11

Energy Conservation for Broadcast and Multicast Routings in Wireless Ad Hoc Networks

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11.1 Introduction

Wireless ad hoc networks have received significant attention in recent years due to their potential applications on the battlefield, in disaster relief operations, festival field grounds, and historic sites. A wireless ad hoc network consists of mobile hosts dynamically forming a temporary network without the use of an existing network infrastructure. In such a network, each mobile host serves as a router. One important issue in ad hoc network routing is energy consumption. In MANETs, mobile hosts are powered by batteries and unable to recharge or replace batteries during a mission. Therefore, the limited battery lifetime imposes a constraint on network performance. To maximize the network lifetime, the traffic should be routed in such a way that energy consumption is minimized.

Broadcast and multicast are important operations for mobile hosts to construct a routing path in a MANET. Broadcast is a communication function in which a node, called the source, sends messages to all the other nodes in the network. Broadcast is an important function in applications of ad hoc networks, such as in cooperative operations, group discussions, and route discovery. Broadcast routing is usually constructing a broadcast tree, which is rooted from the source and contains all the nodes in the network. In addition to broadcasting, multicasting is also an important function in applications, including distributed games, replicated file systems, and teleconferencing. Multicast in a MANET is defined by delivering multicast packets from a single source node to all member nodes in a multi-hop communication manner. The energy cost of all the nodes that transmit the broadcast or multicast message in MANET should be minimized.

To overcome the problems of transmission collision, message storm, and battery exhaustion, several energy conservation schemes for broadcast and multicast routings are proposed in literature.[1–23] This chapter consists of two parts. The first part introduces novel energy conservation schemes for broadcast routing in MANETs, and the second part investigates existing energy conservation schemes for multicast routing in MANETs.

In the first part, existing energy-efficient broadcast protocols can be classified into tree-based and probability-based approaches. The tree-based broadcast protocol is to construct the *minimum-energy broadcast tree,*[1–9] which is a broadcast tree with minimum energy consumption. To establish the minimum-energy broadcast tree, centralized algorithms[1–3] and distributed algorithms[8,9] are investigated in wireless ad hoc networks. For centralized algorithms, we review centralized BIP[1] and EWMA[3] protocols. For distributed algorithms, we describe the DISP-BIP[8]and RBOP[9] protocols. In addition, integer-programming techniques can be used to establish the minimum-energy broadcast tree.[4] Finally, the *approximation ratio* of existing minimum-energy broadcast protocols is calculated in Wan et al.,[5] Clementi et al.,[6] and Li et al.[7]. By considering the probability-based approach, the energy conservation for broadcast routing can be achieved by alleviating the "broadcast storm problem" with a high-performance probabilistic scheme.[10–12] A power-balance broadcast approach is then investigated in Sheu et al.[13] to extend the network lifetime using the probabilistic scheme to determine whether or not the host needs to rebroadcast.

In the second part, some existing power-efficient multicast protocols designed for MANETs are investigated. According to the topology constructed in the protocols, existing power-efficient multicast protocols can be classified into tree-based and cluster-based protocols. In tree-based multicast protocols, an energy-efficient broadcast tree is constructed first. By considering the power consumption of nodes in the tree, these protocols propose tree refining or pruning rules to construct a power-efficient multicast tree. According to the number of source nodes in the tree, the tree-based multicast protocols are further partitioned into two subsets: the single-source and multi-source multicast protocols. In the subset of single-source multicast protocols, power-efficient multicast protocols MIP,[2] S-REMiT,[14] and RBIP[19] are reviewed. The MIP and S-REMiT protocols apply refining and pruning rules on existing broadcast trees to construct a power-efficient multicast tree. Some applications require that the multicast be reliable. The RBIP protocol considers the reliable multicast and takes into consideration the retransmission cost in energy consumption. Another multicast protocol, G-REMiT,[15] is also reviewed in the tree-based multicast category. Different from the protocols mentioned above, the G-REMiT protocol[15] is mainly designed for multi-source energy-efficient multicast trees. In addition to the tree-based multicast protocols, Sub-section 11.3.2 reviews the Cluster-Based Multicast Protocol (CBMP),[16] which applies the existing ODMRP[17] on cluster topology to achieve the purpose of energy-efficient multicast communication.

The remainder of this chapter is organized as follows. Section 11.2 reviews energy-efficient broadcast protocols in MANETs. Section 11.3 introduces energy-efficient multicast protocols in MANETs. Section 11.4 concludes this chapter and gives some possible future works.

11.2 Energy-Efficient Broadcast Protocols in MANETs

This section describes existing valuable energy-efficient broadcasting protocols in MANETs. These energy-efficient broadcast protocols are categorized according to the aspects of *tree-based* and *probability-based* approaches. The detailed operations of these energy-efficient broadcast protocols are described as follows.

11.2.1 Tree-Based Approach

The *minimum-energy broadcast tree* is formally defined in Cagalj et al.[3] as follows. Given the source node r, a set consisting of pairs of relaying nodes and their respective transmission levels is constructed such that all nodes in the network receive a message sent by r, and the total energy expenditure for this task is minimized. The objective of energy-efficient broadcasting protocols herein is to construct the *minimum-energy broadcast tree*. In the following, Section 2.1.1 describes centralized algorithms to establish the minimum-energy broadcast tree; Section 11.2.1.2 expresses distributed algorithms of constructing the minimum-energy broadcast tree; and Section 11.2.1.3 investigates the establishment of minimum-energy broadcast tree using the integer programming technique. Finally, Section 11.2.1.4 calculates the approximation ratio of existing minimum-energy broadcast protocols.

11.2.1.1 Centralized Algorithms

To build a spanning tree with minimum energy consumption, one way is to construct a *minimum spanning tree* (MST).[1–3] A centralized algorithm, called a centralized BIP (*broadcast incremental power*) algorithm, is developed in Wilson and Watkins[1] to construct a *minimum-energy broadcast tree* in MANETs. An improved centralized algorithm, called EWMA (embedded wireless multicast advantage), is proposed in Cagalj et al.[3] to construct a minimum-energy broadcast tree with less power consumption.

