Resource Management in Wireless Networking
M. Cardei, I. Cardei and D.-Z. Du (Eds.) pp. – - –

Energy-Efficient Broadcasting in Wireless Mobile Ad Hoc Networks

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1 Introduction

Mobile networks have emerged as an important component of networking technology and a very challenging research field [40]. After the initial failure of the *UMTS* concept that would have magnified the old *GSM* network, the future of mobile network is now largely opened to innovative concepts. It seems now clear that the mobile network of tomorrow will be based on a multiple interface notion, with the Internet as the natural unifier. Among all these new concepts, mobile ad hoc networks have a prominent place [21].

1.1 Description of wireless ad hoc networks

Wireless ad hoc networks are formed by a set of hosts that operate in a self-organized and decentralized manner, forming a dynamic autonomous network through a fully mobile infrastructure. Communications take place over a wireless channel, where each host has the ability to communicate directly with any other one in its physical neighborhood, which is determined by its range. More accurately, when an host emits a message, every other one in its physical neighborhood will receive it. Another important characteristic of wireless transmissions is that when two nodes emit a message simultaneously, their common neighbors will experience a collision, and will not receive the message correctly.

Hosts in ad hoc networks can be fixed or mobile, and every collection of mobile hosts with appropriate interfaces may form a temporary network. No fixed infrastructure is needed, thus every host has to discover its environment when the network is formed. Ad hoc networks have multiple applications in areas where wired infrastructure may be unavailable, such as battlefields or rescue areas. It might also be infeasible to construct sufficient fixed access points due to cost considerations. As an example, constructing a fixed network infrastructure for the duration of an outdoor assembly is not realistic.

Here is a summary of the main characteristics of ad hoc networks:

Dynamic topology Hosts are mobile and can be connected dynamically in any arbitrary manner. Links of the network vary and are based on the proximity of one host to another one,

Autonomous No centralized administration entity is required to manage the operation of the different mobile hosts,

Bandwidth constrained Wireless links have a significantly lower capacity than the wired ones; they are affected by several error sources that result in degradation of the received signal,

Energy constrained Mobile hosts rely on battery power, which is a scarce resource; the most important system design criterion for optimization may be energy conservation,

Limited security Mobility implies higher security risks than static operations because portable devices may be stolen or their traffic may cross insecure wireless links.

Fig. 1 shows an example of such an ad hoc network. Hosts can be any mobile devices like laptops, cell phones, *PDA*... They communicate via an air interface and detect themselves in real time. New hosts can suddenly appear and old ones can disappear at any time. The topology of this network is very fragile, it can change at any moment and disconnections are frequent due to the mobility or activity status changes.

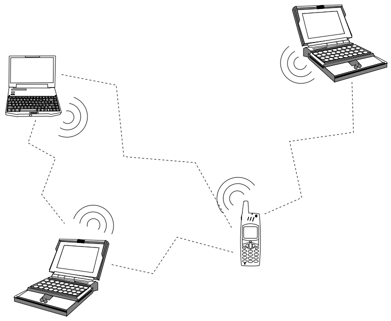


Figure 1: A self-organized network.

1.2 The broadcasting task

As already discussed, two hosts in an ad hoc network can communicate directly only if they are in the physical neighborhood of each other, which is determined by a communication range. Due to propagation path loss, the transmission radii are limited, thus communications must take place via a multihop routing.

To establish a connection between two hosts not directly connected, messages must be routed by intermediate hosts, as shown on Fig. 2. Hosts A and B are not able to communicate directly, every communication between them must be relayed by an intermediate host C. In this example, when A wants to send a message to B, it is simple for C to relay the message, because it is a neighbor of both of them. In larger networks, with hundreds of hosts, it is much more difficult for an host to find a route to another one, because of the lack of fixed infrastructure.

The traditional method used to discover routes is the dissemination of a

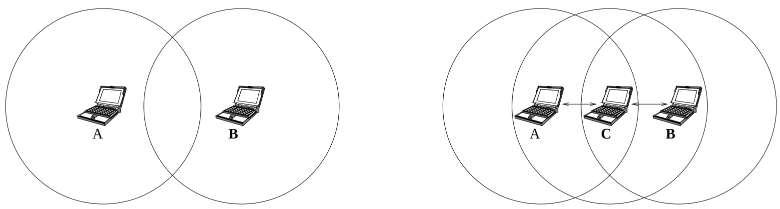


Figure 2: Multihop routing.

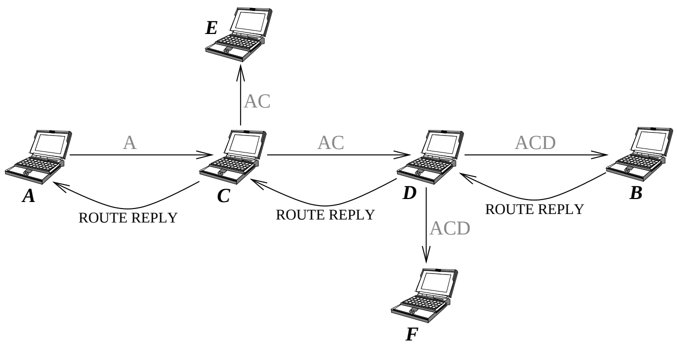


Figure 3: A route request from host A to host B.

message called a *route request*. When an host A wants to find a route to an host B, it sends a route discovery message to its neighborhood. Each of its neighbors adds its name to the message and re-emits it. Every other node in the network does so and finally, the searched host B receives the message with the chain of hosts followed from the source host A. The final step of this process is the emission of a message called a *route reply* by host B to inform A that a route has been found. This procedure is basis for an *IETF* standardized protocol named *DSR* (*Dynamic Source Routing*) [26].

DSR is illustrated by Fig. 3. A wants to find a route to B, so it sends a route request message to its neighborhood with its *id* as the initial chain of hosts. C receives this message, writes its name in the chain and re-emits it. A gets the packet, but ignores it (it already knows it and furthermore, it is the one that first emitted it). D does the same as C (as well as E and F) and finally B receives the request. It then just have to answer to A by emitting a route reply. This last message is addressed directly to A, because B knows the route to it. This one is simply written in the route request message, formed by the chain of hosts that relayed the message. In our example, the chain received by B was ACD so it sends the route reply with DCA as the route to follow.

Route discovery is performed by a broadcasting task, while the route reply is an unicast routing operation. Traditional broadcasting used in *DSR* is called a *blind flooding* because every node in the network retransmits once the message, upon receiving the first copy of it, and will consequently ignore further copies of the same message.

The broadcasting task is therefore a fundamental mechanism in route discovery, so the design of an efficient broadcast in ad hoc networks is of prime importance, in order to decrease the overhead, while maintaining a maximal diffusion. This is achieved by minimizing the number of emissions while still reaching all nodes, or by minimizing the total transmission power if the transmission ranges are adjustable.

1.3 Organization of this chapter

This chapter is organized as follows. The next section gives preliminaries and important definitions for a good understanding of the subject. Sec. 3 gives an overview of the current existing work in energy-efficient broadcasting protocols without range adjustment, where only the number of needed emissions is minimized. Sec. 4 presents energy efficient broadcasting protocols with transmission range adjustments, while Sec. 5 considers broadcasting protocols that use smart antennas, which are able to make directional emissions. Finally, conclusion and direction for future work are given.

