Energy Efficient and Robust Multicast Protocol for Mobile Ad Hoc Networks

Sangman Moh
Electronics and Telecommunications Research Institute
Daejeon, Korea
smmoh@etri.re.kr

Chansu Yu
Dept. of ECE
Cleveland State Univ.
Cleveland, OH 44115
c.yu91@csuohio.edu

Ben Lee
Dept. of ECE
Oregon State Univ.
Corvallis, OR 97331
benl@ece.orst.edu

Hee Yong Youn
School of ECE
Sungkyunkwan Univ.
Suwon, Korea
youn@ece.skku.ac.kr

Abstract

This paper reevaluates the multicast protocols for MANETs in terms of energy efficiency and proposes a new robust multicast protocol, called Two-Tree Multicast (TTM). Multicast protocols can be broadly categorized into two types, tree-based multicast and mesh-based multicast, based on the network structure along which multicast packets are delivered to multiple receivers. Mesh-based protocols are more robust to mobility and result in high packet delivery ratio. On the other hand, multicast trees are more energy efficient than multicast meshes. This is because mesh-based protocols depend on broadcast flooding within the mesh and therefore, mobile nodes in the mesh must receive all multicast packets during the multicast communication. The proposed TTM uses two trees, a primary and an alternative backup tree, to improve energy efficiency compared to the mesh-based protocols and to offer a better energy balance and packet delivery ratio than the tree-based protocols. Performance evaluation study shows that the proposed TTM saves energy consumption by a factor of 1.9~4.0 compared to the mesh-based multicast. In terms of combined performance metric, energy per delivered packet, TTM shows up to 80% and 40% improved performance than the mesh-based multicast and the conventional shared tree multicast, respectively.

1. Introduction

Wireless connectivity with mobility support will become an important enabling technology in future computing infrastructures. In particular, *mobile ad hoc networks* (MANETs) [1, 2] have attracted a lot of attention with the advent of inexpensive wireless LAN solutions such as IEEE 802.11, HIPERLAN, and Bluetooth technologies. In a MANET, each node either communicates directly with other nodes or indirectly through intermediate nodes. Thus, all nodes in a MANET basically act as mobile routers in the process of deciding and maintaining routes without a fixed communication infrastructure, such as base stations. Since MANETs are infrastructure-less, self-organizing, rapidly deployable wireless networks, they are highly suitable for applications such as home-area wireless networking, on-the-fly conferencing, disaster recovery, wireless sensor networks, and GSM (Global System for Mobile telecommunications) service extension to dead spots. Please refer to [3] for an extensive discussion on MANETs.

This paper presents an energy efficient and robust multicast for MANETs. Multicasting has been studied extensively for MANETs because its operation 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 periodically refresh the network structure. It has been shown that *mesh-based protocols* are more robust to mobility than *tree-based protocols* [4] due to many redundant paths between mobile nodes in the mesh. However, a 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.

Based on the aforementioned discussion, this paper proposes the *Two-Tree Multicast* (TTM) protocol for MANETs. By maintaining two trees, called *primary* and *alternative trees*[1], TTM consumes less energy than the mesh-based multicast and performs better than the conventional tree-based multicast in terms of packet

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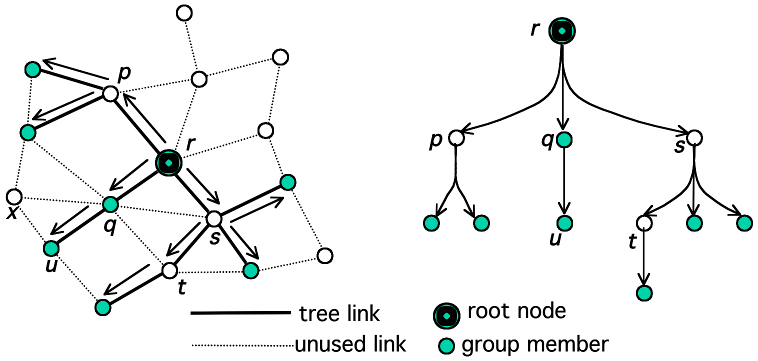
[1] *Alternative path routing (APR)* pursued the similar idea for routing in MANETs, where the main goal is to continually provide a path even though the current path becomes invalid due to node mobility [5].



