that are located within its transmission radius. In a broadcasting task, a source sends the same message to the entire network. The routing problem deals with finding a route between a source and a destination. In the activity-scheduling problem, each node decides between active or passive state. We present a scheme whose goal is to prolong network life while preserving connectivity. Each node is either active or has an active neighbor node. Routing and broadcasting are restricted to active nodes that create such dominating set. Activity status is periodically updated during a short transition period. The main contribution of this thesis is to propose new metrics for previously studied source independent localized dominating sets, based on combinations of node degrees and remaining energy levels, for deciding activity status. Furthermore, our implementation of new metrics enhanced the life span of each node and whole network for 12% to 29%. We argue that our new approach can outperform conventional 802.11, conventional dominating set based ad hoc networks and span in terms of capacity, latency, and power savings.

Thesis Supervisor: Ivan Stojmenovic

Title: Professor, Graduate Programs Coordinator (Computer Science)

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I would first like to thank my research advisor, Ivan Stojmenovic. His guidance has been an invaluable resource throughout all stages of this thesis. My discussions with him have opened up new insights, and on more than one occasion when I was deeply engrossed in intricate implementation details, discussion with him has enabled me to see the larger problem. It was his course in wireless networks that made me interested in the subject. Without his help and support could have been very difficult for me to complete this work. I am also thankful to my employer, Nortel Networks, for keeping me bear the financial burden and continuously support my family so that I can be very focus to this work.

I thank Professor Azhar Rizvi, Head of electronics department at QAU University, provided guidance and help with the electrical issue of the problem. I thank Manohar Lal for the time I spent in the Programming Methodology. We discussed programming issues, design and debugging of the simulator.

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Once again, I would like to express my deep gratitude to my supervisor Professor Ivan Stojmenovic who provided his guidance, encouragement and support during this research, reviewed my drafts of this work accurately to improve its contents and presentation. His dedication to his work is always going to inspire me.

The work is in collaboration with Julio Solano and Jie Wu. I thank them for providing research base and lot of material to complete initial studies. I would like to thank team of the Open Systems Laboratory, UIUC, for providing material and help in designing simulation system based on 802.11.

Finally, I would like to express my eternal gratitude to my parents who give me endless love and support through all my life. I would like to dedicate this thesis to my wife, Rashida Shaikh, who always encouraged me and shared my challenges and achievements during my graduate studies.

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Chapter 1

Introduction

Wireless networks consist of static or mobile hosts (or nodes) that can communicate with each other over the wireless links without any static network interaction. Each mobile host has the capability to communicate directly with other mobile hosts in its vicinity. They can also forward packets destined for other nodes. Examples of such networks are ad hoc, local area, packet radio, and sensor networks, which are used in disaster rescues, wireless conferences in the hall, battlefields, monitoring objects in a possibly remote or dangerous environment, wireless Internet etc.

Since power is often an important issue in many ad hoc networks, there have been many proposals to incorporate power-awareness into the routing layer [CT] or link layer of an ad hoc wireless network. However, several experiments show that the relatively high idle energy consumption in many protocols including 802.11b [FN, SK] plays a very important role in the lifetime of a node in an ad hoc wireless network. With this in mind, Chen et al., introduced new matrice for dominating set based energy efficient activity [CJBM], a new protocol that saves energy in dense wireless ad hoc networks by turning most nodes in sleep mode most of the time, while preserving capacity.

There are numerous different routing protocols presently proposed for ad hoc networks. Unfortunately, few have been extensively simulated, let alone implemented in an actual ad hoc environment. Consequently, independent commentary is rare for many of the protocols talked about in this thesis, where several other ad hoc routing protocols are briefly introduced, highlighting their novel concepts or optimizations over the main routing protocols presented.

In previous work from Jie, Bing and Stojmenovic [WWS], they 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 traffic than nodes outside the set. The main contribution of this thesis is to present a new energy efficient protocol by introducing a new metric for creating dominating sets. In this work, we also describe an implementation of a simulator in the Solaris (UNIX) operating system.

Our implementation has the following desirable features.

1. Real-world problems, such as even and uneven number of units transmitted by the node per transmission cycle
2. Random number of nodes participates in transmission per round
3. We have developed the infrastructure needed to handle node movements.
4. Based on the criteria nodes take responsibility of gateway nodes periodically

The remainder of this introduction presents the motivation for a new metric required to understand the importance of the work in Section 1.1. Section 1.2 discusses the attributes and unique characteristics of ad hoc networks.

1.1 Motivation for a New Metric

Ad hoc networks are best model by the unit graphs constructed in the following way. Two nodes A and B are neighbors if and only if the distance between them is at most R, where R is the transmission radius, which is equal for all nodes. This model is widely used and is applied in our work. In the activity-scheduling problem, each node decides between an active or a passive state so that the network remains connected and its lifetime is maximized. In ad hoc wireless networks, the limitation of power of each host poses a unique challenge for power-aware design. 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. In order to prolong the life span of each node and, hence, the network, power consumption should be minimized and balanced among nodes. Ideally, nodes should be active only when they transmit or receive messages. However, nodes in a sleep state cannot be wake up by any signal; they can only wake up at predetermined time. It was experimentally confirmed in [FN] that the difference in energy consumption between an idle node and a transmitting node is not major, while the major difference exists between idle and sleep states of nodes.An energy cost model given in [CJBM] shows that ratio of Transmit, Receive, Idle and Sleeping node is 13:9:7:1. The difference between idle and sleeping node is large. The actual ratio of energy spent by a node in an active and a sleep state depends on many factors such as network topology and traffic patterns. To be functional, the set of active (idle, transmitting or receiving) nodes must be connected. Further, it is desirable that a delivery of packets to a node in a sleep state be made from one of its neighboring nodes. Other solutions are possible, but they will cause greater delay or greater difficulties in organizing the topology. A subset of nodes which is connected and which has the property that any node not in it is a neighbor of at least one node from the subset is known as dominating set. Therefore, the dominating set appears to be a reasonable solution for the activity-scheduling problem. In a broadcasting task, a source node sends the same message to all the nodes in the network. In the one-to-all model, applied in this thesis, a transmission by a node can reach all nodes that are within radius distance from it. Broadcasting is also refered frequently in literature as flooding. Broadcasting applications include paging a particular host or sending an alarm signal. Broadcasting is also used for route discovery in a source-initiated on-demand routing. It can also be a viable candidate for multicast and routing protocols in very dynamic ad hoc networks. Data broadcasting and gathering are important functions supported in a sensor network to collect and disseminate critical information, such as movement, temperature, pressure, and noise level. The traditional solution to the broadcasting problem is blind flooding, where each node receiving the message retransmits it to all its neighbors. The only 'optimization' applied to this solution is that nodes remember messages received, and do not act when receiving repeated copies of the same message. However, blind broadcasting cause unnecessary collisions and bandwidth waste, and it is the cause for many nodes not to receivthe message. It was observed in [SSZ] that the dominating set could be a good solution for the broadcasting problem. Nodes in a dominating set retransmit the packets, while nodes outside of it do not. It was further observed in [WL] that dominating sets could be used to facilitate the routing task. The route is restricted to nodes in a dominating set, except possibly first and last hops since source or destination may not be in the dominating set. Activity scheduling deals with the way to rotate the role of each node among a set of given operating modes. For example, one set of operating modes is sending, receiving, idles, and sleeping. Different modes have different energy consumption. Activity scheduling judiciously assigns a mode to each node to save overall energy consumption in the network and/or to prolong the life span of each individual node. One such resolution is to make nodes from a dominating set active, while other nodes are in sleep mode. Therefore, dominating sets can be used as a unique structure to intelligent and scalable solutions to broadcasting, activity scheduling, and routing tasks.

Dominating sets defined by using global network information, or quasi-global information (e.g. minimum spanning tree) are not acceptable solutions since maintenance of such structures requires unacceptable communication overhead and energy expenditure. Cluster heads and gateway nodes in a cluster structure define a dominating set, and were first 'intelligent' broadcasting solution proposed in literature. However, the node mobility either worsens the quality of the structure dramatically, or otherwise causes a chain reaction (local changes in the structure could trigger global updates). This solution is therefore 'quasi-local'. Localized connected dominating set concepts, proposed recently [WWS], avoid such chain reactions, and have similar or better rebroadcast savings. Their maintenance does not require any communication overhead in addition to maintaining positions of neighboring nodes, or information about 2-hop neighbors. In several existing concepts, dominating set is source dependent. This is an acceptable solution for broadcasting and routing tasks in networks, where all nodes are active all the time. In order to have some nodes sleeping for a while, a dominating set must be fixed for a while. Therefore dominating sets must be source independent. One such concept is based on creating a fixed dominating set, where nodes that do not have two unconnected neighbors, and nodes that are 'covered' by one or two neighbors (each neighbor of a covered node is neighbor of one of nodes that cover it) are eliminated [WL]. To resolve dominating set priorities among nodes, Wu et al. [WL] used node ids. Node degrees are suggested in [SSZ] as the main key for comparison, resulting in overall decrease of dominating set size.

