Chapter 6
Broadcast in Ad Hoc Networks

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Abstract Broadcast is the process of sending a message from one node to all other nodes in an ad hoc network. It is a fundamental operation for communication in ad hoc networks as it allows for the update of network information and route discovery as well as other operations. The chapter presents a comprehensive review and analysis of existing localized solutions on broadcast, where only local knowledge is required. The techniques reviewed include optimized broadcast techniques, such as multipoint relay and dominating set-based broadcasting with fixed transmission radii, resource awareness, localized minimum energy broadcasting with adjustable transmission radii, and solutions for increasing reliability of broadcasting are also reviewed. Further, the chapter highlights the use of broadcast in route discovery and new approaches to route discovery based upon self-selecting search techniques as opposed to traditional broadcast approaches.

6.1 Introduction

6.1.1 Background

Broadcast forms the basis of all communications in ad hoc networks. The simplest form of broadcast in an ad hoc network is referred to as *blind flooding*. In blind flooding, a node transmits a packet, which is received by all neighboring nodes that are within the transmission range. Upon receiving a broadcast packet, each node determines if it has transmitted the packet before. If not, then the packet is retransmitted. This process allows for a broadcast packet to be disseminated throughout the ad hoc network. Blind flooding terminates when all nodes have received and transmitted the packet being broadcast at least

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once. As all nodes participate in the broadcast, blind flooding suffers from the *Broadcast Storm Problem* [38]. The broadcast storm problem states that, in a CSMA/CA network, blind flooding is extremely costly and may result in the following:

- *Redundant rebroadcasts* – occur when a node decides to rebroadcast a message to its neighbors; however, all neighbors have already received the message. Thus the transmission is redundant and useless.
- *Medium contention* – occurs when neighboring nodes receive a broadcast message and decide to rebroadcast the message. These nodes must contend with each other for the broadcast medium.
- *Packet collision* – because of the lack of the back-off mechanism, RTS/CTS dialog, and the absence of CD, collisions are more likely to occur and result in lost or corrupted messages.

Figure 6.1 shows redundant broadcast and contention of the broadcast storm problem when performing a blind flood. In Fig. 6.1, node *A* initiates a broadcast of a message and the message is received by nodes *B* and *C*. According to blind flooding, *B* and *C* rebroadcast the message if they had not broadcasted it before. Therefore, *D* will receive the message and also rebroadcast the message if there is no collision. It may cause the following problems:

- Since node *A* is within the transmission range of nodes *B* and *C*, it will receive two redundant copies of the message from nodes *B* and *C*. This is also the case with nodes *B* and *C*, which receive the message from node *D* and from each other.
- Nodes *B* and *C* may contend for the broadcast medium in the shadow area as shown in Fig. 6.1. If there are more nodes in the shadow area, there will be an increase in contention for the broadcast medium.

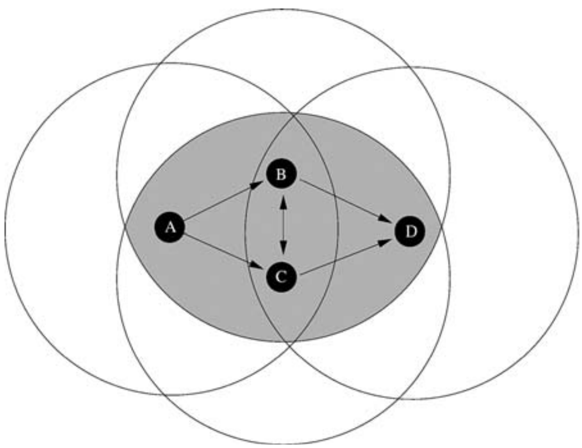

Fig. 6.1 Broadcast storm problem

- If nodes *B* and *C* broadcast at approximately the same time, there is a possibility of a packet collision at node *D*. Even if nodes *B* and *C* broadcast the message at a different time, node *D* will receive a total of two broadcast messages (one each from nodes *B* and *C*).

From Fig. 6.1 only two rebroadcasts (nodes *A* and *B* or nodes *A* and *C*) are actually necessary for all nodes to receive the broadcast from node *A*.

6.1.2 Overview of the Chapter

There exists significant literature describing various approaches to alleviate the broadcast storm problem. These approaches are *localized* or *globalized* methods, depending upon the degree of neighbor topology information, which is required to make broadcast decisions. Globalized approaches are centralized in nature. They require global topology information and attempt to determine an optimal, in terms of energy efficiency, broadcast tree. The computing of such optimal broadcast trees is NP-Hard [33].

However, given the dynamic nature of ad hoc networks, a centralized approach is neither desirable nor feasible as the cost of obtaining global topology information and maintaining the broadcast tree is restrictive in terms of overhead. Localized approaches are distributed in nature and require only localized neighbor topology information. Compared with globalized approaches, localized approaches are able to adapt to the topology change in ad hoc networks. Thus localized approaches are more appropriate to be applied in ad hoc network environments and are the focus of this chapter.

This chapter is organized as follows:

Section 6.2 describes and analyses various approaches of optimized broadcast methods that utilize a fixed transmission radius. These approaches include Multipoint Relay (MPR), Connected Dominating Sets (CDS), and Active/Passive Clustering. Given the resource constrained nature of ad hoc networks, the section also describes a novel resource-aware approach that accounts for a node's resource constraints (such as battery power) and potential device or user constraints.

Mechanisms in Section 6.2 are optimized to alleviate the broadcast storm problem by reducing the number of redundant rebroadcasts. This is achieved by limiting the number of participating nodes. These approaches do not scale well as their performance is degraded when node density increases. Section 6.3 describes the optimized graph theoretic broadcast approaches, which are based upon minimum spanning tree (MST) and relative neighborhood graphs (RNG). MST and RNG utilize radio transmission power control to limit the transmission radius, thereby significantly reducing energy consumption and alleviating the broadcast storm problem.

Optimized broadcast mechanisms alleviate the broadcast storm problem by reducing redundant broadcasts or varying transmission power. However, the very nature of blind flooding and the large number of redundant transmissions is able to achieve higher reliability than optimized broadcast. It has been shown in literature that the reliability of optimized broadcast is drastically affected by background traffic when compared to the blind flooding. Section 6.4 describes new approaches that address reliability issues while providing optimized broadcasting.

Section 6.5 describes the application of broadcast in many reactive and proactive ad hoc routing protocols. The section explores current research that utilizes self-selection as the basis of a search strategy to enhance reactive route discovery. We conclude the chapter in Section 6.6.

6.2 Optimized Broadcast with Fixed Radius

This section explores the optimized broadcast mechanisms that utilize a fixed transmission range and focus on the reduction of unnecessary rebroadcasts, which lead to the broadcast storm problem.

6.2.1 Heuristic-Based Broadcasting

Heuristic-based broadcasting methods require careful selection of parameters and thresholds, which are closely related to ad hoc network environments. Their performance is highly dependent on the selected parameters and thresholds in the heuristic.

Ni et al. [38] and Tseng et al. [56] proposed several heuristics on broadcast:

- *Counter-based* – the decision of rebroadcast is based upon a threshold value for the number of duplicate packets received by the broadcasting node. If the number of duplicate packets is less than the threshold value, then the node will rebroadcast. Otherwise, it will not rebroadcast. An expected additional coverage function may be defined, which shows that the more times a host has heard the same broadcast packet, the less additional coverage the host contributes if it rebroadcasts the packet.
- *Distance/location-based* – the heuristic may involve distance in a relative sense – physical distance between nodes or the transmission power required. Each node is equipped with a GPS device or is able to determine signal strength of a neighboring node. Given the distance or location of broadcasting nodes, it is possible to calculate the expected additional coverage (in terms of area) a node may contribute by rebroadcast.
- *Probability-based* – the decision of rebroadcast is based upon a random probability. This probability may be as simple as flipping a coin or it may be more complex involving probabilities that include parameters such as node density, duplicate packets received, battery power, or a node's participation/benevolence within the network.

