Energy Efficient Multicast in Ad Hoc Networks

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Abstract

In mobile ad hoc networks (MANETs), energy efficiency is as important as general performance measures such as delay or packet delivery ratio since it directly affects the network lifetime. In this article we introduce two different approaches for energy efficient multicast protocols developed for MANETs. The first group of energy efficient multicast protocols is based on the assumption that the transmission power is controllable. Under this assumption, the problem of finding a tree with the least consumed power becomes a conventional optimization problem on a graph where the weighted link cost corresponds to the transmission power required for transmitting a packet between two nodes of the link. The second approach focuses on maximizing sleep mode operation supported by the lower level protocol. A mobile node in tree-based protocols can safely put itself into a low power sleep mode for conserving energy if it is not a designated receiver with the employed broadcast-based mesh protocols. It is shown that mesh-based protocols are more robust to mobility but tree-based protocols may be preferable when energy is a primary concern.

1. Introduction

Wireless connectivity with mobility support has become an important issue in the modern computing infrastructure. Especially, *mobile ad hoc networks* (MANETs) [9,11] attract a lot of attention with the advent of inexpensive wireless LAN solutions such as *IEEE 802.11* [12], *HIPERLAN* [31] and *Bluetooth* [4] technologies. Since they do not need communication infrastructure in their basic forms and utilize *unlicensed ISM (Industrial, Scientific, and Medical) band*, they are highly likely to be rapidly adopted. Applications of MANETs encompass various areas including home-area wireless networking, on-the-fly conferencing, disaster recovery, wireless sensor networks [20], and *GSM (Global System for Mobile telecommunications)* service extension covering dead spots [1]. For an extensive description on MANET, refer to [19].

This article investigates energy efficient multicast for MANETs. Multicasting has been extensively studied for MANETs because it is fundamental to many ad hoc network applications requiring close collaboration of the member nodes. A multicast packet is delivered to multiple receivers along a network structure such as *tree* or *mesh*, which is constructed once a multicast group is formed. However, the network structure is fragile due to node mobility and, thus, some members may not be able to receive the multicast packet. In order to improve the *packet delivery ratio*, multicast protocols for MANETs usually employ control packets to refresh the network structure periodically. It has been shown that *mesh-based protocols* are more robust to mobility than *tree-based protocols* [15] due to many redundant paths between mobile nodes in the mesh. However, multicast mesh may perform worse in terms of energy efficiency because it uses costly broadcast-style communication involving more forwarding nodes than multicast trees. Another important aspect of energy efficiency is balanced energy consumption among all participating mobile nodes. In order to maximize the lifetime of a MANET, care has to be taken not to unfairly burden any particular node with many packet-relaying operations. Node mobility need also be considered along with energy balancing.

The rest of the article is organized as follows. Multicasting for MANETs is discussed in Section 2. Section 3 discusses energy efficient multicast protocols proposed for MANETs and analyzes the energy efficiency assuming a static ad hoc network. Finally, concluding remarks are in Section 4.

2. Multicast Protocols for MANETs

This section briefly overviews the research efforts in multicast protocols for MANETs. They can be largely categorized into two types, *tree-based multicast* and *mesh-based multicast*, based on the multicast delivery structures. Tree-based multicast is generally used in wired and infrastructured mobile networks (*i.e.*, mobile networks with base stations) as well as in MANETs. Depending on the number of trees per multicast group, tree-based multicast can be further classified as *per-source tree multicast* and *shared tree multicast*.

A new approach unique to MANETs is the *mesh-based multicast*. A mesh is different from a tree since each node in a mesh can have multiple parents. Using a single mesh structure spanning all multicast group members, multiple paths exist and other paths are immediately available when the primary path is broken. This avoids frequent network reconfigurations, which results in the minimization of disruption of on-going multicast sessions and reduction of the overhead in implementing the protocol. However, care must be taken to avoid forwarding loops when multicast data is forwarded in a multicast mesh.