11.2.1.1.1 *Centralized BIP (Broadcast Incremental Power) Algorithm*

A centralized algorithm, called a BIP (*broadcast incremental power*) algorithm, is developed to build an energy-efficient broadcast tree in a MANET.[1] The BIP algorithm exploits the broadcast nature of the wireless communication environment and addresses the need for energy-efficient operation. The main objective of the BIP algorithm is to construct a minimum-energy broadcast tree. The BIP algorithm is based on Prim's algorithm,[2] which is an algorithm used to search for minimum spanning trees (MSTs). The wireless communication model is defined as follows. First, omni-directional antennas are used, such that every transmission by a node can be received by all nodes that lie within its communication range. Second, the connectivity of the network depends on the transmission power; each node can choose its power level, not to exceed some maximum value $P_{\max}$. BIP assumed that the received signal power varies as $r^{-\alpha}$, where r is the range and α is a parameter that typically takes on a value between 2 and 4. Without loss of generality, P_{ij} = power needed for link between nodes i and $j = r^{\alpha}$, where r is the distance between nodes i and j.

The BIP algorithm and the following protocols adopt the use of omni-directional antennas; thus, all nodes within the communication range of a transmitting node can receive its transmission. Consider the example shown in Figure 11.1, in which a subset of the multicast tree involves node i, which is transmitting to its neighbors, node j and node k. The power required to reach node j is P_{ij} and the power required to reach node k is P_{ik}. A single transmission at power $P_{i,(j,k)} = \max\{P_{ij}, P_{ik}\}$ is sufficient to reach both node j and node k, based on the assumption of omni-directional antennas. The ability to exploit this property of wireless communication, which is called the *wireless multicast advantage*, makes multicasting an excellent setting in which to study the potential benefits of energy-efficient protocols.

One can explain the basic operation of BIP by offering a simple example of the construction of the broadcast tree, rooted at a source node.

Figure 11.2 shows a wireless network with ten nodes, in which node 10 is the source node. A propagation constant of $\alpha = 2$ is assumed. At first, the tree only consists of the source node. Then BIP begins by determining which node should be selected so that the source node can reach with minimum incremental power. The source node's nearest neighbor, which is node 9, should be added to the tree. The notation $10 \rightarrow 9$ means adding the transmission from node 10 to node 9.

BIP then determines which "new" node can be added to the tree at *minimum additional* cost. There are two alternatives. Either node 10 can increase its power to reach a second node, or node 9 can transmit to its nearest neighbor that is not already in the tree. In this example, node 10 increases its power level to reach node 6. Note that the cost associated with the addition of node 6 to the tree is the incremental cost associated with increasing node 10's power level sufficient to reach node 6.

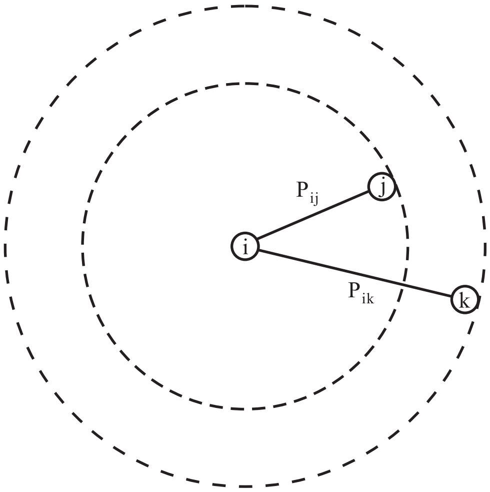

FIGURE 11.1 The "wireless multicast advantage": $P_{i,(j,k)} = \max\{P_{ij}, P_{ik}\}$.

The cost of a transmission between nodes 10 and 9 is $r^{\alpha}_{10,9}$, and the cost of a transmission between nodes 10 and 6 is $r^{\alpha}_{10,6}$. The incremental cost associated with adding node 6 to the tree is $r^{\alpha}_{10,6} - r^{\alpha}_{10,9}$. BIP exploits the broadcast advantage because when node 10 has sufficient power to reach node 6, then node 10 also can reach node 9.

There are now three nodes in the tree, namely nodes 6, 9, and 10. For each of these nodes, BIP determines the incremental cost to reach a new node; that is, 6 → 7, as shown in Figure 11.2.

This procedure is repeatedly performed until all nodes are included in the tree. The order in which the nodes were added is: 6 → 8, 6 → 5, 9 → 1, 9 → 3, 9 → 4, 9 → 2.

11.2.1.1.2 *EWMA (Embedded Wireless Multicast Advantage)*

The EWMA protocol[3] consists of two steps:

A minimum spanning tree (MST) for broadcasting tree is initially established as shown in Figure 11.3, where node 10 is the *source* node and nodes 9, 1, 6, and 8 are *forwarding* nodes. The power consumptions of nodes 10, 9, 1, 6, and 8 are 2, 8, 4, 5, and 4, respectively. The total energy consumption of the MST is 23.

EWMA calculates the necessary power for every node from the constructed MST in Step 1. A node is said to be an *exclude node* if it is a transmitting node in MST but is not a transmitting node in the final EWMA broadcasting tree. The key idea of EWMA is to search for exclude nodes by increasing

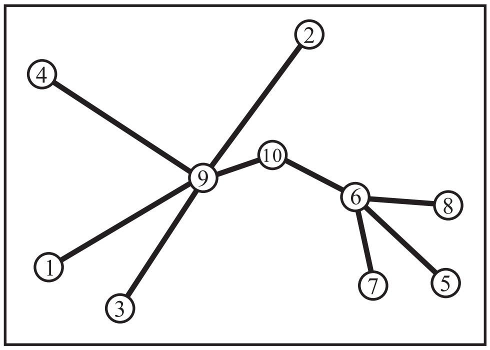

FIGURE 11.2 Broadcast tree using BIP.

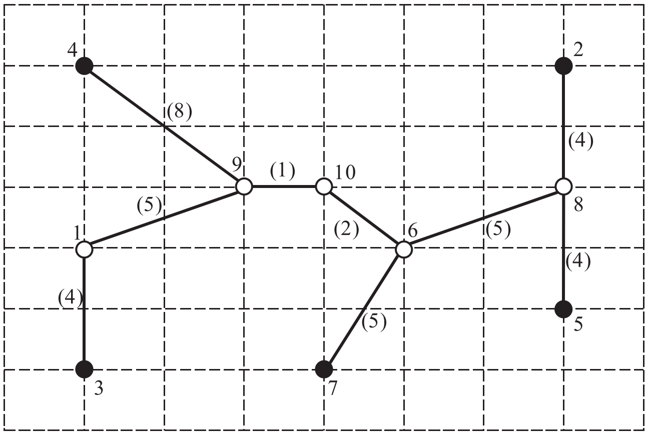

FIGURE 11.3 An MST broadcasting tree.

less power consumption for the exclude node to cover more forwarding nodes. For example, the resultant broadcast tree produced by EWMA is shown in Figure 11.4. After increasing the power consumption of node 10 (from 2 to 13), the original forwarding nodes 9, 6, and 8 in the MST can be excluded in the EWMA broadcast tree. Therefore, only nodes 10 and 1 are used in the EWMA broadcast tree. The total energy consumption of the EWMA broadcast tree is $13 + 4 = 17$. This result is illustrated in Figure 11.4.