6.2.2 Neighbor Coverage–Based Broadcast

In Neighbor Coverage–Based (NCB) broadcast, nodes periodically or dynamically broadcast beacon messages to advertise their own existence and also discover the existence of neighboring nodes within the transmission range (one hop). Beacon messages may typically contain the broadcasting node's address and the neighboring nodes that the node may be aware of. Thus, the information of neighbor topology within two hops can to be obtained. The use of neighbor information allows the link state topology of nodes to be determined. It is also useful in situations where GPS may not work, such as indoor applications. The exchange of beacon messages allows for attaching additional information about neighboring nodes. The additional information may include a node's remaining battery power, any user-based constraint, physical coordinates acquired through a GPS device, signal-to-noise ratio (SNR) measurements (acquired from the MAC layer), and possible device characteristics such as maximum broadcast power.

However, the use of beacons for neighbor discovery may suffer from various problems: (i) Consider a n-node degree network: a node wishing to discover its local two-hop topology must first wait for each of its n neighbors to receive beacons from their neighbors. Thus, at least n^2 messages are required to discover two-hop topology; (ii) Nodes do not transmit beacons simultaneously. Thus multiple exchanges of beacons over an extended period of time may be necessary to discover two-hop topology; (iii) As beacons are sent using broadcast packets, there is a possibility of packet collisions resulting in loss of the beacons. It affects the accuracy of two-hop knowledge; (iv) Node mobility may result in link state errors; (v) Exchange of link state information will increase the packet size of the beacon, which may increase the probability of collision of broadcast packets; (vi) Frequent movement of nodes may require more frequent exchange of beacons, thus introducing additional overhead and packet collisions. Therefore, neighbor discovery over two or more hops using beacon messages becomes less reliable.

The simplest NCB mechanisms are "Self-Pruning" [32] and "Neighbor Coverage" [56]. Both mechanisms are equivalent. Two neighbor sets are maintained at each node. Suppose node i broadcasts a message to node j. Set N_i and N_j denote the neighbors of node i and j, respectively. When node j receives a broadcast packet from a node i for the first time, it determines its coverage set as follows:

$$C_j = N_j - N_i - \{i\}. \tag{1.1}$$

The resulting coverage set C_j is the set of neighbors of node j, which are not covered by node i yet. This keeps track of pending hosts in j's neighborhood, which have not received a direct broadcast from node i as they are outside node i's broadcast range. Node j does not rebroadcast the packet if C_j is an empty set.

An empty set implies that all neighbors of node j are also neighbors of node i. This calculation is performed on each node that receives a broadcast packet prior to rebroadcasting.

The "Scalable Broadcast Algorithm" (SBA) [43] utilizes two-hop neighbor knowledge and a broadcast delay timer to determine whether or not to rebroadcast. Upon receiving a broadcast message from node i, node j utilizes Equation 1.1 to determine if it has any neighbors that are not covered by node i. If the result is an empty set, then the node will not rebroadcast. Otherwise, node j will schedule a broadcast with a specific delay. The delay is calculated based on the node j's degree (D_j) and its neighbor's maximum node degree ($D_{N\max}$) as shown in Equation 1.2. It implies that nodes with the maximum number of neighbors have higher priority to broadcast than those nodes with less neighbors.

$$T_{\text{delay}} = \frac{D_{N\max}}{D_j}. \tag{1.2}$$

"Dominant pruning" [32] makes use of two-hop neighbor knowledge and a greedy set cover algorithm to alleviate the broadcast storm problem. Unlike previous mechanisms, the sender in the dominant pruning specifies a set of nodes in a forward list (attached to the broadcast packet), which are responsible for rebroadcasting the packet so that the packet reaches all nodes within two hops. Finding the minimum forwarding list is equivalent to the minimum set cover problem, which is NP-complete. In [34], dominant pruning is analyzed and two new algorithms, "Total Dominant Pruning" and "Partial Dominant Pruning" are proposed. The algorithms utilize two-hop neighbor knowledge to achieve further reductions in redundant broadcasts.

"Multipoint Relaying" (MPR) [47] is the broadcast scheme in which a sending node selects adjacent nodes as relay nodes to complete the broadcast. The IDs of selected adjacent nodes are appended to the packet as a forward list. An adjacent node that is requested to relay the packet must determine its own forward list. This process is iterated until the broadcast is completed. MPR makes use of two-hop neighbor knowledge and is employed in the OLSR [21] routing protocol for the optimized dissemination of link state information. MPR aims to reduce the number of redundant retransmissions during broadcast by restricting the number of retransmitters to a small set of relay nodes. The method proposed in [47] is based on a "greedy set cover" heuristic that selects the minimal subset of neighbors of a given node A, which will "cover" all two-hop neighbors of node A. A node is called "covered by node A" if it receives (directly or via retransmissions by other nodes) a message originating from A. Relay nodes of node A are A's one-hop neighbors that cover all two-hop neighbors of node A. That is, after all relay nodes of node A retransmit the message, all two hop neighbors of node A will receive the message. The goal is to minimize the number of relay nodes of node A. The proposed greedy set cover heuristic is as follows:

1. Find all two-hop neighbors reachable from only a single one-hop neighbor. Assign the one-hop neighbors as MPRs.
2. Determine the resultant cover set – the set of two-hop neighbors that will receive the packet from the current MPR set.
3. From the remaining one-hop neighbors not in the MPR set, find the ones that cover the most two-hop neighbors not in the cover set.
4. Repeat from Step 2 until all two-hop neighbors are covered.

Figure 6.2 shows the process of selecting multipoint relays in MPR. Nodes *B*, *D*, and *E* are one-hop neighbors of node *A*. Nodes *C*, *G*, and *F* are two-hop neighbors of node *A*. A broadcast is initiated by node *A*. According to the proposed MPR heuristic Step 1, node *B* is selected as a MPR as node *C* may only be reached by node *B*. The remaining nodes *G* and *F* are similarly covered by node *D* that is then added to the MPR list (node *E* covers only node *F*, not node *G*). Node *E* is not added to the MPR list as its neighboring node *F* is already covered by node *D*.

The mechanisms described so far rely upon explicit reasoning to determine whether or not to rebroadcast. In [49], the Lightweight and Efficient Network-Wide Broadcast (LENWB) mechanism is proposed. LENWB utilizes implicit reasoning based upon the information provided by neighboring nodes to implicitly determine which nodes received a broadcast packet. LENWB utilizes two-hop neighbor knowledge to determine the node degree of all neighboring nodes. Each neighboring node is assigned a priority that is proportional to its node degree.

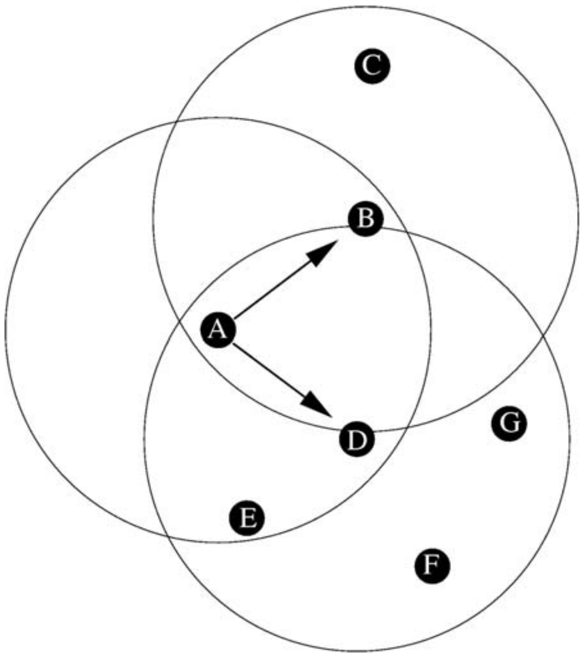

Fig. 6.2 Multipoint relay selection

A node selects its neighboring nodes with higher priority to perform rebroadcasts. Thus, LENWB can proactively determine which neighboring nodes will rebroadcast and also which neighboring nodes will receive the broadcast. If the node determines that some of its neighbors will not receive a broadcast, then it rebroadcasts the message.

