Broadcasting and Activity-Scheduling in Ad Hoc Networks

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Abstract

In a multi-hop wireless network, each node has a transmission radius and is able to send a message to all of its neighbors that are located within the radius. In a flooding or broadcasting task, a source node sends the same message to all the nodes in the network. It is an important task used for paging, alarming, location updates, route discoveries or even routing in highly mobile environments. In the activity-scheduling problem, each node decides between active or passive state so that the network remains connected and its lifetime is maximized. The desirable properties of a scalable flooding or activity-scheduling scheme are reliability (reaching all nodes in a collision free environment), and power and bandwidth efficiency, which can be measured by savings in re-broadcasts. Until recently, blind flooding was used as a solution: each node receiving the message for the first time will re-transmit it. This solution, however, has collision, contention and redundancy problems. This chapter surveys existing methods for flooding a wireless network intelligently (using omni-directional or directional antennas, with equal or adjusted transmission radii) and for scheduling node activities.

Index terms: Broadcasting, clustering, distributed algorithms, dominating sets, wireless networks

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, battlefields, in possibly remote or dangerous environments where monitoring objects is required, wireless Internet etc.

In a broadcasting task, a source node sends the same message to all the nodes in the network. In the *one-to-all* model, transmission by each node can reach *all* nodes that are within radius distance from it, while in the *one-to-one* model, each transmission is directed toward only *one* neighbor (using narrow beam directional antennas or separate frequencies for each node). The broadcasting in literature has been studied mainly for the one-to-all model, and most of this chapter is devoted to that model. The *one-to-many* model can also be considered, where fixed or variable angular beam antennas can be used to reach several neighbors at once.

Broadcasting is also frequently referred to in literature as *flooding*. Broadcasting applications include paging a particular host or sending an alarm signal. Broadcasting task was sometimes studied in the context of address serving [L] in hierarchically clustered packet radio networks. Flooding/broadcasting is also used for route discovery in a source-initiated on-demand routing. Broadcasting can similarly be used in the context of an efficient location-aware routing algorithm as follows. The source *S* may initiate a destination search process by broadcasting a short message that contains the location of *S*, *id* of destination *D*, and some control bits. When the destination search message successfully reaches *D*, *D* applies any location based routing algorithm (e.g. [BMSU] which guarantees delivery if location of destination, in this case *S*, is accurate) and reports back to *S* with a short message containing its location. The source *S* can then apply again the same routing algorithm [BMSU] (or use the path created in the previous step by *D* if that path was recorded in the process) to send the full message to *D*. Ho et all [HOTV] argued that flooding can be a viable candidate for multicast and routing protocols in very dynamic ad hoc networks.

Another application of broadcasting is in the sensor network. Recent advances in technology have made it possible to integrate micro-sensor, low-power signal processing, computation, and low-cost wireless communication into a sensing device, such as the WINS project at UCLA [PK]. Data broadcasting and gathering are important functions supported in a sensor network to collect and disseminate critical information, such as temperature, pressure, and noise level.

Geocasting is a form of broadcasting, where nodes that shall receive messages are restricted to be inside a region. A simple solution to this problem is to route from the source to a node inside the geo-casting region, and then apply broadcasting inside the region [S1]. Solutions proposed in literature do not appear to be more efficient than this one, and we will not survey them here. A survey is given in [JC].

The traditional solution to the broadcasting problem is *blind flooding,* where each node receiving the message will re-transmit 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.

Williams and Camp [WC] classified the broadcast protocols into: simple (blind) flooding, probability based, area based, and neighbor knowledge methods. In this chapter, area based methods are re-classified within other groups while neighbor knowledge methods are divided into clustering based, selecting forwarding neighbors, and internal node based methods. We shall present here a comprehensive taxonomy of broadcasting schemes with one-to-all model in mind (the other models can similarly be considered). All schemes can be classified following the taxonomy consisting of five categories: determinism, network information, reliability, 'hello' message content, and broadcast message content. The underlined terms were used in the summary table given in the conclusion section.

Determinism. A broadcast scheme may use probabilistic or deterministic protocol, based on whether or not a random number selection was used to make decisions. The random number usage here is limited to the network layer decision; the underlying medium access control (MAC) protocol may still use random back-off counters, for example, in a network layer deterministic scheme.

Network information. The second classification is based on the amount of state information used in the algorithm: global or local. Note that the distinction between global and local is not clear-cut. Centralized algorithms can be also applied in the distributed setting, if a deciding node has full global information for the network. Through several rounds of sequential information exchanges, global or partial global information can be assembled based on local information only. However, sequential information propagation (also called chain reaction) could be costly and this can be measured in terms of rounds. The mobility adds another dimension of complexity in measuring state information. The locality of maintenance can be used to measure the adaptiveness of a protocol in the mobile environment. Wu and Lou [WL1] further classified protocols based on neighbor knowledge information: global, quasi-global, quasi-local, and local. The *global* broadcast protocol, centralized or distributed, is based on global state information. A survey of centralized broadcasting algorithms (using global information) is given in [Pe], and they will not be covered in this chapter. The classical approximation algorithm by Guha and Khuller [GK] for connected dominating set is based on global information. In *quasi-global* broadcasting, a broadcast protocol is based on partial global state information. For example, the approximation algorithm in [AWF] is based on building a global spanning tree (a form of partial global state information) that is constructed in a sequence of sequential propagations. Recently, Chen and Liestman [CL] proposed a distributed formation of a weakly connected dominating set by iteratively expanding and connecting fragments similar to the distributed Kruskal's algorithm. In *quasi-local* broadcasting, a distributed broadcast protocol is based on mainly local state information and occasional partial global state information. Cluster networks are such examples: while clusters can be constructed locally for most of the time, the chain reaction does occur occasionally. In *local* broadcasting, a distributed broadcast protocol is based on solely local state information. All protocols that select forward nodes locally (based on 1-hop or 2-hop neighbor set) belong to this category. It has been recognized that *scalability* in wireless networks cannot be achieved by relying on solutions where each node requires global knowledge about the network. To achieve scalability, the concept of *localized* algorithms was proposed. These algorithms, based on local knowledge, achieve a desired global objective.

