Performance Comparison Study of Multicast Routing Protocols for Mobile Ad hoc Networks under Default Flooding and Density and Mobility Aware Energy-Efficient (DMEF) Broadcast Strategies

Natarajan Meghanathan
Department of Computer Science
Jackson State University
Jackson, MS 39217, USA
E-mail: natarajan.meghanathan@jsums.edu

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Recently, we had proposed a novel network density and mobility aware energy-efficient broadcast route discovery strategy (called DMEF) to discover stable routes in mobile ad hoc networks (MANETs). DMEF works by letting each node to dynamically choose its own broadcast transmission range for the route discovery messages depending on the perceived number of neighbour nodes in its default maximum transmission range and the node's own mobility values at the time of route discovery. A node surrounded by more neighbours makes itself available to a smaller neighbourhood and vice-versa. Similarly, a slow moving node broadcasts the route discovery message to a majority of its neighbours so that links formed using this node can be more stable. A fast moving node advertises itself only to the neighbours closer to it. The effectiveness of DMEF has been so far tested only for MANET unicast and multi-path routing protocols. In this paper, we study the impact of DMEF on the performance of MANET multicast routing protocols. We investigate the minimum-hop based Multicast Ad hoc On-demand Distance Vector (MAODV) routing protocol, the minimum-link based Bandwidth-Efficient Multicast Routing Protocol (BEMRP) and our recently proposed non-receiver aware and receiver aware multicast extensions to the Location Prediction Based Routing (NR-MLPBR and R-MLPBR) protocols. Exhaustive simulation studies of these multicast routing protocols with DMEF and the default flooding as the route discovery strategies have been conducted. Performance results for each multicast routing protocol illustrate DMEF to be effective in discovering multicast trees that exist for a longer time with a lower energy consumed per node and without any appreciable increase in the hop count per source-receiver path.

Povzetek: Predstavljeno je testiranje nove metode DMEF za iskanje stabilnih povezav v mobilnih omrežjih.

1 Introduction

A mobile ad hoc network (MANET) is a dynamic distributed system of mobile, autonomous wireless nodes. The network has limited bandwidth and the nodes have limited battery charge. In order to conserve battery charge, each node has a limited transmission range (i.e., transmits the data signals only to a limited distance). As a result, MANET routes are typically multi-hop in nature. As nodes move independent of each other, routes between a source and destination node often break and new routes have to be discovered. MANET routing protocols are of two types. Proactive protocols require the nodes to periodically exchange the table updates to pre-determine routes between any pair of source-destination nodes. Reactive protocols determine routes only when a route is required from a source to a destination. In dynamically changing environments, typical of MANETs, reactive on-demand routing protocols incur lower control overhead to discover routes compared to the proactive routing protocols [5]. In this paper, we work only with the reactive routing protocols.

Flooding is the default route discovery approach for on-demand MANET routing protocols [14]. The flooding algorithm to discover routes can be briefly explained as follows: Whenever a source node needs a route to a destination node, it broadcasts a Route Request (RREQ) message to its neighbours. Neighbour nodes of the source node broadcast the received RREQ further, if they have not already done so. A RREQ message for a particular route discovery process is forwarded by a node exactly once. The destination node receives the RREQs along several routes, selects the best route according to the route selection principles of the particular routing protocol and notifies the selected route to the source through a Route-Reply (RREP) packet. The source starts sending data packets on the discovered route.

Flooding is inefficient and consumes significantly high energy and bandwidth. When a node receives a message for the first time in its neighbourhood, at least 39% of the neighbourhood would have seen it already and on the average only 41% of the additional area could be covered with a rebroadcast [15]. In an earlier work [11], we had proposed a novel density and mobility aware energy-efficient broadcast strategy, referred to as DMEF, to reduce the energy consumption in broadcast route discoveries by letting a node to broadcast only within a limited neighbourhood. The neighbourhood size to which a node advertises itself as part of the route discovery process is independently decided at the node based on the number of neighbours surrounding the node and the mobility of the node. The neighbourhood size for rebroadcast is reduced in such a way that the RREQ packets still make it to the destination through one or more paths with a reduced energy spent per route discovery and such paths are also more stable compared to those discovered using flooding.

The effectiveness of DMEF has been so far studied only for MANET unicast [11] and multi-path routing protocols [12]. In this paper, we study the impact of DMEF on the performance of MANET multicast routing protocols. Multicasting is the process of sending a stream of data from one source node to multiple recipients by establishing a routing tree, which is an acyclic connected subgraph of the entire network. The set of receiver nodes form the multicast group. While propagating down the tree, data is duplicated only when necessary. This is better than multiple unicast transmissions. Multicasting in ad hoc wireless networks has numerous applications [21]: collaborative and distributing computing like civilian operations, emergency search and rescue, law enforcement, warfare situations and etc. We investigate the minimum-hop based Multicast Ad hoc On-demand Distance Vector (MAODV) routing protocol [18], the minimum-link based Bandwidth-Efficient Multicast Routing Protocol (BEMRP) [16] and our recently proposed non-receiver aware and receiver aware multicast extensions to the Location Prediction Based Routing protocol [9], referred to as NR-MLPBR and R-MLPBR protocols [10] respectively. Exhaustive simulation studies of these multicast routing protocols with DMEF and the default flooding as the route discovery strategies have been conducted in this paper. Performance results for each multicast routing protocol illustrate DMEF to be effective in discovering multicast trees that exist for a longer time with a lower energy consumed per node and without any appreciable increase in the hop count per source-receiver path.

The rest of the paper is organized as follows: Section 2 briefly describes the DMEF strategy. Section 3 reviews the multicast routing protocols studied. Section 4 discusses the simulation environment and presents the simulation results illustrating the effectiveness of DMEF vis-à-vis flooding. Section 5 reviews state-of-the-art related work on different optimal broadcast route discovery strategies proposed in the literature and discusses the advantages of DMEF and differences with related work. Section 6 concludes the paper and discusses future work. Throughout this paper, the terms 'path' and 'route', 'link' and 'edge', 'message' and 'packet' are used interchangeably. They mean the same.

2 DMEF strategy

2.1 Terminology and assumptions

Every node (say node u) in the network is configured with a maximum transmission range ($Range_u^{Max}$). If the distance between two nodes is less than or equal to the maximum transmission range, the two nodes are said to be within the "complete neighbourhood" of each other. Each node broadcasts periodically a beacon message in its complete neighbourhood. The time between two successive broadcasts is chosen uniform-randomly, by each node from the range $[0 \ldots T_{wait}]$. Using this strategy, each node learns about the number of nodes in its complete neighbourhood.

2.2 Basic idea of DMEF

The twin objectives of DMEF are to discover stable routes with a reduced energy consumption compared to that incurred using flooding. DMEF achieves this by considering the number of neighbours of a node (a measure of node density) and node mobility. The basic idea behind DMEF is as follows: The transmission range of a RREQ broadcast for route discovery is not fixed for every node. A node surrounded by more neighbours in the complete neighbourhood should broadcast the RREQ message only within a smaller neighbourhood that would be sufficient enough to pick up the message and forward it to the other nodes in the rest of the network. On the other hand, a node that is surrounded by fewer neighbours in the complete neighbourhood should broadcast the RREQ message to a larger neighbourhood (but still contained within the complete neighbourhood) so that a majority of the nodes in the complete neighbourhood can pick up the message and rebroadcast it further. A node rebroadcasts a RREQ message at most once. The density aspect of DMEF thus helps to reduce the unnecessary transmission and reception of broadcast RREQ messages and conserves energy.

To discover stable routes that exist for a longer time, DMEF adopts the following approach: A node that is highly mobile makes itself available only to a smaller neighbourhood around itself, whereas a node that is less mobile makes itself available over a larger neighbourhood (but still contained within the complete neighbourhood). The reasoning is that links involving a slow moving node will exist for a longer time. Hence, it is better for a slow moving node to advertise itself to a larger neighbourhood so that the links (involving this node) that are part of the routes discovered will exist for a longer time. On the other hand, a fast moving node will have links of relatively longer lifetime with neighbours that are closer to it. Hence, it is worth to let a fast moving node advertise only to its nearby neighbours.