6.2.3 Dominating Sets–Based Broadcasting

In [58, 59], the authors describe a simple and efficient distributed algorithm for determining a connected dominating set (CDS). CDS may be used to limit the broadcast storm problem, by limiting broadcasting nodes to those gateway nodes. A dominating set is the set that any node in the network either belongs to the set or is the direct neighbor of some node in the set. The authors define a node i as an "intermediate" node if there exist two neighbors j and k of i, which are not direct neighbors of each other. Two rules are applied:

- *Rule 1* – Given two intermediate neighboring nodes u and v. If neighbors of u are also neighbors of v and the node identifier of node u is less than the node identifier of node v, then node u is not an "inter-gateway" node. Therefore, node u is covered by node v.
- *Rule 2* – Assume three inter-gateway nodes u, v, and w with shared neighbors. If the neighbors of node u are contained within the neighbors of nodes v and w (that are also neighbors of each other) and node u's identifier is less than both node v and w, then node u may be removed from the gateway set (CDS).

Stojmenovic et al. [52] propose a method that replaces the use of node identifier's as a key in Rule 1 and Rule 2 with a node's neighbor degree and its (x,y) coordinates as additional keys. The neighbor degree is defined as a node's total number of neighboring nodes. The use of neighbor degree allows for a significant reduction in size of the dominating set. Nodes that belong to the dominating set are referred to as "internal" nodes. Broadcasting nodes are limited to those nodes selected as internal nodes. Nodes that have unique neighbors as with MPR are always selected as internal nodes.

6.2.4 Combining Multipoint Relay and Dominating Set–Based Broadcasting

The MPR algorithm is source-dependent, requiring that a relay node be aware of the preceding broadcasting node. In [1], a localized algorithm is proposed to make the relay selection source-independent. The algorithm also improves upon MPR by determining a smaller relay set, yet still providing equivalent performance to MPR. The authors proposed to combine MPR and dominating set approaches. Each node computes its forwarding neighbors set and transmits this to its neighbors. Each node then determines whether it belongs to the "MPR-dominating set", if:

- it has the smallest ID in its neighborhood;
- the node is a forwarding neighbor of the neighbor with the smallest ID.

In [57], the authors extend this work to further reduce the size of the relay set without introducing additional cost. The definition of the first condition is enhanced as follows: It has the smallest ID in its neighborhood and it has two unconnected neighbors, or the node is a forwarding neighbor of the neighbor with the smallest ID. In [57], forward node selection is as follows: Free neighbors do not need to be covered (u is a free neighbor of v, if v is not the smallest ID neighbor of u) at all, if a two-hop neighbor is covered by only a single one-hop neighbor, then that neighbor is taken immediately, then after that continue with the explained greedy set coverage heuristic.

6.2.5 Hexagonal and Dominating Set–Based Broadcasting

In [42], a broadcast protocol based on the hexagonal tiling of a plane is proposed, with transmission radius as the edge length of hexagons. The source chooses six nodes, which are closest to points that best approximate a regular hexagon, for retransmitting the message. Each designated node continues the process in a similar manner. The reliability (the broadcast message reaches all nodes) is not proven, but it is possible to provide examples showing that the opposite can be constructed. As observed in [23], the protocol may repeat broadcasting if neighbors do not agree on the choice of node near the common ideal point. Work in [23] introduced a stopping rule to prevent repeated broadcast and applied this type of broadcast as the basis of route discovery.

6.2.6 Cluster-Based Broadcasting

Clustering [15] is the process of grouping nodes together into clusters (groups) as shown in Fig. 6.3. A representative of each cluster is called the *clusterhead* (nodes B and D). A cluster encompasses all nodes within a clusterhead's transmission range. Nodes that belong to a cluster, but are not the clusterhead, are called *ordinary* nodes. Often nodes may belong to more than one cluster. These nodes are called *gateway* nodes (node C). Only clusterhead nodes and gateway nodes are responsible for propagating messages. The process of forming clusters may be either active or passive. In Fig. 6.3, ordinary node A broadcasts a message. The message is received by node B and is relayed to all nodes within node B's broadcast range. Node C is a gateway node that receives the message from node B and rebroadcasts the message. Clusterhead node D receives the message and rebroadcasts it to its neighboring nodes. The

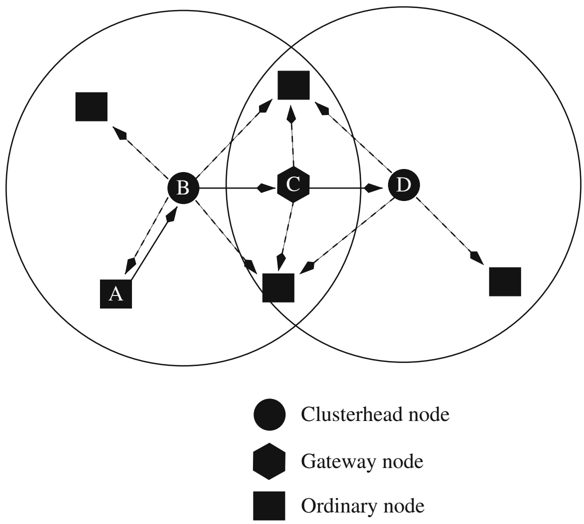

Fig. 6.3 Example of a cluster-based flood initiated from node A with only clusterhead and gateway nodes rebroadcasting

directed solid lines show the propagation of the message among those nodes that are allowed to rebroadcast. Dashed directed lines show the propagation of the message from the clusterheads and the gateway nodes to ordinary nodes.

In *active clustering*, nodes must cooperate in order to elect clusterheads. This is achieved through periodic exchange of control information. The formation of clusters in active clustering is independent of the background data traffic. The selection of a clusterhead may be based upon Lowest ID algorithm or Highest ID algorithm [29]. In [44] and [45], clustering is used as an optimized flooding mechanism, whereby only clusterheads and gateways rebroadcast messages. Additionally, the clusterheads in the mechanism ensure reliable delivery of the message to those nodes belonging to their cluster. In [34], a mechanism that builds a cluster-based backbone for the dissemination of information is proposed. They propose the creation of a static and a dynamic backbone. The static backbone is created using a source-independent connected dominating set. The dynamic backbone is created using a source-dependent connected dominating set.

In *passive clustering* [61, 62], cluster formation is dependent on background data traffic. Therefore, passive clustering will not form clusters until there is background traffic. This is because, in passive clustering, the flow of data traffic is used to propagate cluster control information and collect neighbor information through promiscuous packet reception. Promiscuous packet reception is achieved by allowing the MAC layer to pass all received packets up the TCP/IP stack irrespective of MAC address. Passive clustering is beneficial in that it utilizes the existing data traffic to form clusters. However, without existing data traffic, it is unable to form clusters and provide the benefits of an optimized flood. Active clustering requires that cluster control information be exchanged between nodes and clusterheads. Thus, it requires more overhead than passive clustering or non-clustered flooding mechanisms for the formation of clusters. However, unlike passive clustering, there is no delay involved as it does not require background traffic.