(a) 8-node multicast group (including the root node *r*)

(b) The corresponding multicast tree

Figure 1. An example of tree-based multicast.

delivery ratio. Simulation study based on QualNet simulator [6] shows that the proposed TTM saves energy by a factor of 1.9~4.0 compared to the mesh-based multicast. A combined performance metric, called *energy per delivered packet*, has also been measured to assess the general performance together with energy, which shows that TTM outperforms the mesh-based and tree-based multicast by up to 80% and 40%, respectively.

The rest of the paper is organized as follows: Earlier multicast protocols for MANET are described in the following section. The proposed energy efficient TTM protocol is discussed in Section 3. Section 4 presents our simulation study, which shows the superiority of TTM compared to mesh-based and tree-based multicast. Finally, concluding remarks are given in Section 5.

2. Multicast Protocols for MANETs

This section briefly overviews the research efforts for multicast protocols targeting MANETs. They can be broadly categorized into two types, *tree-based multicast* and *mesh-based multicast*, based on the multicast structure.

Tree-based Multicast

Tree-based multicast is generally used in wired and infrastructured mobile networks (*i.e.*, mobile networks with base stations) as well as in MANETs. Figure 1 shows an example of a multicast tree. The tree consists of a root node (r), three intermediate nodes (p, s, and t), seven member nodes of a multicast group, and ten tree links. A multicast packet is delivered from the root node r to seven group members. For node u, for instance, the packet transmission is relayed through two tree links, *i.e.*, from r to q and then q to u. This requires two transmissions and two receives. Now consider the last transmission from q to u. Even though all nodes within node q's radio transmission range can receive the multicast packet, only node u will receive the packet since the rest of the nodes are not addressed[2] [3, 4].

In order to maintain the tree structure even when nodes move, group members periodically send *join requests* to the root node so that the multicast tree can be updated using the path information included in the join request messages. Joining a multicast group causes reports (*i.e.*, join messages) to be periodically sent, while leaving a multicast group does not lead to any explicit action. The period must be carefully chosen to balance the overhead associated with tree update and the delay caused by the tree not being timely updated when nodes move [4, 8, 9].

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* [10]. While per-source tree is established and maintained for each source node of a multicast group, shared tree multicast utilizes a single shared tree for all multicast source nodes. In the per-source tree, each multicast packet is forwarded along the most efficient path from the source node to each and every multicast group member, but this method incurs a lot of control overhead to maintain many trees. On the other hand, shared tree multicast has lower control overhead because it maintains only a single tree for a multicast group and thus is more scalable [8, 11]. However, the path is not necessarily optimal, and the root node is easily overloaded due to the sharing of the single tree.

Mesh-based Multicast

Aforementioned tree-based protocols, however, may not

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[2] Recent wireless LAN standards, such as IEEE 802.11, usually adopt *sleep period operation* in order to reduce power consumption, *i.e.*, a communication subsystem goes into energy conserving sleep mode if it has no data to send or receive [7]. If a node sends a unicast packet to a receiver, other neighbor nodes except the receiver do not receive the packet, and continue to sleep to save precious energy. However, when a node sends broadcast a packet, all neighbor nodes must wake up and receive the packet.

perform well in the presence of highly mobile nodes because multicast tree structure is fragile and needs to be frequently readjusted as the connectivity changes. 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 links exist and other links are immediately available when the primary link is broken due to node mobility. This avoids frequent network reconfigurations, which minimizes disruptions of on-going multicast sessions and reduces the control overhead to reconstruct and maintain the network structure. Note that these redundant links become available because multicast packets are broadcast forwarded.