1.2 Contribution of the Thesis

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 a recent solution [WDGS, WWS], the remaining energy at each node is proposed as the crieteria for selecting the dominating set. The degree is used as a secondary key, and node id as ternary key. The dominating set is defined again at the beginning of any round, thus power consumption is divided more fairly. Periodic change of dominating set may also be desirable due to node mobility.

This thesis makes a step further in the same direction. We consider variety of choices for the primary key in the dominating set definitions. Some of them perform better, some of them worse than energy metric. For low densities, all metrics have the same network life, defined as the number of rounds before the first node has no energy left to perform the assigned task. In such scenarios, some nodes are force to be active in all rounds due to a lack of neighbors to take the role over and the critical links for connectivity. It proves theoretically and experimentally that an ad hoc network with about 100 nodes is disconnected with high probability if the average degree is below about 15, and connected with high probability when the average degree is above about 15 (the transition is sharp) [L]. Different metrics have moderate impact for medium densities (in ranges up to 30); while for higher densities, the impact of selecting particular metric is significant for the network life. The experimental data show that a network life can be significantly shorter or longer with new metrics, obtained as combinations of degree and remaining energy, with respect to applying either degree or remaining energy as the main key in activity status decisions.

1.3 Thesis Organization

The next chapter gives a relevant literature review on source independent broadcasting and activity scheduling. Capter 3 describes the thesis contribution, while chapter 4 presents simulation data. Chapter 5, conclusion and references complete the thesis.

Chapter 2
Background and Related Work

2.1 Ad Hoc Networking

An ad hoc network is a collection of wireless nodes that form a network without the use of any static infrastructure such as a wireless Access Point. Instead of communicating via a centralized access point, the nodes in the network cooperate to allow information to be exchanged between them. In particular, each node acts as a router, forwarding packets for other nodes in the network.

It is very useful to describe the term ad hoc used in this thesis, as there is some confusion in wireless networking literature about this term. In particular, the IEEE 802.11 speciation uses the term ad hoc to describe "a network composed solely of stations within mutual communication range of each other" [Bd]. In many other contexts, including this thesis, the term ad hoc refers to multi-hop self-configuring wireless networks. This difference in definitions sheds some light on how well the 802.11 MAC layer performs as part of a multi-hop wireless network.

The focus of most research in ad hoc networks is on finding the methods for forwarding packets through the network. A number of protocols for routing in ad hoc networks have been proposed and evaluated [BMSU, CJBM, CSSb, and DW] in the previous relevant work. Although a great deal of research has been done on ad hoc routing protocols, but there is lot of room for protocols to improve power consumption. Though simulation may not completely test the problems of real world, however we have taken many factors to get best possible exposure of real world, which many simulation tested haven't taken into account the We have tested new protocol with number of factors, such as, random number of transmissions, random number of nodes transmitting and receiving at giving time. Number of packets a node transmit at a given time was also varied by nodes own choice. We have tried to be close to any unexpected behavior of nodes with above factors and exit and entry of the nodes in the network.

2.2 Dominating Set

Dominating-set-based routing [SSZ, WL] is a promising routing approach in ad hoc networks. A subset of the vertices of a graph is a dominating set if every vertex not in the sub-set is adjacent to at least one vertex in the subset. More over, this dominating set should be connected for ease of the routing process within the induced graph consisting of dominating nodes only.

Vertices in a dominating set are also called gateway hosts, while vertices outside a dominating set are called non-gateway hosts. In hosts v and w form a connected dominating set of the given unit disk graph. The main advantage of dominating-set-based routing is that it simplifies the routing process to the one in a smaller subnetwork generated from the connected dominating set. This means that only gateway hosts need to keep routing information in a proactive approach and the search space is reduced to the dominating set in a reactive approach. Note that gateway hosts are used not only to route packets but also to disseminate routing information. Clearly, the efficiency of this approach depends largely on the process of finding and maintaining 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 [WL] proposed a simple and efficient distributed algorithm that can quickly determine a connected dominating set in ad hoc networks. This approach uses a localized algorithm called marking process where hosts interact with others in the neighborhood. Each host performs exceedingly simple tasks of maintaining and propagating information markers.

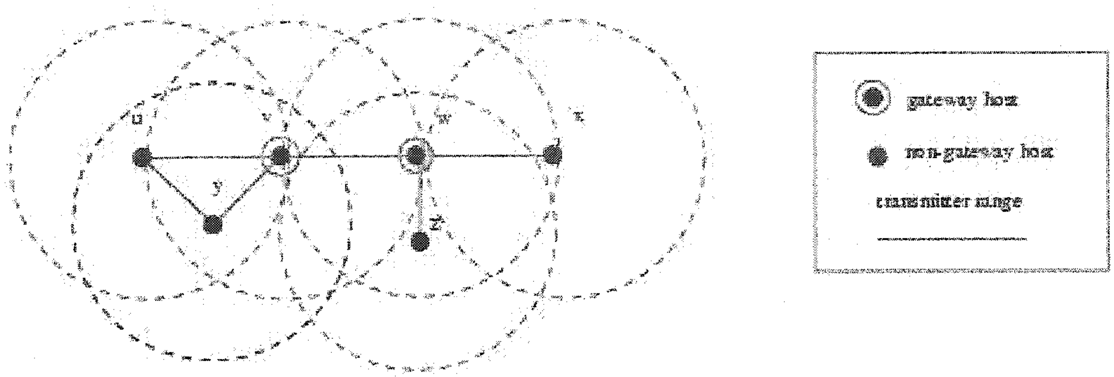


Figure 2.2-1: A sample unit disk graph, representing an ad hoc wireless network.

Nodes that belong to a (fixed, source-independent) dominating set will be called internal nodes (of course, a different definition for dominating set leads to different set of internal nodes). It is desirable, in the context of broadcasting, to create dominating sets with minimum possible ratio of internal nodes. Wu and Li [WL] proposed a simple and efficient distributed algorithm for calculating connected dominating set in ad hoc wireless networks. They introduced the concept of an intermediate node. A is an intermediate node if there exist two neighbors B and C of A that are not direct neighbors themselves.

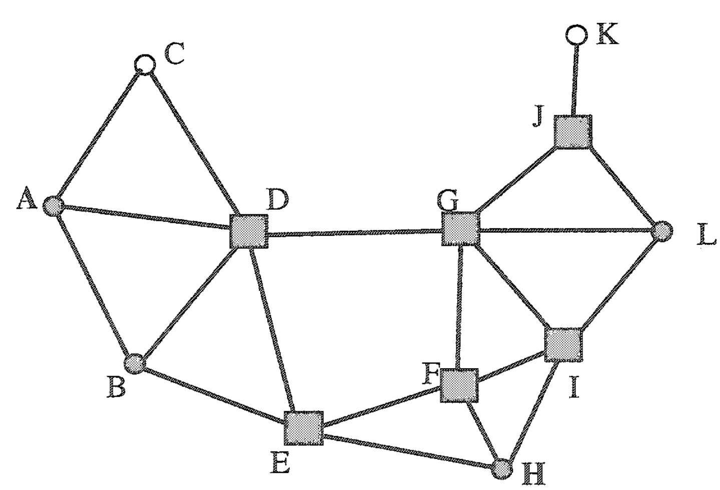


Figure 2.2-2: Nodes C and K are not intermediate, nodes A, B and H are not inter-gateway nodes

For example, nodes C and K in **Figure 2.2-2** are not intermediate nodes, while other nodes are. The concept is simple, but not many nodes are eliminated from the dominating set. If a graph is complete, the definition might be modified to select highest key node as a default dominating set, although no retransmission is needed for reliable broadcast. See appendix for more on dominating set.

2.3 Related Work

There are different areas in which work has been done to enhance the overall life and density of the ad hoc network. These are the most important and relevant areas of work.