2.1 Tree-based Multicast

As mentioned earlier, there are two versions of tree-based multicast in a MANET: *per-source tree* and *shared tree multicast*. Per-source based tree is established and maintained for each multicast source node of a multicast group. The advantage is that each multicast packet is forwarded along the most efficient path from the source node to each and every multicast group member. However, this method incurs a lot of control overhead and cannot quickly adapt to the movements of the nodes in a MANET.

On the other hand, shared tree multicast is a more scalable approach than the per-source tree approach. Instead of building multiple trees for each multicast group, a single shared tree is used for all multicast source nodes. Multicast packets are distributed along this shared tree to all members of the multicast group. To establish a shared tree, a special node is designated as a *core node*, which is responsible for creating and maintaining the shared tree. Hence, a *core selection algorithm* is needed.

The established shared tree can be either *unidirectional* or *bi-directional*. In a unidirectional shared tree, multicast packets must be unicast to the core node, which is the root of the tree. From the core node, the multicast packets are distributed along the shared tree until they reach all the multicast group members. However, in a bi-directional shared tree, multicast packets can enter the shared tree at any point and they are distributed along all the branches of the shared tree. The shared tree approach has lower control overhead, but the path is not necessarily optimal, *i.e.*, the path from a multicast source to a receiver is not necessarily the shortest. Furthermore, in a dynamic network, throughput can be deteriorated dramatically unless the core node and shared tree quickly adapt to the node mobility.

Figure 1 shows an example of a shared unidirectional tree multicast. The tree consists of a root node (r), four intermediate forwarding nodes (p, q, s, and t), seven receiver nodes of a multicast group (gray-colored nodes) and eleven tree links. In the shared tree scheme, receiver nodes periodically send *join requests* to the root node and the root updates the multicast tree using the path information included in the join request messages [3]. Joining a multicast group causes reports (*i.e.*, join messages) to be periodically sent [15], while leaving a multicast group does not lead to any explicit action. The period must be carefully chosen to balance between the overhead associated with tree update and the delay caused by the tree not timely updated when the nodes move [26]. Various tree-based multicast protocols have been proposed, and here some representative ones are briefly reviewed.

Figure 1: An example of tree-based multicast.

Adhoc Multicast Routing Protocol (AMRoute) [2] creates a bi-directional shared tree per multicast group. The tree contains only the group members, and multicast tunnels (*virtual links*) are assumed to exist between each pair of group members based on an underlying routing protocol. Therefore, the tree need not be reconstructed even though the network topology changes as long as routes between the group members exist. **Ad-hoc On-Demand Distance Vector Multicast Protocol (AODV)** [21] is another bi-directional shared tree multicast protocol. Here, if the sender does not belong to the multicast group, it first finds the nearest group member and lets it become a root for delivering the multicast packets.

Ad hoc Multicast Routing protocol utilizing Increasing-idS (AMRIS) [32] is a shared tree multicast approach. Each node has *multicast session member id (msm-id)*. The msm-id provides each node with an indication of its "logical height" in the multicast delivery tree such that it increases as it radiates from the root of the delivery tree. **Lightweight Adaptive Multicast (LAM)** [10] builds a group-shared multicast routing tree centered at a pre-selected node called a *CORE*. LAM runs on top of *TORA (Temporally Ordered Routing)* protocol [18]; each node has information on its neighbors and the correct order of transmission path. Each member prepares a *JOIN message* containing the group id and the target *CORE* id, picks the neighbor with the lowest height as the receiver of the *JOIN* message, and sends the message. Since the *JOIN* message is supposed to travel along only a "downwards" path in the TORA DAG (directed acyclic graph) with respect to the target *CORE*, if a *JOIN* message is received over an upstream link, the tree is considered invalid and a valid one is constructed rooted at the *CORE*.

In **Associativity-Based Multicasting Routing Protocol (ABAM)** [25], a multicast sender builds a per-source multicast tree with *MBQ-REPLY* messages sent by member receivers who received *MBQ (multicast broadcast query)* message from the sender. The multicast sender decides a stable multicast tree based primarily on association stability, which refers to spatial, temporal, connection, and power stability of a node with its neighbors, and it generates an *MC-SETUP* message to establish the multicast tree. **Multicast Routing Protocol based on Zone Routing (MZR)** [5] is another per-source tree approach, in which a multicast delivery tree is created using a concept called the *zone routing mechanism*. A proactive protocol runs inside each zone, maintaining an up-to-data zone routing table at each node. A reactive multicast tree is created for inter-zone routing.