Figure 2 shows an example of the mesh-based multicast for the MANET of Figure 1. Note that it includes six redundant links in addition to ten tree links. A multicast packet is broadcast within a multicast mesh. Thus, sending a packet from *R* to *U* involves three transmissions (*R*, *Q* and *U*) and fourteen receives (5 neighbors of *R*, 6 neighbors of *Q*, and 3 neighbors of *U*). For example, the transmission from node *Q* is received not only by *U* but also by neighbor nodes *R*, *S*, *T*, *W*, and *X*. The redundant link from *Q* to *W* may be useful when the path from *P* to *W* is broken as shown in Figure 2(b). Although these redundant communications can be useful, they also waste more energy in battery-operated mobile nodes. Some redundant links are not used at all. For example, a transmission from *Q* to *X* is of no use because *X* is neither a member nor an intermediate node of the multicast group. Node *X* wastes energy receiving the packet but eventually discards it. In summary, the broadcast forwarding produces redundant links, which improves the packet delivery ratio but spends more energy than the tree-based multicast.

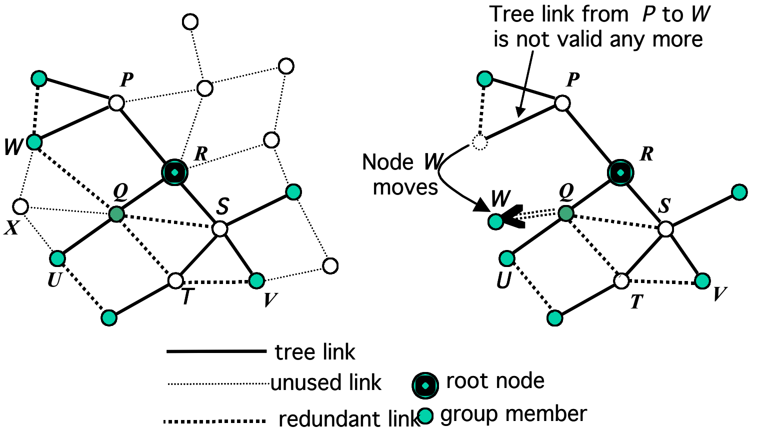
Comparison of Multicast Protocols

Table 1 compares the various multicast protocols. As explained above, mesh-based multicast protocols perform better than tree-based protocols in terms of general performance, such as packet delivery ratio and latency.

However, tree-based protocols are more preferable when energy is the primary concern. A quantitative analysis showed that mesh-based multicast consumes around $(f+1)/2$ times more energy than tree-based multicast, where f is the average node connectivity [12]. Another important aspect of energy efficiency is balanced energy consumption among all participating mobile nodes. Shared tree multicast is particularly bad in this regard because the root of the tree takes on more responsibility for routing, consumes more battery energy, and stops working earlier than other nodes. This leads to MANET partitioning as well as reduced network lifetime. On the other hand, per-source tree-based multicast protocols show better traffic distribution and thus, better energy balance [13]. Table 1 also includes the characteristics of *Two-Tree Multicast (TTM)*, which will be discussed in detail in the next section.

3. Energy Efficient Two-Tree Multicast

This section introduces a new multicast protocol, *Two-Tree Multicast (TTM)*, which not only reduces the total energy consumption but also alleviates the energy balance problem without having adverse effect on the general performance. TTM is a tree-based multicast protocol employing multi-destined unicast-based trees and thus consumes less energy than mesh-based protocols. It uses a shared tree rather than per-source trees in order to avoid the tree construction and maintenance overhead.