2 Preliminaries

2.1 Communication Model

A wireless network can be represented by a graph $G = (V, E)$ where V is the set of nodes (hosts) and $E \subseteq V^2$ the edge set which gives the available communications: (u, v) belongs to E means that u can send messages to v. In fact, elements of E depend on the positions and the communication ranges of the nodes. Let us assume that the maximum communicating range, denoted by R, is the same for all vertices and that $d(u, v)$ is the Euclidean distance between nodes u and v. The set E is then defined as follows:

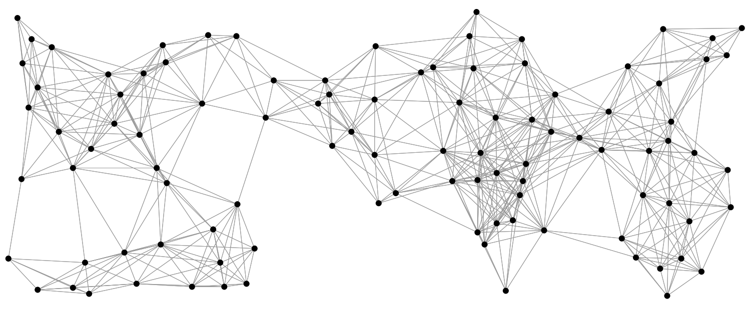


Figure 4: An unit graph with a density of 15 and 100 nodes.

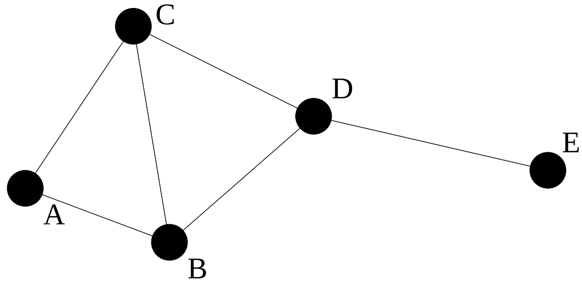


Figure 5: The distance in hops.

$$E = \{(u, v) \in V^2 \mid d(u, v) \leq R\}.$$

So defined graph is known as the *unit graph*, with R as its transmission radius. An example of such a graph is given in Fig. 4. Every node $u \in V$ must be assigned an unique identifier (id). We also define the neighborhood set $N(u)$ of the vertex u as

$$N(u) = \{v \mid (u, v) \in E\}.$$

The neighborhood function is naturally extended to set of nodes: for a given subset A of V, we have $N(A) = \cup_{u \in A} N(u)$. The degree of a given node u is the number of nodes in $N(u)$. The density of the graph is the average degree for each node. We also denote by $n = |V|$ the number of nodes in the network.

We measure the distance between two nodes in term of *number of hops*. It is simply the minimum number of links a message has to cross from a source node to reach its destination. In Fig. 5, the distance between A and B is one hop, while the distance between B and E is two hops. The one-hop neighborhood of E is $\{D\}$, while its two-hops neighborhood is $\{B, C, D\}$.

2.2 Assumptions

There are a variety of different assumptions that can be made about the operation of ad hoc networks and the amount of knowledge available at each node. The simplest assumption is that there are no control messages, and each node reacts to incoming broadcast message without being aware of its neighborhood. The blind flooding solution works with such a minimal overhead, but is suboptimal due to excessive collision impact from redundant transmissions. A beaconless broadcasting solution [4], that requires position information of senders, will be described further in this chapter.

For most protocols, it is vital to have informations about the neighboring nodes. The common method used to gain this knowledge is the use of special short messages named *HELLO* messages (also called *IAM* messages) that are periodically emitted by each node. The concept is very simple:

- each node keeps a table to store the *id* of its neighbors,
- each node emits periodically a *HELLO* message with its *id*; the frequency used for these messages is generally of 1 second,
- when a node u receives a *HELLO* message from a node v, it adds v to its neighborhood table, or updates the entry if it already exists. v and u are necessarily neighbors, since only physical neighbors of the emitter can receive the message,
- old entries are periodically deleted from the table. When an entry is too old (something like 5 seconds old), it is obvious that the corresponding host is no more in the neighborhood of the node, so the entry is simply removed from the table. The host could have simply moved or be in lack of power.

Many of the algorithms described further need the distance between a node and its neighbors to be applied. The easiest way to compute distances is to know the positions of the nodes, for example by using a location system like the *GPS* (*Global Positioning System*) [27]. Some other mechanisms for positioning can be used, such as *TODA* (*Time Difference Of Arrival*) [36], *AOA* (*Angle Of Arrival*) [34], reception power measurement [2] or phase difference [3]. A survey on location systems is available in [18]. If this kind of system is available, each node includes its position in its *HELLO* messages and thus needed distances can be computed.

Although positioning information may require additional hardware, the latest technological advances are remarkable: a very cheap 7mm x 7mm x 2mm *GPS* receiver now exists. Cartigny and Simplot proposed a software "distance" function denoted by μ [9]. It is defined by:

$$\mu(u,v) = \frac{|N(v) \setminus N(u)|}{|N(u)|}. \tag{1}$$

The numerator is the subtraction between the two sets $N(v)$ and $N(u)$. It is based on the fact that the number of common neighbors of two nodes depends on the distance between these nodes. The higher the distance is, the fewer common neighbors are and the higher the value of μ will be. They also showed that this (non-symmetric) estimation of Euclidean distance is sufficient for broadcasting.

To be able to compute the value of $\mu(u,v)$, a node u needs to know its neighbors, but it also needs to know the neighbors of the node v. To spread this information, *HELLO* messages are used again: when a node emits a message of this type, it includes the list of its own neighbors. Nodes have then to store the neighbors of their neighbors in their table. Typically, this is a two-hops information.

2.3 Energy Model

When emitting a message, a node spends a part of its energy and there are a few energy models used to compute this consumption. In the most commonly used one, the measurement of the energy consumption when transmitting a unit message depends on the range of the emitter u:

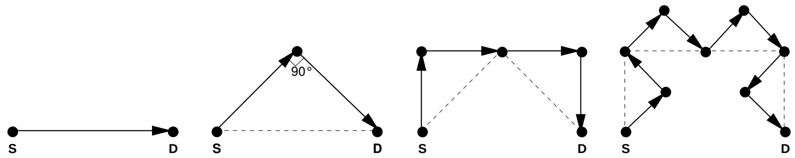
$$e(u) = r(u)^\alpha,$$

where α is a real constant greater or equal than 2 and $r(u)$ is the range of the transmitting node. This model has been used in a few papers, *e.g.* [47].

In reality, however, the model has a constant to be added in order to take into account the overhead due to signal processing, minimum energy needed for successful reception, *MAC* control messages and also possible overhead due to retransmission probability as suggested by Feeney [17]. The general energy consumption formula is:

$$e(u) = \begin{cases} r(u)^\alpha + c & \text{if } r(u) \neq 0, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

For instance, Rodoplu and Meng considered the model with $e(u) = r(u)^4 + 10^8$ [39]. This last one, also used by Cartigny *et al.* [11], is more realistic as illustrated by Fig. 6. With parameters $\alpha = 2$ and $c = 0$, it is clear that the case (b) costs the same energy as (a) by using the Pythagoras theorem. By induction, all illustrated configurations are supposed to have the same energy consumption and can be arbitrary extended.



(a) (b) (c) (d)

Figure 6: Configurations with same energy consumption for $\alpha = 2$ and $c = 0$.

Sometimes, with the required hardware, it is possible to consider directional emissions, that is a node can choose the angle of its emission. In this case, it is necessary to use a particular version of the formula:

$$e(\theta, r) = \begin{cases} \frac{\theta}{2\pi}(r^\alpha + C_1) + C_2 & \text{if } r \neq 0, \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

with θ being the chosen angle for the beam, C_1 a constant representing the overhead for correctly positioning the antenna, and C_2 a constant representing the cost of preparing the message for one or more directional transmissions.

3 Energy efficient broadcasting without range adjustment

The first obvious idea to reduce the energy consumption is to reduce the number of needed communications to achieve the broadcast. Indeed, not all nodes have to relay the broadcast message to obtain a full coverage of the network, as demonstrated by Fig. 7. If the node A sends a broadcast message, its neighbor B is the only needed relay to cover the network. Many protocols have been proposed to minimize the needed number of emissions, that can be grouped into the following families: clustering based, neighbor-elimination based, distance-based, probabilistic, coverage based, and forwarding neighbor based.