Reliability. Reliability is the ability of a broadcast protocol to reach all the nodes in the network. It can be considered at the network layer or at the medium access layer. We will classify protocols according to their network layer performance. That is, assuming that MAC layer is ideal (every message sent by a node reaches all its neighbors), location update protocol provides accurate desired neighborhood information to all nodes, and the network is connected, broadcast protocols can be reliable or unreliable. In a *reliable* protocol, every node in the network is reached. The set of nodes that re-broadcast a message in a reliable broadcasting scheme define a connected dominating set. A dominating set *D(S)* of a set *S* is a set of nodes such that each node from *S* either belongs to *D(S)* or has a neighboring node that belongs to *D(S).* It is easy to observe that all nodes will receive the message if it is re-transmitted only by nodes that belong to a connected dominating set. Connectivity provides propagation through the whole network, while domination assures reachability by all nodes. Broadcasting task can therefore be solved optimally by finding a connected dominating set of minimal size. Optimality here is measured by percentage of saved re-transmissions in a reliable broadcasting scheme. Unfortunately, the problem of finding connected dominating set of minimal size is NP-complete, even if a node has global knowledge about the network [HH, LK, QVL]. Therefore one needs to apply heuristics to flood intelligently. Note also that a protocol, such as blind flooding, that is reliable on the network layer may be very unreliable at the MAC layer. Excess messages in any protocol affect the node power and bandwidth available, thus the main goal is to describe a reliable broadcast protocol with minimal number of re-transmissions, that is, to construct a connected dominating set of minimal size. Note also that MAC layer cannot guarantee 100% reliability, due to the hidden terminal problem (a node simultaneously receiving messages from two other nodes that are not aware of each other's transmission) and the probabilistic nature of protocols used.

'Hello' message content. The broadcast schemes may require different neighborhood information, which is reflected in the contents of messages sent by nodes when they move, react to topological changes, change activity status, or simply periodically send update messages. A commonly seen 'hello' message may contain, in addition to its own ID, its position, one bit for dominating set status (one bit saying to neighbors whether or not node considers itself to be in dominating set), a list of 1-hop neighbors, and its degree (number of its neighbors). Other content is also possible, such as a list of 1-hop neighbors with their positions, or a list of 2-hop neighbors, or even global network information. Global Position System (GPS) provides geographic location information (if required) to hosts in a wireless network by communication with a satellite network.

Alternatively, nodes may measure time delays or signal strengths of incoming messages and determine the relative location of its neighbors.

Broadcast message content. The broadcast message sent by the source, or re-transmitted, may contain broadcast message only. In addition, it may contain a variety of information needed for proper functioning of broadcast protocol, such as the information previously listed for 'hello' messages, message plus one/two bits, or a list of forwarding neighbors, informing them whether or not to re-transmit the message.

The performance of broadcast protocols can be measured by a variety of metrics. A commonly used metric is the number of message re-transmissions (or the total power used in case of broadcasting with adjusted transmission radii) with respect to the number of nodes (alternatively, *rebroadcast savings*, a complementary measure, can be used). The next important metric is *reachability*, or the ratio of nodes connected to the source that received the broadcast message. Time delay or latency is sometimes used, which is the time needed for the last node to receive the broadcast message initiated at the source. Note that re-transmissions at MAC layer are normally deferred, to avoid message collisions. Some authors consider alternative a more restricted indicator, whether or not the path from source to any node is always following a shortest path. This measure may be important if used as part of the routing scheme, since route paths are created during the broadcast process.

Intelligent and scalable broadcasting and activity scheduling solutions are based on the concept of dominating sets. Clusterheads and gateway nodes in a cluster structure define such a set, and were the first 'intelligent' flooding 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). Localized connected dominating set concepts, proposed recently, avoid such chain reaction, and have similar or better re-broadcast savings. Their maintenance does not require any communication overhead in addition to maintaining positions of neighboring nodes, or information about 2-hop neighbors. One such concept is based on covering of all 2-hop neighbors by a minimal set of 1-hop neighbors. The other 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. Neighbor elimination was also applied (solely or in conjunction with other concepts), where nodes give up re-transmitting if they are not aware of any neighbor that did not already receive the same message. This chapter will survey known techniques based on dominating sets, and will discuss their advantages and drawbacks.

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, and is equal for all nodes. This model is widely used (most protocols in this chapter use it), although many solutions surveyed here are valid in more general models as well.

The remaining sections describe known scalable broadcasting techniques, and compare their performance. Most presented schemes are very recent, developed in the last few years, and the reference list is comprehensive in order to provide fairness to all contributing authors. Sections 2-6 describe network layer broadcasting schemes using omni-directional antennas. Section 7 discusses the MAC layer for this one-to-all model. Section 8 discusses activity scheduling and power-aware broadcasting schemes. Section 9 deals with broadcasting based on the use of narrow angular beam directional antennas. Section 10 describes localized schemes for broadcasting with adjusted transmission radii. The conclusion section gives a table with a summary of broadcasting schemes for the one-to-all communication model, following the presented taxonomy.

2. Clustering based flooding

The distributed clustering algorithm [EWB, LG] is initiated at all nodes whose *id* is lowest among all their neighbors (locally lowest *id* nodes). All nodes are initially undecided. If all neighbors of node *A* which have lower *id* sent their cluster decisions and none declared itself a clusterhead (CH), node *A* decides to create its own cluster and broadcasts such decision and its *id* as cluster *id*. If a node receives a message from a neighbor that announced itself as CH, it will send a message (to all its neighbors) declaring itself a non-CH node, to enable more clusters to be created (note that two CHs are not direct neighbors in the algorithm). Thus each node broadcasts its clustering decision after all its neighbors with lower *id* s have already done so. Non-CH nodes that hear two or more CHs will declare themselves as *gateway* nodes. A sophisticated maintenance procedure for cluster formation when nodes move is described in [LG]. To minimize the number of clusters, [CGSS] proposed to apply node degree as the primary key in clusterhead decisions. Nodes with more neighbors are more likely to become clusterhead (CH). In case of ties, lower *id* nodes have advantage. The scheme [AWF] does not apply degree as primary key, but instead reduces the number of gateway nodes. After the clustering process is completed, each CH contacts neighboring CHs (up to 3-hops away) in order to eliminate some gateway nodes, and use only essential gateway nodes to preserve overall connectivity. In Fig. 1, nodes *B* and *F* in the first round create clusters. Then nodes *J* and *C* create two more clusters. Nodes *A*, *D*, *E* and *G* are gateway nodes. If optimization [AWF] is applied (based on a spanning tree maintenance), node *A* can be eliminated. A clustering based algorithm is also reported in [AWF1]. It does not depend on any spanning tree, and each node requires knowledge of its single-hop neighbors, and a constant number of two-hop and three-hop neighbors. The construction is fully localized. The maintenance is also localized using an approach similar to [CWLG] outlined below.