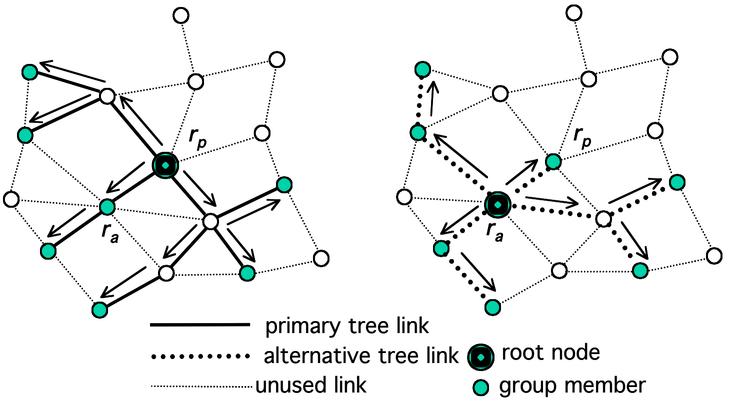
(a) 8- node multicast group (*W* receives from *P*)

(b) The corresponding multicast mesh (*W* receives from *Q* via a redundant link)

Figure 2. An example of mesh-based multicast.

Table 1. Multicast protocols and their comparisons.

Characteristics \ Protocols	Per- source tree multicast	Shared tree multicast	Mesh- based multicast	Two- Tree Multicast (TTM)
Packet delivery ratio	**Bad:** Due to link error	**Bad:** Due to link error	**Good:** Redundant paths	**Moderate:** Alternative tree is always ready
Tree/mesh construction & maintenance overhead	**Bad:** One tree per sender	**Good:** One shared tree is used	**Moderate:** Constructing the forwarding mesh	**Moderate:** Alternative tree is constructed while the primary tree is used
Latency due to link error	**Bad:** Need to construct a new tree	**Bad:** Need to construct a new tree	**Good:** Redundant links are used when tree links become invalid	**Moderate:** Alternative tree is used when the primary tree becomes invalid
Total energy consumption	**Good:** Unicast delivery	**Good:** Unicast delivery	**Bad:** Broadcast flooding	**Good:** Unicast delivery
Balanced energy consumption	**Good:** Multiple trees	**Bad:** Single tree is used	**Good:** Distributed to forwarding nodes in the mesh	**Good:** Alternative tree is used when the primary tree is overloaded



(a) Primary tree for 8- node multicast group

(b) Alternative backup tree for the same multicast group

Figure 3. An example of two trees in TTM.

Unique to TTM is the use of two trees called *primary* and *alternative* trees for a multicast group. When the primary tree becomes unusable or overloaded, the alternative tree takes on the responsibility of the primary tree and a new alternative tree is immediately constructed for future use. A group member with the largest remaining battery energy is selected as the root node of the new alternative tree[3]. Two trees can reduce the latency problem when a link error occurs on the primary tree by immediately switching to the alternative tree. Tree replacement is also useful for alleviating the energy balance problem inherent in shared tree multicast. In short, TTM is designed to take advantages of the three conventional multicast protocols as shown in Table 1.

Using the same examples shown in Figures 1 and 2, Figure 3 shows the two trees constructed for the same multicast group of eight members. The primary tree consists of a *primary root* (r_p), three intermediate nodes, and seven receiver nodes. On the other hand, the alternative tree consists of an *alternative root* (r_a), one intermediate node, and seven receiver nodes including r_p. As in tree-based and mesh-based multicast protocols, TTM reconstructs two trees periodically (e.g., every 3 seconds [4]) using periodic join messages sent by all receiver nodes

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[3] The similar idea has been adopted in the *root relocation scheme*, 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 [14].

Table 2. Host operation for the TTM protocol. (Messages in each procedure are described in time sequence.)