6.2.7 *Resource-Aware Broadcasting*

Resource-aware broadcasting is the process of disseminating information in such a way that mechanisms are aware of and utilize available resources within the network in an efficient and aware manner. It makes sense for mechanisms to strive to extend lifetime of devices in the network. This can be achieved through optimization in utilizing devices that are most suitable based upon their resources and constraints. Optimized broadcast mechanisms are proposed to alleviate the broadcast storm problem. However, they do not address the need for “Resource Awareness”. These two requirements may possibly oppose each other, as an optimal broadcast is not necessarily the most efficient resource-aware broadcast.

In *Activity Scheduling* [54], nodes must actively determine if they are in an active or passive state in order that the network remains connected and the lifetime of both the network and the nodes are maximized. Nodes in a passive state (sleeping) do not consume constant energy. They are not involved in the reception of packets for which they are not specified receivers. In [51], a topology maintenance scheme is proposed with the aim of extending lifetime of the network while preserving network connectivity. A node is either active or has an active neighboring node. Thus, flooding (and routing) activities are restricted to those active nodes. The active nodes create a connected dominating set. Nodes update their activity status periodically during short transition periods when all nodes are active and packets to passive nodes are delivered. It is possible for nodes that have greater remaining energy remain active longer than the nodes with less remaining energy – which may enter a passive state more often and on awakening collect packets from their neighbors, which could not be received in the passive state. In [51], the authors further propose metrics for determining activity status, which are based on the combinations of node-degree and remaining battery power.

In [57], the author extends MPR flooding to reduce size of the relay node set without introducing additional overhead. The process of selecting relay nodes may also be done in a resource-aware manner, which accounts for the remaining battery power of nodes. This mechanism still utilizes “Step 1” of the MPR algorithm, which is to select those nodes with unique neighbors. However, the majority of relay nodes that could be selected to relay a message are selected only because they have unique neighbors. Thus the selection of remaining relay nodes based solely on their resources (battery power) is limited in its results, as these relay nodes only constitute a fraction of all relays selected.

$$U_{\mathrm{f}} = BU_{\mathrm{p}}U_{\mathrm{n}}, \tag{1.3}$$

$$U_{\mathrm{p}}(i) = \frac{1}{1 + e^{(-P_i + S)}}, \tag{1.4}$$

$$U_{\mathrm{n}}(i) = \frac{\text{unallocated two hop neighbours of node } i}{\text{total two hop neighbours of node } i}. \tag{1.5}$$

Lipman et al. [27] describe a distributed optimized broadcast mechanism for ad hoc networks called Utility Based Flooding (UBF). Unlike the existing optimized broadcast mechanisms, UBF is fully resource-aware. UBF selects relay nodes based solely on a forwarding utility U_{f} (Equation 1.3). The utility U_{p} (Equation 1.4) is a sigmoid function where P is the remaining energy at a node while $s = \mathrm{MaxEnergy}/2$ is half the maximal energy. U_{n} (Equation 1.5) is the ratio of unallocated (uncovered) local two-hop neighbors to the total number of two-hop neighbors. The significant point in UBF is that the selection of nodes with unique neighbors is not a priority as in MPR or [57]. In this way the coverage provided by those best nodes (in terms of resources) is accounted for irrespective of unique neighbors as is done in MPR. U_{n} increases the utility of possible relay nodes that may have unique neighbor. However, if a node with a unique neighbor is not suitable because of constraints or low resources, then its utility will remain low such that it may only be selected after all other possible relays are selected. The benevolence (B) is intended to capture or represent any constraints imposed upon a device. A user may allow a device attached to a reliable power source to fully participate in network activities. However, if the device is mobile and the battery power drops below a specified threshold, the user may not wish the device to participate. Existing broadcasting mechanisms do not account for this type of behavior. Thus their performance will be degraded in such a network as they may select restricted nodes as relay nodes that will not rebroadcast messages. UBF is shown to significantly improve broadcast reachability over successive broadcasts in a resource-constrained environment while not adversely affecting performance. Moreover, UBF extends the lifetime of both nodes participating in the ad hoc network and lifetime of the network itself.

6.2.8 Distributed and Efficient Flooding

To solve the broadcast storm problem, Liu et al. [31] propose a distributed and efficient flooding scheme. The authors first study the sufficient and necessary condition of 100% deliverability for flooding schemes that are based on only one-hop neighbor information. It proves that a one-hop flooding scheme achieves 100% deliverability if and only if for each node s the union of coverage disks of s's neighbors is fully covered by the forwarding node set determined by s. The proposed flooding algorithm achieves the local optimality in two senses: 1) the number of forwarding nodes in each step is the minimal; 2) the time complexity for computing forwarding nodes is the lowest, which is $O(n \log n)$, where n is the number of neighbors of a node.

The basic idea of the flooding scheme is as follows. When a node (called the source) has a message to be flooded out, it computes a subset of its neighbors as forwarding nodes and attaches the list of the forwarding nodes to the message. Then it transmits (broadcasts) the message out. According to the sufficient and necessary condition of 100% deliverability, for each node s, the forwarding nodes computed by s, denoted by $F(s)$, should fully cover the union of coverage disks of s's neighbors. After that, every node in the network does the same as follows. Upon receiving a flooding message, if the message has been received before, it is discarded; otherwise the message is delivered to the application layer, and the receiver checks if itself is in the forwarding list. If yes, it computes the next hop forwarding nodes among its neighbors and transmits the message out in the same way as the source. The message will eventually reach all the nodes.

To minimize the unnecessary rebroadcast messages, the set of forwarding nodes should be minimized. Liu et al. proposed an efficient method to compute the minimum forwarding set. For each node s, the strategy of this method is to compute the neighbor's boundary of s, and thus the nodes that contribute to this boundary are the nodes in $F(s)$. The pair-wise boundary merging method is adopted to compute the boundary efficiently. Initially, each node is arbitrarily paired with another node to merge their coverage boundaries. Then, the merged pair's boundary is further merged with another pair's boundary. This merge operation is repeated until eventually there is only one big merged boundary, which is the neighbor's boundary of s. The minimal $F(s)$ consists of the nodes that contribute to this boundary. In the flooding operation, each node computes its minimum forwarding node set based on its one-hop information. After a flooding message is initiated from a source node, only the nodes in the forwarding node set will relay the message. It greatly reduces the unnecessary rebroadcast messages in the network while guaranteeing 100% delivery.

6.3 Variable Radius Optimized Broadcasting

In variable radius optimized broadcasting, nodes utilize transmission power control when broadcasting packets. The use of transmission power control allows for the isolation of broadcasts through reduction of transmission range and is beneficial for the following reasons. The required power for a transmission distance of d between two nodes is proportional to d^{λ}. Typically λ takes a value between 2 and 6, depending on the characteristics of the communications medium [60]. Isolating a broadcast increases the probability of only necessary nodes hearing a broadcast. This helps to both reduce duplicate packet reception and the power consumed with packet reception at receivers. Limiting the nodes that will hear a broadcast reduces medium contention between nodes, increases medium utilization, and reduces the probability of packet collisions. The use of transmission power control may result in one high-power transmission being replaced with two or more low-power transmissions. A common analogy would be, "In a room full of people, it would be better for people to whisper, rather than yell at one another".

Optimized flooding mechanisms that utilize transmission power control require a node's location coordinates in order to determine the required transmission power. These coordinates may be obtained via a positioning system like GPS and shared via periodic exchange of beacon messages. If a positioning system is not available, distances may be determined through received signal strength of beacon messages.