2.3.1 Based on dominating set

Our work is very closely related to fundamental work don in the dominating set based power-aware ad hoc networks by Wu and Li. They [WL] also introduced two rules that considerably reduce the number of internal nodes in the network. Rule 1 [WL] is as follows. Consider two intermediate neighboring nodes, v and u, in **Figure 2.2-1**. If every neighbor of v is also a neighbor of u, and $\text{key}(v) < \text{key}(u)$, then node v is not an inter-gateway node, using $\text{key}(x) = \text{id}(x)$. In **Figure 2.2-1**, node v is 'covered' by node u. Message transmission by v is covered by transmission of u. Any node that receives message from v will receive it from u as well. [SSZ] proposed to replace node ids with a record $\text{key} = (\text{degree}, x, y)$, where degree is the number of neighbors of a node (and is primary key in the comparison), and x and y are its two coordinates in the plane (and serve as secondary and ternary keys). It significantly reduces the size of dominating set. Using such keys, consider example in Fig. 1. Note that node J is forced by node K, for whom it is the only neighbor, to be in dominating set for all possible definitions of connected dominating sets. Nodes A and B are covered by node D, node H is covered by node F, and node L is covered by G. The remaining six nodes are inter-gateway nodes, and are squared in **Figure 2.3-1.**

Note that, when $\text{key} = (\text{primary-key}, \text{secondary-key}, \text{temary-key}, \ldots)$ then $\text{key}(u) < \text{key}(v)$ in the following cases: (1) $\text{primary-key}(u) < \text{primary-key}(v)$, (2) $\text{primary-key}(u) = \text{primary-key}(v)$ *and* $\text{secondary-key}(u) < \text{secondary-key}(v)$, (3) $\text{primary-key}(u) = \text{primary-key}(v)$ and $\text{secondary-key}(u) = \text{secondary-key}(v)$ *and* $\text{ternary-key}(u) < \text{ternary-key}(v) \ldots$

Next, let the gateway nodes be those inter-gateway nodes that are not eliminated by Rule2 [WL], defined as follows. Assume that u, v and w are three inter-gateway nodes that are mutual neighbors. If each neighbor of v is a neighbor of u or w, where u and w are two connected neighbors of v, and v has lowest key among the three, then v can be eliminated from the list of gateway nodes. Node id was used as key, while [SSZ] again proposed to use above defined key instead of id. The reason for elimination of v is that any node that can benefit from retransmission by v will receive the same message instead from either u or w. All inter-gateway nodes in **Figure 2.3-2** remain gateway nodes. Node E is 'covered' by D and F, but D and F are not connected themselves. Although all neighbors of node I are neighbors of either F or G, it does not have lowest id (in this example, x coordinate serves as id). If id is changed appropriately, node I may become covered. This suggests that further improvements to the gateway definition might be possible, but the enhancement may require informing neighbors about dominating set status. In the current definition, nodes may decide their own dominating set status without any message exchange, but cannot decide the same for their neighbors. If location information of neighboring nodes is available, each node can determine whether or not it is an intermediate, inter-gateway or gateway node in $O(K^3)$ computation time (where k is the number of its neighbors), and without any message exchanged with its neighbors for that purpose. Otherwise, the maintenance of internal node status requires the knowledge of neighbors for each neighbor. Experiments in [SSZ] indicate that percentage of gateway nodes decreases from 60% to 45% when average graph degree increases from four to ten.

Dai and Wu [DW] proposed several enhancements to the definition of internal nodes. In [DW], they generalize one and two neighbor coverage of a node to k- neighbor coverage, with fixed and variable k. The case of variable k is even computationally less expensive than two nodes coverage case. In this definition, each node A considers the subgraph of its neighboring nodes with higher keys than A, and constructs connected components in the subgraph (depth first search can be used for this task). If there exist one connected component so that each neighbor of A is neighbor of at least one node from the component, then node A is not a gateway node. Note that the test can be further simplified by observing that, in order to cover A, all neighbors with higher key must be connected, that is, there must be exactly one connected component.

Wu, Dai, Gao, and Stojmenovic [WDGS] and Wu, Wu, and Stojmenovic [WWS] studied dynamic selection of connected dominating nodes for activity scheduling. Specifically, in the selection process of a gateway node, preference to nodes with a higher energy level is given. The effectiveness of the proposed method in prolonging the life span of the network is confirmed through simulation. The most energy efficient methods will select static dominating set for a given round, turning all remaining nodes to a sleep state. Depending on energy left, changes in activity status for the next round will be made. The change can therefore be triggered by changes of power status, in addition to node mobility. In summary, the key for deciding dominating set status can be defined in variety of ways: id(X) [WL], (degree(X), id(X))[SSZ], (energy(X), degree(X), id(X))[WWS], that is, it can have primary, secondary, and ternary keys for comparisons. Here energy(X) denotes the amount of remaining energy at node X.

2.3.2 Source-independent dominating sets

A subset of the vertices of a graph is a dominating set if every vertex not in the sub-set is adjacent to at least one vertex in the subset. More over, this dominating set should be connected for ease of the routing process within the induced graph consisting of dominating nodes only.

Vertices in a dominating set are also called *gateway* hosts or *internal nodes* while vertices outside a dominating set are called *non*-gateway hosts. The main advantage of using the dominating-set is that it simplifies the routing process to the one in a smaller sub-network generated from the connected dominating set. This means that only gateway hosts need to keep routing information in a proactive approach and the search space is reduced to the dominating set in a reactive approach. Note that gateway hosts are used not only to route packets but also to disseminate routing information. Clearly, the efficiency of this approach depends largely on the process of finding and maintaining a connected dominating set and the size of the corresponding sub-network. In this work, we have used the technique presented in [WDGS]. In the process of forming the dominating set, any parameter could be used to break tie among the nodes. For example, node degree, node ID, energy level, and geographical location of vertex in a particular dimension, etc. The most prominent is node degree, however for our work two most important parameters are degree and energy. We have used a key to combine both, degree and energy. Following combination was used to find the key:

Nodes that belong to a (fixed, source-independent) dominating set will be called *internal* nodes (of course, a different definition for dominating set leads to different set of internal nodes). It is desirable, in the context of broadcasting, to create dominating set with minimum possible ratio of internal nodes. Wu and Li [WL] proposed a simple and efficient distributed algorithm for calculating connected dominating set in ad hoc wireless networks. They introduced the concept of an *intermediate* node. A node *A* is an *intermediate* node if there are two neighbors *B* and *C* of *A* that are not direct neighbors themselves. For example, nodes *C* and *K* (see **Figure 2.3-3**) are not intermediate nodes, while other nodes are. The concept is simple, but not many nodes are eliminated from the dominating set. If a graph is complete, the definition might be modified to select highest key node as default dominating set, although no retransmission is needed for reliable broadcast.

Wu and Li [WL] also introducedrtwo rules that considerably reduce the number of internal nodes in the network. *Rule 1* [WL] is as follows.

Rule 1: Consider two intermediate neighboring nodes v and u. If every neighbor of v is also a neighbor of u, and $\mathrm{id}(v) < \mathrm{id}(u)$, then node v is not an *inter-gateway* node. Node v is 'covered' by node u. Message transmission *by N(v)* is covered by retransmission of *N(u)*. It means any node receives message from v also receives it from u. *Stojmenovic et al.* [SSZ] proposed use of the $\text{key} = (\text{degree}, \text{x}, \text{y}, \text{energy or combination of degree} + \text{energy})$ instead of node *id*'s. Where *degree* is the number of neighbors of a node and x & y are two coordinates in the plane (and serve as secondary and ternary keys). It significantly reduces the size of dominating set. Using such keys, consider example in Fig. 1. Note that node *J* is forced by node *K*, being the only neighbor, to be in dominating set for all possible definitions of dominating sets that do not include node *K* in it. Nodes *A* and *B* are covered by node *D*, node *H* is covered by node *F*, and node *L* is covered by *G*. The remaining six nodes are inter-gateway nodes, and are squared in, see **Figure 2.3-4** for detail.

Next, let the *gateway* nodes be those inter-gateway nodes that are not eliminated by Rule 2 [WL], defined as follows.

Rule 2: Assume that *u, v* and *w* are three inter-gateway nodes that are mutual neighbors. If each neighbor of v is a neighbor of u or w, where u and w are two connected neighbors of *v*, and v has lowest *id* among the three, then v can be eliminated from the list of gateway nodes. [SSZ] again proposed to use above defined *key* instead of *id*. The reason for elimination of v is that any node that can benefit from retransmission by v will receive the same message instead from either u or w. All inter-gateway nodes in Fig. 3 remain gateway nodes. Node *E* is 'covered' by *D* and *F*, but *D* and *F* are not connected themselves. Although all neighbors of node *I* are neighbors of either *F* or *G*, it does not have lowest *id* (in this example, x coordinate serves as *id*). If *id* is changed appropriately, node I may become covered. This suggests that further improvements to the gateway definition might be possible, but the enhancement may require informing neighbors about dominating set status. In the current definition, nodes may decide their own dominating set status without any message exchange, but cannot decide the same for their neighbors.