Sender	Primary root (r_p)	Alternative root (r_a)	Member nodes
Tree construction and maintenance procedure			
	Receive join messages from the member nodes. Construct a multicast tree based on the forwarding paths that the join messages traverse.		Periodically send a join message to r_p and r_a.
Multicast message delivery procedure			
Send a multicast message to r_p.	Send a multicast message to the member nodes.		Receive a multicast message from r_p.
Tree replacement procedure			
	Send a control message to r_a about the tree replacement.	Receive a control message from r_p and select a new alternative root (r_a'). Send a control message both to the sender(s) and all the members including r_a' about the tree replacement.	Receive a control message from r_a'. Send a join request message to r_a (*i.e.*, a new r_p) and r_a'.

to r_p and r_a. Note that the join message includes information about the remaining battery energy of the corresponding member node, which will be used to select a root node of a new alternative tree. The two root nodes independently construct multicast trees based on the forwarding paths that the join messages traverse (Tree construction and maintenance procedure). When a sender node intends to send a multicast packet, it forwards the packet to r_p, then r_p delivers the message to the member receivers along tree links of the primary tree [14, 15] (Multicast message delivery procedure).

When a tree connection is broken due to node mobility during the join interval or r_p's residual energy reduces to a predetermined threshold, the primary tree yields its responsibility to the alternative tree, i.e., r_p sends a control message to r_a notifying that the alternative tree will take the role of the primary tree. Upon receiving the control message, the alternative root (r_a) selects a new alternative root (r_a') that has the largest remaining battery energy among the member nodes. Then, r_a informs the sender(s) and all the members including r_a' of the tree replacement. When each member receives a control message from r_a, it sends a join request message to r_a (i.e., the new r_p) and r_a' (Tree replacement procedure). The shared tree multicast protocol described in [11] is used as the basic multicast protocol in our implementation. Table 2 summarizes the operations for implementing the proposed TTM protocol.

4. Performance Evaluation

4.1 Simulation Environment

In this section, the performance of the proposed TTM is evaluated via simulation. Our simulation study is based on *QualNet* simulator [6], which is a commercial version of *GloMoSim* [16]. QualNet is a scalable network simulation tool for wireless and wired networks and supports a wide range of ad hoc routing protocols. QualNet simulates a realistic physical layer that includes a radio capture model, radio network interfaces, and the IEEE 802.11 medium access control (MAC) protocol using the *distributed coordination function (DCF)*. The radio hardware model also simulates collisions, propagation delay, and signal attenuation.

The proposed TTM protocol is implemented within the QualNet simulation framework. We compared TTM with a mesh-based multicast protocol, ODMRP [4], and single shared tree multicast (STM) whose operation principles are described in [11]. For all three simulated protocols, the periodic join message is transmitted every 3 seconds[4]. The overhead due to the control messages, such as the control

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[4] In ODMRP, it is called JOIN DATA message. Other parameters used in simulating ODMRP are the acknowledgement timeout for JOIN TABLE and the maximum number of JOIN TABLE retransmissions: 25 milliseconds and 3, respectively [4].

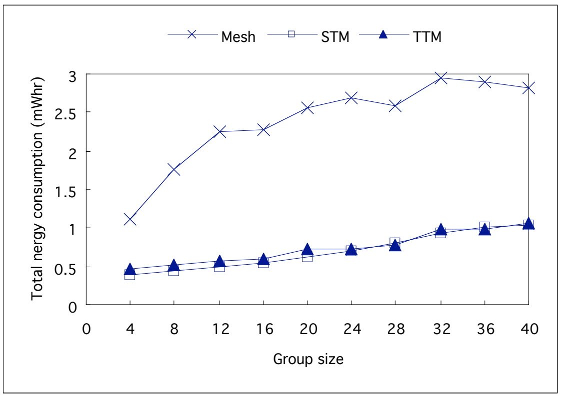
messages transferred during the tree replacement, is included in the simulation.