2.3 DMEF mathematical model

DMEF effectively uses the knowledge of neighbourhood node density and mobility so that they complement each other in discovering stable routes in a more energy-efficient fashion. The transmission range used by a node u, $Range_u^{RREQ}$, to rebroadcast a RREQ message is given by the following model:

$$Range_u^{RREQ} = Range_u^{Max} - \left[\left(\frac{|Neighbors_u|}{\alpha}\right) * v_u^{\beta}\right] \quad (1)$$

The idea behind the formulation of equation (1) is that the larger the value of the term, $\left[\left(\frac{|Neighbors_u|}{\alpha}\right) * v_u^{\beta}\right]$, the lower would be the transmission range chosen by a node for broadcasting the RREQ message. For a fixed value of parameters α and β, the above term in equation (1) could become larger for a node if it has a larger number of neighbours and/or is moving faster with a larger velocity.

In order to make sure, $Range_u^{RREQ}$ is always greater than or equal to zero, the value of parameter *α* should be chosen very carefully. For a given value of parameter *β*, the necessary condition is:

$$\alpha \geq \left[\left(\frac{|Neighbors_u|}{Range_u^{Max}}\right) * v_u^{\beta}\right] \ldots\ldots\ldots\ldots (2)$$

In practice, the value of *α* has to be sufficiently larger than the value obtained from (2), so that the RREQ message reaches neighbours who can forward the message further to the rest of the network. Otherwise, certain source-destination nodes may not be reachable from one another even though there may exist one or more paths between them in the underlying network.

2.4 Dynamic selection of DMEF parameter values

The specialty of DMEF is that it allows for each node to dynamically and independently choose at run-time the appropriate values for the critical operating parameters *α* and *β* depending on the perceived number of nodes in the complete neighbourhood of the node and the node's own velocity. A node has to be simply pre-programmed with the appropriate values of *α* and *β* to be chosen for different values of the number of nodes in the complete neighbourhood and node velocity.

Let the maximum number of neighbours a node should have in order to conclude that the complete neighbourhood density of the node is low and moderate be represented respectively by *maxNeighb_lowDensity*, *maxNeighb_modDensity*. If a node has more than *maxNeighb_modDensity* number of neighbours, then the node is said to exist in a complete neighbourhood of high density. Let *lowDensity_α*, *modDensity_α* and *highDensity_α* represent the values of *α* to be chosen by a node for complete neighbourhoods of low, moderate and high density respectively. Let *maxVel_lowMobility*, *maxVel_modMobility* represent the maximum velocity values for a node in order to conclude that the mobility of the node is low and moderate respectively. If the velocity of a node is more than *maxVel_modMobility*, then the mobility of the node is said to be high. Let *lowMobility_β*, *modMobility_β* and *highMobility_β* represent the values of *β* to be chosen by a node when its mobility is low, moderate and high respectively.

Let $Neighbors_u^t$ and v_u^t represent the set of neighbours in the complete neighbourhood and velocity of a node *u* at time *t*. Note that the set $Neighbors_u^t$ is determined by node *u* based on the latest periodic beacon exchange in the complete neighbourhood formed by the maximum transmission range, $Range_u^{Max}$. The algorithm, *DMEF_Parameter_Selection*, to dynamically choose the values of parameters *α* and *β* (represented as α_u^t and β_u^t) is illustrated below in Figure 1:

Input: $Neighbors_u^t$ and v_u^t

Auxiliary Variables:

$minimum\_\alpha_u^t$ // minimum value of *α* to be chosen to avoid the transmission range of a node from becoming negative

$Range_u^{Max}$ // the maximum transmission range of a node for complete neighbourhood

Density related variables: *maxNeighb_lowDensity*, *maxNeighb_modDensity*, *lowDensity_α*, *modDensity_α*, *highDensity_α*

Node Velocity related variables: *maxVel_lowMobility*, *maxVel_modMobility*, *lowMobility_β*, *modMobility_β*, *highMobility_β*

Output: α_u^t and β_u^t

Begin *DMEF_Parameter_Selection*

  if ($v_u^t \leq maxVel\_lowMobility$)

    $\beta_u^t \leftarrow lowMobility\_\beta$

  else if ($v_u^t \leq maxVel\_moderateMobility$)

    $\beta_u^t \leftarrow moderateMobility\_\beta$

  else

    $\beta_u^t \leftarrow highMobility\_\beta$

  $minimum\_\alpha_u^t \leftarrow \left[\left(\frac{|Neighbors_u^t|}{Range_u^{Max}}\right) * \left(v_u^t\right)^{\beta_u^t}\right]$

  if ($|Neighbors_u^t| \leq maxNeighb\_lowDensity$)

    $\alpha_u^t \leftarrow$ Maximum ($minimum\_\alpha_u^t$, $lowDensity\_\alpha$)

  else if ($|Neighbors_u^t| \leq maxNeighb\_modDensity$)

    $\alpha_u^t \leftarrow$ Maximum ($minimum\_\alpha_u^t$, $modDensity\_\alpha$)

  else

$\alpha_u^t \leftarrow$ Maximum (*minimum_*α_u^t, *highDensity_α*)

return α_u^t and β_u^t

End *DMEF_Parameter_Selection*

Figure 1: Algorithm to Dynamically Select the Parameter Values for DMEF.

3 Review of MANET multicast routing protocols

In this section, we discuss the working of the MANET multicast routing protocols (MAODV, BEMRP, NR-MLPBR and R-MLPBR) whose performance under DMEF and default flooding is studied through simulations in this paper. We also provide a brief overview of LPBR before discussing its two multicast extensions.

3.1 Multicast extension of ad hoc on-demand distance vector (MAODV) routing protocol

MAODV [18] is the multicast extension of the well-known Ad hoc On-demand Distance Vector (AODV) unicast routing protocol [17]. Here, a receiver node joins the multicast tree through a member node that lies on the minimum-hop path to the source. A potential receiver wishing to join the multicast group broadcasts a RREQ message. If a node receives the RREQ message and is not part of the multicast tree, the node broadcasts the message in its neighbourhood and also establishes the reverse path by storing the state information consisting of the group address, requesting node id and the sender node id in a temporary cache. If a node receiving the RREQ message is a member of the multicast tree and has not seen the RREQ message earlier, the node waits to receive several RREQ messages and sends back a RREP message on the shortest path to the receiver. The member node also informs in the RREP message, the number of hops from itself to the source. The potential receiver receives several RREP messages and selects the member node which lies on the shortest path to the source. The receiver node sends a Multicast Activation (MACT) message to the selected member node along the chosen route. The route from the source to receiver is set up when the member node and all the intermediate nodes in the chosen path update their multicast table with state information from the temporary cache. A similar approach is used in NR-MLPBR and R-MLPBR when a new receiver node wishes to join the multicast group.

Tree maintenance in MAODV is based on the expanding ring search (ERS) approach, using the RREQ, RREP and MACT messages. The downstream node of a broken link is responsible for initiating ERS to issue a fresh RREQ for the group. This RREQ contains the hop count of the requesting node from the source and the last known sequence number for that group. It can be replied only by the member nodes whose recorded sequence number is greater than that indicated in the RREQ and whose hop distance to the source is smaller than the value indicated in the RREQ.

3.2 Bandwidth-efficient multicast routing protocol (BEMRP)

According to BEMRP [16], a newly joining node to the multicast group opts for the nearest forwarding node in the existing tree, rather than choosing a minimum-hop count path from the source of the multicast group. As a result, the number of links in the multicast tree is reduced leading to savings in the network bandwidth.

Multicast tree construction is receiver-initiated. When a node wishes to join the multicast group as a receiver, it initiates the flooding of *Join control* packets targeted towards the nodes that are currently members of the multicast tree. On receiving the first *Join control* packet, the member node waits for a certain time before sending a *Reply* packet. The member node sends a *Reply* packet on the path, traversed by the *Join* control packet, with the minimum number of intermediate forwarding nodes. The newly joining receiver node collects the *Reply* packets from different member nodes and would send a *Reserve* packet on that path that has the minimum number of forwarding nodes from the member node to itself.

To provide more bandwidth efficiency, the tree maintenance approach in BEMRP is hard-state based, i.e. a member node transmits control packets only after a link breaks. BEMRP uses two schemes to recover from link failures: *Broadcast-multicast scheme* – the upstream node of the broken link is responsible for finding a new route to the previous downstream node; *Local-rejoin scheme* – the downstream node of the broken link tries to rejoin the multicast group using a limited flooding of the *Join* control packets.