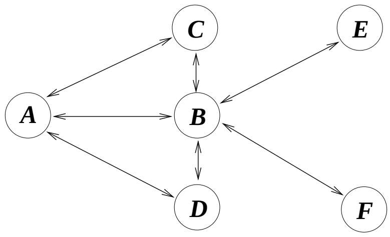


Figure 7: Example where not all nodes have to relay the message.

3.1 Clustering based broadcasting protocols

In a clustering based solution, message is retransmitted once by all clusterheads and border nodes, and it is applicable in conjunction with other methods presented further. Since clustering process has chain effect (local changes may trigger global structure updates), we do not elaborate it further. Jaikaeo and Shen proposed one of variants of such clustering based method to compute a dominating set [25]. Dominating nodes are selected based on their *id*. Each node decides to belong to the set if it has a higher *id* than any of its neighbors, otherwise it associates itself to the nearest dominating set member with highest *id*. Dominating set nodes are then connected to create a backbone. The backbone can also be used for power conservation, with clusterhead nodes deciding which nodes shall go to sleep mode.

3.2 Neighbor elimination based broadcasting protocols

NES (*Neighbor elimination scheme*) has been independently proposed in [35] and [43]. In this source-dependent scheme, a node does not need to rebroadcast a message if all of its neighbors have been covered by previous transmissions. After each received copy of the same message, each node eliminates, from its rebroadcast list, neighbors that are assumed to have received correctly the same message. If the list becomes empty before the node decides to relay the message, the re-broadcasting is canceled.

3.3 Distance-based and probabilistic protocols

In distance-based protocol [33], each node that receives the message for the first time relays it only if the distance between it and the emitter is greater than a fixed threshold.

In the probabilistic approach, messages are relayed with a probability p that can be fixed or computed by the node depending on several parameters. *BRP* (*Border node Retransmission based Probabilistic*) belongs to this family [9]. It consists in a variant of *NES* described above where nodes decide randomly to enter in *NES* mode or to retransmit immediately. The computed probability p is based on the local density of each node, and on distance to the sender. The higher the density is, or the closer the sender is, the lower the probability of relaying will be.

3.4 Coverage and connected dominating set based broadcasting

These protocols are based on the computing of a connected dominating subset $S \subset E$ as small as possible, which has to satisfy two characteristics:

- all nodes in the graph are either in S or a neighbor of a node in S, the subset is then called a dominating set,
- it has to be connected.

Several algorithms that compute these kind of sets have been proposed [1, 16]. The latter, called "Generalized rule", is an algorithm that can be applied locally by each node, without any message exchanged with neighboring nodes, solely using the knowledge of the neighborhood. The protocol can be described as follows (this simplified version of the protocol is given in [5]). First, each node checks if it has an intermediate state, that is every node that has at least two neighbors not directly connected is intermediate. Then each intermediate node A constructs a subgraph G of its neighbors with higher *id*s. If G is empty or disconnected then A is in the dominating set. If G is connected but there exists a neighbor of A which is not neighbor of any node from G then A is in the dominating set. Otherwise A is covered and is not in the dominating set. Non-intermediate nodes are never dominant. Dijkstra's shortest path scheme or a depth-first search (*DFS*) can be used to test the connectivity. The procedure apparently has localized maintenance. This procedure is generalized since it allows coverage by any number of neighbors. There exists special cases proposed earlier by Wu and Li [51], where the coverage was restricted to one or two neighbors only.

Fig. 8, where a dominating set has been computed, illustrates this algorithm. Black nodes are dominants while white ones are non-dominants. In this example, node 0 is not dominant because all of its neighbors with higher

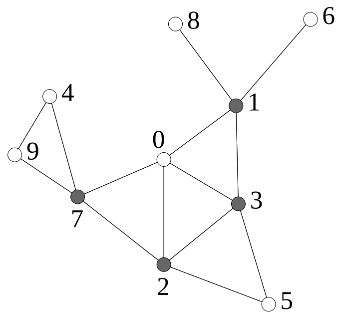


Figure 8: A dominating set computed with Generalized rule.

id form only one (connected) component, while node 2 is dominant because there exists two components in its neighborhood (*e.g.* $\{3, 5\}$ and $\{7\}$) that are not connected. Node 5 is not dominant because it is not intermediate (all its neighbors are directly connected).

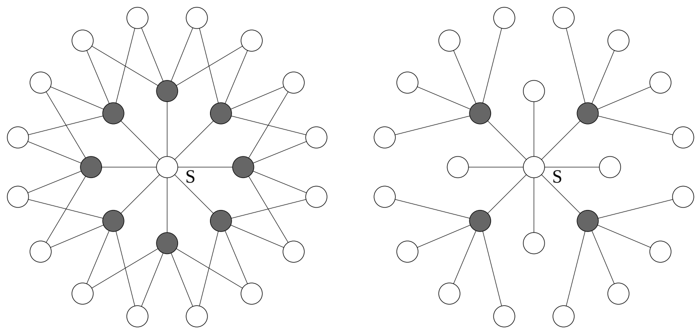
The broadcasting protocol with a dominating set is very easy:

- a dominant node that receives the message for the first time relays it, any further receptions are ignored,
- a non-dominant node that receives the message simply ignores it.

Wu and Dai proposed to construct a dominating set by clustering followed by generalized rule on clusterheads [50]. Two versions are proposed. Clusters are created using transmission ranges $\frac{r}{3}$ and $\frac{r}{4}$, while generalized rule on clusterheads is applied with transmission ranges r and $\frac{3r}{4}$, respectively. Significant reductions in the size of connected dominating sets, compared to generalized rule, are reported. However, these reduction come from using clustering operation that is not fully local (decisions made at one part of network have impact on other parts on network, both during construction and maintenance).

3.5 Forwarding neighbors based broadcasting protocols

Some broadcasting protocols, such as covering based ones, are source-independent, because relays are always the same regardless of the source. With source-dependent protocols, nodes that act as relays are not always the same.



(a) (b)

Figure 9: Application of MPR algorithm.

Depending on the protocol used, nodes can select themselves as relays when they receive a message, or they can select their relays within their neighborhood before the emission. Source-dependent protocols balance better the load of the network between the nodes. With dominating sets, relays are always the same, thus hosts that act as relays will quickly lose their energy when several broadcasts are launched. On the other hand, source-independent protocols allow non-dominating set nodes to go to sleep mode without affecting the network operation, thus prolonging the network life considerably.

The *MPR* (*Multipoint Relay*) protocol belongs to the family of forwarding neighbors based broadcasting protocols [37]. It uses a greedy algorithm to compute an optimal selection of neighbors to act as relays, in order to reach every two-hops neighbors. When a node selects some of its neighbors, it forwards its selection with the broadcast packet, thus increasing the traffic. Fig. 9 shows an example of *MPR* relays, where S wants to broadcast a message, with black nodes being its relays. In the general case (a), each of its neighbors are relays, while in case (b), S has applied *MPR* to choose them. This protocol is very efficient in terms of energy savings, but unfortunately it is not very resistant to node failures due to the low redundancy of chosen relays. Cartigny *et al.* proposed *RRS* (*RNG Relay Subset*) to address this issue [7]. Moreover, this protocol offers the advantage to allow nodes to select themselves as relays, reducing the size of packets and therefore the number of collisions. *RRS* is based on *RNG* (*Relative Neighborhood*

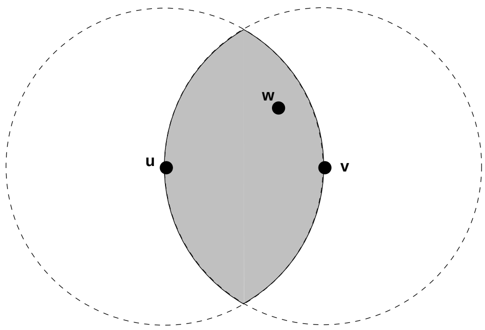


Figure 10: The edge (u, v) is not in RNG because of w.