Mobility, Traffic and Energy Model

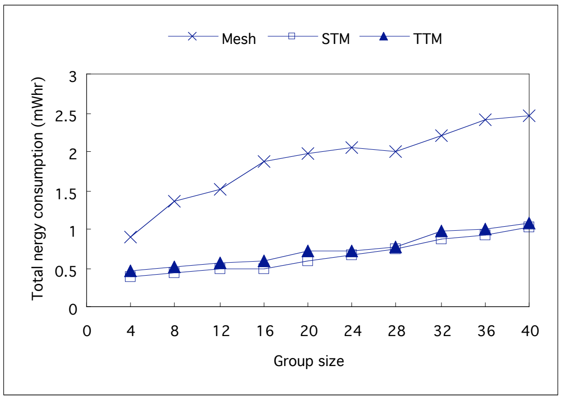
Our evaluation is based on the simulation of 40 mobile nodes moving over a square area of 1000 × 1000 meter^2 for 15 minutes of simulation time. The radio transmission range is assumed to be 250 meter and a free space propagation channel is assumed with a data rate of 2 Mbps. Mobile nodes are assumed to move randomly according to the *random waypoint model* [4]. Two parameters, *maximum node speed* and *pause time*, determine the mobility pattern of the mobile nodes. Each node starts moving from a randomly selected initial position to a target point, which is also selected randomly within the simulated area. Node speed is chosen to be between 0 and the specified maximum speed (2 or 20 meters/second for low and high node speed, respectively). When a node reaches the target point, it stays there for the pause time (30 seconds) and then repeats the movement.

A separate application file specifies the traffic as well as application type: FTP, HTTP, Telnet or *constant bit rate (CBR)*. In our simulation, a *multicast CBR (MCBR)* source and its corresponding destinations are randomly selected among 40 mobile nodes, where the number of destinations is varied from 4 to 40 to see the effect of the group size on the performance. An MCBR source sends a 512-byte multicast packet every 100 milliseconds during the simulation. For simplicity, we assume a multicast message consists of one data packet.

In this paper, we are specifically interested in total energy consumption and energy balance across all mobile nodes. For each node, energy consumption is measured at the radio layer during the simulation. According to the specification of IEEE 802.11-compliant WaveLAN-II from Lucent, the power consumption varies from 0.045 Watts (9mA × 5V) in sleep mode to 1.25 and 1.50 Watts (230mA × 5V and 250mA × 5V) for receiving and transmitting modes, respectively. The instantaneous power is multiplied by time delay to obtain the energy consumed. For example, data transmission of a 512-byte packet consumes 3.1 milli-Joules (1.50W × 512bytes × 8bits/2Mbps).

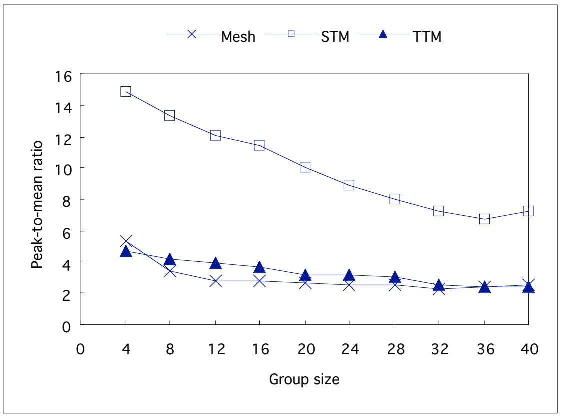


(a) At low node speed (0~2 m/sec)

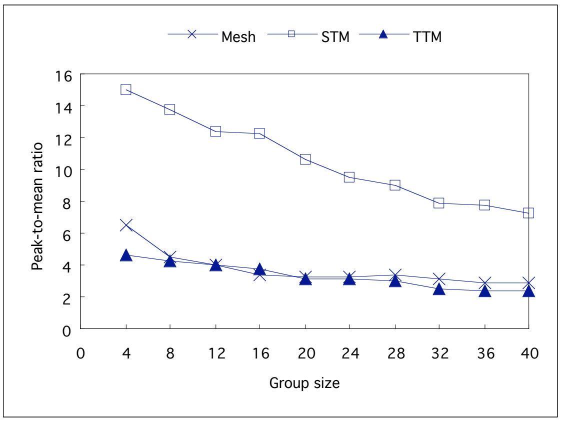


(b) At high node speed (0~20 m/sec)

Figure 4. Total energy consumption.