Figure 2: An example of mesh-based multicast.

2.2 Mesh-based Multicast

Tree-based protocols may not perform well in the presence of highly mobile nodes because multicast tree structure is fragile and needs to be readjusted frequently as the connectivity changes. Mesh-based multicast protocols have been proposed to address the problem by constructing a mesh structure with redundant links between mobile nodes. Figure 2 shows an example of mesh-based multicast for the MANET of Figure 1. Note that it includes three redundant links (marked in the figure) in addition to eleven tree links. As a result, even though the tree link from s' to v' is broken, node v' receives a multicast packet through the redundant link from t' to v'. Mesh-based protocols are more robust to mobility and thus allows better *packet delivery ratio*. We now present several mesh-based multicast protocols.

Multicast Core-Extraction Distributed Ad hoc Routing (MCEDAR) [24] is an extension to the *CEDAR routing protocol* [23], and it provides the robustness of mesh based routing protocols while approximating the efficiency of tree based protocols. As CEDAR extracts core nodes, MCEDAR extracts a subgraph (called as *mgraph*) for each multicast group consisting only of core nodes as the routing infrastructure used for data forwarding. **Clustered Group Multicast (CGM)** [16] employs *advertising agents* to reduce traffic, which act as both a server and client for advertising join requests on behalf of its local clients. Multicast backbone is also used to reduce the control overhead. By implementing CGM over the multicast infrastructure, the cluster head works as an advertising agent if one or more subscribers are within its cluster, and the inter-cluster routing approach lets the number of nodes in the backbone be smaller. **Core-Assisted Mesh Protocol (CAMP)** [6] adopts the same basic architecture used in IP multicast. A node wishing to join a multicast mesh first consults a routing table to determine whether it has neighbors which are already members of the mesh. If so, the node announces its membership via a *CAMP UPDATE*. Otherwise, the node either propagates a *JOIN REQUEST* towards one of the multicast group "cores," or attempts to reach a member router by an expanding ring search of broadcast requests.

On-Demand Multicast Routing Protocol (ODMRP) [13] employs on-demand routing techniques to avoid channel overhead and improve scalability. It uses the concept of *forwarding group*, a mesh of nodes responsible for forwarding multicast data on shortest paths between any member pairs. During the control message exchange between senders and group receivers (*JOIN REQUEST* and *JOIN TABLE*), a node realizes that it is part of the forwarding group when it is on the path from a receiver to the source. **Neighbor Supporting Multicast Protocol (NSMP)** [13] utilizes node locality to reduce the overhead of route failure recovery and mesh maintenance. A new source initially sends a *FLOOD REQ (FR)* packet containing an upstream node field. When an intermediate node receives it, it caches its upstream node and updates the field with its own address before forwarding it. When a receiver receives the *FR* packet, it sends an *REP* packet. The upstream node receives the *REP* packet and adds an entry for the group to its routing table, and the *REP* packet is forwarded eventually to the source node.

3. Energy Efficient Multicast Protocols

There are two approaches proposed for energy efficient multicast in MANETs. The first one is based on the assumption that the transmission power is controllable. Under this assumption, the problem of finding a tree with the least consumed power becomes a conventional optimization problem on a graph where the weighted link cost corresponds to the transmission power required for transmitting a packet between two nodes.

The second approach for energy efficiency comes from the difference of tree-based multicast with mesh-based multicast. One general idea of the power-saving mechanism is to put a mobile node in sleep (low power) mode while it is not sending or receiving packets. Since every mobile node in the mesh must not sleep and be ready to receive packets during the entire multicast session, it would consume more energy. Even though data transmission through wireless medium is broadcast in nature, it does not necessarily mean that all neighbor nodes have to receive the broadcast packets. Unicast transmission along the multicast tree is quite different from the intentional broadcast within the multicast mesh in that only the designated receiver needs to receive the transmitted data. A mobile node in tree-based protocols can safely put itself into a low power sleep mode conserving energy if it is not a designated receiver.