6.3.1 Relative Neighborhood Graph

The Relative Neighborhood Graph (RNG) [55] shown in Fig. 6.5 is formed when two nodes are connected with an edge if their *lune* contains no other nodes of the graph. The lune of two nodes u and v, shown in Fig. 6.4 (in gray), is defined as the intersection of two spheres of radius $d(u,v)$, one centered at node u and the other at node v. Use of a localized RNG was first proposed in [7] as a topology control algorithm to minimize node degrees, hop diameter, and maximum transmission range and ensure connectivity. The resulting RNG graph is the same irrespective of whether it is calculated in a distributed or centralized manner.

In [11], the authors propose a distributed flooding protocol based upon the RNG called RNG Relay Subset (RRS). RRS allows for self-selection of forwarding neighbors. In RRS a node v will select itself as a relay for a node u if and only if node v is also neighbor of node u. Node v must also have a RNG neighbor that is not covered by node u. RRS alleviates the broadcast storm problem by reducing the transmission range of a broadcasting node to include

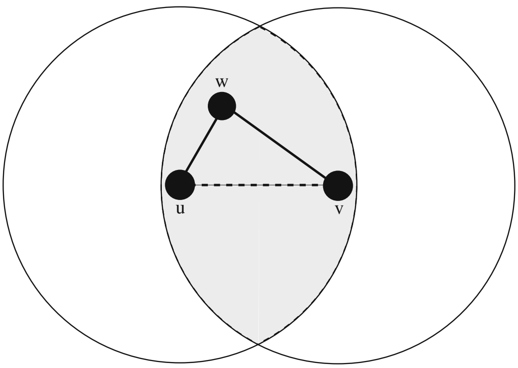

Fig. 6.4 Formation of relative neighborhood graph using a lune

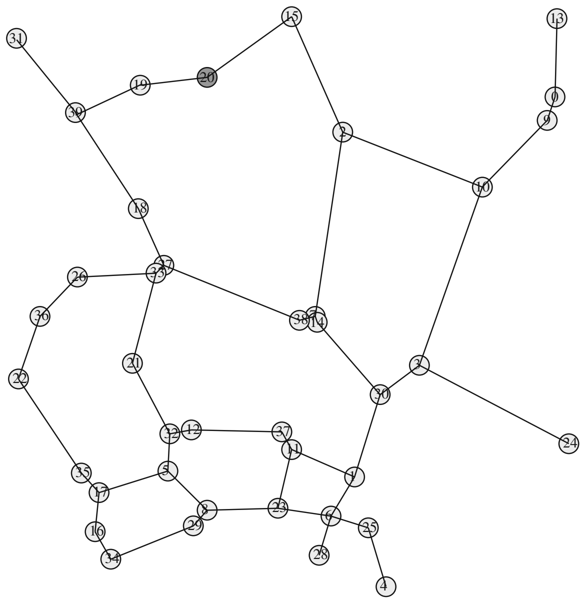

Fig. 6.5 Relative neighborhood graph

only those RNG neighbors that must receive the broadcast, thereby ensuring the flood propagates. The use of self-selection by nodes using RRS allows nodes to determine if they need to rebroadcast, without the need for additional information attached to the broadcast packet.

6.3.2 Minimum Spanning Tree Graph

The Minimum Spanning Tree (MST) [55] graph, as shown in Fig. 6.6, is a connected graph (path of edges between any two vertices) that uses the minimum sum of edge weight. This results in a graph with one less edge than the number of vertices. The MST has traditionally been used in networks for determining broadcast trees using global topology information. The MST is a subgraph of RNG and may be computed from the RNG by removing edges that create a cycle in the graph. This results in the formation of a tree or directed acyclic graph from all nodes back to the broadcasting node. Thus the MST generates a more optimal broadcast path than RNG, but suffers as there is no fault tolerance in the resulting graph [7]. Fault tolerance refers to the number of alternative paths a message may travel toward a node, thus improving the probability of delivery.

Lipman et al. [26] and Cartigny et al. [12] proposed to apply the MST algorithm in a distributed manner to improve the performance of flooding in ad hoc networks. In the localized MST approach, the topology available to the MST algorithm is restricted to one hop, yet still allows for an optimal broadcast set of nodes with minimal transmission range to be determined as with the

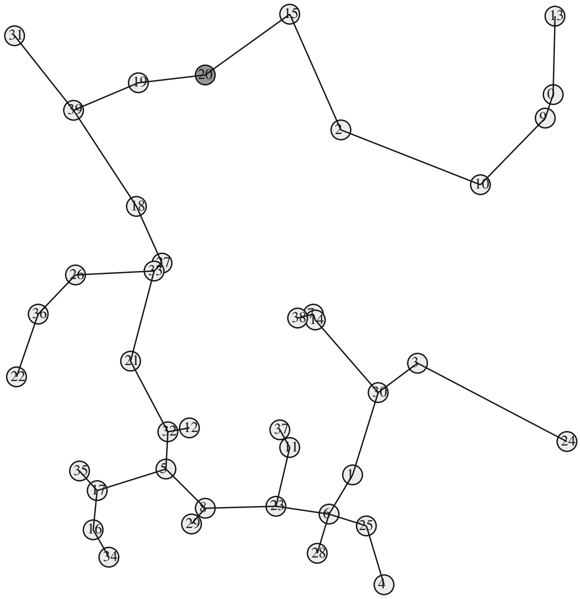

Fig. 6.6 Centralized minimum spanning tree

centralized approach within that one hop. The resulting localized MST graph does not exhibit the tree-like structure of the centralized MST with global topology knowledge. It can be seen by comparing Figs. 6.5, 6.6, and 6.7 that MST $\subseteq$ Localized MST $\subseteq$ RNG as described in [30]. Thus many of the benefits of MST are maintained with the addition of fault tolerance not found in the centralized approach.

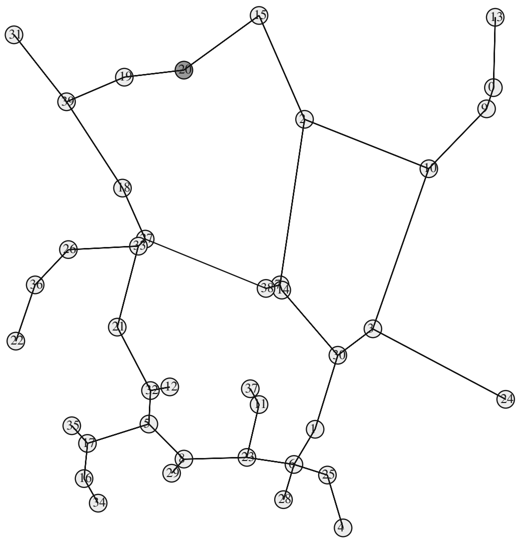

Fig. 6.7 Localized minimum spanning tree

6.3.3 Determining Common Transmission Radius and Constructing MST

To maintain network connectivity in an ad hoc network, the minimum transmission range R that may be utilized by nodes is equal to the longest edge in the minimum spanning tree [40]. Existing algorithms for determining R require globalized network knowledge or use distributed approaches that are based upon straightforward adaptations of centralized algorithms. Ovalle et al. [39] propose to use the longest edge as determined by localized *MST (LMST)* to approximate R. This is achieved by using a wave propagation quazi-localized algorithm, which allows nodes to make decisions based on both local knowledge and additional information obtained by wave propagation. Each node maintains a record of the longest edge it knows so far (initially its own longest edge in its *LMST)*. In each round, each node receiving a larger edge in the previous round will broadcast its new longest edge. At the end, all nodes will receive the same longest edge, which is then used as the transmission radius. Thus, the wave propagation allows for the longest R to be determined locally by all nodes and disseminated globally. It was observed that, although *LMST* has less than 5% additional edges than *MST,* the edges tend to be longer, hence the longest *LMST* edge selected as transmission radius may double the energy consumption with respect to selecting the longest *MST* edge.