If location information of neighboring nodes is available, each node can determine whether or not it is an intermediate, inter-gateway or gateway node in $O(k^3)$ computation time (where k is the number of its neighbors), and without any message exchanged with its neighbors for that purpose. Otherwise, the maintenance of internal node status requires the knowledge of neighbors for each neighbor. Experiments in [SSZ] indicate that percentage of gateway nodes decreases from 60% to 45% when average graph degree increases from four to ten.

Dai and Wu [DW] proposed several enhancements to the definition of internal nodes. In [DW], they generalize one and two neighbor coverage of a node to k- neighbor coverage, with fixed and variable k. The case of variable k is even computationally less expensive than two nodes coverage case. In this definition, each node A considers the subgraph of its neighboring nodes with higher keys than A, and constructs connected components in the subgraph (depth first search can be used for this task). If there exist one connected component so that each neighbor of A is neighbor of at least one node from the component, then node A is not a gateway node. Note that the test can be further simplified by observing that, in order to cover A, all neighbors with higher key must be connected, that is, there must be exactly one connected component.

A source independent definition of dominating set in applications where the dominating set status of each node must be communicated to its neighbors (this is the case in routing and activity scheduling applications) can be described as follows. Each node initially calculates it's dominating set status based on the original gateway node definition [WL]. Using some back-off mechanism, each gateway node decides when to transmit its decision to its neighbors (non-gateway nodes remain silent). While waiting, it may hear several announcements from its gateway node neighbors. After each announcement, *A* reevaluates its gateway node decision. If the subgraph of all neighboring nodes with higher key value or with announced gateway node decision is connected, and each neighbor of *A* is a neighbor of at least one of these nodes, then A decides to withdraw from the dominating set and never transmits such decision to neighbors.

A 2-hop dominating set concept, which can be further generalized to *k*-hop dominating set concept, and can be viewed as a clustering scheme with localized maintenance property is proposed in [S2]. It has the following properties: two neighboring clusterheads can be at distance one or two, each node in a cluster is at distance one or two from its clusterhead, and two clusters are thus connected if there exist a node that is neighbor to both clusterheads, or the two clusterheads are directly linked. The structure is a generalization of Wu's dominating set concept [WL]. We shall define similarly 2-hop intermediate, inter-gateway, and gateway nodes as follows:

Two-hop rule: A node *X* is 2-hop intermediate if it has two 2-hop neighbors B and C that are not 2-hop neighbors themselves. *X* is a 2-hop inter-gateway if it has no 2-hop neighbor *Y* such that every 2-hop neighbor of *X* is also a 2-hop neighbor of *Y* and $\mathrm{key(X)} < \mathrm{key(Y)}$. The *key(X)* can be one of *id(X), degree(X) or energy-level(X).* There can be primary, secondary, ternary keys etc. for comparisons. A 2-hop inter-gateway node *X* is 2-hop gateway if it has no two neighbors *Y* and *Z* such that every 2-hop neighbor of *X* is 2-hop neighbor of *Y* or *Z*, and $key(X)<key(Y)$, $key(X)<key(Z)$.

Adjih, Jacquet and Viennot [AJV] proposed to combine multi-point relay and dominating set approaches. Each node computes its forwarding neighbors set and transmits it to its neighbors. Each node then determines whether it belongs to 'MPR-dominating set' if it either has the smallest ID in its neighborhood or the node is forwarding neighbor of the neighbor with the smallest ID.

We have proposed to combine both degree and energy as a new key for selection of gateway nodes. Wu, GAO, and Stojmenovic [WGS] were first to propose to use energy metrics in dominating set-based routing. Using the Wu and Li's marking process we first construct the dominating set by using the rules discussed in [WGS] and then reduce the dominating set by using Key to reduce the size of dominating set. The election process is localized, so each node is assigned a key, calculated using above formula.

The new *key* (combination of degree and energy) is replaced in rule 1 and rule 2 with *id*. We have examined the effect of following on the selection of the gateway nodes in the dominating set and effect to over all network life. Following four keys are used in this work.

Key 1:

$$\text{Key} = \text{degree}$$

Degree as a key in selecting dominating set gateway nodes has been used in [WWS, CJBM]. Degree gives most-efficient results in calculating smallest dominating set in the network. However, our goal is to enhance network life. Intuitively smaller, the size of dominating set longer should be the life of the network. However, this is not always true in the real life, as the life of the node is limited to its total energy. Even a node may have higher degree compare to its neighbor but due to energy constraint, it may only live for next one round.

Key 2:

$$\text{Key} = \text{energy}$$

Experimental result shows that using only energy in selecting gateway nodes in dominating set does not give good result compare to degree. Key = energy, result to large number of nodes in the dominating set, on average. That led to more energy consumption per round.

Key 3:

$$Key = a \times \deg ree + b \times energy$$

Using degree and energy together as above lead to improved network life compare to Key 1 in certain cases (see, chapter 4, Performance Evaluation). Energy always contributes in the selection of dominating set. Value energy is normalized. Values of '*a*' and '*b*' are experimental. We have generated best value for the simulation environment used. More combination of degree and energy is used to define key, see section 3.1.4, Combined metrics for keys in connected dominating set.

2.3.3 Sleep Node Schedule

Xu, Heidemann, and Estrin [XHE] discuss the following sensor sleep node schedule. The tradeoff between network lifetime and density for this cell-based schedule was investigated in [BS]. 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 selected in an alternative fashion as a representative. The adjacent squares form a 2-D grid and the broadcast process becomes trivial. Note that the selected nodes in [XHE] make a dominating set, but the size of it 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. Selection of gateway nodes for the dominating set is without using any global parameters.

2.3.4 Span

The Span algorithm [CJBM] selects some nodes as coordinators. These nodes form dominating set. A node becomes coordinator if it discovers that two of its neighbors cannot communicate with each other directly or through one or two existing coordinators. In addition, a node should withdraw if every pair of its neighbors can reach each other directly or via some other coordinators, (they can also withdraw if each pair of neighbors is connected via possibly non-coordinating nodes, to give chance to other nodes to become coordinators). Since coordinators are not necessarily neighbors, three-hop neighboring topology knowledge is required. However, the energy and bandwidth required for maintenance of three-hop neighborhood information is not taken into account in experiments [CJBM]. On the other hand, if the coordinators are restricted to be neighboring nodes, then the dominating set definition [CJBM] becomes equivalent to one given by Wu and Li [WL]. Next, protocol [CJBM] heavily relies on proactive periodic beacons for synchronization, even if there is no pending traffic or node movement. The recent research on energy consumption [FN] indicates that the use of such periodic beacons or hello messages is an energy expensive mechanism, because of significant start up cost for sending short messages. Next, [BS] observed that the overhead required for coordination with SPAN tends to 'explode' with node density, and thus counterbalances the potential savings achieved by the increased density. Finally, remaining energy of a node is not use to select active nodes. Therefore, there will be no activity changes in static networks.

2.3.5 Addressing Sleep Period

Feeney [F] described a power saving protocol in which each station is awake a bit over half the time, to ensure that awake periods of any two neighboring stations will overlap, allowing communication between them. The energy savings with this method are therefore limited to one half. Pearlman, Deng, Liang and Haas [PDLH] described a method in which the probability of a node to be awake is proportional to the ratio of the remaining energy over its initial energy, and show experimentally that the network lifetime can be increased by over 50%.

2.3.6 Activity Scheduling

Tian and Georganas [TG] considered somewhat related problem, the area coverage, where sensors shall decide about their activity status to prolong network lifetime but still provide continuing monitoring of the whole area assigned. In their solution, nodes observe that their monitoring area is already covered by other active sensors, and send a message announcing their withdrawal from monitoring status and move to a passive state. An alternative method follows a dominating set based approach where nodes instead announce their activity status by one added bit, and is used for both area coverage or dominating set creation with reduced size of the forwarding node set.