Graph), which is a geometric concept proposed by Toussaint [45]. The relative neighborhood graph of G, denoted by $RNG(G) = (V, E_{rng})$ is defined by:

$$\begin{aligned} E_{rng} = \quad & \{(u, v) \in G \mid \nexists w \in N(u) \cap N(v), \\ & d(u, w) < d(u, v) \wedge d(w, v) < d(u, v)\} \end{aligned}$$

This condition is illustrated by Fig. 10. The shaded area is the intersection of the two circles centered at u and v with radius $d(u, v)$. An edge (u, v) belongs to the *RNG* if there does not exist a node w in the gray area, which is not the case here, so (u, v) does not belong to the *RNG*. In other words, an edge belongs to the *RNG* if it is not the longest edge in any triangle. In Fig. 10, if there exists a neighbor w in the shaded area, uv would have been the longest edge in triangle uvw and therefore would not belong to the *RNG*.

The protocol *RRS* is a variant of *NES* (see Sec.3.2) where nodes survey only a restricted part of their neighborhood: their non-covered *RNG*-neighborhood.

Recently, Kim and Suh proposed a forwarding set selection method and an efficient scheme for broadcasting with transmission power control [28]. The goal of this protocol is not to minimize the total transmission power but to reduce delays at *MAC* layer of forwarding set by avoiding collisions when scheduling transmissions of nodes in forwarding set. Indeed, the node not only decides its forwarding neighbors but makes as well the schedule for their transmissions (with similar iterative scheme, where each next node is either included in an existing transmission spot or a new spot is created for it if it collides with all already scheduled spots) to avoid collisions. An attempt to include a new transmitting node into each existing spot is made by considering reduction of transmission power to minimal necessary to cover designated nodes. Its principle is quite similar to the one of *MPR*, but the forwarding node selection criterion is modified. First, all 1-hop neighbors which are the only ones that cover some 2-hops neighbors are chosen. Then, instead of choosing neighbors which cover maximal number of remaining nodes, a node that shares 2-hops neighbors with minimal number of already selected nodes is taken.

This technique and two previous ones (*Neighbor Elimination Scheme* and *Dominating Sets*) have been unified in a generic protocol proposed by Wu and Dai [49].

3.6 Impact of realistic physical layer

Qin and Kunz [38] considered the impact of a realistic physical layer model on on-demand routing in ad hoc networks. Assuming that each node uses the same transmission radius, in an ideal environment the received signal power only depends on the distance between nodes. With a shadowing model, the received signal power has a Gaussian distribution fluctuation. The signal strength is therefore a function of distance between two nodes (which decides the distribution function) and a random number which is used to choose a number from the distribution. Given two nodes at distance d, there exists therefore probability $f(d)$ that the signal is received correctly. This observation can be used to derive new broadcasting schemes with better expected performance than the existing schemes that assume ideal physical layer. In [41], the following broadcast scheme is proposed. Each node is assumed to know whether or not it belongs to a dominating set, and also knows for each of its neighbors whether or not they belong to a dominating set. Recall that this knowledge can be gained by adding just one bit to any communication between any two neighboring nodes, or by knowing the geographic coordinates of two-hop neighbors of each node. Upon receiving the first copy of a broadcast message, node A will set a timeout, which is short for a node from dominating set, and long for a node which is not in dominating set. Neighbor elimination scheme is applied to eliminate neighbors that are believed to have received the message (that is, have high corresponding probability $f(d)$, where d is their distance from the transmitting node) and are not in dominating set. Neighbors that are in dominating set and are believed to have received the message are not eliminated. They are eliminated only if a message directly from them is received. At the end of the timeout, if the set of neighboring nodes to be covered is not empty, message is retransmitted, otherwise retransmission is canceled. Thus the difference from the existing approach is that each node only recognizes transmissions which are correctly received, when eliminating neighbors. That is, coverage is only accepted from neighbors whose transmission was correctly received. Note that the timeout function does not need to be a constant function, but could depend on the number of received messages, or percentage of node transmission area that has been covered. The distinction is made, however, between timeout for nodes in dominating set and nodes outside it. The dominating set itself may follow any of existing approaches, such as forwarding neighbors (*e.g. MPR*), covering (definitions by Jie Wu *et al.*), or clustering.

3.7 Beaconless broadcasting

In [4], 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 the 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 the 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 the timeout interval.

3.8 Double-dominating sets

Koubaa and Fleurry [29] proposed to enhance reliability of multicasting by requesting that each node is adjacent to at least two clusterheads. This idea is further developed in [42], 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

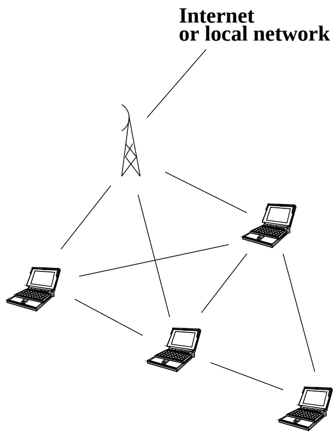


Figure 11: Example of an hybrid network.

a neighbor of at least two of such nodes.

3.9 Broadcasting in hybrid networks

Hybrid networks are ad hoc networks with some fixed access points. Correctly used, these ones bring many advantages, mainly in the energy consumption. Indeed, as they are fixed, we suppose they have an unlimited amount of energy, when mobiles use a battery. They can also offer some services that are inaccessible to simple mobiles, like an access to the Internet or a local network. If an access point has such an access, we can assume that every mobile in the network will be able to use it also, thanks to the multi-hop routing. Fig. 11 illustrates such a network.

In [22], 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 the source node of a broadcasting task, with packet arriving at node A. A will retransmit if A is in dominating set and there exists neighbor B of A such that $hc(S,A) < hc(S) + hc(B)$, where $hc(S,A)$ is the number of hops between S and A, and $hc(S)$ and $hc(B)$ are hop counts of S and B to their nearest access nodes. If access nodes are assumed to have significantly larger transmission radius than ad hoc nodes, the condition can be modified to $hc(S,A) < hc(S) + 1$.

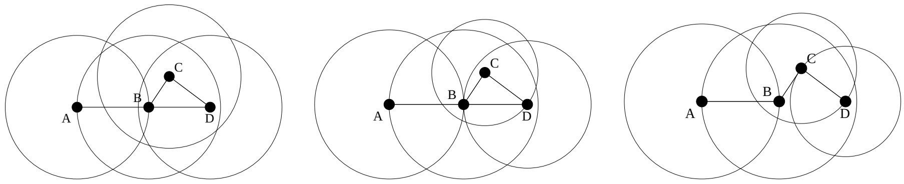
3.10 Effects of MAC layer and mobility

In [48], Williams and Camp classified the broadcast protocols into: blind flooding, probabilistic based, area based, and neighbor knowledge based. They studied twelve broadcast protocols through detailed simulations, particularly focusing on the effects of MAC layer and mobility. The comparison is made with same simulator and same parameters, and same scenarios involving bandwidth congestion and topology variations. Results showed that simple protocols like probabilistic do not work well in a congested network. Further, methods using knowledge of neighborhood offer better results than area based methods.

4 Energy efficient broadcasting with range adjustment

Topology control protocols aim to minimize the needed radius for a transmission at each node, while preserving the connectivity of the network. The connectivity here requires non-directional links (that is any two neighbors in the connected graph must be able to reach each other). In a broadcast oriented variant of the problem, the graph may contain directional edges, and connectivity from source node to all other nodes only is required. When a node has to transmit a message, it does not always have to do it at full power. It is possible to limit the needed range for various reasons (for instance, some neighbors may have already received the message) and thus some energy can be saved. The problem is now to assign transmission ranges to all nodes so that the network remains connected and the sum of selected transmission powers is minimized. This minimum-energy range assignment problem has been shown to be a NP-hard one by Clementi *et al.* [15].

Fig. 12 shows the effects of radius adjustment. Case (a) is the unit graph, circles being the areas of communication of each node, which is determined by their original communication range. Case (b) shows the same unit graph, where nodes have adapted their radii to the minimum needed range to reach their furthest neighbor. Finally, case (c) shows the RNG of the unit graph with radii adjusted to reach the furthest RNG-neighbor of each node. This last case clearly illustrates the fact that the graph becomes directed with radius adjustment, with D receiving the communications from B without being able to communicate with him.