Furthermore, Ovalle et al. [39] propose a scheme for converting the distributed *LMST* graph into the equivalent centralized *MST* graph. They first prove that *MST* is a subset of *LMST*. The conversion is achieved through a two-step iteration that traverses and eliminates dangling (tree) edges and breaks loops found in *LMST* that differentiate it from the *MST*. The process terminates at a node (the network leader), which through the two-step process has learned the longest *MST* and *LMST* edges. The value of the longest *MST* edge may then be broadcast to other nodes in the ad hoc network. Additionally, a simple algorithm is proposed, which allows for the determined *MST* to be updated if a node is added or deleted.

6.3.4 RNG- and LMST-Based Broadcasting

Cartigny et al. [12] propose the use of RNG and LMST as the basis of a localized minimum energy broadcast protocol. Lipman et al., [26] also applied LMST to describe a minimum energy-broadcasting scheme. In this protocol, each node will apply neighbor elimination scheme after receiving the first copy of a message. When timeout expires, the node will not retransmit packet if all its RNG (or LMST) neighbors are eliminated. Otherwise, the transmission radius is selected to be the distance to the furthest RNG (or LMST) neighbor that is not eliminated.

Work in [18] showed that, if $c>0$ in the power energy consumption model $d^{\lambda}+c$, the algorithm may produce energy-inefficient solution (compared to existing globalized protocols). The reason is that, for dense networks, the protocol tends to select short transmission radius. Therefore, many nodes need to retransmit the message. However, each of these nodes spends constant amount c of energy at least, which can accumulate. It may be better, for dense networks, to apply a minimal "target" transmission radius, which can be derived by considering an ideal hexagonal network and the radius that minimizes the two energy consumption terms in the expression. For $c>0$ and $\lambda>2$, the target radius, found theoretically, is $[2c/(\lambda-2)]^{1/\lambda}$. The transmission radius computed by the above procedure is then increased to that target radius, so that a number of nodes are covered with a single transmission.

Work in [9] considered the impact of energy needed to overhear transmissions in dense networks on the construction of minimum energy broadcast trees. In effect, they consider the power energy consumption model $d^{\lambda}+c$, with three values of c: $c1=0$ when only transmitting energy is considered, $c2>0$ when electronic cost of transmission is also considered, and $c3>c2$ when also electronic cost of intended receiver and nodes overhearing transmission are added. They conclude that minimum energy tree becomes "bushier" with increasing c value. It corresponds to the observations made by [18] about the choice of target radius $[2c/(\lambda-2)]^{1/\lambda}$, with consequence of reducing the number of transmitting nodes when c increases.

6.3.5 Neighbor-Aware Adaptive Power Broadcasting

Lipman et al. [28] describe the following efficient broadcast mechanism: Upon receiving a broadcast message from a node, say h, each node, say 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 (which 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. A node i may decide to perform local optimization whereby it determines a reduced set of its closest neighbors that still provide coverage of its remaining further neighbors. Thus node i may adapt the transmission power (limiting the transmission range) to include only those closest neighbors.

6.3.6 Incremental Power Broadcasting

In ad hoc networks, the radios installed in nodes generally use omni directional antennae. When a node transmits a message with a given transmission power, each node with the transmission range will receive the message. This characteristic of broadcast radio transmission is referred to as the *wireless multicast advantage* [60]. To take advantage of this characteristic, they proposed the *Broadcast Incremental Power* (BIP) protocol. BIP constructs an efficient broadcasting tree from a source node to all other nodes in the ad hoc network while considering the multicast advantage. Although BIP is energy-efficient, it requires global knowledge of the ad hoc network topology, which is counterproductive as this would then introduce significantly more overhead to acquire first and thus reduces the energy efficiency. To resolve this global knowledge problem, some distributed versions have been proposed. However, these distributed extensions usually result in significant message exchange and overhead to gather topology information, and hence also suffer from energy efficiency issues. In [17], the authors propose an incremental localized protocol that locally applies the BIP heuristic method. Given an initial connected graph, it enables a node to broadcast a message with high energy efficiency. The localized protocol allows each node to calculate its own BIP within its k-hop neighborhood based on prior knowledge from the preceding node. The localized tree is then forwarded to the next nodes with the broadcast packet. In this way, the global broadcasting structure is incrementally constructed.

6.4 Reliable Broadcasting

Blind flooding in ad hoc networks may be used as a “fall back” mechanism that provides more reliable broadcasting in situations of increased mobility, channel noise, or packet traffic where optimized broadcasting mechanisms may fail. This reliability is due to the inherently high degree of redundancy present in blind flooding – whereby all nodes retransmit received broadcast packets at least once. However, as stated earlier, blind flooding results in the broadcast storm problem. Optimized broadcast mechanisms reduce the level of redundancy during a broadcast, thereby reducing the broadcast storm problem. However, there exists a significant problem in broadcast environments where a broadcast transmission may be lost due to packet corruption, packet collision, or hidden node transmissions. Therefore, it is possible that nodes may not receive a broadcast transmission. Furthermore, those nodes that do not receive a broadcast transmission may be required to receive a transmission. This is especially true in the case of optimized broadcast mechanisms, where selected nodes are responsible for retransmission. Given that optimized broadcast mechanisms greatly reduce the redundancy found in blind flooding, there may be situations where a packet may be lost and a broadcast may not propagate due to reduced redundancy.

A reliable flooding mechanism described in [44] and [45] is based on the use of a clustering. Each cluster consists of a single clusterhead that is responsible for nodes within its cluster. Clusterheads are responsible for ensuring messages flooded are received by nodes they are responsible for. The clusterhead will wait for acknowledgements from each node within its cluster. The gateway nodes will then forward the message to the clusterheads of other clusters that may also belong to. In this way a message is reliably propagated from cluster to cluster. The mechanism ensures reliability by utilizing unicast messages between cluster heads, and the collection of unicast acknowledgements from nodes belonging to a cluster. Gateway nodes will delay acknowledgement of a received message from the preceding clusterhead while they transmit the message to another clusterhead. Once the last cluster is reached, then acknowledgements will start flowing back toward the originating clusterhead and ultimately the source of the flood. In this way the source of the flood is able to determine which nodes the flood was received by. The problem with a cluster-based approach is the formation and maintenance of the clusters, which is costly especially in the presence of mobility. The formation of the cluster tree does not ensure that all nodes are covered by a clusterhead as nodes may leave a cluster. Therefore, it is possible for some nodes to be excluded from receiving a broadcast. Additionally, given node mobility, the reverse path back to the source node may be destroyed. To solve this problem, nodes may flood acknowledgements back to the clusterhead of the originating node.

In [16], a flooding mechanism is proposed to limit the broadcast storm problem and also to provide reliability. The mechanism consists of three phases. The first phase is the *scattering phase*, in which the source of node initiates a flood that utilizes the counter-based [38] flooding mechanism. The idea is to disseminate the message to as many nodes as possible. A handshake procedure as described in [6] is utilized to ensure neighboring nodes have received the same messages. During the scattering phase, a tree graph is formed from all nodes back to the original source of the flood. The second phase is *gathering phase*, in which acknowledgements are collected from all nodes. Acknowledgements travel back toward the source of the flood via the acyclic graph formed during the scattering phase. Unicast packet transmission is used for the transfer of acknowledgement. The third stage is the *purging phase* and is initiated by the source node, which floods a request for all data structures maintained during the reliable flood at each node to be deleted.

