# New Metrics for Dominating Set Based Energy Efficient Activity Scheduling in Ad Hoc Networks

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## *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 flooding task, a source sends the same message to all the network. 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 article 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.*

## 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.

Ad hoc networks are best modeled 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 transmission radius, which is equal for all nodes. This model is widely used and is also applied in this article.

In the activity-scheduling problem, each node decides between active or passive state so that 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 wakening 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. 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 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 topology. A subset of nodes which is connected and which has the property that any node not in it is neighbor of at least one node from the subset is known as dominating set. Therefore dominating set appears to be a reasonable solution for 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 article, transmission by each node can reach *all* nodes that are within radius distance from it. Broadcasting is also frequently refereed to in literature as *flooding*. Broadcasting applications include paging a particular host or sending an alarm signal. Flooding/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 will retransmit it to all its neighbors. The only 'optimization' applied to this solution is that nodes remember messages received for flooding, and do not act when receiving repeated copies of the same message. However, blind flooding causes unnecessary collisions and bandwidth waste, with many nodes not receiving the message as a consequence.

It was observed in [SSZ] that dominating set can be a good solution for broadcasting problem. Nodes in dominating set retransmit the packets, while nodes outside of it do not. It was further observed in [WL] that dominating sets can be used to facilitate 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 dominating set. 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, idles, 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. One such resolution is to make nodes from 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 a global network information, or quasi-global information (e.g. minimal spanning tree) are not acceptable solution since maintenance of such structures requires unacceptable communication overhead and energy expenditure. Clusterheads and gateway nodes in a cluster structure define a dominating set, and were first 'intelligent' flooding solution proposed in literature. However, the node mobility either worsens the quality of the structure dramatically, or otherwise causes chain reaction (local changes in the structure could trigger global updates). This solution is therefore 'quasi-local'. Localized connected dominating set concepts, proposed recently, avoid such chain reaction, 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 acceptable solution only for broadcasting and routing tasks in network where all nodes are active all the time. In order to have some nodes sleeping for a while, 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, [WL] used node *id*s. Node degrees are suggested in [SSZ] as the main key for comparison, resulting in overall decrease of dominating set size.

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 a recent solution [WDGS, WWS], the remaining energy at each node is proposed as the main key for defining dominating sets. Degree is used as 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 paper makes a step further in the same direction. We considered alternative choices for the primary key in dominating set definitions. Some of them performed better, some of them worse than energy only metric. For low densities, all metrics had 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 forced to be active in all rounds due to lack of neighbors to take the role over and also the critical links for connectivity. It was proven theoretically and experimentally that an ad hoc network with about $n$=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 had moderate impact for medium densities (in ranges up to 30), while for higher densities the impact of selecting particular metric was significant for the network life. The experimental data show that the 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.

The next section gives a relevant literature review on source independent broadcasting and activity scheduling. The contribution of this paper is described in section 3, while section 4 presents simulation data. Conclusion and references complete this article.

## 1. Literature review

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 minimal 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 exist two neighbors *B* and *C* of *A* that are not direct neighbors themselves. For example, nodes *C* and *K* in Fig. 1 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 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*. If every neighbor of *v* is also a neighbor of *u*, and *key(v) < key(u)*, then node *v* is not an *inter-gateway* node, and *key(x)=id(x)*. We may also say that node *v* is 'covered' by node *u*. Observe that retransmission by *v*, in this case, is covered by retransmission of *u*, since any node that might receive message from *v* will receive it instead from *u*. [SSZ] proposed to replace node *id*s with a record *key=(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 Fig. 1.

Note that, when *key=(primary-key, secondary-key, ternary-key,…)* then *key(u) < key(v)* in the following cases: (1) *primary-key(u) < primary-key(v)*, (2) *primary-key(u)=primary-key(v)* and *secondary-key(u) < secondary-key(v)*, (3) *primary-key(u)=primary-key(v)* and *secondary-key(u)=secondary-key(v)* and *ternary-key(u) < ternary-key(v)…*

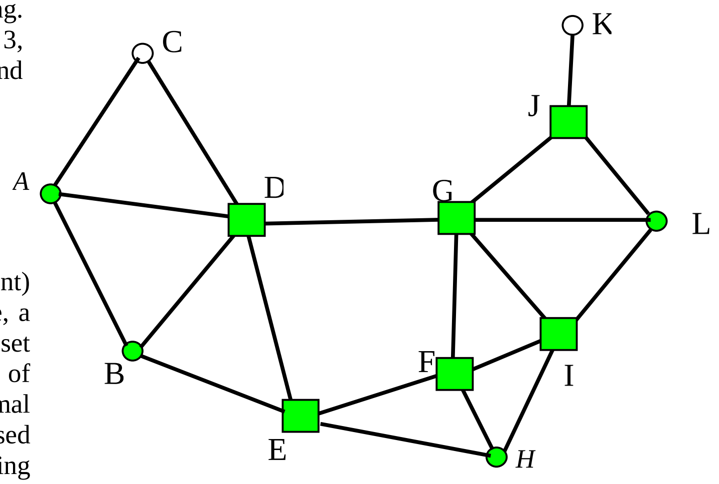

**Figure 1. Nodes *C* and *K* are not intermediate, nodes *A*, *B* and *H* are not inter-gateway nodes**

Next, let the *gateway* nodes be those inter-gateway nodes that are not eliminated by Rule 2 [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 Fig. 1 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 4 to 10.