(a) (b) (c)

Figure 12: Consequences of radius adjustment.

4.1 Centralized protocols

Wieselthier *et al.* proposed two centralized greedy heuristics to compute an energy-efficient broadcast tree by assigning a range to each node, called *BLU* and *BIP* [47]. The first one, *BLU* (*Broadcast Least-Unicast-cost*), applies the Dijkstra's algorithm, while the second one, *BIP* (*Broadcast Incremental Power*), is a variant of the Prim's algorithm that uses the broadcast nature of wireless transmissions. Although the authors considered an energy model using a constant c equal to zero, *BIP* fits well in the general model with any other arbitrary value and its performances are the best known ones. Some small improvements have since been proposed but always in a centralized manner and with an energy model using constant $c = 0$ [20, 44, 46].

Wieselthier *et al.* also defined a topology control algorithm based on the *MST* (*Minimum Spanning Tree*) [47], which is used to determine the transmission range of nodes: a node selects the transmission power that permits it to cover all its neighbors in this subgraph. As, by definition, the *MST* is always connected, the graph derived from the new range assignment is also always connected.

4.2 Localized protocols that minimize needed radii

As centralized solutions cannot really be applied in ad hoc networks without an huge overhead of communications, some localized protocols have been proposed. Cartigny *et al.* [11] proposed a protocol named *RBOP* (*RNG Broadcast Oriented Protocol*) that uses the *RNG* as a connected subgraph instead of the *MST* in the algorithm from Wieselthier *et al.* , the obvious advantage being that the *RNG* can be computed in a totally decentralized manner. Li *et al.* proposed an algorithm to compute a graph named *LMST*

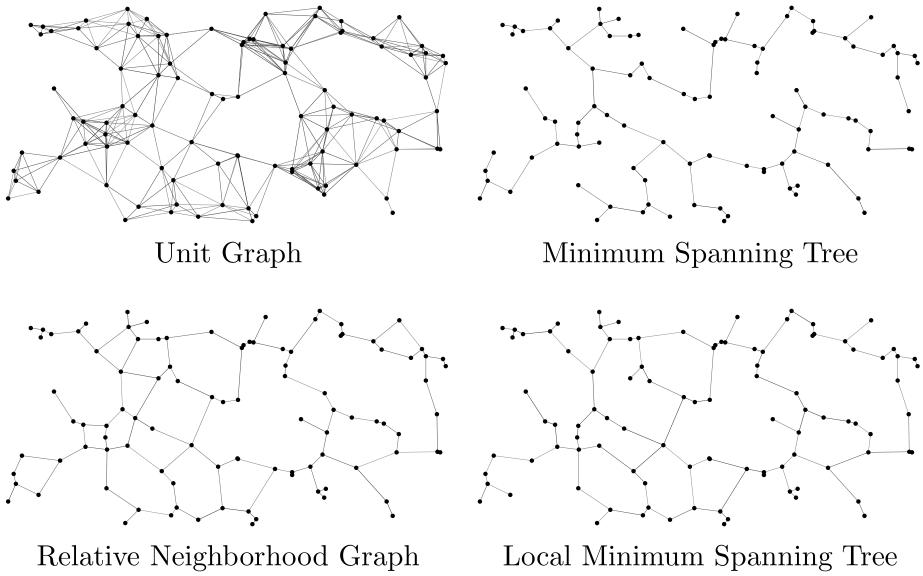


Figure 13: An unit graph with its subgraphs (100 nodes with an average degree of 14).

(*Local Minimum Spanning Tree*) that keeps connectivity [30] and that have since been demonstrated to be a subgraph of the *RNG* [8]. This inclusion proves that *LMST* always performs better than *RNG* when used in this algorithm. This version of *RBOP* is called *LBOP* (*LMST Broadcast Oriented Protocol*) and have been proposed in the same paper [8]. An example of an unit graph and its associated *MST*, *RNG* and *LMST* subgraphs is given in Fig. 13. It can also be noticed that *MAC* layer for *LMST*/*RNG* based broadcasting may use acknowledgments from *LMST*/*RNG* neighbors only.

Some improvements to *RBOP* have since been proposed. Indeed, in *RBOP* and *LBOP* protocols, a subgraph is used (respectively *RNG* and *LMST*) to compute a minimal selection of needed neighbors to keep the connectivity. In the description, it is said that only nodes that receive the broadcast message from a neighbor not present in the subgraph enter a *NES* (see Sec. 3.2), otherwise the message is immediately retransmitted. So, the *NES* is used only to ensure a total connectivity, in case of a non-retransmission from a needed node (in case of a collision for example).

This behavior is not always optimal, and it is possible to further enhance the energy savings by allowing every node to enter a *NES*, regardless of the emitter. Indeed, it is possible for a needed node to have all its neighbors covered by other transmissions, allowing it to cancel its own transmission. Using this improvement, the new version of the protocol can be described as follows:

1. the source node u of a broadcast emits its message with its range $r(u)$ determined by the appropriate subgraph (*RNG* or *LMST*),

2. when receiving a new broadcast message, the node generates, for this broadcast, the list of needed neighbors (computed with the appropriate subgraph) that have not received this message. After a given timeout, if the list is not empty, the node retransmits the message with a range allowing it to reach its furthest neighbor left in its list,

3. when receiving an already received message:

   (a) the node ignores the message if it has already forwarded it or if the associated neighborhood list is empty,

   (b) the node removes nodes that are reached by the message from the associated neighborhood list.

This version of the protocol based on the *RNG* is designated by *RBOP-T* (*RNG* Broadcast Oriented Protocol with full Timeout) and the one based on *LMST* in called *LBOP-T*. They have been proposed in [8]

The use of the full *NES* (*e.g.* applied to all nodes in the network) in *RBOP-T* brings a decrease up to 15% in the energy consumption to standard *RBOP*. The substitution of *RNG* by *LMST* in *LMST-T* leads to an improvement of 20% that corresponds to the average degree reduction (from 2.6 for *RNG* to 2.04 for *LMST*). While obviously *BIP* is still the best algorithm with its global knowledge, the overhead of *LBOP-T* is less than 45% with the model $\alpha = 2, c = 0$ and less than 65% with $\alpha = 4, c = 10^8$. This example illustrates the fact that optimized localized algorithms can be very competitive with centralized ones.

Li and Hou independently also proposed to apply *LMST* structure for broadcasting [31], and analytically concluded that multi-hop broadcast is more power efficient than single message with full transmission power when $\alpha \geq 2.2$. This article challenges the generality of such conclusion independently on constant c, which tends to suggest that it is always better to minimize the transmission radius to the minimal one, decided by the structure of $LMST$.

Huang and Shen proposed another algorithm to compute the needed range [19]. Each node broadcasts at each power level and verifies whether the subgraph of all its 1-hop neighbors (when the maximum transmission radius is used) is still connected. Then, each node chooses the minimal range which preserves the connectivity of the subgraph as its transmission radius. The communication overhead that occurs when determining the transmission radius seems significant, although it is limited to 1-hop neighbors, that is, procedure is localized. The advantage of this scheme is that no position information is needed. This method can also be seen as the discrete version of $LMST$ structure presented above.

Chen *et al.* proposed a localized minimum energy scheme where each node decides transmission power based on 2-hops information [13]. Upon receiving the first copy of a message, node A sets a timeout and eliminates all neighbors that already received the same message in this or subsequent transmissions by other nodes before timeout expires. All neighbors of current node A are sorted, from furthest to closest, and examined in that order. If, for an examined neighbor B, there exist a common neighbor C such that the power to reach C from A plus the power to reach B from C is lower than power needed for direct transmission from A to B, node A decides not to cover node B, and reduces transmission power and examines, in turn, the next closer node in the list. This continues until a node is found for which this optimization step cannot be performed. The distance to that node is selected for transmission radius and message is retransmitted (unless the set becomes empty, in which case A decides not to transmit at all). Although the scheme is very promising, unfortunately it is compared only with scheme that uses maximum transmission power at each node, not with other existing localized scheme such as [11].