Several authors [CMWZ, QVL, LK, and SL] proposed independently reliable broadcasting schemes in which the sending node selects adjacent nodes that should relay the packet to complete broadcast. The IDs of selected adjacent nodes are recorded in the packet as a forward list. An adjacent node that is requested to relay the packet again determines the forward list. This process is iterated until broadcast is completed. The methods differ in details on how a node determines its forward list. The multi-point relaying method, discussed in detail by Qayyum, Viennot and Laouiti [QVL], and dominant pruning method, proposed by Lim and Kim [LK], are both based on a heuristics that selects a minimum size subset of neighbors of a given node S that will 'cover' all two-hop neighbors of S. A node is called 'covered' if it received (directly or via retransmissions by other nodes) message originating at S. Relay points of S are 1-hop neighbors of S that cover all 2-hop neighbors of S. That is, after all relay points of S retransmit the message; all 2-hop neighbors of S will receive it. The goal is to minimize the number of relay points of S. The computation of a multipoint relay set with minimum size is NP-complete problem, as proven in [LK, QVL]. A heuristic algorithm, called greedy set cover algorithm, is proposed in [Lo]. This algorithm repeats selecting node B in which the number of neighbor nodes that are not covered yet is maximized. Lipman, Boustead, and Judge [LBJ, LBJ1] proposed to modify the selection of best neighbor criterion to include remaining energy at nodes as part of criterion. Each node is assigned a key UpUn, where '$Up = 1/(1+e^{-P+s})$' is energy metric (P is the remaining energy at a node, while $s = Maxenergy/2$ is the half of the maximum energy. Un is the ratio of unallocated (uncovered) local two hop neighbors and the total number of two hop neighbors. However, all nodes are active all the time in the approach, and the selection of forwarding nodes is source-dependent.

Chapter 3
Architecture and Implementation

Wireless networks consist of static or mobile hosts (or nodes) that can communicate with each other over the wireless links without any static network interaction. Each mobile host has the capability to communicate directly with other mobile hosts in its vicinity. They can also forward packets destined for other nodes. A new protocol is designed with the consideration of the the following properties.

a) The key design goal is to minimize energy consumption by letting as many nodes to sleep as possible, further discussed in sections 3.1 and 3.2.
b) Minimize energy required per routing task. We assume that the ransmission power of nodes is fixed. We can simply use the hop count to measure the energy requirement of a routing task, thus using constant metric per hop.
c) Nodes communicate their location and power level periodically that helping assigning the gateway responsibility.
d) Maximize the number of routing tasks that a network can perform. Some nodes participate in routing packets for many source-destination pairs, and the increased energy consumption may result in their failure. Thus, pure power consumption metric may be misguided in the long term. Our design selects nodes based on a key that is a combination of degree and energy.
e) Minimize communication overhead.
f) Avoid memorizing past traffic or route.
g) Localized algorithms: Localized algorithms are distributed algorithms that resemble greedy algorithms, where a simple local behavior achieves a desired global objective. In a localized routing algorithm, each node makes a decision regarding which neighbor to forward a message based solely on the location of itself, its neighboring nodes, and destination. Algorithms that require global knowledge is not scalable, since location updates cause excessive communication overheads. Even if a network

is static, global knowledge of nodes in sleep mode is required. We assume that the accurate destination information is made available to a sender node. [WWS]

h) Single-path routing algorithms [BMSU]: It is shown in previous works that single-path strategies may be even more robust.

i) Guaranteed delivery: We use localized power and cost aware routing algorithms [SL1] that achieve a very high delivery rates for dense networks, but low delivery rate for sparse networks.

j) A combined metric of degree and energy is formed to defin akey to use in generating connected dominating set.

3.1 Design

Due to the multi-hop routing involved, we must put enough nodes awake to provide routing paths to every node in the network. Energy-star elects gateway nodes by calculating minimum dominating sets based on the node energy and degree. The gateway nodes remain awake (in idle, sleep or transmit mode) during the cycle. New nodes are elected and older nodes are taken out of the dominating set at next cycle if there is any change in the parameters of gateway nodes or if nodes have changed their position. All other nodes in the network go to sleep unless they want to transmit for the cycle.

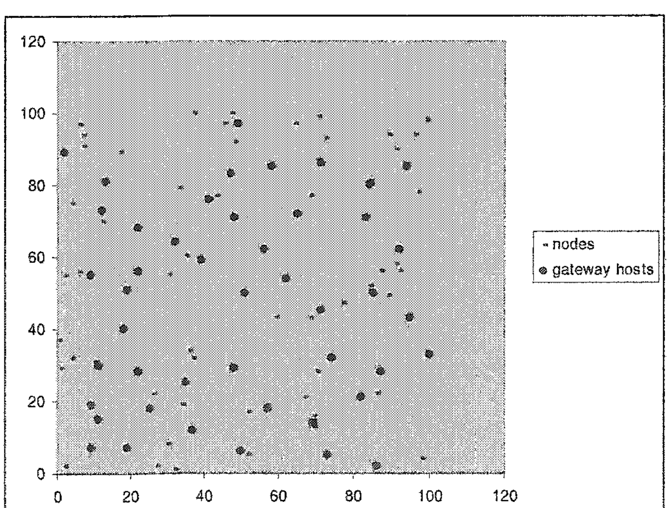


Figure 3.1-1: *A sample network of 100 nodes and 45 gateway hosts with a transmission range of 15 units. All the nodes are reachable.*

Node rotation using re-calculation of the dominating set is done periodically or when energy of any of a gateway host goes below a threshold level. Nodes connectivity is guaranteed during the network life. Only the gateway nodes are actively involved in forwarding the messages to neighbors. Each node knows only a gateway node (buddy) to keep the knowledge and node memory usage simple. A node sends a broadcast message, which is picked up by the buddy for delivery to the destination node. After receiving the message, it is the responsibility of the buddy to deliver the message to the buddy of destination node. In the situation when the destination node is sleeping, its buddy gets hold of the message for the next refresh cycle when all the nodes should be awake. The approach has to make sure messages are delivered to destinations. Sleeping period directly relates to the network delay. The Longer the time nodes go to sleep the longer time it may takes a message to reach the destination.

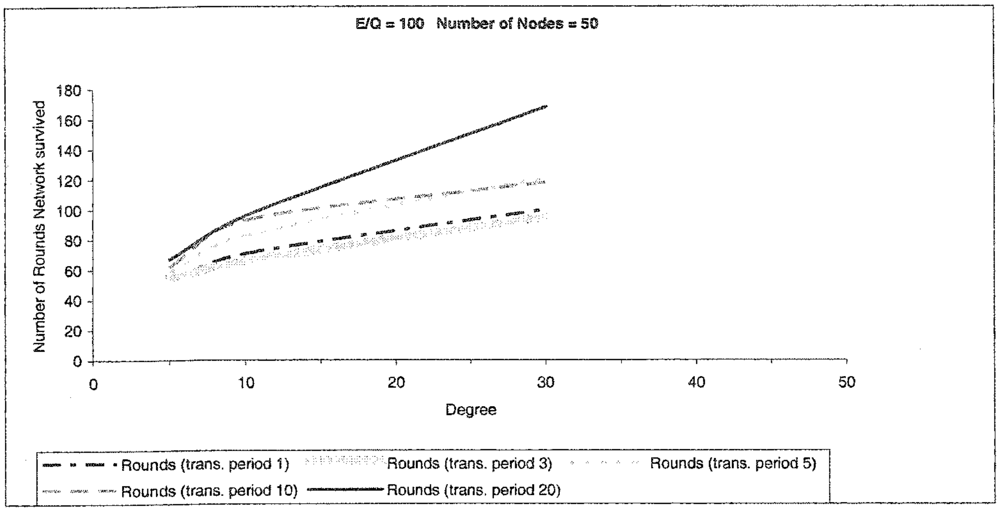
3.1.1 Broadcasting and Message Delivery

Broadcast is used to deliver the messages as well as for route discovery and formation of the connected dominating set during transition periods. Non-gateway hosts only *receive* the broadcast packet whereas gateway hosts *receive* and *send* the broadcast packet. Each gateway host only sends (also called forwards) the broadcast packet once. If the broadcast message is for delivery, it is only picked up by the buddy of the node (neighboring gateway host) and forwarded to the next gateway by broadcasting the message. Message is cached at the destination buddy host. It means receiver buddy must have to wait for sleeping nodes to wake up. Delivery message of broadcasts can be performed on the connected dominating set only. If the message is of route discovery or destination search type, it must only be sent during the transition period.

3.1.2 Transition period

Gateway nodes are elected during this phase. It is periodic function runs after a pre-defined time. Budy nodes are synchronized each transition period. There is a transition period after every round. During transition period, undelivered messages are delivered, routing path rediscovered and a message is broadcasted. Each node in the network knows at least one node of the connected dominating set. All the nodes lose power level after every round and every transition period. Delay between transition periods plays some role in energy saving as well. Higher the delay means lesser overall energy use for this overhead. However, it adds delay in message delivery to the sleeping nodes.