As mentioned in Introduction, another important aspect of energy efficiency is the balanced energy consumption among all participating mobile nodes. For example, consider a multicast tree shared by a number of multicast senders. In the shared tree, the root node of the tree consumes more battery energy and stops working earlier than the other nodes. This affects the network connectivity and may lead to partitioning of the MANET and reduced network lifetime. Per-source tree-based multicast protocol alleviates this problem by using a separate tree per sender at the cost of increased tree management overhead [28,30]. Node mobility need also be considered along with energy balancing.

This section discusses the two approaches in Section 3.1 and 3.2, respectively. Section 3.3 quantitatively evaluates the multicast protocols in terms of energy efficiency.

3.1 Energy Efficiency via Adaptive Transmission Power Control

Network performance in a MANET greatly depends on the connectivity among nodes and the resulting topology. To create a desired topology for multicast, some multicast protocols adjust the nodes' transmission power assuming that it is controllable.

Broadcast Incremental Power (BIP) and Multicast Incremental Power (MIP) [28,29]

The object of BIP is the determination of the minimum-cost (in this case, minimum-power) tree, rooted at the source node, which reaches all the other nodes in the network. The total power associated with the tree is simply the sum of the powers of all transmitting nodes. Initially, the tree consists of the source node. BIP begins by determining the node that the source node can reach with minimum power consumption, *i.e.*, the source' nearest neighbor. BIP then determines which new node can be added to the tree at minimum additional cost (power). That is, BIP finds a new node that can be reached with minimum incremental power consumption from the current tree node. This procedure is repeated until there is no new (unconnected) node left. BIP is similar to *Prim's algorithm* for the formation of *MST (minimum spanning tree)*, in the sense that new nodes are added to the tree one at a time on the basis of minimum cost until all nodes are included in the tree. Unlike Prim's algorithm, however, BIP does not necessarily provide minimum-cost trees for wireless networks.

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. That is, the nodes with no downstream destinations will not transmit, and some nodes will be able to reduce their transmitted power (*i.e.*, if their distant downstream neighbors have been pruned from the tree). MIP is basically source-initiated tree-based multicasting of session (connection-oriented) traffic in ad hoc wireless networks. In both BIP and MIP, for simplifying trade-offs and evaluation of total power consumption, only the transmission energy is addressed and it is assumed that the nodes do not move and a large amount of bandwidth are available. Advantages over traditional network architectures come from the fact that the performance can be improved by jointly considering physical layer issues and network layer issues (*i.e.*, by incorporating the vertical integration of protocol layer functions). That is, the networking schemes should reflect the node-based operation of wireless communications, rather than link-based operations originally developed for wired networks. The quantitative analysis of BIP in terms of approximation ratios can be found in [26].

Single-Phase Clustering (SPC) and Multi-Phase Clustering (MPC) [22]

The two distributed, time-limited energy conserving clustering algorithms for multicast, SPC and MPC, minimize the transmission power in 2-tiered mobile ad hoc networks. In SPC, each master node pages the slave nodes at the same maximum power, and each slave node acknowledges the corresponding master node having the highest power level. The highest power at a slave node means that the paging master node is nearest to it; hence the transmission power could be saved when the slave node selects the master node that provides the highest receive power. When slave nodes send acknowledgement to each master node, the master nodes set the transmission power level to support all acknowledged slave nodes.

MPC consists of the *dropping-rate-down phase* and *power-saving phase*. In the dropping-rate-down phase, master nodes search the slave nodes which could receive the multicasting stream from only one master node. The corresponding master nodes set the transmission power level to support those slave nodes, and then the searched slave nodes belong to the corresponding master node. In subsequent power-saving phase, each master node pages the information about current power level. Paged slave nodes must have two or more candidate master nodes; hence each slave node selects one master node based on the difference of the current power (P_0) and the power to support the master node (P_n). When the master node is selected, the slave node acknowledges the master node with P_n, and each master node resets the transmission power level with the maximum value between the acknowledged P_n values.