11.2.1.1.3 *Integer Programming Technique*

It is interesting that three different integer programming models are used for an optimal solution of the minimum power broadcast problem.[4] The main idea is to use the *power matrix P*, where the (i, j)-th element of the power matrix P defines the power required for node i to transmit to node j. For example, as shown in Figure 11.5, the power matrix P is

$$\begin{bmatrix} 0 & 8.4645 & 12.5538 & 13.6351 \\ 8.4645 & 0 & 0.5470 & 3.8732 \\ 12.5538 & 0.5470 & 0 & 5.7910 \\ 13.6351 & 3.8732 & 5.7910 & 0 \end{bmatrix}.$$

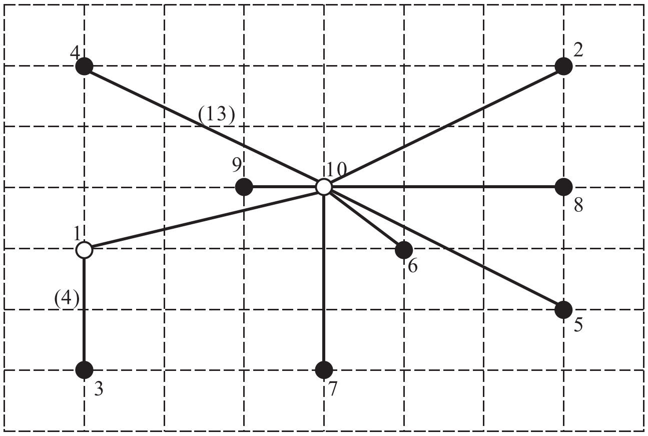

FIGURE 11.4 The EWMA broadcast tree.

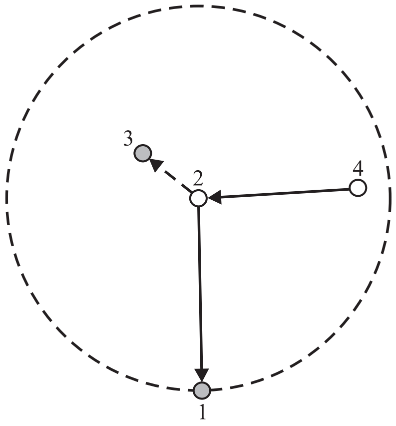

FIGURE 11.5 Example of a MANET and node 4 is the source node.

In addition, a *reward matrix R* is defined by

$$R_{mn}(p) = \begin{cases} 1, \text{ if } P_{mp} \leq P_{mn} \\ 0, \text{ otherwise} \end{cases}$$

The example shown in Figure 11.5 explains the meaning of the reward matrix. A binary encoding is produced of all the nodes covered (or not covered) by all possible transmissions in the network. For example, the transmission 2 → 1 results in nodes 1, 3, and 4 being covered; therefore, $R_{21} = [1011]$ is encoded in the (2, 1) cell of the reward matrix. Therefore, the reward matrix is:

$$R = \begin{bmatrix} [0\ \ 0\ \ 0\ \ 0] & [0\ \ 1\ \ 0\ \ 0] & [0\ \ 1\ \ 1\ \ 0] & [0\ \ 1\ \ 1\ \ 1] \\ [1\ \ 0\ \ 1\ \ 1] & [0\ \ 0\ \ 0\ \ 0] & [0\ \ 0\ \ 1\ \ 0] & [0\ \ 0\ \ 1\ \ 1] \\ [1\ \ 1\ \ 0\ \ 1] & [0\ \ 1\ \ 0\ \ 0] & [0\ \ 0\ \ 0\ \ 0] & [0\ \ 1\ \ 0\ \ 1] \\ [1\ \ 1\ \ 1\ \ 0] & [0\ \ 1\ \ 0\ \ 0] & [0\ \ 1\ \ 1\ \ 0] & [0\ \ 0\ \ 0\ \ 0] \end{bmatrix}.$$

To utilize the information of the calculated *power matrix P* and *reward matrix R*, the minimum power broadcast tree is constructed using integer programming formulations.[4]

11.2.1.1.4 *Calculating Approximation Ratios on Static Ad Hoc Networks*

A wireless ad hoc network is called a *static* ad hoc wireless network[5–7] if the nodes in the ad hoc network are assumed to be a point set randomly distributed in a two-dimensional plane and there is no mobility. The minimum-energy broadcast routing in static ad hoc wireless networks was first considered in Wan et al.[5]. By exploring geometric structures of Euclidean MSTs, it is proven[5] that the *approximation ratios* of MST and centralized BIP are between 6 and 12, and between $\frac{13}{3}$ and 12, respectively, where the approximation ratio means that the results obtained by their executions are how close to the optimal value. Furthermore, the approximation ratio of the MST-based heuristic for the energy-efficient broadcast problem in static ad hoc networks is investigated in Clementi et al.[6] The main result of Clementi et al.'s[6] work shows that the approximation ratio is about 6.4. In addition, energy-efficient broadcasting routing is developed in static ad hoc wireless networks.[7] This work proposed three heuristic algorithms — (1) shortest path tree heuristic, (2) greedy heuristic, and (3) node weighted Steiner tree-based heuristic — which are centralized algorithms. The approximation ratio of the node weighted Steiner tree-based heuristic is proven to be $(1 + 2\ln(n - 1))$.[7]