The delay between transition periods plays a very important role in improving the network life. Lower the sleeping period, the higher the energy overhead due to more frequent transition period. We can increase the overall network life by increasing the sleeping period. We performed a number of experiments to find suitable sleeping periods. See Figure 3.1-2. One can trade higher network life with higher sleeping period for higher delay in message delivery. The best sleeping period the graph shows is 10 units.



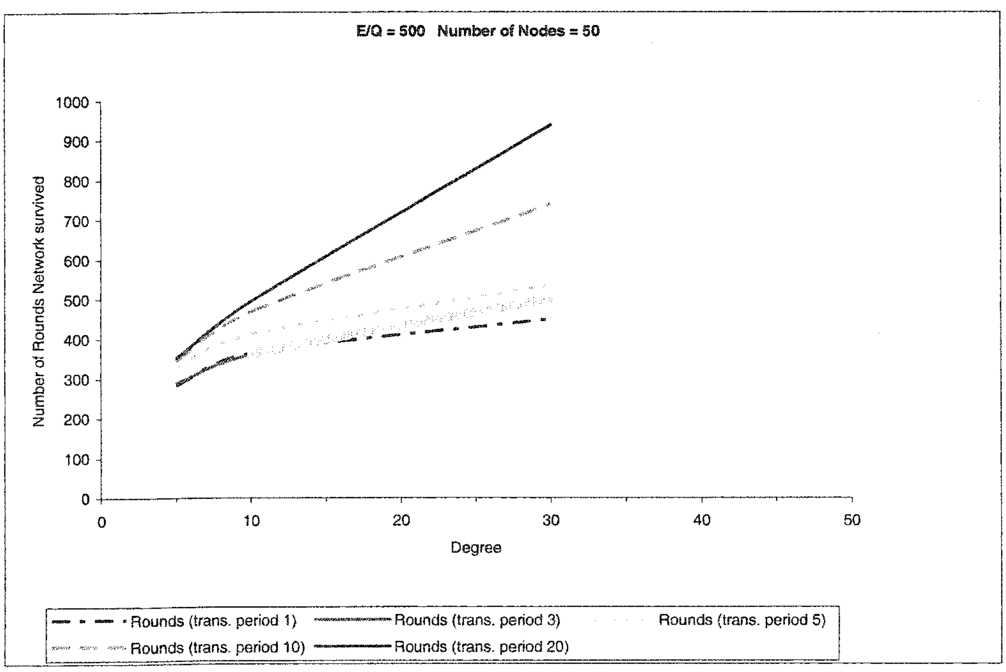


Figure 3.1-2: Performance varies with the sleeping periods (transition period). Each graph shows relation of degree vs. number of rounds network survived for networks with transition period of 1, 3, 5, 10 and 20 units.

3.1.3 Formation of connected dominating set

The main advantage of using the dominating-set is that it simplifies the routing process to the one in a smaller sub-network generated from the connected dominating set. This means that only gateway hosts need to keep routing information in a proactive manner and the search space is reduced to the dominating set in a reactive approach. Note that gateway hosts are used not only to route packets but also to disseminate routing information. Clearly, the efficiency of this approach depends largely on the process of finding and maintaining a connected dominating set and the size of the corresponding sub-network. In this work, use the technique presented in [WDGS]. In the process of forming a dominating set, any parameter could be used to break tie among the nodes. For example, node degree, node ID, energy level, and geographical location of vertex in a particular dimension, etc. The most prominent is node degree, however for our work two most important parameters are degree and energy. Instead of using the above combination, we use a key to form the dominating set, see next section.

3.1.4 Combined metrics for keys in connected dominating set

Previous experiments and discussions clearly isolated degree and energy as two main factors for network life. They were investigated as separate metrics [SSZ, WDGS, and WWS]. In this work, we investigate combinations of node degree and remained energy of node for increased network life, which is here measured as the number of rounds before a node in the network has no energy left to perform the task assigned to it. It was observed previously and confirmed in our experiments that the number of rounds are fixed for low degree networks. Where in order to maintain connectivity many nodes are forced to be always the part of the dominating set. That causes faster energy consumption of the network and fewer nodes can switch the role. Eventualy it leads to lower network life. Theoretically, connectivity is a very critical issue for, average degrees below 15 [L] and our experiments show also that up to such degree metrics selected has no impact on the selected measure of the network life. However, notable differences were observed for medium and higher densities in the performance.

The justification for studying such combined metrics is the observation that a key based only on remained energy tends to select more nodes in dominating set than a key based on degree. In addition, a key based on energy tends to change frequently the nodes in dominating status thus balancing energy consumptions and prolonging network life.

While there is a better balance with energy as the key, more nodes are also selected, and therefore the overall network consumption is increased. On the other hand, a degree based metric tends to reduce the size of dominating set thus reducing energy spending in each round. However, shifting roles between nodes is slow with degree based metric, which makes higher degree nodes energy critical. We have therefore investigated combinations that should provide better trade-off between the two basic metrics.

The first combination we propose is $key(u) = a \times \deg ree(u) + (1-a) \times energy(u)$, where 'a' is a parameter (between zero and one) that gives relative weights to degree or remained energy at the node. The proposed combination is an attempt to increase the weight for degree up to a point where overall energy spent per round by all active nodes is better balanced with the choice of nodes with higher energy in dominating set. The best choice of parameter a may depend on some network factors. We expect that it will depend on network density but not on number of nodes in the network, and such expectation was confirmed by experiments. The best choice of *'a'* is a global network information, and may not be available to nodes running in localized manner. In order to preserve localized behavior at each node, the approach suggested is to find best *'a'* by simulation, record them at each node in its parameter table. Then use that value by the node, with table entries taken based on local information. For example, node may use its own degree or average degree of itself and its one or two hop neighbors as the approximation for the overall network density, and then takes the table entry corresponding to this value in its key value.

In order to avoid having any parameter in the metric selected, we considered parameter-less product and sum combinations. The first such combination that we propose studied is $key(u) = \deg ree(u) \times energy(u)$. This combination is expected to balance the choice of nodes in dominating set between those with high degree and high remaining energy, giving importance to both. Along the same lines, we also investigated $\deg ree(u) \times energy(u)$, $\log 10(\deg ree(u)) \times energy(u)$, and

'$degree^{energy/maxenergy}$ x energy', where maxenergy is the initial maximum energy at nodes. Next, we considered $\deg ree(u)/energy(u)+energy(u)$. We were not able to improve across all ranges with energy metrics that further emphasized degree of a node, and then attempted metric that put higher degree node at slight disadvantage. We tested also metric $energy/\deg ree+energy$ and obtained finally superior results with respect to energy only metric. Refere to Appendix A for algorithm detail.

Chapter 4

Performance Evaluation

In this section, we compare different approaches for defining connected dominating sets. More precisely, we compare different choices of keys used in defining dominating sets. Gateway dominating sets definition [WL] was applied. The other approaches in literature are not considered here because of their discussed deficiencies and the comparisons already being made in [WDGS, WWS] with the basic key choices here. We have performed experiments with number of nodes ranging from n=25 to n=100. Since no significant differences were found, we present data only for n=100 nodes. Each node is selected uniformly at random within a square [100, 100]. Only connected graphs were considered in measurements. In the first round of simulations, all nodes remain static all the time. We shall add mobility in the next round of simulations. We assumed that all active nodes spend equal amount of energy, to simplify the measurements. We are planning to investigate different scenarios with separate charges for receiving and transmitting messages with respect to active but idle only nodes.

The energy level of each node is initialized to *maxenergy*=10,000 units (other values are considered, but the same conclusions were made). Transition period is one that has closest idea about fixed energy charge, because of predictable amount of traffic: delivery of all pending traffic to previously sleeping nodes, location updates, updating activity status at each node. Then we charged every node with energy $E_n=1$ for each transition period between two iterations. The length of sleeping mode can vary with respect to transition period. We decided to measure such length not in time units, but in energy units. Thus, each sleeping node is charged with energy E_s that is a parameter. Suggested values for investigation are E_s= 0.1, 1, 10, 100. We have used 0.1 in our experiments.