In [53], a reliable flooding mechanism is described. The mechanism consists of two schemes: Duplicate Broadcast Scheme (DBS) and Broadcast Acknowledgement Scheme (BAS). In DBS, a node maintains its local set of one-hop neighboring nodes in a table called Local Connectivity Table (LCT). When a node broadcasts a message, it relies upon the BAS to determine which neighbors receive the message. Given the number of successfully received messages and the number of nodes in the LCT, the authors propose to determine whether or not it is necessary to perform an additional broadcast, thus attempt to reach those nodes that did not receive the message yet. The BAS is a positive acknowledgement scheme that involves modifying the IEEE 802.11 MAC while maintaining compatibility. The BAS requires that all nodes successfully receiving a broadcast message respond with an acknowledgement. The scheme allows receiving nodes to utilize the DIFS period after receiving the data frame to transmit an acknowledgement. The DIFS period is divided into mini-slots, and nodes select a mini-slot in which to send their acknowledgement to the broadcasting node.

In [35], the authors propose a simple broadcast algorithm that provides a high delivery ratio for packets being flooded in an ad hoc network and provides limited reduction of redundant broadcasts. The algorithm allows for only selected forward nodes (one hop neighbors) of a broadcasting node to send acknowledgements, confirming reception of a broadcast packet. Forward nodes are selected so as to ensure that all two-hop neighbors of the broadcasting node are covered. Moreover, no acknowledgment is needed from one-hop neighbors that are covered by at least two forwarding neighbors. The broadcasting node waits for acknowledgements from its entire forwarding one-hop neighbor nodes. If not all acknowledgments are received, the broadcast node will rebroadcast the packet until a maximum number of retries is reached.

In [22], the authors proposed to apply the concept of double domination for providing more reliable service in ad hoc networks. A node in a double cluster structure is said to be covered if it has at least two clusterheads in its neighborhood. This means that each node that traditionally needs to be covered by one clusterhead is no longer covered by a unique clusterhead, but at least two clusterheads. They describe several double-clustering schemes based on some early clustering schemes that were already reported to not always work correctly. Work in [22] generalized the double cluster definition to a set of nodes that are up to k hops away from a clusterhead, i.e., a k-hop double dominating set. This means that, in a k-hop double dominating set, a node is covered by at least two clusterheads that are at a distance up to k hops.

In [35] and later improved in [36], the authors proposed a simple but reliable broadcast algorithm, called double-covered broadcast (DCB), which takes advantage of broadcast redundancy to improve the delivery ratio in environments that have a high transmission error rate. Among the one-hop neighbors of the sender, only selected forward nodes retransmit the broadcast message. Forward nodes are selected in such a way that (1) the sender's two-hop neighbors are covered and (2) the sender's one-hop neighbors are either a forward node or a non-forward node, but covered by at least two forwarding neighbors. The retransmissions of the forward nodes are received by the sender as confirmation of their receiving the packet. The non-forward one-hop neighbors of the sender do not acknowledge the reception of the broadcast. If the sender does not detect all its forward nodes' retransmissions, it will resend the packet until the maximum times of retry is reached. Simulation results show that the algorithm provides good performance for a broadcast operation under high transmission error rate environment. However, the channel errors are assumed to follow uniform distribution with fixed probability, which may not be realistic. A realistic physical layer model shows that the error rate depends on the distances between nodes.

In [25], a reliable and optimized broadcast mechanism called Reliable Minimum Spanning Tree (RMST) broadcasting is proposed. RMST utilizes a combination of the unique properties of the localized MST and unicast packet transmission to improve the reliability of optimized broadcasting. Each node in RMST uses one-hop topology information to calculate its local MST and determine those closest neighboring nodes that must be included within any transmissions to ensure a broadcast propagates throughout the ad hoc network. The distributed calculation of the localized MST results in a connected graph with a neighbor degree greater than one but less than six, and an average neighbor degree of less than 2.04 nodes [30]. Therefore, if the prior transmitting node is removed, the average neighbor degree is reduced to 1.04 nodes. This low neighbor degree results in a reduced set of neighboring nodes to which a broadcasting node must transmit a message, and allows for IEEE 802.11 broadcast transmission (as used by existing broadcast mechanisms) to be replaced with IEEE 802.11 unicast transmission. Unicast transmission provides a more reliable transport mechanism than broadcast transmission, as it may implement a RTS/CTS exchange at the MAC layer prior to transmission in order to reduce the problems associated with the hidden node problem. More importantly, unicast transmission utilizes a frame retransmission mechanism at the MAC layer based on a positive acknowledgement scheme (ARQ). Thus, a transmitting node will retransmit a frame if it does not receive a positive acknowledgement from the destination node. The IEEE 802.11 ARQ is not completely reliable and packet loss may occur. However, it provides a more reliable transport mechanism than broadcast and requires no modifications of the IEEE 802.11 MAC layer. The number of retransmissions before a timeout occurs is adjustable and is generally 4–7 retransmissions. If a node fails to retransmit a message to a destination node, it is able to detect the failure and may utilize an alternative approach to continue dissemination.

6.5 Broadcasting in Routing

Ad hoc network routing protocols allow for point-to-point communication in ad hoc networks. Routing protocols are responsible for delivering packets between nodes not within the transmission range. This requires the use of cooperative intermediate nodes that are able to act as routers in a distributed manner, thus allowing for data packets to be forwarded toward their destination. Ad hoc network routing protocols may be classified as proactive or reactive (on-demand) depending on how they determine routes. In this section we explore how broadcasting is utilized in reactive routing for route discovery and in proactive routing for link dissemination.

6.5.1 Proactive Routing Protocols

Proactive routing protocols [8] require that each node maintains route information to every other node in the network. Route tables are periodically or dynamically updated if the network topology changes. Proactive routing protocols differ in how they detect changes in network topology, how they maintain route tables, and how they disseminate this information to other nodes in the network. Proactive routing protocols experience minimal delay when routing packets as routes are available immediately from constantly maintained route tables. Although there is no initial penalty when a route to a destination is required, there is a constant overhead associated with disseminating link state or route table information throughout the network. This results in a reduction in network capacity due to constant and possibly heavy control traffic delivery. This is made worse in the presence of node mobility. Additionally, proactive protocols do not scale effectively as node density and node numbers increase [50]. Constant dissemination of control information throughout the ad hoc network also results in increased power consumption.

The majority of proactive routing protocols disseminate control information throughout the ad hoc network using blind flooding. Examples of proactive routing protocols that utilize blind flooding are Destination-Sequenced Distance Vector (DSDV) [41] and Wireless Routing Protocol (WRP) [37]. Other proactive routing protocols such as Fisheye State Routing (FSR) [13] limit the rate at which they update route information depending on the distance. Routes to closer nodes are maintained more regularly, whereas routes to remote nodes are maintained less regularly. Source-Tree Adaptive Routing (STAR) [14] eliminates periodic dissemination of control information in favor of conditional dissemination, thus reducing the constant overhead. However, blind flooding is still required. In Cluster-head Gateway Switch Routing (CGSR) [10], a hierarchy is created based on node clustering. Clusterheads control the flow of route information within or among their clusters, thus reducing the amount of route information and limiting the dissemination of the route information. The Optimized Link State Routing (OLSR) [21] protocol attempts to reduce the problems associated with blind flooding by utilizing an optimized flooding algorithm called Multipoint Relay (MPR) flooding [47]. The use of an optimized flooding algorithm reduces the problems associated with blind flooding and allows OLSR to scale more effectively, given an increased number of nodes.

6.5.2 Reactive Routing Protocols

Reactive routing protocols [8] are designed to reduce the overheads associated with proactive routing protocols. They do this by only maintaining information for active routes. Reactive routing protocols do not proactively maintain routes to all nodes; therefore, they must perform route discovery when a route to a destination node is required. Route discovery requires that a “route request” (RREQ) packet be blind flooded throughout the network. When the destination (or a node with an active route to the intended destination) receives the RREQ a “route reply” (RREP) is sent back to the source of the route request. The RREP may either be blind flooded back to the source or it may be unicast back along the path followed by the RREQ. The inherent nature of blind flooding is that it always chooses the shortest path, as the broadcast packet follows all possible paths in parallel. This is one reason why most reactive routing protocols use blind flooding to perform route discovery.