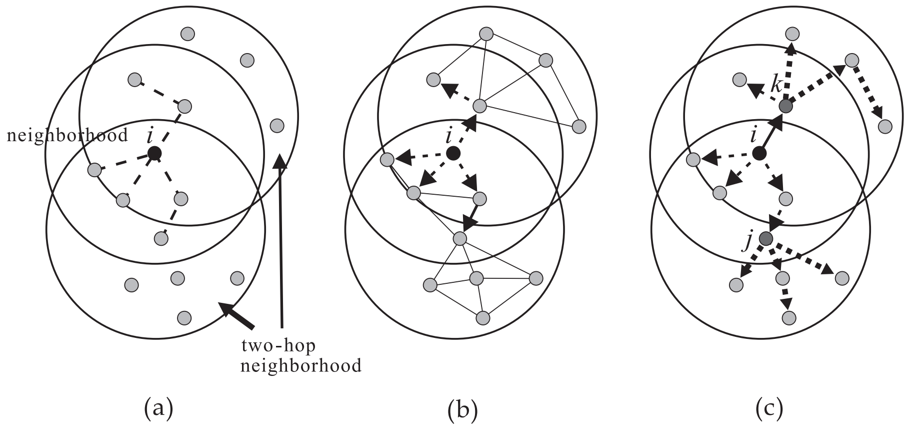

FIGURE 11.6 (a) Local BIP tree for node i, (b) Dist-BIP-A tree, and (c) Dist-BIP-G tree.

11.2.1.2 Distributed Algorithms

A distributed version of the BIP algorithm, called DIST-BIP, is then proposed in Wieselthier et al.[8]. A localized minimum-energy broadcasting protocol is developed in Cartigny et al.[9] such that each node only requires the local information.

11.2.1.2.1 *DIST-BIP (Distributed Broadcast Incremental Power)*

Two distributed BIP algorithms[8] are proposed. One is Dist-BIP-A (distributed-BIP-All), and the other is Dist-BIP-G (distributed-BIP-gateway). In the Dist-BIP-A algorithm, each node constructs its local BIP tree using the *centralized-BIP* algorithm[1] within the one-hop transmission range. After constructing local BIP trees for every node, each node hears and broadcasts messages from or to its neighbors to connect many local BIP trees to form a global BIP tree. For example, node i constructs a local BIP tree as shown in Figure 11.6a. A Dist-BIP-A tree is established as shown in Figure 11.6b by connecting many local BIP trees, which are constructed by all neighboring nodes. The gateway nodes are jointed to hear and broadcast messages in the Dist-BIP-G protocol to form a Dist-BIP-G tree. An example of the Dist-BIP-G tree is illustrated in Figure 11.6c. Nodes i, j, and k are gateway nodes. The Dist-BIP-G tree is established by connecting local BIP trees, which are constructed by gateway nodes i, j, and k. In general, the message overhead of constructing a Dist-BIP-G tree is less than that of constructing a Dist-BIP-A tree. But the Dist-BIP-A tree is near the centralized BIP tree.

11.2.1.2.2 *RBOP (RNG Broadcast Oriented Protocol)*

A localized minimum-energy broadcasting protocol, called the RNG Broadcast Oriented Protocol (RBOP), which utilizes the relative neighborhood graph (RNG), is developed in Cartigny et al.[9] The protocol only requires the local information to design the minimum-energy broadcasting protocol. Unlike most existing minimum-energy broadcasting protocols that use the global network information, RBOP only maintains the local information, thus saving the communication overhead for obtaining global information.

To substitute minimum spanning tree (MST) in the protocol by utilizing the *relative neighborhood graph* (RNG), the wireless network is represented by a graph $G = (V, E)$, where V is the set of nodes and $E \subseteq V^2$ denotes the edge set that represents the available communications. Note that (u, v) belongs to E means that u can send message to v, and *RNG* is a sub-graph of G. An edge (u, v) belongs to the RNG if no node w exists in the intersection area for nodes u and v, as illustrated in Figure 11.7. This topology control scheme is called the RNG Topology Control Protocol (RTCP), which is used to build the relative neighborhood graph (RNG).

The main idea of the RBOP is that when a node u receives a message from neighbor nodes, the node selects an edge (u, v) in RNG as far as possible to broadcast the message within radius $d(u, v)$. For example, as shown in Figure 11.8, node S broadcasts a message to *A, B, and C* with radius $d(S, A)$,

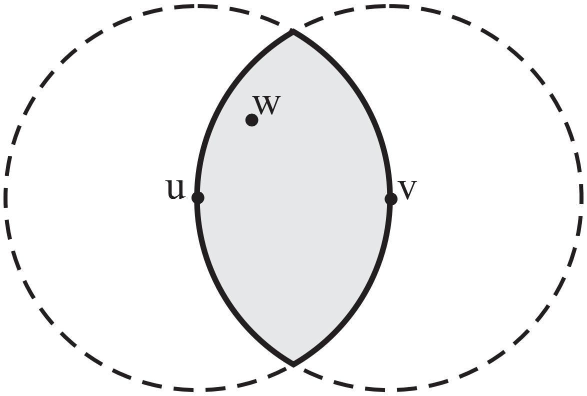

FIGURE 11.7 The edge (u, v) does not belong to RNG because of the existence of node w.

because $d(S, A) > d(S, C) > d(S, B)$, where (S, A), (S, C), and (S, B) are edges belonging to RNG. Then node C broadcasts with radius $d(C, D)$. Finally, node A broadcasts with radius $d(A, G)$. This method can reduce the total number of broadcast messages and efficiently transmit the broadcast messages. In the simulation results reported in Cartigny et al.,[9] the centralized BIP protocol can save about 50 percent energy compared to the RBOP. However, the communication overhead of centralized BIP is higher than that of the RBOP.

11.2.2 Probability-Based Approach

A probability-based approach also can be applied to determine whether or not a node should transmit the received packet during broadcasting. Some protocols[10–12] apply the probability-based approach to resolve the broadcast storm problem, hence saving the power consumption for redundant transmission. A power-balance protocol proposed in Sheu et al.[13] also adopts a probability-based approach to balance the power consumption on each node, thus improving the network lifetime. This sub-section introduces the probability-based protocols that help improve the network lifetime.

In a MANET, flooding is a basic requirement and is frequently used to broadcast a message over the MANET. However, blind flooding will cause the broadcast storm problem,[10] resulting redundant message rebroadcasts, contentions, and collision. Alleviating the retransmission, contention, and collision situations will not only improve the success rate for receiving packet, but also reduce the power consumption.