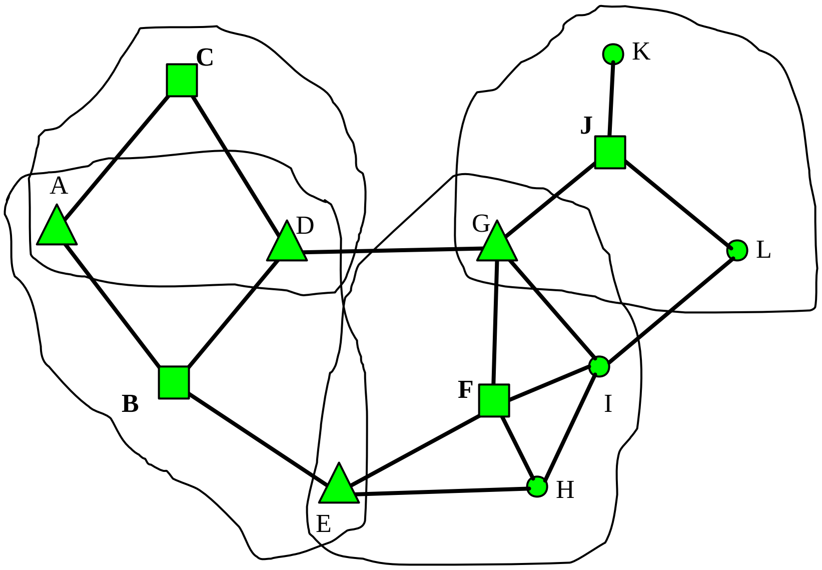


Figure 1. Four clusters *B, C, F, J* with three or four gateway nodes

Blind flooding has been replaced in [L, PR] by a method where each CH and gateway node in a clustered wireless network forwards the message exactly once. CHs and gateway nodes together form a connected dominating set. When their scheme is applied, 8 out of 12 nodes need to re-transmit the message in Fig. 1 (or 7 if node *A* is eliminated). The experiments in [SSZ] gave surprisingly stable ratios of nodes in clustering based dominating sets, with respect to number of nodes in network and average node degrees. About 65% of nodes in lowest ID based and 52% of nodes in degree based cluster structure belong to dominating set. The maintenance of cluster structure, however, requires excessive communication overhead due to 'chain effect' caused by mobility [GKP, WL]. Although either lowest-ID or highest node degree cluster algorithm is localized (with delayed decisions), it has no localized maintenance property. To achieve localized maintenance property, the cluster maintenance can use a different algorithm to make the update a localized one [CWLG]: once the cluster is constructed, a non-CH will never challenge the current CH. If a CH moves into an existing cluster, one of the CHs will give up its role of CH based on some predefined priority. The localized maintenance is preserved, at the price of increasing number of clusters with node mobility.

Gerla, Kwon and Pei [GKP] proposed a combined clustering and broadcasting algorithm that has no communication overhead for either maintaining cluster structure or updating neighborhood information. In their passive clustering algorithm, the cluster structure is updated with existing traffic by adding two bits to each ongoing message. The source *S* of a broadcasting task will transmit the message to all its neighbors. *S* will declare itself a CH (for the timeout period that is a parameter in the method) if it has no neighboring active CH. Upon receiving the message, each node *A* will declare itself a CH using the same criterion as the source *S*. Otherwise, *A* will check the ratio of neighboring CHs and neighboring gateway nodes and declare itself a gateway if that ratio is above a certain threshold, which is also a parameter of the method. If *A* decides to be a gateway, it will re-transmit the message. Otherwise *A* decides to be an ordinary node and does not re-transmit the message. The method is not reliable (there are pathological cases of poor delivery ratio) and has global parameters.

To reduce overhead in constructing a connected dominating set among clusterheads, Wu and Lou [WL1] recently proposed the 2.5-hop coverage, instead of the traditional 3-hop coverage (i.e., CHs within 3 hops) to ensure CH connectivity and full coverage. Instead of using a 3-hop coverage area (i.e., CHs within 3 hops), each CH just covers the CHs that have members (including CHs) within 2 hops. In Fig. 1, suppose the network is partitioned to four clusters *B* (with member *E*), *C* (with members *A* and *D*), and *F* (with members *G, H*, and *I*), and *J* (with members *K* and *L*). The coverage area of *F* includes *C* (which is 3 hops away) since *C*'s member *D* is 2 hops away. The coverage area of *B* does not include *J* because none of *J*'s member is within 2 hops.

3. *Probabilistic, counter, and location based schemes*

Ni, Tseng, Chen and Sheu [NTCS] studied the broadcast storm problem. A straightforward broadcasting by flooding is usually very costly and will result in serious redundancy, contention, and collision. They identified this broadcast storm problem by showing how serious it is through analyses and simulations. Several schemes (probabilistic, counter-based, distance-based, location-based, and cluster-based) to reduce redundant re-broadcasts and differentiate timing of re-broadcasts to alleviate this problem are proposed in [NTCS]. These schemes achieve high percentage of delivery rate with low number of re-transmissions. However, they are not reliable. In the probabilistic scheme [NTCS], each node re-broadcasts the first copy of a received message with a given probability p. In the counter-based scheme [NTCS], each node re-broadcasts the message if and only if it received the message from less than C neighbors. In the distance-based scheme [NTCS], the message is re-transmitted if and only if the distance to each neighbor that already re-transmitted the message is $>D$. In the location-based scheme [NTCS], the message is re-transmitted if and only if the additional area that can be covered if the node rebroadcasts the message (divided by the area of circle with transmission radius) is greater than the threshold A. A simplified version of the method is to re-broadcast the message if the node is not located inside the convex hull of neighboring nodes that already re-transmitted the message. In the cluster-based scheme, lowest ID clustering algorithm [LG] is applied, and one of above four methods is then applied on CHs and gateway nodes. All described methods are not reliable, and the experimental data [NTCS, SSZ] indicate low saved re-broadcasts for high reachability.

Sasson, Cavin and Schiper [SCS] observe that probabilistic flooding [NTCS] in random unit graphs behaves differently for low and high density networks. For low density networks, the success rate varies linearly with probability, making the method inefficient. For high average degrees, there exists an ideal value of probability, and success rate drops by increasing or decreasing it. Beyond ideal value, packet collisions become more frequent and network performance degrades.

Cartigny and Simplot [CS] described a distancebased method without using position information. The distance between two neighboring nodes is measured by a formula that depends on the number of common neighbors. Broadcast message is piggybacked with a list of 1-hop neighbors. Neighbor elimination (see section 6) is also used to enhance the performance. The method is suitable for highly mobile environments, since 'hello' message content is minimized.

4. Source-dependent dominating sets

We shall now present, in the coming sections, methods that are reliable and fully localized. That is, node mobility impacts only local structure. This section deals with methods where the selection of forwarding nodes depends on the source of broadcasting task.

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 the 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.