The schemes are motivated by the fact that the most hierarchical networks such as *Bluetooth scatternet* are 2-tier networks. The amount of energy consumption in 2-tier mobile ad hoc networks could be varied with cluster configuration (*e.g.*, the master node selection). However, the optimal cluster configuration cannot be obtained within a limited time required for running heuristic multicast algorithm. It is assumed that a slave node must be connected to only one master node and the direct connection between the master node and a slave node is prohibited. MPC is desirable when energy conservation is more important than computation speed. Otherwise, SPC is preferable.

3.2 Energy Savings by Avoiding Broadcast-based Multicast

As described in Introduction, recent wireless LAN standards usually adopt sleep mode operation in order to reduce power consumption, *i.e.*, a communication subsystem goes into a sleep mode conserving energy if it has no data to send or receive. If a node sends a packet in unicast mode specifying a receiving node, other nodes except the receiver can continue to sleep. However, when a node sends a packet in broadcast mode, all neighbor nodes have to wake up and receive the packet even though they may eventually discard them. Since mesh-based multicast protocols depend on broadcast-style communication, they are not suitable in energy-constraint environment. Based on this observation, the following multicast protocol employs multicast tree but tries to improve the packet delivery ratio to the level achieved by mesh-based protocols.

Two-Tree Multicast (TTM) [17]

This protocol tries to reduce the total energy consumption while alleviating the energy balance problem without deteriorating the general performance. Since TTM is based on multicast trees, it inherits all the advantages of tree-based multicast protocols in terms of total energy consumption. TTM adopts shared-tree multicast rather than per-source tree multicast in order to avoid the tree construction overhead. It consumes less energy than mesh-based protocols by employing multi-destined unicast-based trees. As for the energy balance problem found in conventional single shared tree-based multicast (STM), TTM uses two trees called *primary* and *alternative* tree. When the primary tree becomes unusable or overloaded, the alternative tree takes the responsibility of the primary tree and a new alternative tree is immediately constructed. By doing so, TTM maintains only two trees at a particular time instance, but, in fact, it uses many trees per multicast group as time advances. This is in contrast with a multicast mesh which can be regarded as a superposition of a number of trees at a time instance.

It is similar to the relocation scheme [7], where the root node is periodically replaced with the one near to center location to achieve the shortest average hop distance from the root to all receiver nodes. In TTM, a group member with the largest remaining battery energy is selected to replace the root node and the corresponding alternative tree is constructed and maintained to replace the primary tree. The selection of an alternative root is made in advance to provide a better quality of communication service.

Using the same example of Figure 1, Figure 3 shows the two trees constructed for a multicast group of eight members (one sender and seven receiver nodes). The primary tree consists of a primary root (r_p), four forwarding nodes (p, q, s, and t) and seven receiver nodes, while the alternative tree consists of an alternative root (r_a), four forwarding nodes (p, r_p, s, and t) and seven receiver nodes.

Figure 3: An example of two trees in TTM.

The TTM protocol performs as follows: Two trees are periodically reconstructed (*e.g.*, every 3 seconds [15]) by periodic join messages (with the information on remaining battery energy) sent by all receiver nodes to r_p and r_a. The two root nodes independently construct multicast trees based on the forwarding paths that the join messages traverse. When a sender node intends to send a multicast message, it forwards the multicast message to r_p to be broadcast by the root node as in most shared multicast tree protocols [7,15].

3.3 Tree-Based versus Mesh-Based Multicast Protocols

This subsection compares tree-based multicast protocol with mesh-based protocols as briefly introduced in Section 3.2, followed by quantitative evaluation in terms of energy efficiency. For the example of

Figure 1, receiver node *u* receives packets through node *r*, *s*, *t*, and *u*. It requires three transmissions and three receives. Now, consider the last transmission from node *t* to *u*. Even though it can be received by all neighbor nodes within node *t*'s radio transmission range, those nodes except node *u* would not receive the multicast packet but stay in sleep mode because the packets are not addressed to them.