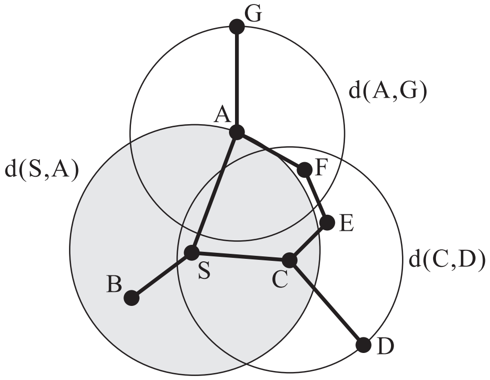

FIGURE 11.8 Example of the RNG Broadcast Oriented Protocol (RBOP).

To resolve the broadcast storm problem and achieve the goal of energy conservation, the *probabilistic*, *counter-based*, *location-based, polygon-based*, and *cluster-based* schemes were first investigated in Tseng et al.[10]

Sheu et al.,[13] proposed a power-balance broadcast algorithm to extend the network lifetime. The power-balance broadcast algorithm uses the residual battery energy to determine whether or not the host needs to rebroadcast messages. The host with more residual energy will have higher probability to rebroadcast messages than the host with less residual energy. Therefore, the host with less residual energy will reduce the rebroadcast probability and reserve more energy for extending its lifetime. The proposed algorithm consists of two steps. First, each node i has an initial rebroadcast probability P_i according to its remaining energy. Second, the algorithm uses the average remaining energy of the neighbors of host i, the number of neighbors of host i, and the number of broadcast messages received by host i to refine the rebroadcast probability.

11.3 Energy-Efficient Multicast Protocol in MANETs

Energy-efficient multicasting has also been intensively discussed in wireless ad hoc networks. Multicasting is another important routing operation to transmit the message from one mobile host to a number of mobile hosts. Many applications require disseminating information to a group of mobile hosts in a MANET. These applications include distributed games, replicated file systems, teleconferencing, etc. A single-source multicasting in MANET is defined by delivering multicast packets from a single-source node to all member nodes in a multi-hop communication manner. A multi-source multicast is the one that each member can be the source of message sender of the other members. Although multicasting can be achieved by the multiple point-to-point routes, constructing a multicast topology for delivering the multicast packets always provides a better performance. A number of articles[20,21] have recently investigated multicast protocols in a MANET, by only considering how to reduce the tree level or the number of forwarding nodes. It is very important to take into consideration the factors of energy reservation and network lifetime to investigate the energy-efficient multicast protocol, because the wireless device in a MANET is mainly limited and constrained by the life of the battery. According to the topology constructed in the previous protocols, existing energy-efficient multicast protocols can be classified into *tree*-based and *cluster*-based protocols. This section reviews the existing power-efficient multicast protocols for MANETs.

11.3.1 Tree-Based Energy-Efficient Multicast Protocol

According to the number of source nodes in networks, existing tree-based energy-efficient multicast protocols are classified into two categories: the single-source and multi-source multicast protocols. Some articles construct the power-efficient multicast tree by pruning the broadcast tree, which is established by existing power-efficient broadcasting protocols such as MST,[2,3] BIP,[1,8] and BLiMST.[2] By taking into consideration the power consumption of the nodes in a broadcast tree, these protocols propose tree refining and pruning rules to construct a power-efficient multicast tree. Section 11.3.1.1 first reviews existing single-source multicast protocols, and Section 3.1.2 then reviews multi-source multicast protocols.

11.3.1.1 Single-Source Multicast Protocol

11.3.1.1.1 *MIP (Multicast Incremental Power) Algorithm*

Operations of the MIP algorithm can be partitioned into three phases. In the first phase, a power-efficient broadcast tree is constructed by a centralized BIP (*broadcast incremental power*) algorithm, as described in Section 11.2.1.1.1. By considering the characteristics of wireless transmission, the second phase applies sweep operations to the constructed broadcast tree to eliminate any unnecessary transmission. Nodes in the broadcast tree are examined in ascending ID order and leaf nodes are ignored because they do not transmit. The non-leaf node with the lowest ID will be the first candidate for restructuring. If the candidate's transmission range can reach a neighbor's node k and its downstream neighbor node j, then the link between node j and k can be eliminated. To obtain the multicast tree, the broadcast tree is pruned by eliminating all transmissions that are not needed to reach the members of the multicast group. More specifically, nodes with no downstream destinations will not transmit, and some nodes will be able to reduce their transmitted power. A similar technique can also be applied to broadcast trees produced by alternative algorithms, such as BLiMST (broadcast link-based MST), resulting in the algorithm of another energy-efficient multicast protocol MLiMST (multicast link-based MST).[2]

11.3.1.1.2 *S-REMiT (Distributed Energy-Efficient Multicast) Protocol*

Different from the MIP protocol,[2] S-REMiT tries to minimize the total energy cost for multicasting in a distributed manner.[14] The S-REMiT algorithm is divided into two phases. In the first phase, S-REMiT uses a minimum-weight spanning tree (MST) as the initial solution. In the second phase, S-REMiT tries to improve the energy efficiency of the multicast tree by switching some tree nodes from their respective parent nodes to new corresponding parent nodes. In the first phase, the algorithm starts with each individual node as a fragment. Each fragment finds its adjacent edge with minimum weight and attempts to combine with the fragment at the end of the edge. Finally, an MST that combines all the fragments will be constructed in a distributed manner.

The second phase of S-REMiT is organized in rounds in order to reduce the energy consumption of the constructed MST. In each round, the depth-first search (DFS) algorithm is used to pass the S-REMiT token, which gives permission to a node to refine the tree topology, thus improving the energy consumption of the tree. For each node i on the multicast tree T rooted by source s, S-REMiT uses $E_i(T, s)$ to evaluate the energy metric cost of each node i, where

$$E_i(T, s) = \begin{cases} E^T + Kd_i^{\alpha} \\ E^T + Kd_i^{\alpha} + E^R \\ E^R \end{cases}$$

where E^T denotes a constant that accounts for real-world overheads of electronics and digital processing, E^R denotes the energy cost at the receiver side, K is a constant that depends on the properties of the antenna, and α denotes a constant that depends on the propagation losses in the medium. Let $TEC(T, s)$ denote the total energy cost of nodes in the multicast tree T. In a round, assume that node i in the MST obtains the S-REMiT token. The S-REMiT protocol is described as follows.