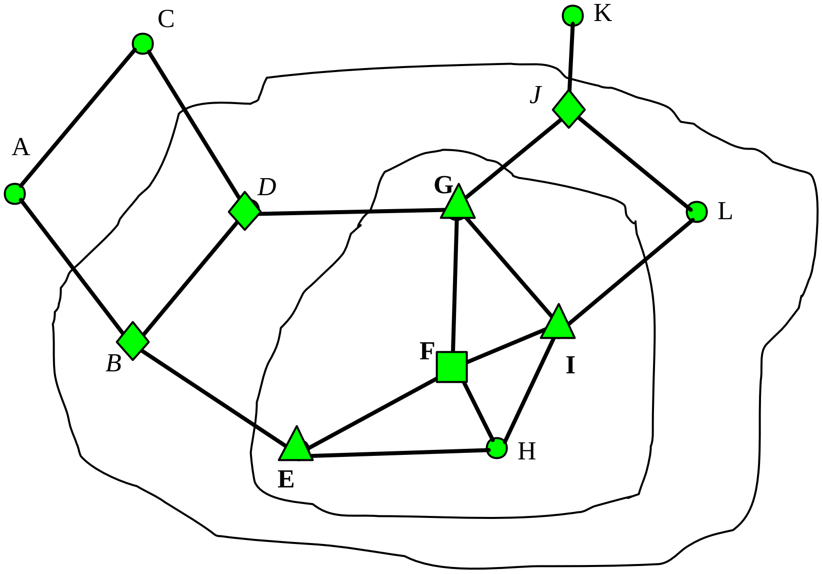


Figure 2. Selecting forwarding neighbors *G, E, I* for node *F, D* and *J* for *G,* and *B* for *E*

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 heuristic 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 re-transmissions by other nodes) the 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* re-transmit 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. Consider the network in Fig. 2, with node *F* being the source of broadcasting or a relay node. Its 1-hop neighbors are *E, G, H* and I, and two-hop neighbors are *B, D, J* and *L*. *E* covers only *B, G* covers *D* and *J, I* covers *L* and *H* does not cover any two-hop neighbor. In the first round, node *G* is selected to forward the packet. Nodes *L* and *B* are still not covered. Nodes *B* and *I* must be selected to cover them, while node *H* does not need to be in the list. Thus forwarding set for node *F* is *{G, E, I}*. Each of them then selects its own forward list. They can optimize the selection by ignoring nodes covered by other nodes in the forward list, if they are aware of their neighbors. Node *G,* for instance, considers 1-hop neighbors *D* and *J* to forward to *B, C* and *K* (it learns that its 2-hop neighbor L is covered by *I),* and must select both. Node *I* will not select any forwarding node, while node *E* will select *B* to cover *A* and *D.* In total, 7 out of 12 nodes will re-broadcast. The performance evaluation in [SSZ] gave quite stable ratio with respect to average graph degree of medium density, with 59-64% of nodes in the dominating set.

Lou and Wu [LW] discuss two extended dominant pruning methods: total dominant pruning (*TDP*) and partial dominant pruning (*PDP*), both using 1-hop neighbors to cover 2-hop neighbors. *TDP* requires the sender piggyback information about its 1-hop and 2-hop neighbor sets (simply called neighbor set within 2 hops) along with the broadcast packet. With this information, the receiver can prune all the nodes in the sender's neighbor set within 2 hops from the receiver's neighbor set within 2 hops that needs to be covered. Apparently, *TDP* will generate a smaller forward node set than Lim and Kim's dominant pruning (*DP*), but it also introduces some overhead when the broadcast packet piggybacks the 2-hop neighborhood information. *PDP,* without using the piggybacking technique, directly extracts the neighbors of the common neighbors of both sender and receiver from the receiver's neighbor set within two hops. In Fig. 2, suppose *I* is the sender and *F* is the receiver, the 2-hop neighbor set for *I* includes *D, E, F, G, H, I, J,* and *L* and the 2-hop neighbor set for *F* includes *B, D, E, F, G, H, I, J,* and *L*. The coverage set for *F* is reduced to *B* based on both *TDP* and *PDP*. If *F* is the sender and *E* is the receiver, *D* can be pruned from *E*'s coverage area using *TDP,* but not for *PDP* since the link between *D* and *G* is not included in *E*'s 2-hop neighborhood information. Simulation results in [LW] show that the *PDP* algorithm avoids the extra cost as in the *TDP* algorithm introduced by piggybacking 2-hop neighborhood information with the broadcast packet, but achieves almost the same performance improvement.

Note that the pruning approach that is based on neighbor position rather than 2-hop neighbor set can also be used [SSZ]. In Fig. 2, once *F* determines that the distance between its neighbor *G* and the incoming node *I* is less than the transmission radius, there is no need to cover *G*. However, neighbor position alone is not sufficient to detect neighbors of common neighbors as used in *PDP*. Therefore, neighbor position information only is weaker than information of the neighbor set within 2 hops.

The extended pruning methods perform well in the average case. However, they do not have a good approximation ratio (the worst case ratio of selected forward set size with respect to the minimum connected dominating set), especially in a dense network. Wu and Lou [WL1] propose to extend the pruning method to the cluster network. The extended pruning method is applied to the cluster graph consisting of clusterheads only. Basically, the notion of cluster graph converts any dense graph to a sparse one to guarantee a constant approximation ratio. The 2.5-hop coverage model is used and it is shown in [WL1] that the resultant cluster graph is a connected directed graph if the original graph is connected. The authors refer to a version with localized maintenance property (applying [CWLG] variant). However, this may create an excessive number of clusters, thus cluster based broadcasting solutions appear to be far from optimal localized solutions for dynamic ad hoc networks.

The adaptation of multihop relaying presented in [PL2] improves its performance by the following observations: broadcasting node transmits a list of its neighbors at time of broadcast packet transmission, not as part of any ‘Hello’ message. 2-hop neighbor knowledge is used to determine which neighbors also received the broadcast packet in the same transmission, and these nodes are already covered and are removed from the neighbor graph used to choose the next hop relaying nodes. Finally, if a broadcast message is received from a node that is not listed as a neighbor, the message is re-transmitted, to deal with high mobility issues. In connected dominating set based broadcast algorithm [PL1], sender node establishes priorities between forwarding nodes, and each forwarding node should eliminate from the consideration not only neighbors of the sender node, but also neighbors of each relaying node with higher priority.