Nodes in active mode spend a constant factor of energy of nodes in sleep mode. We selected factor 10 in our experiments, thus energy charged to each active node is

$Ea = 10 \times Es$ in any given iteration. For each of degree 8, 10, 15, 20, 25, 30, 40, 45, 50 100 different graphs were generated, and the simulation was performed on each of them. Averages then were taken. The transmission radius *R* is approximated from $d = \pi R \times R/(m \times m) \times (n-1)$, where m=100 is the length of each square side. The iteration count stops when a node has no energy left to perform the task assigned (that is, its energy becomes negative).

In addition to measuring the number of iterations, we also measured the size of connected dominating sets generated from different key definitions, which is good indicator of network life, but not the only one (one needs small size dominating sets and a good rotation strategy for gateway nodes to get extended network life).

Table 4-3: The number of iterations that network survives for n=100 and selected densities.

Degree	ID	degree	Energy	d*e	Log(d)*e
8 - 15	980	980	980	90	980
20	980	980	1100	1040	1014
25	980	980	1617		1219
30	980	980	2150	1500	1655
40	980	980	3238	2458	2505
45	980	980	3631		2892
50	980	980	4222	2754	3057

Table 4-4: The number of iterations that network survives for n=100 and selected densities.

Degree	$\sqrt{d}$*e	$d^{(e/maxe)}$*e	d/e + e	e/d + e	$e+a*d^{(e/maxe)}$
8 - 15	980	980	980	980	980
20	1008	1147	980	1150	1850
25	1290	1447	1445	1785	2431
30	1726	1646	2041	2442	3548
40	2377	1780	2187	4290	4230
45	2672	2762	3977	5010	5052
50	2878	3254	4344	5623	6150

Table 4-5: The average number of gateway nodes for considered metrics

Degree	ID	Degree	Energy	d*e	Log(d)*e
20	27	24	34	32	33
25	21	18	28	28	25
30			20		20
40	13	11	12	11	11
45			9		8
50	8	4	7	6	5

Table 4-6: The average number of gateway nodes for considered metrics

degree	$\sqrt{d}$*e	$d^{(e/maxe)}$*e	d/e+e	e/d+e	$E+a*d^{(e/maxe}$
20	33	34	30	40	40
25	25	28	28	31	39
30	19	22	22	25	23
40	11	13	14	16	17
45	9	9	9	14	14
50	5	6	6	12	11

We shall discuss first the metric that gave further advantage to nodes with higher degrees. It can be observed that we succeeded in increasing the number of iterations with some of the new metrics and some of average degrees with respect to the same count for energy only metric. The metric '*degree (u)*$^{energy\ (u)\ y/maxenergy\ (u)}$ *x energy (u)*' appears best for degree 20, while metric $\deg ree(u)/engerg(u)+energy(u)$ appears best for degrees in 20 and above. Tables 1, 2, 3 and 4 give the obtained iteration counts and average number of gateway nodes for considered densities and metrics. We then considered two choices involving a parameter, the keys of the form $a\times\deg ree(u)+(1-a)\times energy(u)$ and '*energy + a x degree(u)*$^{energy(u)/max\_energ'y}$, where *degree* is the node degree, and *energy* is the remaining energy at the round. It was learned that the reight choices of *a* may lead toward 10% improvement in the network life. We observed that the number of nodes in the network has no significant impact on the best choice for a, while network density has. To avoid the need for a parameter in the network that may require global network information, it was assumed that best choices for different network densities are provided to nodes, which then select one that corresponds to their own degree or average density in their locality. The best value for *'a'* approached 0 when density increased, so real advantage was noted only for medium densities. For higher densities, the energy only metrics *(a* close to 0) remained best choice. However we have observed that rounds for key '*energy(u) + a x degree(u)* $^{energy(u)/max\_energy}$', are about 50% higher than for metric $a \times \deg ree(u) + (1-a) \times energy(u)$. Interestingly, the best choice of '*a*' was not monotone with the degree (see Tables 5 and 6).

Table 4-7: The number of gateway nodes and iterations for metric $a \times \deg ree(u) + (1-a) \times energy(u)$

degree	gateway	iterations	best *a*
20	32	1150	**0.5**
25	25	1870	**0.1**
40	12	3238	**0**
50	7	4222	**0**

Table 4-8: The number of gateway nodes and iterations for metric energy(u) + a x degree(u) $^{energy(u)/max\_ener)}$

degree	gateway	iterations	best *a*
20	44	1810	**0.8**
25	24	2607	**0**
40	16	4495	**0.9**
50	11	16075	**1**

The next to the last columns in Tables 2 and 4 refers to the metric with key *energy/degree + energy,* which gives disadvantage to nodes with higher degrees, that is, prefers somewhat nodes with smaller degrees. We finally, and surprisingly, obtained superior iteration counts with respect to energy only metric, as seen in these two tables. The iteration count for the key $engerg(u)/\deg ree(u) + energy(u)$, was 4.5%, 10.4%, 13.6%, 32.4%, 38%, and 33.2% higher than for the *energy* only key for densities 20, 25, 30, 40, 45, and 50, respectively (and same for degrees below 20), which is a significant improvement. The primary reason can be extracted from Tables 3 and 4. Such metric selects more nodes in dominating sets, but also shifts the roles rapidly between nodes. It appears that the rate of shifts in the roles is such that additional energy spent overall is compensated and overall iteration count increases significantly.

Chapter 5

Conclusion and Future Work

In this thesis, we have suggested further improvements to the metrics used in dominating set definitions that balance energy consumption at nodes and consequently increase the network life. The advantages of new metrics over existing ones are expected to be notable for dense graphs, while no advantage may exist for sparse ones. The reason for not improving number of rounds in sparse networks by any kind of keys is that some nodes may be forced to belong to all possible dominating sets. Examples are static nodes that are the only neighbors of a node with degree one. Such nodes are considerably more likely to exist in sparse networks than in dense ones. Such a node equally and rapidly spends its own energy until it dies, which is the measure for network life used in this work.

We considered some other measures of network life such as network partition, but concluded that it also has some drawbacks, like preserving one component for a long time with little energy over the case of having two or more components with lot of energy. Thus, we were not convinced that different measure would give better overall insight.

The dominating set definitions from [WL], used in this thesis, can be replaced by dominant pruning method [DW], but we do not expect major improvements or affect the selecting the best metric.

The problem is important and further research is desirable. A source independent definition of dominating set in applications where the dominating set status of each node must be communicated to its neighbors (this is the case in routing and activity scheduling applications) can be described as follows [CSS]. Each node A initially calculates it's dominating set status based on the original gateway node definition [WL]. Using some back-off mechanism, each gateway node decides when to transmit its decision to its neighbors (non-gateway nodes remain silent). While waiting, it may hear several announcements from its gateway node neighbors. After each announcement, *A* reevaluates its gateway node decision. If the subgraph of all neighboring nodes with higher key value or with announced gateway node decision is connected, and each neighbor of *A* is a neighbor of at least one of these nodes, then *A* decides to withdraw from the dominating set and never transmits such decision to neighbors. The performance evaluation of this improvement will be studied in [CSS]. When the neighbor coverage is replaced by area coverage, possibly with adding messages with non-gateway decisions, the protocol has applications in sensor area coverage [CSS].

Adjih, Jacquet and Viennot [AJV] proposed to combine multi-point relay and dominating set approaches. Each node computes its forwarding neighbors set and transmits it to its neighbors. Each node then determines whether it belongs to 'MPR-dominating set' if either it has the smallest *id* in its neighborhood, or the node is forwarding neighbor of the neighbor with the smallest *id*. This definition is source-independent, and involves node *id*. It is therefore a possible candidate for energy-efficient dominating sets, with node *id* being replaced by energy related metrics. This option will be studied in our further research.

We will review also some upcoming work related to dominating sets and broadcasting problem. In [CSSb], a beaconless broadcasting method is proposed. All nodes have the same transmission radius, and nodes are not aware of their neighborhood. That is, no beacons or hello messages are sent in order to discover neighbors prior to broadcasting process. The source transmits the message to all neighbors. Upon receiving the packet (together with geographic coordinates of the sender), each node calculates the portion of its perimeter, along circle of transmission radius, that is not covered by this and previous transmissions of the same packet. Node then sets or updates its timeout interval, which inversely depends on the size of the uncovered perimeter portion. If the perimeter becomes fully covered, the node cancels retransmissions. Otherwise, it retransmits at the end of timeout interval.