On the other hand, a multicast packet is broadcast within a multicast mesh as shown in Figure 2. From node r' to u', it involves four transmissions and seventeen receives incurring much larger energy consumption than the tree-based multicast. For example, the transmission from node t' is received not only by node u' but also by node s', v' and w'. The neighbor nodes receive the data packet because the mesh-based protocol relies on the broadcast-style communication for improved packet delivery ratio. The redundant link from node t' to v' may be useful when the path from node s' to v' is broken. Node *w* receives the multicast packet from node *t* because the packet is broadcast. However, the transmission from node t' to w' is of no use at all because node w' is neither a member nor an intermediate node (forwarding group) of the multicast group. Thus, it discards the packet but wastes energy to receive the packet (refer to as discarded links). Note here that node t' also sends the packet back to node s' since the packet is broadcast. Node s' will ignore the packet but waste additional energy for receiving it.

Based on the discussion above, we compare tree-based and mesh-based protocols with an analytic energy model. For simplifying our analysis, static ad hoc networks are assumed.

Energy Model (First-Order Radio Model)

Let the total energy consumption per unit multicast message be denoted as E, which includes the transmission energy as well as the energy to receive the packet. We consider only data packets to analyze the total energy consumption for simplicity. According to the first-order radio model [8],

$$E = E_{TX} + E_{RX} = N_{TX} \times e_{TX} + N_{RX} \times e_{RX}$$

where N_{TX} and N_{RX} are the number of transmissions and receives, respectively, and e_{TX} and e_{RX} are the energy consumed to transmit and receive a unit multicast message via a wireless link, respectively. If e_{TX} and e_{RX} are assumed to be the same and denoted by e, the total energy consumption is simply $E = (N_{TX} + N_{RX})e$.

Thus, it is straightforward to show that in a multicast tree N_{TX} is the number of tree nodes except the leaf receiver nodes (*i.e.*, root and intermediate nodes) and N_{RX} is the number of tree links. In a multicast mesh, N_{TX} is the number of tree nodes (*i.e.*, root, intermediate, and receiver nodes) for the multicast group and N_{RX} can be obtained by *(the number of tree links + the number of redundant links)* $\times$ *2 + the number of discarded links*. Along a tree or a redundant link, two receives occur as exemplified in Figure 2 (*i.e.*, node t' receives a multicast packet from node s' and, then, node s' receives the packet from node t' along the same tree link).

Figure 4: Examples of tree-based multicast on an 8×8 grid network.

Example Network Model (Static Ad Hoc Network)

Consider a static ad hoc network consisting of k^2 nodes placed in a $k \times k$ grid. Figure 4 shows examples of tree-based multicast on an 8×8 grid network with node connectivity of 4 and 8. Figure 5 shows examples of mesh-based multicast on an 8×8 grid network. For upper bound analysis, we focus on complete multicast, where all the nodes in a network are member nodes as in Figures 4(a), 4(d), 5(a) and 5(d). Figures 4(b), 4(e), 5(b) and 5(e) show the worst cases where the total energy consumption is about the same as the complete multicast but with fewer number of member nodes, *i.e.*, member nodes reside at the edges of the network. Figures 4(c), 4(f), 5(c) and 5(f) show the best cases where a multicast tree or mesh consists of only member nodes and, thus, the total energy consumption is the least with the given number of member nodes.

Quantitative Analysis [17]

The following two theorems formally analyze the upper and lower bounds of total energy consumption in a static ad hoc network stated above. Theorem 1 analyzes the tree-based multicast, while Theorem 2 analyzes the mesh-based multicast.

Theorem 1: For a static ad hoc network of $k \times k$ grid topology with node connectivity of f, the total energy consumed to transfer a multicast message in a tree-based multicast method, E_{tree}, is bounded by $(2n - O(n^{1/2}))e \leq E_{tree} \leq (2k^2 - O(k))e$, where n is the number of member nodes and e is the energy consumed to transmit or receive a multicast message via a link.