Sun and Lai [SL, SL1, SL2], and Calinescu, Mandoiu, Wan and Zelikovsky [CMWZ] presented heuristics that aimed at covering the whole area where 2-hop neighbors could be located by a minimal set of 1-hop neighbors, and analyzed the performance of their schemes. The problem is equivalent to selecting a minimal set of disks that still cover the same area as the area covered by all disks centered in neighboring points. Their forwarding sets contain, on average, more nodes than the one based on set cover heuristic [Lo], since the forwarding sets are given larger areas to cover, and no 2-hop information is used. Thus only 1-hop position information is used. The solutions are based on the notion of curved convex hull, and have sophisticated details that are beyond the scope of this tutorial. Each forwarding node in variants [SL, CMWZ] includes a forwarding set as part of the message. In variant [SL1, SL2], this is avoided by transferring the overhead to hello messages, which contain the position of the sender and the list of its neighbors (without position information). The 2-hop neighbor information and 1-hop position information are used to calculate the local cover set of the sender's node at the receiver's node.

Sisodia, Manoj, and Murthy [SMM] propose to select forward nodes based on the notion of stability. A weight function that indicates the temporal stability and spatial stability of a node's neighbors is used as the criterion in the selection process.

The Lightweight and efficient network-wide broadcast protocol by Sucec and Marsic [SM] relies on 2-hop neighbor knowledge obtained from 'Hello' packets. Each node decides to re-broadcast based on knowledge of which of its other one and two-hop neighbors are expected to re-broadcast. Neighbors with high degree have higher priority to re-broadcast. Since a node relies on its higher priority neighbors to re-broadcast, it can proactively compute if all of its lower priority neighbors will receive those re-broadcasts; if not, the node re-broadcasts.

Rogers [R] proposed GPS screening angle technique where the nodes take the forwarding decision based on angle between the previous node, itself, and the next node. If the angle is greater than a threshold value, the message is forwarded to the corresponding neighbor; otherwise, it is not forwarded. Stojmenovic and Seddigh [SS] described a method where each node re-transmits the message if and only if it has at least one neighbor further from the source than itself. It will do so also in the case a closer neighbor to the source remained silent. The two techniques [R, SS] are not reliable. Boukerche [B] proposed to replace the flooding method in the route discovery phase of *DSR* routing algorithm, where the message is forwarded to each neighbor of any node receiving it, with the GPS screening angle technique [R] or further neighbor scheme [SS]. It was shown in [B] that occasional failure to discover the destination still causes fewer problems in routing than the extensive overhead of 'blind' flooding method that can easily congest the network.

5. Source-independent dominating sets

Most methods presented in the previous section include a forwarding set of neighbors as part of the message. They therefore have message overhead, and the set of re-transmitting nodes depends on the source node. The approach presented in this section does not require inclusion of forwarding set in the message, and has a fixed set of re-transmitting nodes, regardless of source choice. Its maintenance does not require more communication overhead, and has competitive performance (enhanced with neighbor elimination, see the next section) according to experiments in [SSZ].

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 a 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. 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 re-transmission is needed for reliable broadcast.

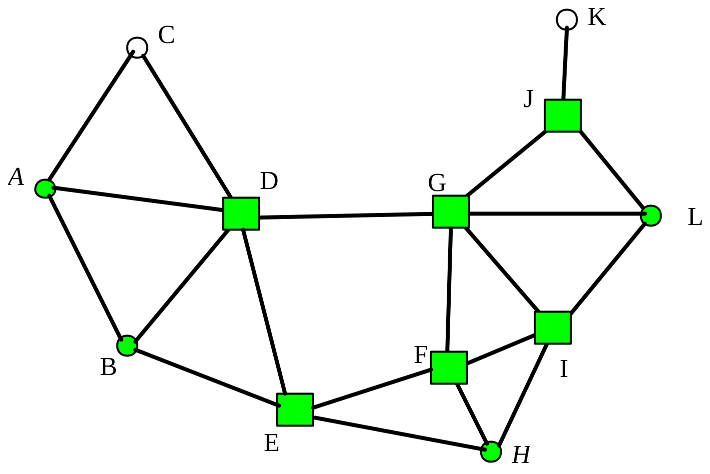


Figure 3. Nodes *C* and *K* are not intermediate, nodes *A*, *B* and *H* are not inter-gateway nodes

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 $id(v) < id(u)$, then node v is not an *inter-gateway* node. We may also say that node v is 'covered' by node u. Observe that re-transmission by v, in this case, is covered by re-transmission of u, since any node that might receive the 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 the dominating set. Using such keys, consider example in Fig. 3. Note that node *J* is forced by node *K*, for whom it is the only neighbor, to be in the 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 Fig. 3.

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 *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 re-transmission 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 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 exists one connected component so that each neighbor of A is a 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 [S3]. Each node A initially calculates its 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 re-evaluates 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 exists 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: A node *X* is 2-hop intermediate if it has two 2-hop neighbors B and C that are not 2-hop neighbors themselves. A 2-hop intermediate node *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 *key(X)< key(Y)*. The value *key(X)* can be one of *id(X), (degree(X), id(X)), (energy-level(X), degree(X), id(X))*, that is, it can have primary, secondary, ternary keys etc. for comparisons. A 2-hop inter-gateway node *X* is a 2-hop gateway if it has no two neighbors *Y* and *Z* such that every 2-hop neighbor of *X* is a 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 a forwarding neighbor of the neighbor with the smallest ID.

6. Neighbor elimination

Neighbor elimination scheme has been independently proposed in three papers [LK, PL, SS, SSZ]. In this source-dependant scheme, a node does not need to re-broadcast a message if all its neighbors have been covered by previous transmissions. In order to apply the method, the same assumption as in the previous section is taken: either nodes learn geographic positions of their neighbors, or receive a list of neighbors from each of their neighbors. After each received copy of the same message, the node eliminates from its re-broadcast list, neighbors that are assumed to receive correctly the same message. If the list becomes empty before the node decides to re-broadcast, the re-broadcasting is canceled. The neighbor elimination scheme version from [PL] uses 2-hop neighbor information instead of location of 1-hop neighbors.