In [ISS], broadcasting and dominating sets are generalized to hybrid networks. Access nodes, which are mutually connected by fast high bandwidth backbone network, are all assumed to be in dominating set, with highest priority. Other nodes then follow given definitions of dominating sets. Let *S* be source node of a broadcasting task, with packet arriving at node A. *A* will retransmit if *A* is in dominating set and there exists neighbor *B* of *A* such that $hc(S, A) < hc(S) + hc(B)$, where $hc(S,A)$ is the number of hops between *S* and A, and $hc(S)$ and $hc(B)$ are hop counts of *S* and *B* to their nearest access nodes. If access nodes are assumed to have significantly larger transmission radius then ad hoc nodes, the condition can be modified to $hc(S, A) < hc(S) + 1$. In [YLCLZ], sensors are placed in the field to monitor the environment and report an event upon discovery to a fixed monitoring station. The monitoring station can also move. The basic scenario is that the closest sensor to the moving object will route the report to the monitoring station, and this will be done periodically. The goal is to extend the network life as much as possible. Multiple mobile sources send information constantly to mobile multiple destinations. [YLCLZ] proposes a two-tier approach, source to destination and destination to source, with grid subdivision of the area and greedy forwarding. Grid division is unnecessary overhead, and greedy forwarding may fail. *GFG* [BMSU] or power-cost aware localized algorithms with guaranteed delivery [SD] can replace greedy forwarding, and grid structure can be replaced by dominating set structure discussed in this thesis. Path extension can be applied up to certain distance, then new destination position *D'* can initiate routing toward the source until it reaches a node *A'* that is neighbor of a node *A* on the original path *SAD*. The new path, instead of *SADD'*, is then *SAA'D'*.

Viswanath and Obraczka [VO] proposed different heuristics to deal with broadcast reliability in highly mobile environments. Based on local movement velocity, each node decides between three modes for the broadcasting task. In the scoped flooding [VO], periodical hello messages contain 1-hop neighbors list. If the receiving node's neighbor list is a subset of the transmitting node's list, then it does not re-broadcast the packet. We note that this is a special case of the neighbor elimination scheme [SSZ]. The plain flooding mode is the same as blind flooding. In the hyper flooding mode, additional re-broadcasts can be triggered upon receiving a packet from a new neighbor. Hahner, Becker, and Rothermel [HBR] modified hyperflooding scheme [VO] in two ways. Instead of sending full message as in [VO], a short message containing advertisement is sent. The short message uniquely identifies the full message, and the receiving node may request the full message or ignore it if it already has it or does not want it. While [VO] is designed for one-to-many medium access layer, [HBR] has one-to-one model in mind, where message sent by one node to another node are not received simultaneously by other neighbors of sender node. More precisely, advertising can reach all neighbors at once, but these neighbors in need of listed items need to respond by separate messages, and receive separate copies of the same message. It is possible to consider also the model where one response by any neighbor triggers message transmission to all neighbors, including perhaps few more in need of same message. Thus, to disseminate information across partitions, an approach similar to hyperflooding [VO] is added: whenever a node discovers a new neighbor, it is allowed to re-advertise observations as long as TTL (time to live) has not expired. When TTL reaches zero, the message is erased form database. The authors propose few variants on the advertising priorities and ordering of several messages that may be broadcast simultaneously (but not necessarily with the same source or star time). In [Sb], it is proposed not to act each time two nodes discover each other as new neighbors, which is what hyperflooding [VO] does. The reduction should be made such that not many messages are lost in the process, therefore nearly preserving success rate while reducing flooding rate (overall number of messages sent). This is achieved by observing that the new neighbors might be assumed to have already the same information if they were already connected via common 1-hop neighbor. This can be generalized to a common k-hop neighbors, although inpractice probably only $k=2$ can be considered in addition to $k=1$. Therefore new neighbors, after discovering each other, exchange other type of information according to given location update scheme (that is, their position, perhaps list of their 1-hop or 2-hop neighbors) but not the information about broadcast items they have unless they become neighbors from otherwise partitioned network, with network partition judged locally, as in another upcoming thesis [HJSS]. The advantage of new scheme becomes notable for larger lists of items being broadcasts, which is the scenario in [HBR].

The proposed method is essentially the application of [HJSS] method in reverse scenario, that is, creation of a critical link by two nodes coming into each other's range rather than the existing link between two nodes becoming critical. The localized partition detection protocol [HJSS] works as follows: *AB* is a critical link if the sets of k-hop neighbors of *A* and *B* are disjoint. A k-hop neighbor is a node at distance at most *k* hops from given node. A graph is k-connected if it is still connected after removing any *k-1* nodes. Clearly, in a k-connected graph, each node has at least *k* neighbors; otherwise, the removal of its neighbors will disconnect it from the rest of graph. Localized algorithms that test k-connectivity or minimum degree *k* can be described as follows [HJSS]: each node verifies whether each node up to *p* hops away (each p-hop neighbor) has degree at least k. This method is reasonably accurate due to result from [B]: if a graph has minimum degree *k* with high probability, it is k-connected with high probability.

Koubaa and Fleurry [KF] proposed to enhance reliability of multicasting by requesting that each node is adjacent to at least two clusterheads. This idea is further developed in [Sd], by defining double dominating sets and double reception based broadcasting, to increase reliability and make a step toward secure broadcasting. Each node *X* decides not to be in double dominating set if higher priority neighbors make a connected component, and each neighbor of *X* is neighbor of at least two nodes from the connected component. During broadcasting, the definition can be converted into source-dependent broadcasting, as follows: Node *X* decides not to re-transmit the message after timeout if all neighbors that transmitted message already, and all neighbors with higher priority together satisfy the property that each neighbor of X is a neighbor of at least two of such nodes.

Sensor networks monitor the environment by first constructing broadcast tree from the monitoring center, and then using the tree in reverse direction for reporting. It is proposed in [Ss] to enhance the security of the reporting by using one or two neighboring branches of broadcast tree, with branches defined from the monitoring center, for sending the second and possibly the third copy of the report along these branches. Border sensors (those having neighbor from a different branch) need to offer their access to alternative branch to other nodes in the same branch by restricted broadcasting.

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ACRONYMS

AIN	Advanced Intelligent Network
AMA	Automatic Message Accounting
ANSI	American National Standards Institute
BCSM	Basic Call State Model
CCF	Call Control Function
CDR	Call Detail Record
CS-n	Capability Set n
CTIA	Cellular Telecommunications Industry Association
DFP	Distributed Functional Plane
ECR	Enhanced Call Routing
FAM	Fleet and Asset Management
FE	Functional Entity
FM-CMM	Formal Methods-Capability Maturity Model
HLR	Home Location Register
IMSI	International Mobile Station Identity
IN	Intelligent Network
INAP	Intelligent Network Application Protocol
IP	Intelligent Peripheral
ISDN	Integrated Services Digital Network
ITU	International Telecommunications Union
LBC	Location-Based Charging
LBIS	Location-Based Information Service
MPC	Mobile Positioning Center
MS	Mobile Station
MSC	Mobile Switching Center
NE	Network Entity
NRM	Network Reference Model
PDE	Position Determining Entity

PN	Project Number
PSTN	Public Switched Telephone Network
SCE	Service Creation Environment
SCF	Service Control Function
SCP	Service Control Point
SDF	Service Data Function
SMS	Service Management System
SN	Service Node
SRD	Standards Requirements Document
SSF	Service Switching Function
SS7	Signaling System 7
SSP	Service Switching Point
TD	Trigger Detection Point
TIA	Telecommunications Industry Association
WIN	Wireless Intelligent

APENDIX A:

Algorithm

The algorithm using new metrics for selection of dominating set.

Preminalaries:

Sleeping mode(***Es***)	0.1 units
Idle mode (***Ei***)	7*Es units
Energy charged to node (***Ea***)	10*Es units

For degree all degree {20, 25, 30, 40, 45, 50};

1. For Graph $G = (V,E)$
2. Each node in $G(v)$ has initial energy E.
3. Choose transmission radius R such that average node degree is equal to d.
4. Go to step 1, if graph G is not connected for average degree d.
5. For the keys, defined in section 3.1.4., find the minimum connected dominating set, G'.
6. Applying Wu, et al. [WDGS] extended marking process 2b' with the key to break the tie.
7. Reduce energy of all the nodes by Ei
8. Entire $G - G'$ nodes goes to sleep.
9. Round: transmit and receive messages between randomly generated nodes.
10. Reduce energy of active nodes by Ea and sleeping nodes by Es
11. Transition round
12. Reduce nodes energy by Ei.
13. If E of $G(v)$ is less than Ea delete the node from graph.
14. Stop if STOP CRITERIA achieved otherwise continue.
15. Select the dominating set G' on the key used in step 5.
16. Go to step 7.