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*.

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 and is chosen without using any global parameter (size of square, which has to be carefully selected and propagated with node relative positioning in solution [XHE]).

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. Also, 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, remained energy at nodes is not used to select active nodes, thus there will be no activity changes in static networks.

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 andHaas [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%.

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 [S3] 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, 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 minimal 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 minimal 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 $U_pU_n$, where $U_p=1/(1+e^{-P+s})$ is energy metric ($P$ is the remaining energy at a node, while $s=Maxenergy/2$ is the half of the maximal energy. $U_n$ 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.

## 2. Combined metrics for keys in dominating sets

Previous experiments and discussions clearly isolated degree and energy as two main factors for network life. They were investigated as separate metrics [SSZ, WDGS, WWS]. In this article 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 allocated to it. It was observed previously and confirmed in our experiments that the number of rounds was fixed for low degree networks, where connectivity is critical issue forcing many nodes to be always in dominating set, thus consequently spending their energy rapidly. Theoretically, connectivity is critical issue for average degrees below 15 [L] and our experiment 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 the key based only on remained energy tends to select more nodes in dominating set than the key based on degree. Also, the key based on energy tends to frequently change 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 overall network consumption is increased. On the other hand, 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 $key(u)=a*degree(u)+(1-a)*energy(u)$, where $a$ is a parameter (between 0 and 1) 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 for $a$ then may be 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 values for $a$ by simulation, record them at each node in its parameter table, and 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 parameterless product and sum combinations. The first such combination that we propose studied is $key(u)=degree(u)*energy(u)$. 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 investigated also $\sqrt{degree(u)}*energy(u)$, $\log_{10}(degree)*energy(v)$, and $degree^{energy/maxenergy}*energy$, where *maxenergy* is the initial maximal energy at nodes. Next, we considered $degree(u)/energy(u)+energy(u)$. 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/degree+energy* and obtained finally superior results with respect to energy only metric.

## 3. 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 $En=1$ 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 $Es$ which is a parameter. Suggested values for investigation are $Es$= 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 $Ea=10*Es$ in any given iteration. For each of degree 8, 10, 15, 20, 25, 30, 40, 45, 50, 20 different graphs were generated, and the simulation was performed on each of them. Averages then were taken. The transmission radius $R$ is approximated from $d= \pi R*R/(m*m)*(n-1)$, 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 1. 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 | 980 | 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 2. The number of iterations that network survives for n=100 and selected densities.**

| Degree | √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 3. 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. The average number of gateway nodes for considered metrics**

| Degree | √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 $degree^{energy/maxenergy} * energy$ appears best for degree 20, while metric *degree(u)/energy(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*degree+(1-a)*energy* and $energy + a*degree^{energy/max\_energy}$, where *degree* is the node degree, and *energy* is the remaining energy at the node. It was detected that different choices for *a* may lead toward 10% differences in network lives. 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 $energy + a*degree^{energy/max\_energy}$, are about 50% higher than for metric *a*degree + (1-a)*energy*. Interestingly, the best choice of *a* was not monotone with the degree (see Tables 5 and 6).

**Table 5. The number of gateway nodes and iterations for metric a*degree+(1-a)*energy**

| Degree | Gateway | Iterations | Best *a* |
|---|---|---|---|
| 20 | 32 | 1150 | 0.5 |
| 25 | 25 | 1870 | 0.1 |
| 40 | 12 | 3238 | 0 |
| 50 | 7 | 4222 | 0 |

**Table 6. The number of gateway nodes and iterations for metric $energy+a*degree^{energy/max\_energy}$**

| Degree | Gateway | Iterations | Best *a* |
|---|---|---|---|
| 20 | 44 | 1810 | 0.8 |
| 25 | 24 | 2607 | 0 |
| 40 | 16 | 4495 | 0.9 |
| 50 | 11 | 6075 | 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 *energy/degree + energy*, 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.

## Conclusions and future works

In this article we have suggested further improvements to the metrics used in dominating set definitions which 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 paper. 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 will give better overall insight.

The dominating set definitions from [WL], used in this article, can be replaced by dominant pruning method [DW], but we do not expect major improvements or impact on selecting 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 it either 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 assumed to be 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 iff *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 acces 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 article. 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 neighbour 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 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 is assumed not to be simultaneously received 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 al long as TTL (time to live) has not expired. When TTL reaches 0, 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 in practice 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 article [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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