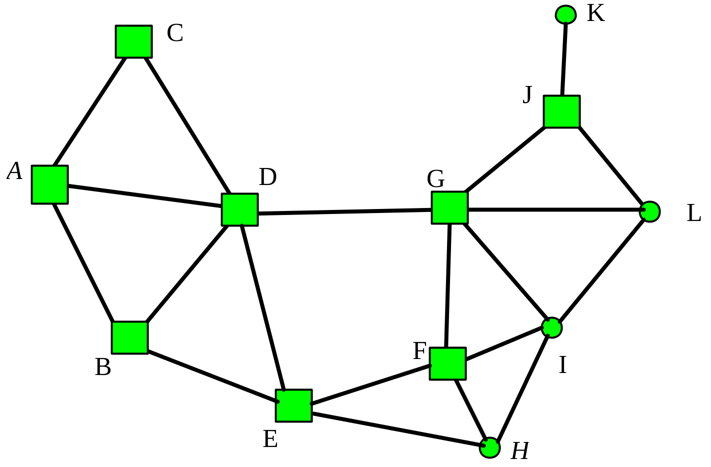


Figure 4. Re-transmitting nodes (square shaped) in neighbor elimination method with source *A*

The method depends on the selected medium access scheme. If IEEE 802.11 is used, Peng and Li [PL] propose to let nodes with more neighbors re-broadcast earlier, so that more nodes can be covered by one transmission, but experiments in [SSZ] did not find significant difference from the scheme where nodes choose back-off times at random within a fixed interval. Consider, for example, the network in Fig. 4, and let us assume that the order of re-transmissions corresponds to *x*-coordinate, that is, from left to right. Node *A* is the source. Node *B* re-transmits, followed by node *C* which is not aware that *D* already received the message from *B*. Re-transmissions from *D, E, F, G* and *J* then follow. Node *I*, for instance, does not re-transmit since all its neighbors are covered by previous re-transmissions from *F* and *G*. Note that there exist some additional re-transmissions with respect to the gateway node set, but also some gateway nodes (e.g. *I*) may not need to re-transmit.

While neighbor elimination scheme alone was not competitive with other dominating set definitions, it was able to improve the performance of all of them as an added feature. For instance, if a gateway node (e.g. *I* in Fig. 4) realizes that all its neighbors are covered by previous transmissions, it will not re-broadcast. Further, in [SSZ], each non-internal node *A* will assign itself to neighboring internal node *B* that has the largest degree. In case of ties, use lowest *id* among candidate neighbors. This rule attaches more neighbors to higher degree nodes thus possibly 'emptying' the assigned list of low degree internal nodes. If both internal node status and neighbor elimination schemes are applied, then the algorithm works as follows: When an internal node receives a message, it re-transmits the message if it has a non-eliminated neighboring node which is either a non-internal node assigned to it, or an internal node. Similar enhancements can be made to multipoint relay, and all methods come from [NTCS]. Better methods (like gateway dominating set) can be improved by about 1%, while others had benefits up to 10% in saved re-broadcasts.

Wu and Dai [WD] described a scheme that can be viewed as a combination of generalized internal node based dominating set [WL] and neighbor elimination, generalized to several last hops in the broadcast path. In that scheme, gateway nodes are defined on the fly, and the status may depend on the source node. The sub-graph consists of all *k*-hop neighbors (for small *k* such as 1 or 2) of *A* with higher priority value (say, id), and all *k*-hop neighboring nodes that have previously forwarded the message (if the routing history up to certain number of hops is included in the packet). If there exists a connected component of that sub-graph so that any neighbor of *A* is a neighbor of at least one node from the component then *A* is a non-gateway node. A more generalized rule is also proposed in

[WL]: A node *A* is non-gateway node, if every pair of its neighbors is connected via nodes with either higher priority value or nodes that have forwarded the message.

Cartigny, Ingelrest and Simplot [CIS] described *RNG* relay subset scheme, where a node *v* re-transmits the message received from *u* if *v* has an *RNG* (the concept is described below) neighbor which is not covered by *u*'s transmission. The algorithm can be interpreted as the neighbor elimination method where each node immediately eliminates all its non-RNG neighbors from its forward list. After this preliminary step, each node behaves as in the neighbor elimination scheme. Euclidean distance and neigborhood-based distances are considered.

7. Reliable broadcasting

In this section we shall discuss the broadcasting problem at the medium access layer. The design of reliable broadcast depends on the following three decisions [P]: by whom errors are detected, how error messages are signaled (these two are normally handled jointly), and how missing packets are re-transmitted. In the sender-initiated approach, the sender is responsible for the error detection. Error messages are signaled using ACK signals sent from each receiver. A missing data at a receiver is detected if the sender does not receive an ACK from the receiver. In this case, missing packets are re-transmitted from the source through a unicast. When several receivers have missing packets, the sender may decide to re-broadcast the missing packets to all the receivers. In the receiver-initiated approach, each receiver is responsible for the error detection. Instead of acknowledging each broadcast packet, each receiver sends a NACK once it detects a missing packet. Suppose broadcast packets are time stamped using a sequence number, a missing packet can be detected by a gap between sequence numbers of the receiving packets.

When the sender-initiated approach is applied, only the sender (that keeps the history of broadcast packets) is responsible for re-transmitting the missing packet and the corresponding re-transmitting method is called sender-oriented. Note that when the sender receives ACK signals from all the receivers, the corresponding packet can be removed from the history.

There are three ways to re-transmit the missing packet when the receiver-initiated approach is used: sender-oriented, neighborhood-oriented, and fixed-neighborhood-oriented. These methods differ by the locations of the copies of missing packets. These locations are also called copy sites, which include the sender. Note that when there are several receivers that have the same missing packet, broadcast NACK signals will be sent to the copy site(s). To ensure that at most one NACK is returned to the sender per packet transmission, when a receiver detects a missing error, it waits a random period of time before broadcasting a NACK to the sender and all other receivers. This process is called NACK suppression since a receiver will cancel its broadcast if it receives a NACK that corresponds to a packet it has missed. In the sender-oriented approach, senders can either unicast to a receiver (that needs the missing packet) or broadcast to all the receivers. In the neighborhood-oriented approach, the receiver that needs the missing packet searches its neighborhood for a group member that keeps a copy of the missing packet. The search process uses a TTL-based unicast process or TTL-based broadcast process. The search space is either limited to the broadcast tree (but now it is rooted at the receiver) or without limitation. In the fixed-neighborhood-oriented approach, the copy sites are fixed to a sub-group or each receiver has a ``buddy" to backup each other.

Mobility of mobile ad hoc networks adds complexity in achieving reliability. When a host moves from one neighborhood to another, proper hand-off protocols are needed. For example, when host U has just completed its forwarding process to its neighbor V, host W, a neighbor of V, moves away from the neighborhood of V and enters the neighborhood of U. To ensure that host W gets a copy of the packet, *U* needs to keep the copy for a while and will re-forward the packet (with a proper tag indicating this is a re-forwarding packet) whenever a change of its neighborhood is detected.