3.3 Location prediction based routing (LPBR) protocol

LPBR works as follows: Whenever a source node has data packets to send to a destination node but does not have a route to that node, it initiates a flooding-based route discovery by broadcasting a Route-Request (RREQ) packet. During this flooding process, each node forwards the RREQ packet exactly once after incorporating its location update vector (LUV) in the RREQ packet. The LUV of a node comprises the node id, the current X and Y co-ordinates of the nodes, the current velocity and angle of movement with respect to the X-axis. The destination node collects the LUV information of all the nodes in the network from the RREQ packets received through several paths and sends a Route-Reply (RREP) packet to the source on the minimum hop path traversed by a RREQ packet.

The source starts sending the data packets on the path learnt (based on the RREP packet) and informs the destination about the time of next packet dispatch through the header of the data packet currently being sent. If an intermediate node could not forward a data packet, it sends a Route-Error packet to the source node, which then waits a little while for the destination to inform it of a new route predicted using the LUVs gathered from the latest flooding-based route discovery. If the destination does not receive the data packet within the expected time, it locally constructs the current global topology by predicting the locations of the nodes. Each node is assumed to be currently moving in the same direction and speed as mentioned in its latest LUV. If there is at least one path in the predicted global topology, the destination node sends the source a LPBR-RREP packet on the minimum hop path in the predicted topology. If the predicted path actually exists in reality, the intermediate nodes on the predicted route manage to forward the LPBR-RREP packet to the source. The source uses the route learnt through the latest LPBR-RREP packet to send the data packets. A costly flooding-based route discovery has been thus avoided. If an intermediate node could not forward the LPBR-RREP packet (i.e., the predicted path did not exist in reality), the intermediate node sends a LPBR-RREP-ERROR packet to the destination informing it of the failure to forward the LPBR-RREP packet. The destination discards all the LUVs and the source node initiates the next flooding-based route discovery after timing out for the LPBR-RREP packet.

3.4 Multicast extensions to the LPBR protocol (NR-MLPBR and R-MLPBR)

Both the multicast extensions of LPBR, referred to as NR-MLPBR and R-MLPBR, are aimed at minimizing the number of global broadcast tree discoveries as well as the hop count per source-receiver path of the multicast tree. They use a similar idea of letting the receiver nodes to predict a new path based on the locally constructed global topology obtained from the location and mobility information of the nodes learnt through the latest broadcast tree discovery. Receiver nodes running NR-MLPBR (Non-Receiver aware Multicast extensions of LPBR) are not aware of the receivers of the multicast group, whereas each receiver node running R-MLPBR (Receiver-aware Multicast Extension of LPBR) is aware of the identity of the other receivers of the multicast group. NR-MLPBR attempts to predict a minimum hop path to the source, whereas R-MLPBR attempts to predict a path to the source that has the minimum number of non-receiver nodes.

The multicast extensions of LPBR work as follows: When a source attempts to construct a multicast tree, it floods a Multicast Tree Request Message (MTRM) throughout the network. The location and mobility information of the intermediate forwarding nodes are recorded in the MTRM. Each node, including the receiver nodes of the multicast group, broadcasts the MTRM exactly once in its neighbourhood. Each receiver node of the multicast group receives several MTRMs and sends a Multicast Tree Establishment Message (MTEM) on the minimum hop path traversed by the MTRMs. The set of paths traversed by the MTEMs form the multicast tree rooted at the source. If an intermediate node of the tree notices a downstream node moving away from it, the intermediate node sends a Multicast Path Error Message (MPEM) to the source. The source does not immediately initiate another tree discovery procedure. Instead, the source waits for the appropriate receiver node (whose path to the source has broken) to predict a path to the source. The receiver predicts a new path based on the location and mobility information of the nodes collected through the MTRMs during the latest global tree discovery procedure. The receiver attempts to locally construct the global topology by predicting the locations of the nodes in the network using the latest location and mobility information collected.

NR-MLPBR and R-MLPBR differ from each other based on the type of path predicted and notified to the source. NR-MLPBR determines and sends a Multicast Predicted Path Message (MPPM) on the minimum hop path to the source. R-MLPBR attempts to choose a path that will minimize the number of newly added intermediate nodes to the multicast tree. In pursuit of this, R-MLPBR determines a set of node-disjoint paths to the source on the predicted topology and sends the MPPM on that path that includes the minimum number of non-receiver nodes. If there is a tie, R-MLPBR chooses the path that has the least hop count. The source waits to receive a MPPM from the affected receiver node. If a MPPM is received within a certain time, the source considers the path traversed by the MPPM as part of the multicast tree and continues to send data packets down the tree including to the nodes on the new path. Otherwise, the source initiates another global tree discovery procedure by broadcasting the MTRM. R-MLPBR has been thus designed to also reduce the number of links that form the multicast tree, in addition to the source-receiver hop count and the number of global tree discoveries.

4 Simulations

The network dimension used is a 1000m x 1000m square network. The transmission range of each node is assumed to be 250m. The number of nodes used in the network is 25, 50 and 75 nodes representing networks of low, medium and high density with an average distribution of 5, 10 and 15 neighbours per node respectively. Initially, nodes are uniformly randomly distributed in the network. We implemented all of the four multicast routing protocols (MAODV, BEMRP, NR-MLPBR and R-MLPBR) in the ns-2 simulator [4]. The broadcast tree discovery strategies simulated are the default flooding approach and DMEF. The DMEF parameter values are given in Table 1.

Table 1: DMEF Parameter Values.

DMEF Parameter	Value
maxNeighb_lowDensity	5
maxNeighb_modDensity	10
lowDensity_α	5
modDensity_α	10
highDensity_α	20
maxVel_lowMobility	5

maxVel_modMobility	15
lowMobility_β	1.6
modMobility_β	1.3
highMobility_β	1.1
T_{wait}	10 seconds

The signal propagation model used is the Two-ray ground reflection model [4]. The Medium Access Control (MAC) layer model is the IEEE 802.11 [3] model. The channel bandwidth is 2 Mbps. The node queues operate on a First-in First-Out (FIFO) basis, with a maximum queue size of 100 packets. The node mobility model used is the Random Waypoint model [2], with the node velocity chosen from [v_{min},…, v_{max}]; v_{min} was set to 0 and the values of v_{max} used are 10m/s, 30m/s and 50m/s representing scenarios of low, moderate and high node mobility respectively. The pause time is 0 seconds. Simulations are conducted with a multicast group size of 2, 4 (small size), 8, 12 (moderate size) and 24 (larger size) receiver nodes. For each group size, we generated 5 lists of receiver nodes and simulations were conducted with each of them. Traffic sources are constant bit rate (CBR). Data packets are 512 bytes in size and the packet sending rate is 4 data packets/second. The multicast session continues until the end of the simulation time, which is 1000 seconds. The transmission energy and reception energy per hop is set at 1.4 W and 1 W respectively [6]. Initial energy at each node is 1000 Joules. Each node periodically broadcasts a beacon message within its neighbourhood to make its presence felt to the other nodes in the neighbourhood.

4.1 Performance metrics

The performance metrics studied through this simulation are the following. The performance results for each metric displayed in Figures 2 through 14 are an average of the results obtained from simulations conducted with 5 sets of multicast groups and 5 sets of mobility profiles for each group size, node velocity and network density values. The multicast source in each case was selected randomly among the nodes in the network and the source is not part of the multicast group. The nodes that are part of the multicast group are merely the receivers.

- **Number of Links per Multicast Tree:** This is the time averaged number of links in the multicast trees discovered and computed over the entire multicast session. The notion of "time-average" is explained as follows: Let there be multicast trees T1, T2, T3 with 5, 8 and 6 links used for time 12, 6 and 15 seconds respectively, then the time averaged number of links in the multicast trees is given by (5*12+8*6+6*15)/(12+6+15) = 6 and not merely 6.33, which is the average of 5, 8 and 6.
- **Hop Count per Source-Receiver Path**: This is the time averaged hop count of the paths from the source to each receiver of the multicast group and computed over the entire multicast session.
- **Time between Successive Broadcast Tree Discoveries:** This is the time between two successive broadcast tree discoveries, averaged over the entire multicast session. This metric is a measure of the lifetime of the multicast trees discovered and also the effectiveness of the path prediction approach followed in NR-MLPBR and R-MLPBR.
- **Energy Throughput:** This is the average of the ratio of the number of data packets reaching the destination to the sum of the energy spent across all the nodes in the network.
- **Energy Consumed per Node:** This is the sum of the energy consumed at a node due to the transfer of data packets as part of the multicast session, broadcast tree discoveries as well as the periodic broadcast and exchange of beacons in the neighbourhood.
- **Energy Consumed per Tree Discovery:** This is the average of the total energy consumed for the global broadcast based tree discovery attempts. This includes the sum of the energy consumed to transmit (broadcast) the MTRM packets to the nodes in the neighbourhood and to receive the MTRM packet sent by each node in the neighbourhood, summed over all the nodes. It also includes the energy consumed to transmit the MTEM packet from each receiver to the source of the multicast session.