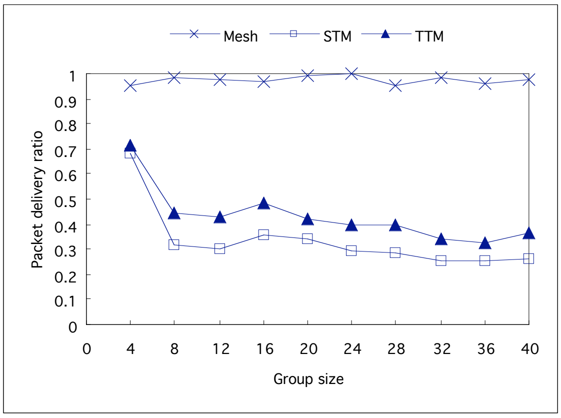


(a) At low node speed (0~2 m/sec)

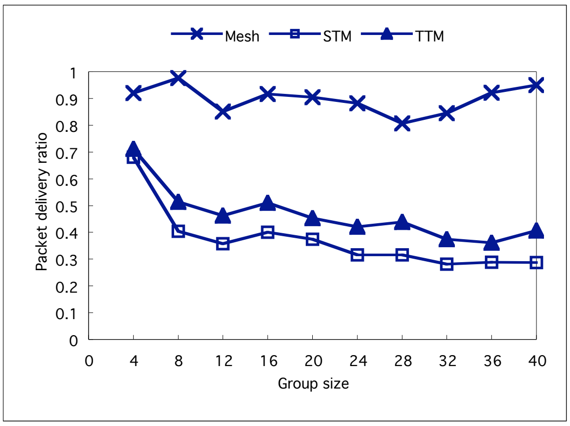


(b) At high node speed (0~20 m/sec)

Figure 5. Peak-to-mean ratio.

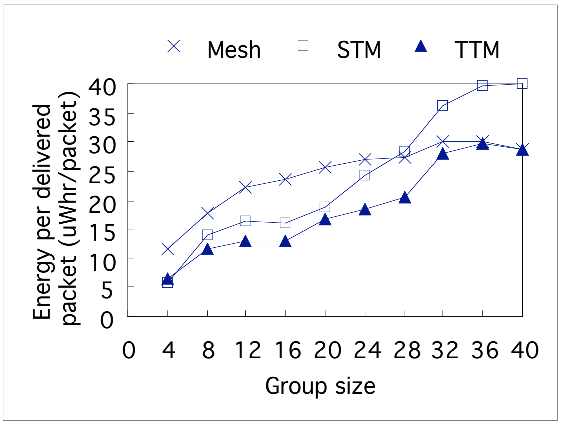


(a) At low node speed (0~2 m/sec)

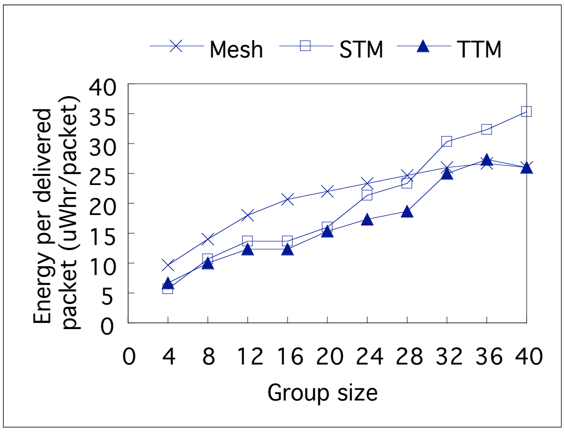


(b) At high node speed (0~20 m/sec)

Figure 6. Packet delivery ratio.