In [LW], Lou and Wu study two environments to handle mobility. In the "static" environment, mobile hosts are allowed to roam freely in the working space. However the broadcast process (including forward node selection and the broadcast process itself) is done quickly so that both 1-hop and 2-hop neighbor sets remain the same during the process for each host. In addition, each host has updated and consistent 1-hop and 2-hop neighbor sets when the broadcast process starts. Clearly, delivery of the broadcast packet is guaranteed as long as the selected forward nodes cover all hosts. In the "dynamic" environment, the broadcast process is still done quickly as in the static environment, so that both 1-hop and 2-hop neighbor sets remain the same during the process for each host. However, a host cannot update its 1-hop and 2-hop neighbor sets in a timely and consistent manner because mobile hosts are moving in a fast speed. Under this model, the broadcast delivery rate is no longer 100 percent. A simulation result in [LW] shows that the broadcast delivery rate still remains high in an ad hoc network with slow- to moderate-speed mobile hosts (with respect to the transmission range) using an ideal MAC layer without contention and collision. This high delivery rate is partly because of the broadcast redundancy in selecting the forwarding nodes. Therefore, while excessive broadcast redundancy is harmful and will cause the broadcast storm problem, some degree of redundancy is useful for reliability purpose.

Hsu, Tseng, and Sheu [HTS] propose an efficient reliable broadcast protocol based on end-to-end acknowledgement, i.e., all acknowledgements will be sent back to the source following the reverse of the broadcast tree. The tree is constructed redundantly where each node has multiple parent nodes (one primary and several backups). However, if all parent nodes are lost (due to the movement of hosts), flooding is needed to guarantee that all the acknowledgements will eventually be sent to the source.

Pagani and Rossi [PR] propose a 2-level hierarchical scheme for reliable broadcast. Two phases are used: scattering and gathering. In the scattering phase, the broadcast packet is forwarded to all clusterheads that in turn send it to its local members. In the gathering phase, the acknowledgements are collected by each clusterhead and sent along the broadcast tree, built on the clusterheads, back to the source.

In order to approach 100% reachability rate in an IEEE 802.11 environment, [SSZ] designed *RANA* (Retransmission After Negative Acknowledgements) broadcasting algorithm. When a node *A* re-transmits a message, if a collision at receiving node *B* occurs before the sender is recognized, no re-transmission request is issued. If the collision occurred after recognizing the sender node *A*, but before receiving the full message, *B* will send negative acknowledgement to *A*, asking it to repeat the transmission. The reachability in [SSZ] improved from over 94% to over 98%, but with a trade-off (up to 10% more re-transmissions). Hidden terminal problem (two non-neighboring nodes receiving message simultaneously and re-broadcasting it to a common neighbor) is the main obstacle to achieving 100% reliability in a network operating IEEE 802.11 medium access scheme.

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 [PL, SSZ, LK]. 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.

8. Activity scheduling and power-aware broadcasting

In ad hoc wireless networks, the limitation of power of each host poses a unique challenge for power-aware design [RW]. 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. 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.

Wu, Wu, and Stojmenovic [WWS] study dynamic selection of dominating nodes, also called activity scheduling. Activity scheduling deals with the way to rotate the role of each node among a set of given operation modes. For example, one set of operation modes is sending, receiving, idles, and sleeping. Different modes have different energy consumptions. Activity scheduling judiciously assigns a mode to each node to save overall energy consumption in the networks and/or to prolong life span of each individual node. Note that saving overall energy consumption does not necessarily prolong life span of a particular individual node. Specifically, they propose to save overall energy consumption by allowing only dominating nodes (i.e., gateway nodes) to re-transmit the broadcast packet. In addition, in order to maximize the lifetime of all nodes, an activity scheduling method is used that dynamically selects nodes to form a connected dominating set. Specifically, in the selection process of a gateway node, we give preference to a node with a higher energy level. The effectiveness of the proposed method in prolonging the life span of the network is confirmed through simulation.

Source dependent forwarding sets appear to be more energy balanced. However, 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. Therefore 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. From this point of view, internal nodes based dominating sets provide static selection for a given round and more energy efficiency than the forwarding set based method that requires all nodes to remain active in all the rounds. In [SSW], the key for deciding dominating set status is a combination of remaining energy and node degree.

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 a 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 parameter (size of square, which has to be carefully selected and propagated with node relative positioning in solution [XNE]).

The Span algorithm [CJBM] selects some nodes as coordinators. These nodes form a 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 the 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. Finally, [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.

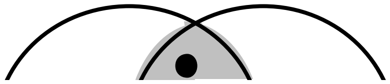
Feeney [F] described a power saving protocol in which each station is awake a bit over half the time, to ensure that awake periods of any two neighboring stations will overlap, allowing communication between them.

Tian and Georganas [TG] considered a somewhat related problem, the area coverage, where sensors shall decide about their activity status to prolong network lifetime but still provide continued 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 passive state. An alternative method [S3] follows a dominating set based approach where nodes instead announce their activity status by one added bit, and the method is used for both area coverage or dominating set creation with reduced size of the forwarding node set.

9. Broadcasting with directional antennas

We shall now discuss the case of broadcasting in the one-to-one model, corresponding to narrow beam directional antennas. A broadcasting algorithm called *SPIN* for sending a message from a node in a sensor network to all other nodes is described in [HKB]. Each node that receives the datum (i.e., the message) that is being broadcast will forward corresponding *meta-datum* that has considerably shorter bit length (e.g. 16 bytes instead of 500) to all its neighbors. Sensor's *id*, message *id* or sensor's location are examples. The meta-datum is thus flooded. The actual datum could be information that a particular sensor collects. Neighboring nodes that did not yet receive the meta-datum will reply with a request to get the actual datum. The node will respond by sending the actual datum to all nodes that requested it. The power consumed by SPIN protocol [HKB] is $(n-1)E + 2E'$ where n is the number of nodes, e is the number of edges in the graph, and E and E' are mean powers consumed for sending long and short messages along one hop, respectively. In any broadcast scenario, the energy $(n-1)E$ consumed is inevitable and is a lower bound that needs to be utilized.

An improved broadcasting scheme is described in [SSS] and is based on the relative neighborhood graph (RNG) concept [T] defined as follows. An edge (u,v) exists between vertices u and v if the distance between them, $d(u,v)$, is not strictly the largest side in any triangle uvw for every common neighbor w of u and v. In other words, *"w ¹ u,v: d(u,v) £ max (d(u,w), d(v,w)).* Thus, for an edge (u,v) to be included, the intersection of two circles centered at u and v and with diameter uv in Fig. 5 (shaded area) should not contain any vertex w from the set. In Fig. 2, uv is not in *RNG* because



of witness node *w*. Figure 6 shows the *RNG* on a set of six nodes (in this case the *RNG* is a spanning tree, which is not always the case).

Fig. 5. *(u,v)* is not in *RNG* graph because of a witness *w*

Figure 6. *RNG* graph

Toussaint [T] proved several important properties of relative neighborhood graphs, which are necessary for their application in the broadcasting task. *RNG* is a connected graph, and is a planar graph. The planarity of the graph assures that it is a sparse graph. Each node has on average about 2.5 neighbors independent of unit graph density.