4.2 Number of links per multicast tree

The number of links per multicast tree (refer Figures 2 and 3) is a measure of the efficiency of the multicast routing protocol in reducing the number of link transmissions during the transfer of the multicast data from the source to the receivers of the multicast group. The smaller is the number of links in the tree, the larger the link transmission efficiency of the multicast routing protocol. If fewer links are part of the tree, then the chances of multiple transmissions in the network increase and this increases the efficiency of link usage and the network bandwidth. Naturally, the BEMRP protocol, which has been purely designed to yield bandwidth-efficient multicast trees, discovers trees that have a reduced number of links for all the operating scenarios. This leads to larger hop count per source-receiver paths for BEMRP as observed in Figures 4 and 5.

R-MLPBR, which has been designed to choose the predicted paths with the minimum number of non-receiver nodes, manages to significantly reduce the number of links vis-à-vis the MAODV and NR-MLPBR protocols. R-MLPBR attempts to minimize the number of links in the multicast tree without yielding to a higher hop count per source-receiver path. But, the tradeoff between the link efficiency and the hop count per source-receiver path continues to exist and it cannot be nullified. In other words, R-MLPBR cannot discover trees that have minimum number of links as well as the minimum hop count per source-receiver path. Nevertheless, R-MLPBR is the first multicast routing protocol that yields trees with the reduced number of links and at the same time, with a reduced hop count (close to the minimum) per source-receiver path.

Performance with Flooding as Tree Discovery Strategy

- *Impact of Node Mobility*: For a given network density and multicast group size, we do not see any appreciable variation in the number of links per tree for each of the multicast routing protocols studied.

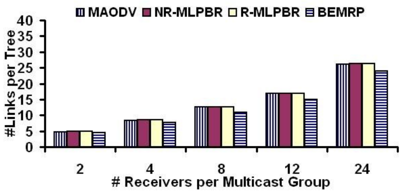

Figure 2.1: 25 nodes, 10 m/s.

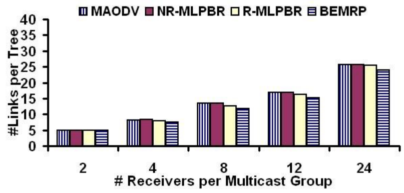

Figure 2.2: 25 nodes, 30 m/s.

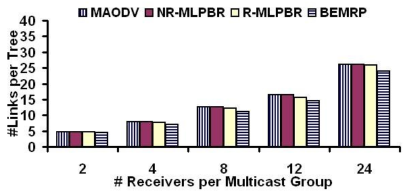

Figure 2.3: 25 nodes, 50 m/s.

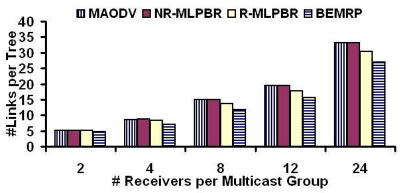

Figure 2.4: 50 nodes, 10 m/s.

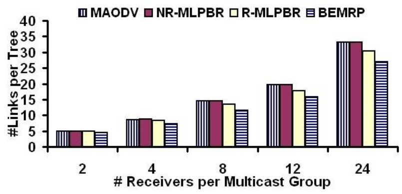

Figure 2.5: 50 nodes, 30 m/s.

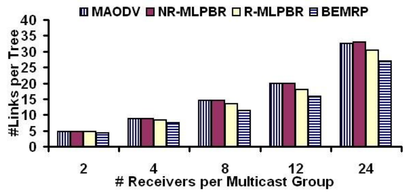

Figure 2.6: 50 nodes, 50 m/s.

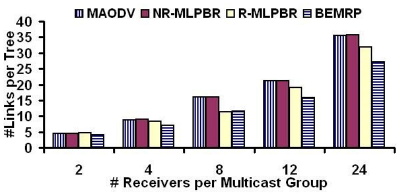

Figure 2.7: 75 nodes, 10 m/s.

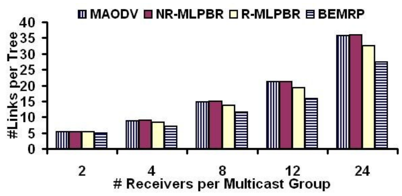

Figure 2.8: 75 nodes, 30 m/s.

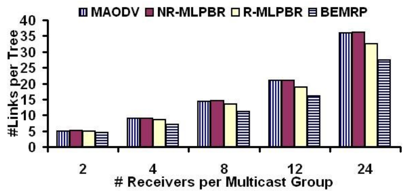

Figure 2.9: 75 nodes, 50 m/s.

Figure 2: Average Number of Links per Multicast Tree (Tree Discovery Procedure: Flooding).

- *Impact of Network Density*: For a given multicast group size, the number of links per tree for MAODV and NR-MLPBR is about 4-15%, 8-28% and 10-38% more than that incurred with BEMRP in networks of low, moderate and high density respectively. This illustrates that as the network density increases, BEMRP attempts to reduce the number of links per tree by incorporating links that can be shared by multiple receivers on the paths towards the source. On the other hand, both MAODV and NR-MLPBR attempt to choose minimum hop paths between the source and any receiver and hence exploit the increase in network density to discover minimum hop paths, but at the cost of the link efficiency. On the other hand, R-MLPBR attempts to reduce the number of links per tree as we increase the network density. For a given multicast group size, the number of links per tree for R-MLPBR is about 4-15%, 8-18% and 10-21% more than that incurred by BEMRP. This shows that R-MLPBR is relatively more scalable, similar to BEMRP, with increase in the network density.
- *Impact of Multicast Group Size*: For a given level of node mobility, for smaller multicast groups (of size 2), the number of links per tree for MAODV, NR-MLPBR and R-MLPBR is about 3-7%, 8-11% and 9-14% more than that incurred for BEMRP in low, medium and high-density networks respectively. For medium and large-sized multicast groups, the number of links per tree for both MAODV and NR-MLPBR is about 7-15%, 17-28% and 22-38% more than that incurred for BEMRP in low, medium and high-density networks respectively. On the other hand, the number of links per tree for R-MLPBR is about 6-15%, 12-18% and 16-21% more than that incurred for BEMRP in low, medium and high-density networks respectively. This shows that R-MLPBR is relatively more scalable, similar to BEMRP, with increase in the multicast group size.

Performance with DMEF as the Tree Discovery Strategy

- *Impact of Node Mobility*: For each multicast routing protocol, as the maximum node velocity is increased from 10 m/s to 30 m/s, the number of links per multicast tree increases as large as up to 24% (for multicast groups of small and moderate sizes) and 3% (for larger multicast groups). As the maximum node velocity is increased from 10 m/s to 50 m/s, the number of links per tree increases as large as up to 15% (for multicast groups of small and moderate sizes) and 5% (for larger multicast groups). Thus, DMEF can yield multicast trees with reduced number of links in low node mobility, especially for multicast groups of small and moderate sizes.
- *Impact of Network Density*: For a given group size, the number of links per tree for MAODV and NR-MLPBR is about 4-15%, 8-28% and 10-35% more

than that incurred with BEMRP in networks of low, moderate and high density respectively. For a given group size, the number of links per tree for R-MLPBR is about 3-9%, 8-18% and 9-24% more than that incurred by BEMRP. The results are more or less similar to what has been obtained using flooding as the tree discovery strategy.

- *Impact of Multicast Group Size*: For a given level of node mobility, for smaller multicast groups (of size

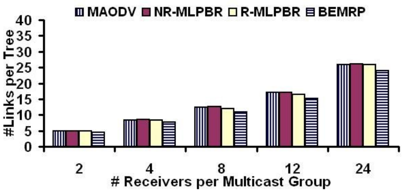

Figure 3.1: 25 nodes, 10 m/s.

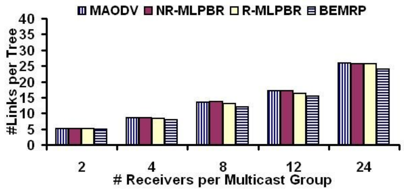

Figure 3.2: 25 nodes, 30 m/s.