Proof : Given a static ad hoc network of $k \times k$ grid topology with node connectivity of f, the total energy consumption of a tree-based multicast method for complete multicast can be regarded as the upper bound. In a complete multicast, $N_{TX} = k^2 - O(k)$, where $O(k)$ is mainly due to the boundary nodes having smaller node connectivity than f, and $N_{RX} = k^2 - 1$ since, given a tree with n nodes, the number of edges is $n - 1$. Hence, $E_{tree} \leq (N_{TX} + N_{RX})e \leq (2k^2 - O(k))e$. In the best case, where a multicast tree consists of only member nodes, $N_{TX} = n - O(n^{1/2})$ and $N_{RX} = n - 1$. Hence, $(2n - O(n^{1/2}))e \leq E_{tree}$. **Q.E.D.**

Figure 5: Examples of mesh-based multicast on an 8×8 grid network.

Theorem 2: For a static ad hoc network of $k \times k$ grid topology with node connectivity of f, the total energy consumed to transfer a multicast message in a mesh-based multicast method, E_{mesh}, is bounded by $((f+1)n - O(n^{1/2}))e \leq E_{mesh} \leq ((f+1)k^2 - O(k))e$. n and e are defined as in Theorem 1.

Proof: Given a static ad hoc network of $k \times k$ grid topology with node connectivity of f, the total energy consumption in a complete mesh-based multicast can be regarded as the upper bound. In the complete multicast, $N_{TX} = k^2$ and $N_{RX} = fk^2 - O(k)$ since the mesh-based multicast protocol uses broadcast-style communication $(O(k)$ is due to the boundary nodes having smaller node connectivity than f). Hence, $E_{mesh} \leq (N_{TX} + N_{RX})e \leq ((f+1)k^2 - O(k))e$. In the best case, where a multicast mesh consists of only member nodes, $N_{TX} = n$ and $N_{RX} = fn - O(n^{1/2})$. Hence, $((f+1)n - O(n^{1/2}))e \leq E_{mesh}$. **Q.E.D.**

According to Theorems 1 and 2, $E_{mesh}/E_{tree} \approx (f+1)/2$ in the worst and best cases. Since node connectivity, f, is usually much larger than 2 to avoid MANET partitioning, mesh-based multicast protocols consume around $(f+1)/2$ times more energy than tree-based multicast protocols. The analysis above is based on the assumption that all nodes are located in a grid style. Even when the nodes are located in an arbitrary manner, if the variance of node connectivity is small enough, the analysis is still valid because the node connectivity is directly related to the tree structure and the number of transmissions.

4. Conclusion

We have discussed energy efficient multicast protocols proposed for MANETs. There are two different approaches. The first one is based on the assumption that the transmission power is controllable. Under this assumption, the problem of finding a tree with the least consumed power becomes a conventional optimization problem. The second approach is to exploit low power sleep mode as much as possible by avoiding costly broadcast operations. Unicast transmission along the multicast tree is more energy efficient than the broadcast-style communication used in the multicast mesh. A mobile node in tree-based protocols can safely put itself into energy conserving sleep mode if it is not a designated receiver. Quantitative analysis is also presented to show that mesh-based protocols consume around $(f+1)/2$ times more energy than tree-based protocols, where f is the node connectivity $(f >> 2)$.

The need for energy efficiency is due to the constraints imposed by battery capacity and heat dissipation. The battery and heat remove technology have been traditionally improved at a slower pace than the rate of computation power increase and the size of wireless device decrease. The key to energy efficiency in future wireless terminals will be at the higher levels of network protocols: low-energy protocols, energy-cognizant user interfaces, context dependent, and predictive shutdown management. The networked operation of a wireless device opens up additional techniques for increasing energy efficiency. Techniques for dynamically offloading computation from local terminals to remote, energy rich nodes are also interesting. Other techniques include making various network protocols energy aware such as links, MAC routing, and transport protocols so that they continually strive to provide the most energy efficient transport of application data while meeting the desired QoS.

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