(a) At low node speed (0~2 m/sec)



(b) At high node speed (0~20 m/sec)

Figure 7. Energy per delivered packet.

4.2 Simulation Results and Discussion

Energy Performance: Total Energy Consumption and Energy Balance

Figures 4(a) and 4(b) show the total energy consumption for mesh-based multicast, STM, and TTM at low node speed (0~2 m/sec) and high node speed (0~20 m/sec), respectively. As shown in the two figures, both STM and TTM consume less energy than the mesh-based multicast by a factor of 1.9~4.0. Moreover, even with high node mobility, STM and TTM consume almost the same amount of energy as those with low node mobility, while the mesh-based multicast consumes less energy than that of the low node mobility case. Thus, it can be inferred that STM and TTM are less sensitive to node mobility in terms of total energy consumption compared to the mesh-based multicast. Also, note that the total energy consumption increases linearly with the group size.

In order to measure the energy balance, we observed the *peak-to-mean ratio*; i.e., the energy consumption of the most utilized node divided by the average energy consumption over all nodes. In the ideal case, this ratio becomes one when the total energy consumption is evenly distributed. In practice, the ratio is larger than one and a smaller peak-to-mean ratio indicates better energy balance. Figures 5(a) and 5(b) show the peak-to-mean ratio for the mesh-based multicast, STM, and TTM. As can be seen in the two figures, the mesh-based multicast and TTM result in smaller peak-to-mean ratio than STM. For STM, the ratio in some cases is over 10, which means the energy consumption of the most overloaded node is 10 times more than the average energy consumption indicating a serious energy imbalance. With high node speed, all three methods become slightly worse (i.e., peak-to-mean ratios increase) compared to those with low node speed. Also note that for all three methods, the energy balance is improved with the increase in group size.

General Performance: Packet Delivery Ratio and Energy per Delivered Packet

Packet delivery ratio is compared in Figures 6(a) and 6(b). Since the data traffic during the simulation is based on UDP rather than TCP, some data packets may be lost. As can be seen in the two figures, the mesh-based multicast performs better than STM and TTM mainly due to the redundant links within the mesh. However, TTM is better than STM because it uses two trees. At fast node speed, as shown in Figure 6(b), the packet delivery ratio of the mesh-based multicast becomes worse than that at slow node speed. On the other hand, the packet delivery ratios of STM and TTM with fast node mobility are almost the same as those with slow node mobility and thus, it can be inferred that STM and TTM are less sensitive to node mobility in terms of packet delivery ratio compared to the mesh-based multicast.

From the above simulation results, it is clear that TTM is the choice when energy is the primary concern. However, it is also clear that mesh-based protocol performs best when packet delivery ratio is important. To better understand the tradeoff between energy consumption and general performance, we introduce a new performance metric, *energy per delivered packet*, which is the ratio of the total energy consumption over the total number of effectively delivered packets. Figures 7(a) and 7(b) show the energy per delivered packet for the mesh-based multicast, STM, and TTM with low node speed (0~2 m/sec) and high node speed (0~20 m/sec), respectively. In both cases, TTM outperforms the mesh-based multicast and STM by factors of 1.0~1.8 and 1.0~1.4, respectively.

5. Conclusion

This paper reevaluated the multicast protocols proposed for MANETs in terms of energy efficiency, and proposed an energy efficient multicast protocol called Two-Tree Multicast (TTM). TTM consumes less energy than the mesh-based multicast because it uses multi-destined unicast-based multicast trees. TTM results in improved energy balance and packet delivery ratio compared to the conventional shared tree multicast (STM) because it can switch to the alternative tree when the primary tree is overloaded or becomes invalid.

According to our simulation study, the proposed TTM protocol saves energy consumption by a factor of 1.9~4.0 compared to the mesh-based multicast. In terms of a combined performance metric, energy per delivered packet, TTM resulted in up to 80% and 40% improved performance over the mesh-based multicast and STM, respectively.

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