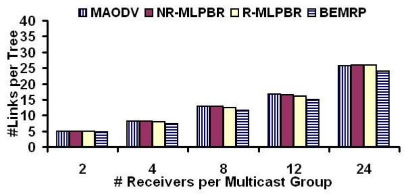

Figure 3.3: 25 nodes, 50 m/s.

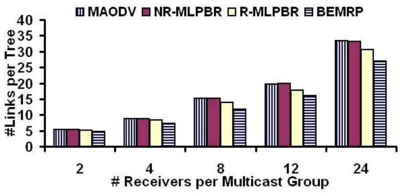

Figure 3.4: 50 nodes, 10 m/s.

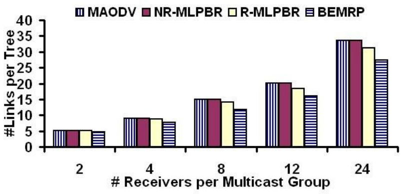

Figure 3.5: 50 nodes, 30 m/s.

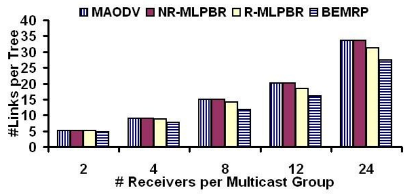

Figure 3.6: 50 nodes, 50 m/s.

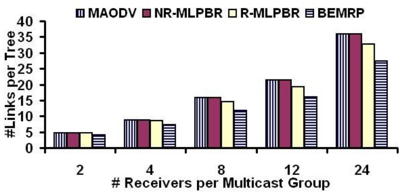

Figure 3.7: 75 nodes, 10 m/s.

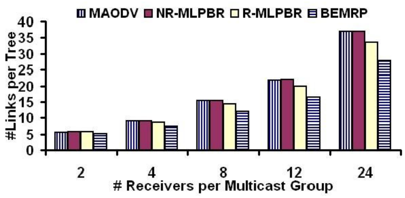

Figure 3.8: 75 nodes, 30 m/s.

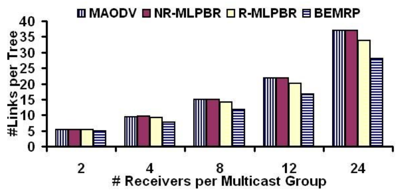

Figure 3.9: 75 nodes, 50 m/s.

Figure 3: Average Number of Links per Multicast Tree (Tree Discovery Procedure: DMEF).

2), the number of links per tree for MAODV, NR-MLPBR and R-MLPBR is about 4-7%, 8-9% and 9-14% more than that incurred for BEMRP in low, medium and high-density networks respectively. For medium and large-sized multicast groups, the number of links per tree for both MAODV and NR-MLPBR is about 7-15%, 17-28% and 21-35% more than that incurred for BEMRP in low, medium and high-density networks respectively. On the other hand, the number of links per tree for R-MLPBR is about 6-8%, 11-18% and 15-24% more than that incurred for BEMRP in low, medium and high-density networks respectively. These results are almost the same as that obtained when flooding is used as the tree discovery strategy.

4.3 Hop count per source-receiver path

All the three multicast routing protocols – MAODV, NR-MLPBR and R-MLPBR, incur almost the same average hop count per source-receiver and it is considerably lower than that incurred for BEMRP. The hop count per source-receiver path is an important metric and it is often indicative of the end-to-end delay per multicast packet from the source to a specific receiver. BEMRP incurs a significantly larger hop count per source-receiver path and this can be attributed to the nature of this multicast routing protocol to look for trees with a reduced number of links. When multiple receiver nodes have to be connected to the source through a reduced set of links, the hop count per source-receiver path is bound to increase. In performance Figures 4 and 5, we can see a significant increase in the hop count per source-receiver path as we increase the multicast group size. In the case of flooding, the hop count per source-receiver path for BEMRP can be as large as 41%, 57% and 59% more than that of the hop count per source-receiver path incurred for the other three multicast routing protocols. In the case of DMEF, the hop count per source-receiver path for BEMRP can be as large as 36%, 49% and 53% more than that of the hop count per source-receiver path incurred for the other three multicast routing protocols. The increase in the hop count per source-receiver path for BEMRP is slightly less than that obtained under flooding.

Performance with Flooding as the Tree Discovery Strategy

- *Impact of Node Mobility*: For a given network density and group size, we do not see any appreciable variation in the hop count per source-receiver path for each of the multicast routing protocols studied.
- *Impact of Network Density*: As we increase the network density, the hop count per source-receiver path decreases. This is mainly observed in the case of the minimum-hop based MAODV, NR-MLPBR

and R-MLPBR. In the case of BEMRP, the impact of network density on the decrease in the hop count is relatively less as it is a bandwidth-efficient multicast routing protocol attempting to reduce the number of links in the tree. In networks of moderate density (50 nodes), the hop count per source-receiver path for the three minimum hop based multicast protocols is about 6%, 9-12% and 15-19% less than that incurred in low-density networks for multicast groups of small, medium and larger sizes respectively. In high density networks (75 nodes), the hop count per source-receiver path for the three minimum-hop based multicast protocols is about 7-9%, 11-18% and 15-19% less than that incurred in low-density networks for multicast groups of small, medium and larger sizes respectively. In the case of BEMRP, the maximum reduction in the hop count with increase in network density is within 10%.

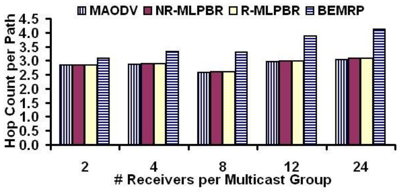

Figure 4.1: 25 nodes, 10 m/s.

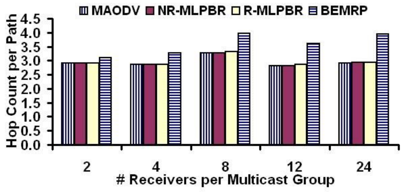

Figure 4.2: 25 nodes, 30 m/s.

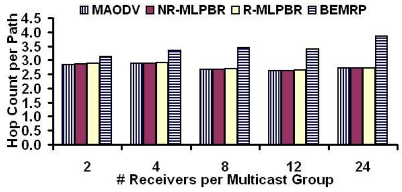

Figure 4.3: 25 nodes, 50 m/s.

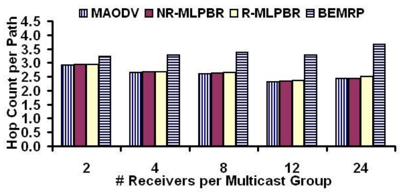

Figure 4.4: 50 nodes, 10 m/s.

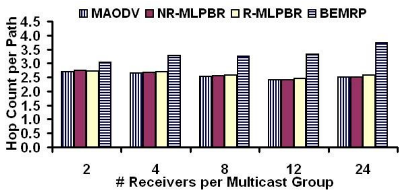

Figure 4.5: 50 nodes, 30 m/s.

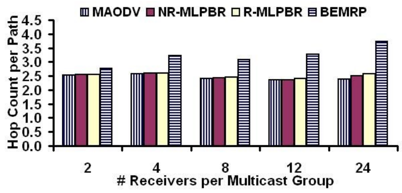

Figure 4.6: 50 nodes, 50 m/s.

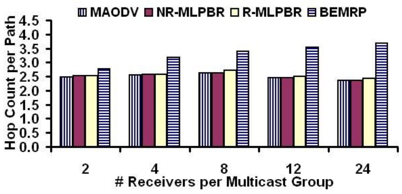

Figure 4.7: 75 nodes, 10 m/s.

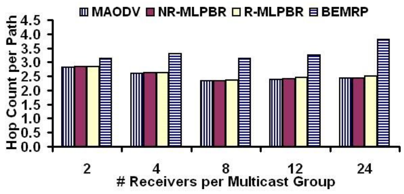

Figure 4.8: 75 nodes, 30 m/s.

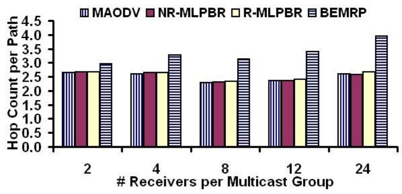

Figure 4.9: 75 nodes, 50 m/s.

Figure 4: Average Hop Count per Source-Receiver Path (Tree Discovery Procedure: Flooding).