Thus we will only try to optimize the number of short messages. In flooding algorithm [HKB], the number of short messages is equal to the total number of edges in the network. A huge reduction in the short message count can be obtained by applying concepts of *RNG* graph and dominating sets, as described in [SSS]. In the RNG based broadcast, starting from the source, the message is sent once over each edge of RNG. Thus instead of *nd/2* messages in complete unit graph with average density *d*, it is sent on about *1.25n* edges, with a reduction factor of *d/2.5* over the scheme [HKB]. The scheme, however, requires the distance information between any two neighboring nodes, which can be obtained from time delay or signal strength measurements. If that information is not available, [SSS] proposes to apply dominating set concept that requires 2-hop neighbor information at each node. Since any node in the network has an internal node neighbor, it suffices that only internal nodes re-transmit the message. Messages are only sent on edges connecting two internal nodes (one message per edge). The number of short messages is then equal to the number of edges in the subgraph of internal nodes. Each non-internal node, knowing all its internal node neighbors, will choose one of them and inform that one to send all broadcast messages to it. The number of non-internal nodes is therefore added to the number of edges connecting internal nodes. Experiments in [SSS] show that under 10% more messages are needed in that approach compared to RNG based one.

10. Broadcasting with adjusted transmission radii

In the minimum energy broadcasting problem, each node can adjust its transmission power in order to minimize total energy consumption but still enable a message originated from a source node to reach all the other nodes in an ad-hoc wireless network. The problem is known to be NP-complete [HH]. There exist a number of approximate solutions in literature (cited in [CSS1]) where each node requires global network information (including distances between any two neighboring nodes in the network) in order to decide its own transmission radius. Cartigny, Simplot and Stojmenovic [CSS1] described a localized protocol where each node requires only the knowledge of its distance to all neighboring nodes and distances between its neighboring nodes (or, alternatively, geographic position of itself and its neighboring nodes). In addition to using only local information, the protocol is shown experimentally to be competitive even with the best-known globalized BIP solution [WNE], which is a variation of Dijkstra’s shortest path algorithm. The solution [CSS1] is based on the use of *RNG* that preserves connectivity and is defined in a localized manner. The transmission range for each node is equal to the distance to its furthest *RNG* neighbor, excluding the neighbor from which the message came. Localized energy efficient broadcast for wireless networks with directional antennas are described in [CSS2], and are also based on *RNG*. Messages are sent only along *RNG* edges, requiring about 50% more energy than BIP based [WNE] globalized solution. However, when the communication overhead for maintenance is added, localized solution becomes superior.

Lipman, Boustead and Judge [LBJ] described the following broadcasting protocol. Upon receiving a broadcast message(s) from a node *h*, each node *i* (that was determined by *h* as a forwarding node) determines which of its one-hop neighbors also received the same message. For each of its remaining neighbors *j* (which did not receive a message yet, based on *i*'s knowledge), node *i* determines whether *j* is closer to *i* than any one-hop neighbors of *i* (that are also forwarding nodes of *h*) who received the message already. If so, *i* is responsible for message transmission to *j*, otherwise it is not. Node *i* then determines a transmission range equal to that of the farthest neighbor it is responsible for.

11. Conclusion

method	determinism	network info	reliability	hello' msg	broadcast msg
cluster tree [AWF]	deterministic	quazi-global	Yes	global	message only
clustering [L,LG]/[SSZ]	deterministic	quazi-local	Yes	ID/degree	message only
passive clustering [GKP]	deterministic	local	Yes	none	message + 2 bits
probabilistic [NTCS]	probabilistic	local	No	ID/degree	message only
counter / distance, location [NTCS]	probabilistic	local	No	ID/position	message only
border retransmit [CS]	probabilistic	local	No	ID	1-hop
forwarding neighbors [SMM, QVL, LK]	deterministic	local	Yes	1-hop	forwarding neighbors
curved convex hull [SL, CMWZ]	deterministic	local	Yes	position	forwarding neighbors

curved convex hull [SL1, SL2]	deterministic	local	Yes	position+1-hop	message only
forwarding node cluster [WL1]	deterministic	local	Yes	ID	forwarding neighbors
partial dominant prunning [LW]	deterministic	local	Yes	1-hop	forwarding neighbors
lightweight [SM]	deterministic	local	Yes	1-hop	message only
MPR-dominating [AJV]	deterministic	local	Yes	1-hop	message only
screening angle [R]/ further neighbor [SS]	deterministic	local	No	position	message only
intermediate, Rule 1 & 2 [WL]	deterministic	local	Yes	position or 1-hop	message only
intermediate, inter(gateway) [SSZ]	deterministic	local	Yes	[Wl] + degree	message only
Rule k / connected component cover [DW]	deterministic	local	Yes	ID	message only
k-hop dominating set [S2]	deterministic	local	Yes	(k-1)-hop	message only
announced gateway [S3]	deterministic	local	Yes	Id/degree + 1 bit	message only
k-hop gateway+neighbor elimination [WD]	deterministic	local	Yes	(k-1)-hop	message + last hops
neighbor elimination [LK, PL, SS, SSZ]	deterministic	local	Yes	position/1-hop	message only
gateway + neighbor elimination [SSZ]	deterministic	local	Yes	pos./1-hop+degr.	message only
RNG relay subset + neighbor elim. [CIS]	deterministic	local	Yes	pos./1-hop+degr.	message only

Table 1. Taxonomy of broadcast schemes for one-to-all model with fixed transmission range

Table 1 presents a taxonomy of broadcast protocols for omni-directional antenna (one-to-all) model with fixed transmission range, following our discussion. Only network layer methods are included, that is, MAC layer methods discussed in section 7 are not included. Also not included are a variety of global solutions, which were not within the scope of this chapter.

Despite rapidly increasing publications on the broadcasting problem, no comprehensive performance evaluation exists. Williams and Camp [WC] compared some selected protocols using contention based 802.11 MAC scheme, under various network and mobility scenarios. However, they did not include internal node based dominating sets [WL, SSZ] in their experiments. The articles that did compare their methods with the internal node based dominating sets [JLMV, SL1] used an inefficient version [WL] of it instead of the improved one in [SSZ] (neighbor elimination scheme is the main improvement) and have even misunderstood the method claiming communication overhead for its construction (to their defense, the description in [WL] used ‘marking process’ which is misleading).

There are some issues not discussed in this survey. For example, Mosko and Garcia-Luna-Aceves [MG] considered a series of broadcasting tasks, and the impact of such flow on the performance and reliability. Our discussion was restricted to the performance of one broadcast task at a time. They obtained some initial results, and this and other relevant issues will be studied further in literature. Thus we expect increased research activity on the transport layer of the broadcasting problem.

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