As routes are not immediately available, reactive protocols have a much higher initial delay at the start of communication than proactive routing protocols. Given that flooding forms the basis of route discovery, reactive routing protocols suffer from the broadcast storm problem. This is made worse by increasing node density, heightening node mobility and the number nodes of performing route requests for peer-to-peer communications. It is important for mobile devices that there is no constant power usage due to periodic flooding of link state or route table information as with proactive routing protocols.

Both Dynamic Source Routing (DSR) [20] and Ad hoc On-Demand Distance Vector Routing (AODV) [46] protocols utilize blind flooding as a means of performing route discovery. However, they differ in the way they maintain routes to destination nodes and also in the amount of information required to route packets. To reduce the effects of blind flooding, these protocols use route caching as well as limiting the number of hops for route discovery. The Routing On-demand Acyclic Multi-path (ROAM) [48] protocol limits the effects of flooding by using directed acyclic subgraphs based on distance between the source and the destination for the propagation of a flood. This eliminates the propagation of a flood in a direction along a subgraph if the destination is not reachable along that subgraph. In Relative Distance Micro-discovery Ad-hoc Routing (RDMAR) [5], overhead associated with route discovery is reduced and localized by limiting each RREQ packet to a certain number of hops. However, this localization of route requests can occur only if the source and destination node have communicated before and exchanged position information. If the nodes have not communicated before, then the route request is not localized. Location Aided Routing (LAR) [24] requires that each node is equipped with a GPS device and therefore is aware of its location. Overhead associated with route discovery is reduced by limiting the direction and scope of flooding. This protocol defines zones specifying which direction a RREQ packet may travel toward. Route request packets therefore only travel in the approximate direction of the intended destination. Cluster-Based Routing Protocol (CBRP) [19] is a hierarchal routing protocol based on clustering. Clusterheads are defined and responsible for the nodes within each cluster. To reduce the effects of route discovery, only clusterheads exchange and propagate RREQ packets.

6.5.3 Self-selecting Route Discovery

Existing research in ad hoc network routing has contributed significantly to improve routing through maximizing the usage of prior knowledge of nodes, improving stability of routes, and creating a collaborative environment between nodes. However, little work has been done in improving the process of route discovery when no prior node or topology knowledge is available. In the case of reactive routing, improving the efficiency of route discovery is one key to providing higher scalability as network density increases. Moreover, if only a blind flooding is performed, then the route determined is generally the shortest path (as all routes are searched in parallel during a blind flood) and is not necessarily the best route in terms of efficient usage of resources.

In [4], the authors propose novel distributed search strategies that may be incorporated into reactive route discovery in heterogeneous ad hoc networks. The proposed search strategies are self-selecting and aim to be resource-aware, avoid unidirectional links, and reduce control packet overhead associated with traditional route discovery caused by blind flooding. The first proposed search strategy allows for efficient resource-aware route discovery in ad hoc networks where heterogeneous nodes may have varying transmission ranges. The second proposed search strategy addresses route discovery issues associated with the existence of unidirectional links experienced when nodes have varying transmission ranges or as a result of a varying wireless propagation environment.

In [2] and [3], authors present a number of different self-selecting route discovery strategies, which allow for intermediate nodes to selectively participate in route discovery. The aim of these strategies is to reduce the broadcast storm problem in terms of the number of control packets exchanged and the level of medium contention in the network, thereby achieving higher levels of scalability. Additionally, such strategies are able to provide more control to individual nodes to better manage their limited resources (such as battery power) and to determine more effective routes between end nodes.

6.6 Thoughts for Practitioners

Broadcast/flooding is widely utilized in the applications of wireless ad hoc networks. To improve energy efficiency and shorten communication latency, cross-layer design could be adopted for specific applications of ad hoc networks. For example, improved performance can be obtained by jointly considering physical and network layer issues. Such novel approaches incorporated protocol layer functions will provide advantages over traditional network architectures.

In some broadcast protocols, there are several parameters that should be determined to optimize the performance before applying the protocols. For example, it may be required to decide predetermined thresholds and whether or not to employ the acknowledgement scheme in the broadcast protocols. A suggestion is to set the simplest environment and apply the protocol to the real applications. Based on the feedback of the parameters, the system can iteratively adjust the parameters to achieve a stable and good performance of the broadcast protocols. It is better than directly setting the parameters as required in the protocols. The reason is that there is always a gap between research work and real applications. Even for the works based on real testbed, performance of the protocols is significantly affected by different environments.

6.7 Conclusions and Directions for Future Research

As can be seen from this chapter, a significant amount of research on designing efficient broadcast schemes in ad hoc networks has been carried out in the past few years. This has resulted in significant advances in the state of the art. The most notable are the developments of efficient localized broadcast schemes where each node requires only one or possibly two-hop neighbor knowledge about the network. The performance of the protocols is close to the performance of protocols that require global network knowledge. This chapter also identifies how broadcast is used and optimized in routing protocols and introduces new research on route discovery and the transition away from standard broadcast and optimized broadcast techniques to more search-oriented route discovery for routing protocols.

Although broadcast in ad hoc networks has been well studied, there are challenges for future research. Most existing solutions for efficient broadcasting are usually designed for static networks or the networks where nodes do not move fast. It is because that these efficient broadcast protocols are normally based on the information of neighbors, which is hard to maintain in mobile environment. Therefore, design of efficient broadcast protocol in highly mobile networks is expected in future work.

Moreover, we observe that there are more and more applications in which ad hoc networks are integrated with other wireless networks. For instance, wireless sensor actuator networks consist of actuator networks (ad hoc networks) and wireless sensor networks. Broadcast in wireless sensor actuator networks is normally from an actuator to all sensors or the sensors in a specific area. Another example is the integration of ad hoc networks and wireless mesh networks.

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Terminologies

Broadcast – Sending a message from one node to all other nodes in the network.

Blind flooding – Each node in the network retransmits the flooding message at the first time it receives the message.

Broadcast storm problem – Blind flooding may cause serious problems of redundant retransmissions, medium contention and packet lost.

Covering with disks – Given a set of points in the plane, the problem is to identify the minimum set of disks with prescribed radius to cover all the points.

Localized method – Each node uses the information of only its neighbors or nature information.

Globalized method – Some node or all nodes have entire network information.

Dominating Set (DS) – A subset of the vertices of a graph if every vertex in the graph is either in the subset or is adjacent to at least one vertex in the subset.

Connected Dominating Set (CDS) – A connected DS.

Clusterhead – A representative of each cluster.

Gateway nodes – The nodes that belong to several clusters.

Active clustering – Nodes cooperate with each other to elect clusterheads. This is achieved through periodic exchange of control information.

Passive clustering –Cluster formation is dependent on background data traffic.

Activity scheduling – Nodes must actively determine if they are in an active or passive state in order that the network remains connected and the lifetime of both the network and the nodes are maximized.

Questions

1. What is the difference between broadcast and multicast?
2. What is blind flooding? Why it may cause broadcast storm problem?
3. Describe the basic idea of Multipoint Relaying (MPR) [47]?
4. What is the basic idea of self-pruning [32]?
5. What are the basic steps of dominating sets–based broadcasting?
6. What is resource-aware broadcasting?
7. What are the advantages and disadvantages of passive clustering and active clustering?
8. What is the sufficient and necessary condition to guarantee 100% deliverability for the flooding algorithms based only on one-hop information?
9. Descript Broadcast Incremental Power (BIP) protocol.
10. What is the difference between proactive routing and reactive routing?

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