- *Impact of Multicast Group Size*: For smaller multicast groups (of size 2), the hop count per source-receiver path for BEMRP can be 6-10%, 8-12% and 10-12% more than that of the other three multicast routing protocols in networks of low, moderate and high density respectively. For medium sized multicast groups, the hop count per source-receiver path for BEMRP can be 14-29%, 21-30% and 23-37% more than that of the other three multicast routing protocols in networks of low, moderate and high density respectively. For large-sized multicast groups, the hop count per source-receiver path for BEMRP can be 27-41%, 35-57% and 33-59% more than that of the hop count per source-receiver path for the other three multicast routing protocols in networks of low, moderate and high density respectively.

Performance with DMEF as the Tree Discovery Strategy

- *Impact of Node Mobility*: For each of the multicast routing protocols, as the maximum node velocity is increased from 10 m/s to 30 m/s, we observe that the hop count per source-receiver path increases as large as up to 17% (for multicast groups of small and moderate sizes) and 7% (for multicast groups of larger size). As the maximum node velocity is increased from 10 m/s to 50 m/s, we observe that the number of links per multicast tree increases as large as up to 13% (for multicast groups of small and moderate sizes) and 15% (for multicast groups of larger size). This shows that DMEF can yield multicast trees with reduced hop count per source-receiver path under low node mobility, especially for multicast groups of small and moderate sizes.
- *Impact of Network Density*: The impact is similar to that observed in the case of flooding. For the minimum-hop based multicast protocols, with increase in network density, the hop count per source-receiver path decreases significantly. On the other hand, in the case of BEMRP, the decrease in the hop count per source-receiver path is relatively less, with increase in the network density.
- *Impact of Multicast Group Size*: For smaller multicast groups (of size 2), the hop count per source-receiver path for BEMRP can be 6-9%, 9-12% and 10-12% more than that of the other three multicast routing protocols in networks of low,

moderate and high density respectively. For medium sized multicast groups, the hop count per source-receiver path for BEMRP can be 13-28%, 20-29% and 23-34% more than that of the other three multicast routing protocols in networks of low, moderate and high density respectively. For large-sized multicast groups, the hop count per source-receiver path for BEMRP can be 24-36%, 33-50% and 36-54% more than that of the hop count per source-receiver path for the other three multicast routing protocols in networks of low, moderate and high density respectively.

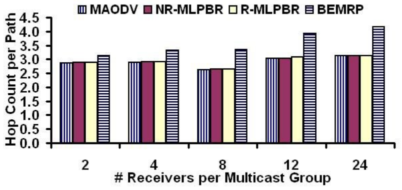

Figure 5.1: 25 nodes, 10 m/s.

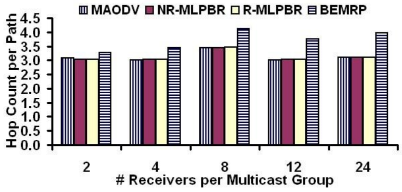

Figure 5.2: 25 nodes, 30 m/s.

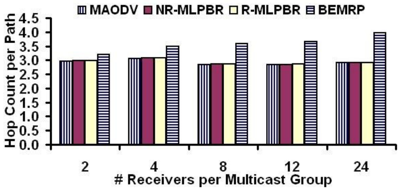

Figure 5.3: 25 nodes, 50 m/s.

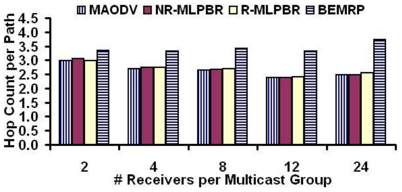

Figure 5.4: 50 nodes, 10 m/s.

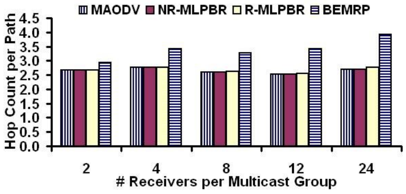

Figure 5.5: 50 nodes, 30 m/s.

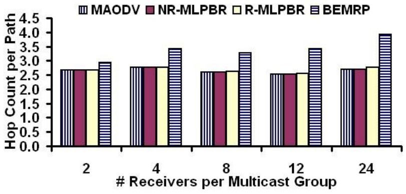

Figure 5.6: 50 nodes, 50 m/s.

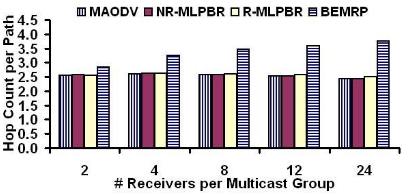

Figure 5.7: 75 nodes, 10 m/s.

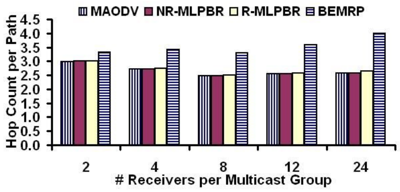

Figure 5.8: 75 nodes, 30 m/s.

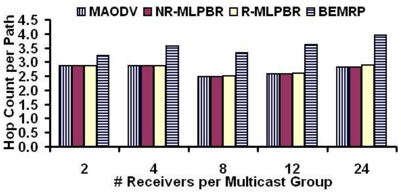

Figure 5.9: 75 nodes, 50 m/s.

Figure 5: Average Hop Count per Source-Receiver Path (Tree Discovery Procedure: DMEF).

4.4 Time between successive broadcast tree discoveries

The time between successive broadcast tree discoveries is a measure of the stability of the multicast trees and the effectiveness of the location prediction and path prediction approach of the two multicast extensions. For a given condition of node density and node mobility, both NR-MLPBR and R-MLPBR incur relatively larger time between successive broadcast tree discoveries for smaller and medium sized multicast groups. MAODV tends to be more unstable as the multicast group size is increased, owing to the minimum hop nature of the paths discovered and absence of any path prediction approach. For larger multicast groups, BEMRP tends to perform better by virtue of its tendency to strictly minimize only the number of links in the tree. On the other hand, NR-MLPBR attempts to reduce the hop count per source-receiver path and ends up choosing predicted paths that increase the number of links in the tree, quickly leading to the failure of the tree. The time between successive tree discoveries for R-MLPBR is 15-25%, 15-59% and 20-82% more than that obtained for MAODV in networks of low, moderate and high density respectively. For a given level of node mobility and network density, MAODV trees become highly unstable as the multicast group size increases. For multicast groups of size 2 and 4, the time between successive broadcast tree discoveries for NR-MLPBR and R-MLPBR is greater than that obtained for BEMRP, especially in networks of low and moderate network density. For larger multicast group sizes, when we employ flooding, BEMRP tends to incur larger time between successive broadcast tree discoveries compared to NR-MLPBR and R-MLPBR. On the other hand, when we employ DMEF, R-MLPBR tends to incur larger time between successive broadcast tree discoveries compared to BEMRP, even for larger group sizes.

Performance with Flooding as the Tree Discovery Strategy

- *Impact of Node Mobility*: For a given multicast group size, network density and multicast routing protocol, the time between successive broadcast tree discoveries at maximal node velocity of 30 m/s is roughly about 28-47% of that obtained at maximal node velocity of 10 m/s. The time between successive broadcast tree discoveries at maximal node velocity of 50 m/s is roughly about 21-36% of that obtained at maximal node velocity of 10 m/s.
- *Impact of Network Density*: For each multicast routing protocol, for a given multicast group size and level of node mobility, as the network density increases, the time between successive broadcast tree discoveries decreases. This is mainly observed for

the minimum-hop based multicast protocols (especially MAODV and NR-MLPBR) which incur a reduced hop count per source-receiver path as we increase the network density. But, such minimum hop paths obtained in moderate and high-density networks are relatively less stable than those obtained in low-density networks. For a given multicast group size and low node mobility, the time between successive tree discoveries in networks of moderate density (50 nodes) for MAODV and NR-MLPBR is 67-90% and for R-MLPBR and BEMRP is 73-96% of those incurred in low-density networks.

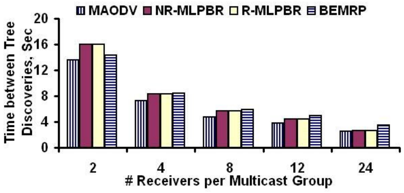

Figure 6.1: 25 nodes, 10 m/s.

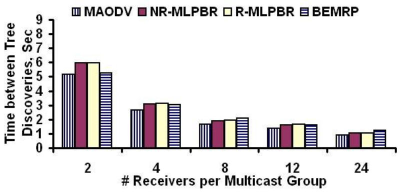

Figure 6.2: 25 nodes, 30 m/s.

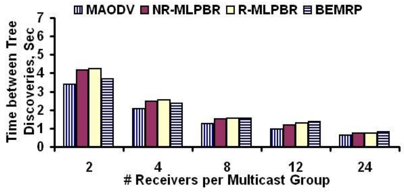

Figure 6.3: 25 nodes, 50 m/s.