These algorithms are also studied for applications in sensor networks. Cheng *et al.* proved that the problem of assigning transmission power to each sensor, such that the induced topology composed only by bidirectional links is strongly connected, is NP-complete [14]. They proposed two heuristics, one based on selecting the furthest MST-neighbor at each node, and the other based on incremental power (adding one node at a time to already constructed connected tree so that the added power is minimized).

Wu and Wu proposed to dynamically reduce the transmission power of each node in the broadcast process based on some observations on the maximal distances from each node to all its neighbors, and based on the

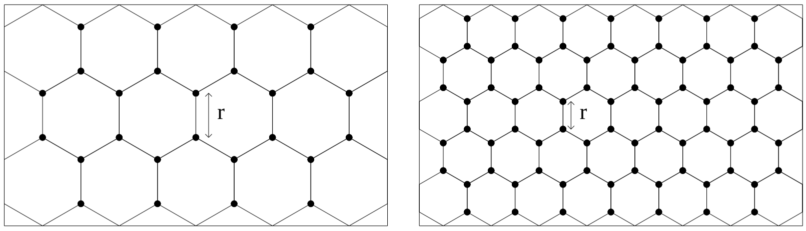


Figure 14: Hexagonal tiling of a surface S for different ranges r.

dominating set status of each node [52]. Nodes which are not in dominating set may still retransmit, and the comparison is made with blind flooding, and methods presented in [53] which were aimed at scheduling node activities, not at minimizing total energy.

4.3 Localized protocol that uses a target radius

All the presented algorithms that use range adjustment are based on the assumption that the shortest radius is always the optimal one. Indeed, the constant α (see Eq. 2) makes long emissions expensive. Unfortunately, this assertion is not always valid when considering cases with c not equal to zero, because short radii will lead to an increase of needed relays to cover the network and thus to an increase of the energy consumption (the constant c is supported by each of these transmitting nodes). So, it can be assumed that there exists a target radius for a given broadcast that balances the cost of α and c, leading to an optimal energy consumption for a given broadcast. A protocol that uses this idea has been proposed in [23] and is named *TR-LBOP*. Its description goes as follows.

Optimal radius value

The value of the optimal radius is computed by considering a geometrical area S on which some nodes that can adjust their radii are placed. To do this, an honeycomb mesh is used, that is the area is divided into several hexagons of side r, where nodes are placed on vertices, with a radius of r. Obviously, the quantity of vertices (*i.e.* nodes) depends of r. Fig. 14 shows the tiling for two different values of r.

To find the optimal radius, the value of r that minimizes the total power consumption must be computed. The needed energy is simply computed by considering that each node will have to emit the message once with a radius of r. A high value can be chosen, which would allow nodes to cover a large part of the area with only one emission, or a low value can be chosen, in which case only a small part of the area would be covered. In the first case, only a few emitting nodes would be needed, while in the second one, a lot more of relays would be needed to cover the entire area. A radius that balances between these two behaviors must be found.

The number of hexagons h is computed by using the formula

$$\text{h} \simeq \frac{\text{Surface of the area}}{\text{Surface of an hexagon}} = \frac{2S}{3r^2\sqrt{3}}.$$

As two nodes are placed on each hexagon, the number of nodes $n = 2h$ is then:

$$n = \frac{k}{r^2}, \quad k = \frac{4S}{3\sqrt{3}}.$$

When a broadcast occurs, all these nodes will emit once the message, the power consumption is then:

$$PC(r) = (r^\alpha + c)\frac{k}{r^2}.$$

Minima of this function give optimal radii, depending of the value of α and c. Fig. 15 clearly shows that with the hexagonal tiling, when $\alpha = 4$ and $c = 10^8$, the optimal radius is 100. Below this value, there are too many nodes (vertices), making the constant c a problem while a radius greater than 100 makes the constant α a disadvantage.

Given that $\alpha \geq 2$, $c \geq 0$ and $r > 0$, there are only a few possible cases that are enumerated by table 1. It can be noticed that $\alpha = 2$ brings special cases. In the first one ($c \neq 0$), it is better to emit with the maximal possible range, while in the second one ($c = 0$) the chosen radius does not influence the power consumption.

TR-LBOP protocol

Obviously, the position of nodes cannot be controlled in ad hoc networks, but fortunately radii can be modified, making possible a control of the topology. Roughly, chosen radii will have to be as close as possible from the optimal one, while still guaranteeing the original connectivity of the network.

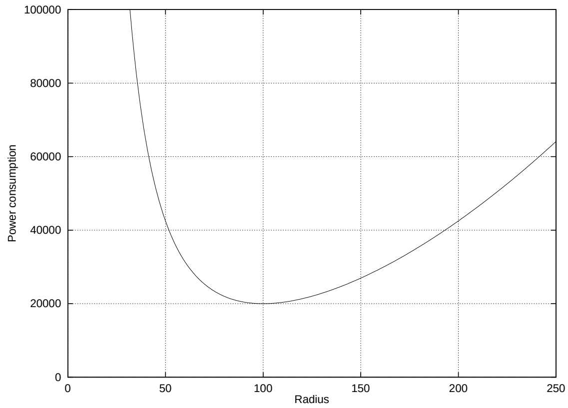


Figure 15: Power consumption vs. chosen radius with $\alpha = 4$ and $c = 10^8$

LBOP is used as a based broadcast protocol because of its advantages: it uses a localized algorithm, the subgraph *LMST* keeps the connectivity and is composed only by small edges. Its only disadvantage is to try to minimize transmission radii, which is not always an optimal behavior. To include the concept of optimal radius, some parts of the protocol have been modified, so that each node increases its radius up to the optimal one when a retransmission is needed. This variant of *LBOP* is called *TR-LBOP* for *Target Radius LMST Broadcast Oriented Protocol* and can be described as follows.

Each node manages two lists L and L' during the *NES*. The first one, L, stores the neighbors needed to keep the connectivity of the network. As *LBOP* uses the *LMST*-subgraph, L is defined by:

R_{opt}	$c = 0$	$c \neq 0$
$\alpha = 2$	-†	R
$\alpha > 2$	0	$\sqrt[\alpha]{\frac{2c}{\alpha-2}}$.

† when $\alpha = 2$ and $c = 0$, the radius has no influence, we use 0 as an arbitrary value.

Table 1: Theoretical optimal emitting radius R_{opt} for each α and c.

$$\forall u \in V \quad L(u) = N_{LMST}(u).$$

The list L' stores every other neighbors of the node, and is defined by:

$$\forall u \in V \quad L'(u) = N(u) \setminus L(u).$$

During the *NES*, a node u will monitor every transmission that occurs in its neighborhood, and each time one of its neighbor receives the broadcast message, its removes from the corresponding list (L if it is a $LMST$-neighbor, L' otherwise) this node. Of course, the node u can immediately remove the node from which it gets the message and their common neighbors.

When the timeout is up, two cases can happen:

- The list L is empty, in which case the node does not need to re-emit the message to keep the network connectivity, so the retransmission is canceled, as with *LBOP*.
- There is at least one node in L. In this case, the node u has to rebroadcast the message to reach the nodes left in L.

In the second case, when the retransmission is needed, the node will have to support the cost of the constant c in the energy model (regardless of its radius). So, as explained previously, it can be clever to increase the needed radius up to the optimal one, when it is possible. Two values, D_L and $D_{L'}$, are used. The first one, D_L is defined by:

$$D_L = \max\{d(u,v) \mid v \in L(u)\},$$

with $d(u,v)$ being the Euclidean distance between u and v. The second one, $D_{L'}$ is defined by:

$$\begin{aligned} D_{L'} &= \{d(u,v) \mid v \in L(u) \cup L'(u) \wedge \\ \delta_{uv} &= \min\{\delta_{uw} \mid w \in L(u) \cup L'(u)\}\}, \end{aligned}$$

with $\delta(u,v)$ being defined by

$$\delta_{uv} = |d(u,v) - R_{opt}|.$$

In other words, the chosen distance is the length of the edge between the node u and its non-reached neighbor which is the nearest one from R_{opt}. The final chosen radius is simply:

$$r(u) = \max\{D_L, D_{L'}\}.$$

This modification leads to a situation where nodes mostly emit with a radius as close as possible to R_{opt}. The increased number of reached neighbors is balanced with the full neighbor elimination scheme of *LBOP*, so the number of relays does not increase dramatically.