S-REMiT multicast protocol:

Step 1: Node i selects a neighboring node x in MST that link $\overline{ix}$ has a highest energy cost tree. Node i then selects a new parent candidate j with the highest positive gain $g_i^{x,j} := ((E_x(T,s) + E_j(T,s)) - (E_x(T',s) + E_j(T',s)))$, which does not result in tree disconnection if node i replaces link $\overline{ix}$ with link $\overline{ij}$. If there is no such node j available, then it sets token with *flag = false*.

Step 2*:* Node i replaces link $\overline{ix}$ with link $\overline{ij}$ and notifies nodes j, x, and its neighbors about the replacement.

Step 3*:* Node i passes the token to next hop node according to the DFS algorithm.

Step 4: If node s gets back the token with *flag = false*, which means there are no energy *gains*in this DFS round, s will request all of the tree nodes to prune the redundant transmissions that are not needed to reach the members of the multicast group from the tree.

Figure 11.9 provides an example of S-REMiT. The execution of Phase I will construct an MST T rooted by node 5, as shown in Figure 11.9. Assume node 1 obtains the S-REMiT token; it selects node 2 from tree neighbors because link $\overline{12}$ is the highest energy cost tree link of node 1. Then, node 1 will try to replace link $\overline{12}$ with some other link to reduce the total energy consumption of the tree. To achieve this goal, node 1 considers those communicative neighbors as candidates to refine the multicast tree. Node 1 selects node 4 from candidates and then evaluates the gain $g_1^{2,4} := (E_1(T,5) + E_2(T,5) + E_4(T,5)) - (E_1(T',5) + E_2(T',5) + E_4(T',5))$, where T' denotes the tree after replacing link $\overline{12}$ by link $\overline{14}$. In case that gain is positive, node 1 will replace link $\overline{12}$ by $\overline{14}$, and then notify its communicative neighbors about this change. Hereafter, node 1 passes the S-REMiT token to node 2 to refine the multicast tree.

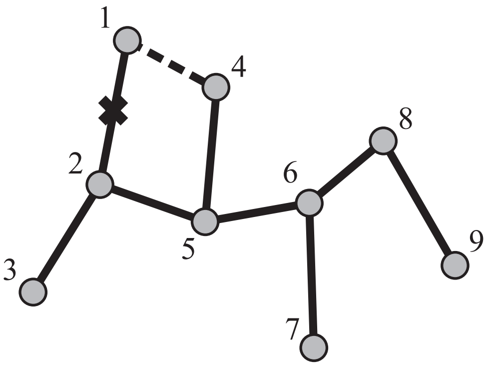

FIGURE 11.9 An example of executing the S-REMiT protocol.

11.3.1.1.3 *Reliable Energy-Efficient Multicast Protocol (RBIP)*

The BIP, BLU, and BLiMST heuristic algorithms for computing energy-efficient trees for unreliable wireless broadcasting and multicasting were presented in Wieselthier et al.[2]. In wireless environments, individual links often have high error rates. This might result in reliable delivery potentially requiring one or more retransmissions because the number of retransmissions needed clearly depends on the error rates of the associated links. Banerjee et al.[19] present appropriate modifications to these algorithms (BIP, BLU, and BLiMST) to compute energy-efficient data delivery trees that take into account the costs for necessary retransmissions. Unlike most energy-efficient multicast protocols, this protocol selecting neighbors in the multicast tree is based not only on the link distance, but also on the error rates associated with the link.

Let $p_{i,j}$ denote the packet error probability of link (i, j). The expected number of transmissions to reliably transmit a single packet across this link is $1/(1 - p_{i,j})$. The expected energy requirements to reliably transmit a packet across the link (i, j) is given by $E_{i,j}$ (reliable) $= E_{i,j}/(1 - p_{i,j})$. The computation of a minimum-cost multicast tree will follow three steps as described below:

Step 1: Similar to Prim's algorithm, RBIP greedily adds links to an existing tree such that the incremental cost is minimized. However, because RBIP works on reliable transmission costs, these costs are a function of both the link distance and link error rates. The RBIP algorithm iteratively adds the minimum cost link from the set of eligible links to an existing tree. Hereafter, an energy-efficient broadcast tree has been formed.

Step 2: RBIP prunes those nodes from the tree that do not lead to any multicast group member. This processing is performed in a single post-order traversal.

Step 3: Finally, the sweep operations are performed on the remaining tree in post-order. A node x is transferred from being a child of its parent y to being a child of its grandparent z if doing so reduces overall energy requirements for reliable packet transmission costs.

The article also proposes two other reliable multicast protocols (RBLU and RBLiMST), which are the extensions of the protocols BLU and BLiMST, by considering $E_{i,j}$ (reliable) as the link cost in constructing the broadcast tree. Then Step 3 of RBIP can be applied to RBLU and RBLiMST to construct a reliable energy-efficient multicast tree.

11.3.1.2 Multi-Source Energy-Efficient Multicast Protocol

The multi-source multicasting problem is investigated in Wieselthier et al.[2] A multicast protocol G-REMiT is proposed[15] to reduce the energy cost of the constructed tree. G-REMiT consists of two phases. Similar to the S-REMiT protocol, G-REMiT constructs an MST in phase I and then refines the MST in phase II to reduce the energy cost of the constructed multicast tree.

G-REMiT employs an equation to evaluate the weight of each node. The energy consumption of each node in a multicast tree highly depends on the highest energy cost link and the second highest energy cost

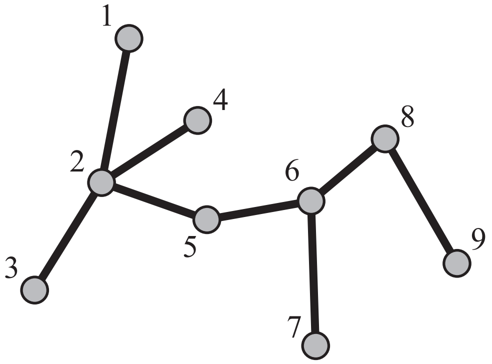

FIGURE 11.10 An example of evaluating the gain.

link. Take the multicast tree shown in Figure 11.10 as an example. Let the first and second highest energy cost links of node 2 be links $\overline{12}$ and $\overline{24}$, respectively. In the case that node 1 is a source node, node 2 will receive the multicast packet from node 1 and then transmit to its neighboring nodes 3, 4, and 5. The power consumption thus depends on the link $\overline{24}$, which is the second highest energy cost link. However, in the case that the source node is some other node rather than 1, node 2 will relay the message to neighboring nodes, including node 1. The power consumption of node 2 thus depends on the energy cost of link $\overline{12}$, which is the highest energy cost link. Thus, the energy cost of each node in MST could be evaluated by the following equation:

$$E_i = w_i[1](d_i[2])^\alpha + (|G| - w_i[1])(d_i[1])^\alpha + |G|E_{elec}$$

where $w_i[1]$ is the number of group nodes that depend on node i using the second furthest transmitted power to forward the multicast packets and G is the set of multicast group nodes; $d_i[j]$ is the distance of the j-th furthest neighboring node of node i; and E_{else} is a constant that accounts for real-world overheads of electronics and digital processing.