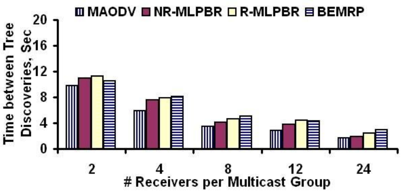

Figure 6.4: 50 nodes, 10 m/s.

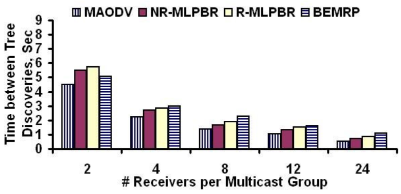

Figure 6.5: 50 nodes, 30 m/s.

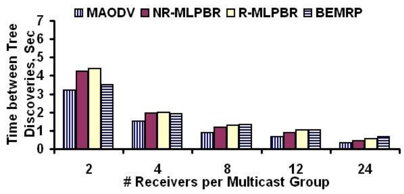

Figure 6.6: 50 nodes, 50 m/s.

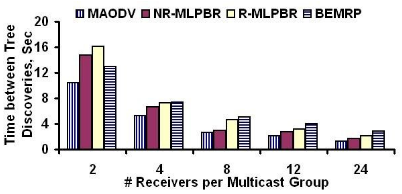

Figure 6.7: 75 nodes, 10 m/s.

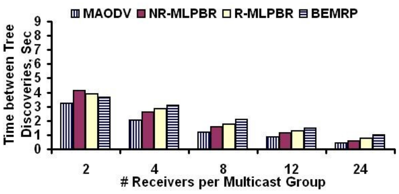

Figure 6.8: 75 nodes, 30 m/s.

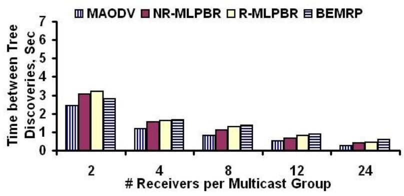

Figure 6.9: 75 nodes, 50 m/s.

Figure 6: Average Time between Successive Tree Discoveries (Tree Discovery Procedure: Flooding).

For a given multicast group size and low node mobility, the time between successive tree discoveries in networks of high density (75 nodes) is 51-80% for MAODV and NR-MLPBR and for R-MLPBR and BEMRP is 70-90% of those obtained in networks of low-density.

In low-density networks, the time between successive route discoveries for R-MLPBR and NR-MLPBR is about 10-15% more than that obtained for BEMRP for smaller multicast groups and is almost the same as that of BEMRP for moderately sized multicast groups. For larger multicast groups, the time between successive route discoveries for R-MLPBR and NR-MLPBR can be about 10-23% less than that obtained for BEMRP. In moderate and high density networks, the time between successive route discoveries for R-MLPBR is about 7-25% more than that obtained for BEMRP for smaller multicast groups and is about the same of moderately size multicast groups. For larger multicast groups, the time between successive route discoveries for R-MLBPR can be about 15-25% less than that obtained for BEMRP. In both moderate and high-density networks, R-MLPBR incurs larger time between successive route discoveries (as large as 30%) compared to NR-MLPBR.

- *Impact of Multicast Group Size*: For a given network density and node mobility, the time between successive route discoveries decreases as the multicast group size increases. For smaller group sizes, the time between successive broadcast tree discoveries for MAODV and BEMRP is respectively about 80%-90% and 85%-94% of that incurred for NR-MLPBR and R-MLPBR. For larger group sizes, the time between successive broadcast tree discoveries for MAODV is about 70%, 51% and 41% of that incurred for BEMRP in networks of low, moderate and high density respectively. Similarly, for larger group sizes, the time between successive broadcast tree discoveries for NR-MLPBR is about 76%, 64% and 57% of that incurred for BEMRP in networks of low, moderate and high density respectively. On the other hand, R-MLPBR tends to incur relatively larger time between successive tree discoveries even for larger multicast group sizes. For larger multicast groups, the time between successive tree discoveries for R-MLPBR is about 75%-80% of that incurred for BEMRP for all network densities.

Performance with DMEF as the Tree Discovery Strategy

- *Impact of Node Mobility*: For a given multicast group size, network density and multicast routing protocol, the time between successive broadcast tree discoveries at maximal node velocity of 30 m/s is roughly about 38-59% of that obtained at maximal node velocity of 10 m/s in networks of low, moderate and high density respectively. The time between successive broadcast tree discoveries at maximal node velocity of 50 m/s is roughly about 34-50% of that obtained at maximal node velocity of 10 m/s. In each instance, the increase in the time between successive route discoveries while using DMEF is at least 10-15% more than that obtained due to flooding.

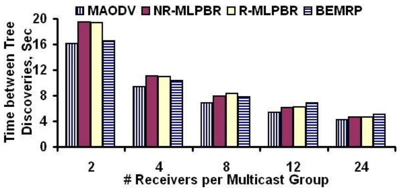

Figure 7.1: 25 nodes, 10 m/s.

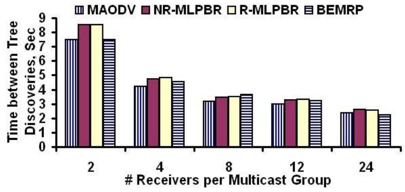

Figure 7.2: 25 nodes, 30 m/s.

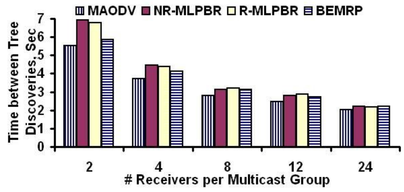

Figure 7.3: 25 nodes, 50 m/s.

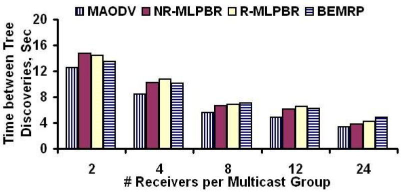

Figure 7.4: 50 nodes, 10 m/s.

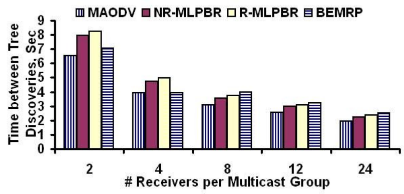

Figure 7.5: 50 nodes, 30 m/s.

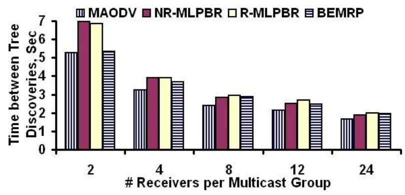

Figure 7.6: 50 nodes, 50 m/s.

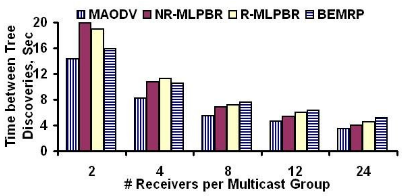

Figure 7.7: 75 nodes, 10 m/s.

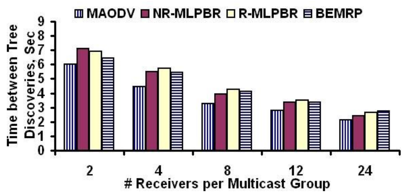

Figure 7.8: 75 nodes, 30 m/s.

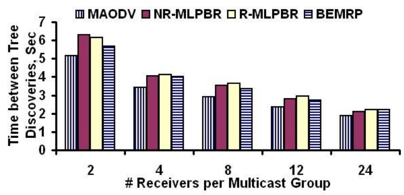

Figure 7.9: 75 nodes, 50 m/s.

Figure 7: Average Time between Successive Tree Discoveries (Tree Discovery Procedure: DMEF).

- *Impact of Network Density*: As we increase the network density from 25 nodes to 50 nodes, we observe that the time between successive broadcast tree discoveries for MAODV, NR-MLPBR, R-MLPBR and BEMRP decreases by 13%, 9%, 6% and 6% respectively. On the other hand, as we increase from 25 nodes to 75 nodes, we notice that the larger number of nodes in the neighbourhood is taken into account by DMEF to discover stable routes and there is no appreciable difference in the time between successive tree discoveries for NR-MLPBR, R-MLPBR and BEMRP. In the case of MAODV, the time between successive tree discoveries decreases by 8%.
- *Impact of Multicast Group Size*: For a given network density and node mobility, the time between successive route discoveries decreases as the multicast group size decreases. For smaller group sizes, the time between successive broadcast tree discoveries for MAODV and BEMRP is respectively about 82% and 87% of that incurred for NR-MLPBR and R-MLPBR. For moderate group sizes, the time between successive broadcast tree discoveries for MAODV, NR-MLPBR and BEMRP is about 77-86%, 96% and 96% of those incurred for R-MLPBR. For larger group sizes, the time between successive broadcast tree discoveries for MAODV and NR-MLPBR is about 80-89% and 92-94% of that obtained for R-MLPBR and BEMRP.