The results were obtained by simulating 500 broadcasts in randomly generated static networks composed by 200 nodes with a maximum radius set to 250 meters. They showed that there really exists an optimal radius for which the global energy consumption is minimal. *TR-LBOP* improves *LBOP* by about 10% with the use of this optimal radius, for the density of 50 and using a constant $c = 10^8$. This improvement becomes greater as c increases, while the overhead with *BIP* always stays under 50%. That is, *TR-LBOP* follows *BIP* on all ranges, while the overhead of *LBOP* becomes greater as c increases. The experimental optimal radius observed for $\alpha = 4, c = 10^8$ seems to be around 80 meters, which is near to the theoretical value of 100 meters (see Fig. 15), the small difference can be attributed to various border effects. The consideration of the non-zero value of the constant c leads a good improvement of *LBOP*, approaching the performances of *BIP*.

In an upcoming paper, we further explore this idea by using connected dominating sets in the topology control step [24]. This way, nodes that are not dominant can go into sleep mode and thus reduce the energy consumption, instead of being active (Nodes in *TR-LBOP* that enter a *NES* are active and consume some energy).

5 Energy efficient broadcasting with directional antennas

There exists another method to further improve energy savings when using smart antennas, that are able to make directional emissions. Recently, these antennas have been designed to allow the transmission of a packet from a given node in a particular direction, with signal being sent only inside an angle (or cone in 3-D) oriented in any desired direction. Omnidirectional emissions are then just special cases with an angle of 360°, consuming the full energy possible, as the smaller the angle is, the smaller the energy consumption will be. For this directional case, special protocols must be used to take this possibility into account and thus take advantage of it.

5.1 Centralized protocols

Wieselthier *et al.* proposed two extensions of *BIP* for directional antennas [47]. The first one is called *RB-BIP* (*Reduced Beam BIP*) and uses one-to-one communication model (with minimal angle) to join neighbors in the *BIP* tree. Because of its construction, the *BIP* spanning tree is exactly the same as the tree constructed by the *MST* algorithm, which is confirmed in experiments. The second improvement is named *D-BIP* (*Directional BIP*). Each node can send only one message, so they have to change the angle of the beam or increase their range to join more neighbors. The tree construction is different from *RB-BIP*, because the protocol has to decide, at each step, if it is better to extend the beam and/or the range of a node, or to add a new communication beam for a neighboring node. This decision is made with respect to the energy consumption of the two algorithms. Hence, the natural tendencies of *D-BIP* are to favor transmissions with large radii and beam angles and to avoid retransmissions by every node (this is especially valid if the constants C_1 and C_2 have a high value, see Equ. 3).

5.2 Localized protocols

As all these variants of *BIP* are still centralized, Cartigny *et al.* proposed an adaptive localized variant of *DRBOP* (*Directional RBOP*) [10] which takes advantage of both one-to-one and one-to-many schemes [12]. In fact, in a sparse network, it is easy to see that one-to-one communication model with narrow beams fits better than large beams. At contrary, in a dense network, one-to-many communication model fits better since it allows to cover several neighbors with a single beam. In order to fulfill the need of adaptive algorithm, the authors give a one-to-one broadcast protocol called *DLBOP* and a one-to-many broadcast protocol called *OM-DLBOP*.

The first one, *DLBOP* (*Directional LBOP*), is a variant of *DRBOP* where the *RNG* is replaced by the *LMST*. Hence, each node u sends to its *LMST*-neighbors v an unicast message, with a narrow beam of fixed angle β and a range $d(u, v)$. We can notice that *NES* is not applicable here since packets sent to a neighbor by a narrow beam are normally not received by other *LMST*-neighbors. However, a sending node can include in its message the list of neighbors it is supposed to send. Hence by increasing the size of packets, a neighbor elimination scheme can be achieved.

The energy consumption of the *DLBOP* protocol with directional antennas can be derived by summing the power consumption of one-to-one messages from each node. Because the degree of each node is approximately 2 for the *LMST* subgraph (including the local forwarder of the broadcast message) we can expect that each node will broadcast in average one unicast message. Let us denote by d_{lmst} the average distance between *LMST*-neighbors. The energy consumption of the *DLBOP* protocol for n nodes is approximately:

$$E_{DLBOP} = n \times e(\beta, d_{lmst}).$$

The one-to-many variant of *DLBOP*, denoted by *OM-DLBOP* (*One-to-Many Directed LMST Broadcast Oriented Protocol*), consists of sending a single variable angle beam instead of several narrow beams. A node which decides to retransmit the message (because of *LMST*-neighbor elimination scheme reason) uses a single beam with an appropriate angle which allows it to reach its non-covered *LMST*-neighbors. To increase energy savings, it can be useful to extend the range in order to avoid excessive retransmissions that can be expensive if constants C_1 or C_2 are not equal to zero. It is shown that for a given angle γ, there exists an optimal angle. These angles are given by Table 2.

We are now in position to describe *OM-DLBOP* algorithm. We choose to send beams with angle $4\pi/3$ which minimizes the overlap communication zone and provides a good coverage of the neighborhood as illustrated by Fig. 16. The angle is positioned symmetrically with respect to the line uv as shown in the same figure where v is the current sender and u the node which sends the broadcast message to v. We denote by $R_{opt}(4\pi/3)$ the function which computes the optimal radius, by taking into account the chosen angle

	$C_1 = C_2 = 0$	$C_1 \neq 0 \vee C_2 \neq 0$
$\alpha = 2$	constant No $R_{opt}(\gamma)$	monotone decreasing $R_{opt}(\gamma) = R_{max}$
$\alpha > 2$	monotone increasing $R_{opt}(\gamma) = 0$	minimal at $r(\gamma) = \sqrt[\alpha]{\frac{2C_1 + \frac{4\pi C_2}{\gamma}}{\alpha - 2}}$ $R_{opt}(\gamma) = min(r(\gamma), R_{max})$

Table 2: Behavior of total energy consumption function and optimal radius.

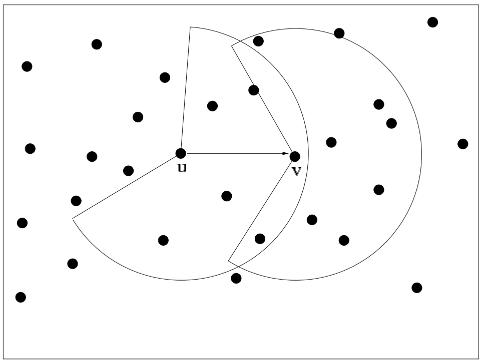


Figure 16: A *OM-DLBOP* broadcast.

$4\pi/3$. After applying *NES* restricted to *LMST*-neighbors, a node v which decides to retransmit computes its transmitting angle and range as follows:

- let A be the set of uncovered neighbors and $B \subseteq A$ the set of uncovered *LMST*-neighbors.

- The node u computes the set of nodes closer than $R_{opt}(4\pi/3)$:

$$A' = \{v \in A \mid d(u,v) \leq R_{opt}(4\pi/3)\}.$$

  The "goal" of u is to reach nodes of $C = A' \cup B$, *i.e.* nodes closer than $R_{opt}(4\pi/3)$ and *LMST*-neighbors. If $C_1 = C_2 = 0$, the optimal radius cannot be evaluated. In this case, we consider $R_{opt}(4\pi/3) = 0$. This implies that $A' = \emptyset$ and that the goal of the node is limited to its *LMST*-neighbors.