In phase I, a link-based minimum weight spanning tree is constructed as the initial tree. Phase II of G-REMiT improves the initial tree by exchanging some existing branches in the initial tree for new branches so that the total energy cost of the tree is lower. The difference in total energy cost of the trees before and after the branch exchange is called *gain*.

The second phase of S-REMiT is organized in rounds. In a round, assume node i in the MST obtains the G-REMiT token. One of the furthest connected neighbors in MST, say x, will be selected by node i. Another node j will be selected from candidate nodes that are communicative neighbors but not tree neighbors of i in the tree. Node i will replace link $\overline{ix}$ by link $\overline{ij}$ if this change improves the gain of power consumption of the tree.

Assume that node i obtains the G-REMiT token. Each node evaluates its energy cost E_i according to parameters that would include its largest link distance and the power consumption of data transmitting and receiving. The following algorithm details the second phase of the G-REMiT multicast protocol *G-REMiT multicast protocol:*

Step 1: Node i selects a farthest connected neighbor node x in the tree. If there is no such node x available, go to Step 6.

Step 2: Node i selects a new candidate node j that is located in its communicative range, to estimate the saving energy cost, called *gain*, after the link changes from $\overline{ix}$ to $\overline{ij}$. The gain $g_i^{x,j} := (E_i + E_x + E_j) - (E'_i + E'_x + E'_j)$, where E_i, E_x, E_j respectively, denote the energy cost at nodes i, x, and j in the original tree; and E'_i, E'_x, E'_j respectively, denote the energy cost at nodes i, x, and j after link change.

Step 3: Node i sends *Path_Exploring(path_gain)* message along $path_{j,i}$.Every node on the $path_{j,i}$ may change the *path_gain* value if its longest link is on $path_{j,i}$, and forwards hop-by-hop along $path_{j,i}$.

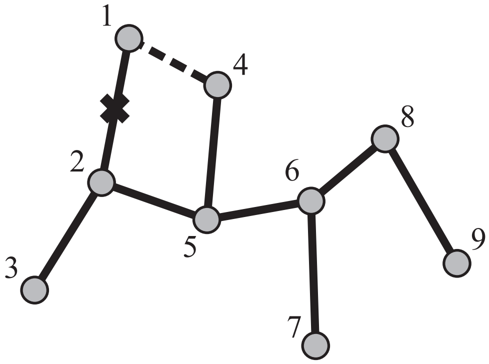

FIGURE 11.11 An example of executing the G-REMiT protocol.

When node i gets back *Path_Exploring*, it checks if *path_gain* is positive. Node i will go back to the first step to select another node x if *path_gain* is negative.

Step 4: Node i changes link $\overline{ix}$ to link $\overline{ij}$.

Step 5: Node i sends path-updating information along $path_{x,i}$ to update the local information of each node. Node i will locally broadcast to nodes located in its communicative range about the link change.

Step 6: Node i passes the token to the next node according to the DFS algorithm.

Figure 11.11 gives an example of G-REMiT. The execution of phase I will construct an MST as shown in Figure 11.11. Assume node 1 obtains the G-REMiT token; it selects node 2 from tree neighbors because node 2 has a largest energy cost. Then, node 1 replaces link $\overline{12}$ with some other link to reduce the total energy consumption of the tree. Node 1 considers those communicative neighbors as candidates to refine the multicast tree. Node 1 selects node 4 from candidates and then evaluates the gain $g_1^{2,4} := (E_1 + E_2 + E_4) - (E'_1 + E'_2 + E'_4)$, and checks if the path gain of $Path_{41}$ is positive. In the case that both gains are positive, node 1 will replace link $\overline{12}$ by $\overline{14}$, and notify its communicative neighbors about this change. Node 1 then passes the G-REMiT token to node 2 to refine the multicast tree.

The chapter proposes a distributed multicast protocol that dynamically refines the tree topology to reduce the energy consumption of the tree node and extend the network lifetime. However, operations designed for preventing the constructed tree from disconnection also creates a lot of control overheads.

11.3.2 Cluster-Based Power-Efficient Multicast Protocol

Numerous mechanisms have been proposed for reducing packet retransmission. Cluster management has been widely discussed to alleviate the packet flooding phenomenon. A network can be partitioned into several clusters, each consisting of a header, gateway (optional), and members. The information from two clusters can be directly exchanged by their headers if their distance is smaller than the communicative range, or it can be relayed by gateway, which is a common member shared by more than one cluster. Cluster headers and gateways can be treated as the nodes or backbone of the network and are responsible for relaying broadcast (or multicast) packets to all nodes (or all multicast members), thus preventing large amounts of packet retransmission and saving power consumption.

Tang et al.[16] applied the existing ODMRP[17] to cluster topology to achieve energy-efficient multicast communication. First, a clustering protocol was proposed for constructing a cluster where all nodes are capable of communicating with each other within that cluster. After executing the clustering algorithm, the network is partitioned into a set of disjoint clusters with a cluster head in each cluster. The cluster heads can be thought of as supernodes and they form a supernode network topology. The adaptation of ODMRP is proposed for the supernode topology. For balancing the energy consumption, nodes in the cluster take turns becoming cluster headers using some round-robin schedule. The work in Tang et al.[16]

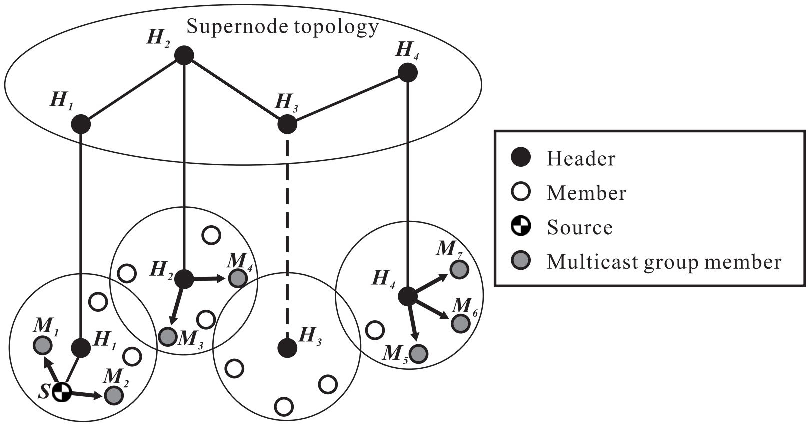

FIGURE 11.12 Adaptation of ODMRP.

takes advantages of balancing energy consumption from cluster management and the good multicast features of the existing multicast protocol to develop a power-efficient multicast protocol.