- The node calculates the angle θ needed to cover C and the distance d to the furthest node of C. If $\theta < \beta$ then set $\theta = \beta$. If C is empty, the retransmission is canceled.

- If $d > R_{opt}(\theta)$ then send θ-beam with d range. Otherwise, the node sets the range of θ-beam (without modifying the orientation) in order to reach all nodes of A closer than $R_{opt}(\theta)$ (thus the selected radius is generally somewhat lower than $R_{opt}(\theta)$).

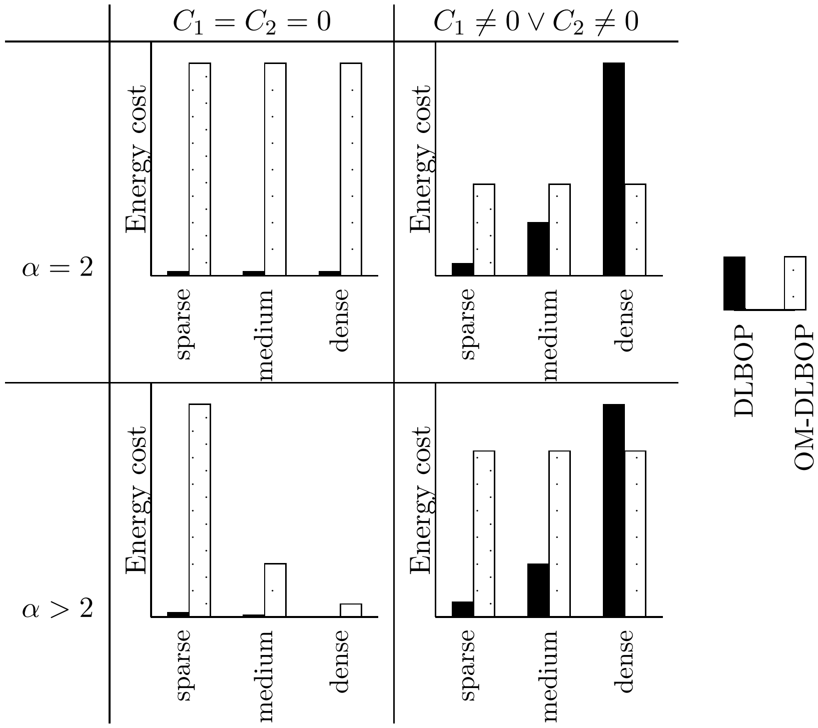


Figure 17: Behavior of one-to-one and one-to-many variants of DLBOP.

5.3 Adaptive Directed *LMST* Broadcast Oriented Protocol (*A-DLBOP*)

It seems that both approaches are valid. To illustrate this fact, Fig. 17 shows the behaviors of both protocols for sparse, medium and dense networks and for the different energy models. In this comparison, *OM-DLBOP* energy consumption is evaluated by considering an ideal $4\pi/3$ tessellation.

From this observation, we describe the *A-DLBOP* (*Adaptive Directed LMST Broadcast Oriented Protocol*) algorithm which combines one-to-one and one-to-many communication models [12]. Each node which receives the broadcast message starts a *NES* limited to its *LMST*-neighbors (for narrow beam transmissions, *NES* has limited effectiveness and we suppose that a transmitting node includes the *id* of nodes it targets in all its transmissions). At the end of the timeout period, the node has to choose between one-to-one or one-to-many communication models. For a given node u, the decision algorithm is the following one:

- Let A be the non-covered neighbors set and $B \subseteq A$ the non-covered $LMST$-neighbors set. We denote by A' the set of nodes belonging to A closer than $R_{opt}(4\pi/3)$. As previously, if $C_1 = C_2 = 0$ we consider that $R_{opt}(4\pi/3) = 0$. The "goal" of the node u is to cover the set $C = A' \cup B$. If the set C is empty, the retransmission is canceled.

- The communication model choice is made from a comparison of the energy consumption needed to cover C:

  One-to-one communication: in a flooding over the subset C with one-to-one communication model, each node retransmits the message to its non-covered $LMST$-neighbors. On average, each node has only one non-covered $LMST$-neighbor. Hence the energy consumption with one-to-one communication model using β-beams can be evaluated by:

  $$E_{1-to-1} = |C| \times e(\beta, d_{lmst}).$$

  The node u can estimate the average $LMST$ edge length d_{lmst} from the average distance between itself and its $LMST$-neighbors (it may also use more precise average distance in its local minimum spanning tree):

  $$d_{lmst} \simeq \frac{1}{|B|} \sum_{v \in B} d(u, v).$$

  One-to-many communication: let θ be the angle needed to cover C (if $\theta < \beta$ we consider that $\theta = \beta$) and d the distance between node u and the furthest node of C. The energy consumption of a single beam which covers C is:

  $$E_{1-to-many} = e(\theta, d).$$

- If $E_{1-to-1} < E_{1-to-many}$, then the node u decides to use the one-to-one communication model and sends a β-beam to each of its $LMST$-neighbors (nodes of B).

- Otherwise, the node u decides to use one-to-many communication model and sends a β-beam to cover nodes of C. If $d < R_{opt}(\theta)$, the range of the beam is increased in order to reach nodes of A closest than $R_{opt}(\theta)$.

To resume this process, each node makes its decision based on the comparison $|C|.e(\beta, d_{lmst}) < e(4\pi/3, d)$, where C is the number of nodes covered by a single $4\pi/3$ beam. Alternatively, but leading to a similar conclusion, each node may compare $k.e(\beta, d_{lmst}) < a.e(4\pi/3, R_{opt})$, where k is the number of nodes in the circle of radius R, and a is the ratio between the area of the circle of radius R and the $4\pi/3$ beam of radius R_{opt}. Since, $|C|$ is approximately equal to k/a, it is basically the same comparison.

Experimentations were done by simulating broadcasts in randomly generated networks of 500 nodes, a minimal angle beam of $\pi/9$ and a target radius varying from 10 meters to 250 meters. They showed that the conversion between the two models is beneficial, offering significant energy savings, for full range of densities of networks. The hybrid protocol *A-DLBOP* is able to take the best decision depending on its local density (its number of neighbors). Since each node locally independently chooses between two behaviors, it is possible that, in the same network for the same broadcasting task, different nodes make different choice between the two. The localized protocol *A-DLBOP* gives very good results compared with centralized *D-BIP* protocol. For instance, when $C_1 = C_2 = 0$ the energy overhead is about 30%. The additional spending for other energy model ($C_1 \neq 0$ or $C_2 \neq 0$) grows significantly with C_1 and C_2. For instance, with Rodoplu model [39] ($\alpha = 4$, $C_1 + C_2 = 10^8$), the energy overhead against *D-BIP* is about 500% but the energy reduction against blind flooding is about 95%. The interesting fact is that *A-DLBOP* always gives better results than *DLBOP* and *OM-DLBOP*. Hence, the protocol *A-DLBOP* is an adaptive broadcast protocol where decision is made locally by each node.

6 Conclusion

Broadcasting is an important task in ad hoc networks. In this chapter, we presented several broadcasting methods designed to guarantee delivery to all nodes connected to the source (providing the *MAC* layer is ideal), while maximizing energy savings. We have considered different assumptions and scenarios, depending on the available hardware (such as *GPS* receiver, radius adjustment option, and directional emissions). The techniques described here can also be used for solving similar problems. One of such problems is area coverage in sensor networks. Typical applications of sensor networks are regular reports such as temperature monitoring, where monitoring stations have to gather information from sensors. Monitoring center typically broadcasts its position and request to all the sensors in the network. To prolong network life, most sensors shall be placed into sleep mode. Active sensors should cover the monitoring area. It turns out that covering area can be done with similar methods as covering neighbors, as described in detail in [6]. The final step is to report events using reverse broadcast trees, as described in [5]. A solution based on energy efficient *MPR* method is given in [32]. We anticipate more research on the currently very active research problem of broadcasting in the near future.

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