Based on the constructed supernode topology, the work in Tang et al.[16] proposes an adaptation scheme using the existing ODMRP to achieve the goal of energy conservation multicasting. Packets flow from the sender to its cluster header, then along the supernode topology, and finally get disseminated within the clusters. The following gives an example to illustrate the adaptation scheme. In Figure 11.12, a multicast source node S intends to send a multicast packet to receivers M_1, M_2, M_3, M_4, M_5, M_6, and M_7. Node S first broadcasts the message to all nodes within the same cluster. On receiving the multicast packets, header H_1 then forwards the packets to headers H_2 and H_4 along the supernode topology. The multicast packets thus can be received by all receivers from their headers.

The multicast data transmission highly relies on the supernode topology. Nodes in a cluster may take turns playing the header role, balancing the power consumption of nodes in the same cluster. However, supernode election in the clustering process does not take into consideration the energy cost among headers. This may introduce a large energy cost for transmitting multicast packets on supernode topology.

11.4 Conclusions and Future Works

Mobile ad hoc networks comprise mobile nodes that are power constrained because they operate with restricted battery power. Energy consumption is one of the most important issues in ad hoc networks. Selection of nodes to be active and control of the emitted transmission power are the most important issues in designing an energy-efficient protocol in MANETs. Broadcast and multicast routings are important operations in the network layer. Developing energy-efficient broadcast and multicast routing protocols reduces the power consumption of nodes and hence improves network lifetime.

This chapter reviewed existing, important energy-efficient broadcast and multicast protocols. Table 11.1 summarizes all reviewed energy-efficient broadcast protocols in this chapter. According to their different mechanisms, the broadcast routing protocols are categorized into two families: tree-based and probability-based approaches. The tree-based broadcast routing protocols[1–9] construct a *minimum-energy* broadcast tree by greedily selecting some nodes from networks and control their power level to maintain a broadcast tree with minimal energy consumption. By applying the probability-based approach, another family of protocols[10–13] was developed to reduce power consumption, alleviate the broadcast storm situation, or balance the power consumption. In addition to the study of broadcast routing protocols, this chapter also investigated some important energy-efficient multicast protocols. Table 11.2 summarizes all reviewed energy-efficient multicast protocols. According to the constructed topology, existing power-efficient multicast protocols are classified into tree-based and cluster-based protocols. The tree-based multicast

TABLE 11.1 Summary of Energy-Efficient Broadcast Protocols

	Tree-Based Approach				Probabilistic Approach	
Property Protocol [Ref.]	Centralized Algorithm	Distributed Algorithm	Integer Programming	Static Network	Broadcast Storm	Power-Balance
Centralized BIP [1]	•					
EWMA [3]	•					
IP [4]	•					
Minimum-Energy Broadcast in Static MANET [5]	•			•		
MST-based Heuristic in Static MANET [6]	•			•		
Weighted Steiner tree-based [7]	•			•		
DIST-BIP [8]		•				
RBOP [9]		•				
Alleviating "Broadcast Storm Problem" [10–12]					•	
Power-Balance Broadcast Protocol [11]						•

protocols^{2,4,15,19}consider the power consumption issue and obtain an energy-efficient multicast tree by applying refining and pruning rules to the existing energy-efficient broadcast tree. Another approach, which uses cluster topology to achieve the goal of energy-efficient multicasting, was also investigated in this chapter.

Numerous protocols address the broadcast and multicast problems with the goal of reduced power consumption, but most existing approaches were developed under the assumption of low mobility. Therefore, some future works should include the following:

1. A possible future work is how to design energy-efficient broadcast/multicast tree maintenance mechanisms with a mobility-tolerant capability. Because an ad hoc network is characterized by a highly dynamic topology, the impact of mobility should be incorporated into the protocol design, especially for some applications of wireless sensor networks (e.g., the object-tracking problem). Improved performance can be obtained by jointly considering the node failure, node move, and node join situations. To design tree maintenance protocols by reconstructing and reconfiguring the tree or cluster topologies with minimal changes to the original topology.
2. A major challenge in protocol design in MANETs is how to develop reliable broadcast and multicast routing protocols to simultaneously address the energy consumption cost and the number of packet retransmissions.
3. An interesting topic for future research is how to investigate the energy-efficient broadcast and multicast routing protocols by fully adopting the location information. Several algorithms are known to provide a node's location information in ad hoc and sensor networks. Location information is likely to be useful in calculating the node mobility and the power level required to maintain the constructed energy-efficient topology.

TABLE 11.2 Summary of Energy-Efficient Multicast Protocols

Property Protocol [Ref.]	Topology	Pruning or Refining Rules	Source in Tree	Characteristics
MIP [2]	Tree	Yes	Single	Power-efficient
S-REMiT [14]	Tree	Yes	Single	Power-efficient
RBIP [19]	Tree	No	Single	Reliable and power-efficient
G-REMiT [15]	Tree	Yes	Multiple	Group Communication and power-efficient
CBMP [16]	Cluster/tree	Yes	Multiple	Clustering and power-efficient

4. In addition, the use of directional antenna may benefit from the elimination of unnecessary interferences and the less power consumption by focusing the transmitting power in a specific direction. Involving directional antenna and location information in the design of broadcast and multicast routing protocols expectably provides advantages of increasing the network lifetime.

Consequently, how to utilize the location information, along with consideration of mobility, unreliable transmission, and the use of directional antenna, will possibly be the next challenge in the design of energy-efficient broadcast and multicast protocols.

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