4.5 Energy consumed per node

Energy consumption in multicast routing is directly proportional to the number of links in the tree. Larger the number of links, more the transmissions and more will be the energy consumption in the network and vice-versa. The simulation results in Figures 8 and 9 clearly illustrate this. BEMRP incurs the least energy consumption per node and MAODV incurs the largest energy consumption per node. The energy consumed per node for the two multicast extensions is in between these two extremes. The energy consumed per node for R-MLPBR is less than that of NR-MLPBR as the former also attempts to simultaneously reduce the number of links as well as the hop count per source-receiver path. The energy consumption per node increases as the multicast group size increases. For a given multicast group size and multicast routing protocol, the energy consumed per node increases with increase in network density as well as with increase in node mobility.

Performance with Flooding as the Tree Discovery Strategy

- *Impact of Node Mobility*: For a given multicast group size, network density and multicast routing protocol, the energy consumed per node at maximal node velocity of 30 m/s can grow as large as 10-35% of that obtained at maximal node velocity of 10 m/s. The energy consumed per node at maximal node velocity of 50 m/s can grow as large as 10-40% of that obtained at maximal node velocity of 10 m/s. BEMRP and MAODV incur the largest increase in energy consumed per node with increase in node mobility. NR-MLPBR and R-MLPBR incur a relatively lower increase in the energy consumed per node with increase in node mobility. This can be attributed to the tendency of these multicast routing protocols to reduce the number of broadcast tree discoveries using effective tree prediction.

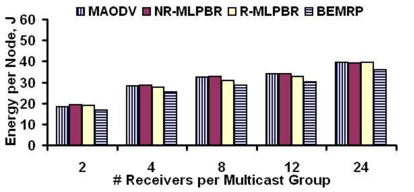

Figure 8.1: 25 nodes, 10 m/s.

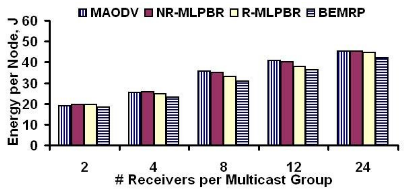

Figure 8.2: 25 nodes, 30 m/s.

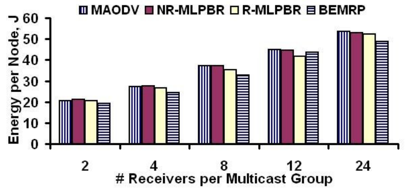

Figure 8.3: 25 nodes, 50 m/s.

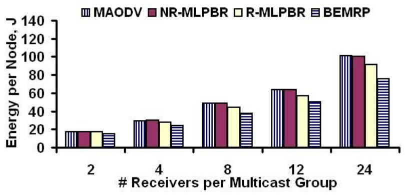

Figure 8.4: 50 nodes, 10 m/s.

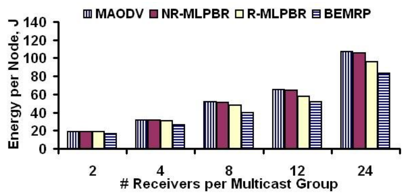

Figure 8.5: 50 nodes, 30 m/s.

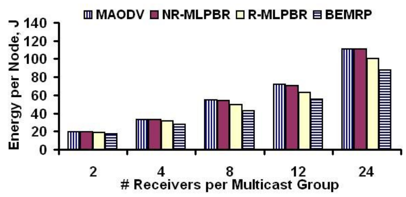

Figure 8.6: 50 nodes, 50 m/s.

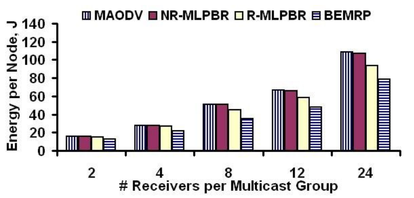

Figure 8.7: 75 nodes, 10 m/s.

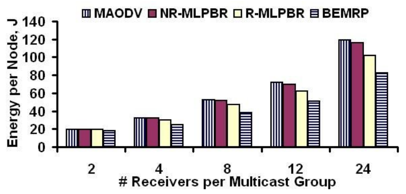

Figure 8.8: 75 nodes, 30 m/s.

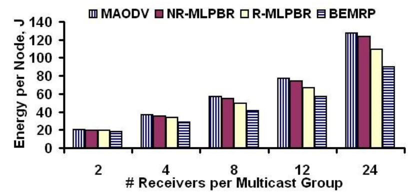

Figure 8.9: 75 nodes, 50 m/s.

Figure 8: Average Energy Consumed per Node (Tree Discovery Procedure: Flooding).

- *Impact of Network Density*: For multicast groups of size 2 and 4, we observe that with increase in network density from 25 to 50 nodes and from 25 to 75 nodes, the energy consumed per node decreases. This can be attributed to the smaller group size, leading to the effective sharing of the data forwarding load among all the nodes in the network. For larger group sizes, all the nodes in the network end up spending more energy (due to transmission/reception or at least receiving the packets in the neighbourhood). As a result, for multicast group sizes of 8, 12 and 24, as we increase the network density from 25 nodes to 50 nodes, the increase in the energy consumed per node for MAODV, NR-MLPBR, R-MLPBR and BEMRP is by factors of 47%-134%, 46%-133%, 42%-122% and 30%-96% respectively. As we increase the network density from 25 nodes to 75 nodes, the increase in the energy consumed per node for MAODV, NR-MLPBR, R-MLPBR and BEMRP is by factors of 52%-158%, 50%-154%, 42%-125% and 25%-100% respectively. MAODV and NR-MLPBR incur a relatively larger energy consumed per node at high network densities due to the nature of these multicast routing protocols to discover trees with minimum hop count. R-MLPBR and BEMRP discover trees with reduced number of links and hence incur relatively lower energy consumed per node at high network density.
- *Impact of Multicast Group Size*: As we increase the multicast group size from 2 to 24, the energy consumed per node for MAODV and NR-MLPBR increases by a factor of 2.1 to 2.6, 5.7 to 5.9 and 6.0 to 7.0 for low, medium and high density networks respectively. In the case of BEMRP and R-MLPBR, as we increase the multicast group size from 2 to 24, the energy consumed per node increases by a factor of 2.1 to 2.5, 4.9 to 5.2 and 4.6 to 6.2 in networks of low, medium and high density respectively. The increase in the energy consumed per node is below linear. Hence, all the four multicast routing protocols are scalable with respect to the increase in multicast group size.

Performance with DMEF as the Tree Discovery Strategy

- *Impact of Node Mobility*: For a given multicast group size, network density and multicast routing protocol, the energy consumed per node at maximal node velocity of 30 m/s and 50 m/s can grow as large as 5-20% of that obtained at maximal node velocity of 10 m/s. This indicates the effectiveness of DMEF vis-à-vis flooding in reducing the energy consumed per node. DMEF discovers relatively more stable trees by involving only slow moving nodes in the tree. As a result, the multicast trees exist for a long time and incur less energy for tree discoveries. Similar to that observed for flooding, BEMRP and MAODV incur the largest increase in energy consumed per node with increase in node mobility. NR-MLPBR and R-MLPBR incur a relatively lower increase in the energy consumed per node with increase in node mobility.

- *Impact of Network Density*: Similar to the observed for flooding, for multicast groups of size 2 and 4, we observe that with increase in network density from

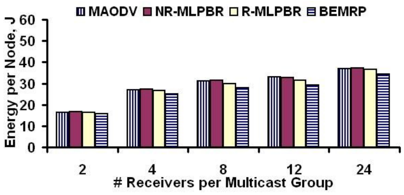

Figure 9.1: 25 nodes, 10 m/s.

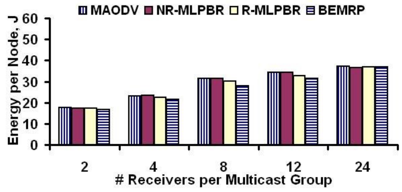

Figure 9.2: 25 nodes, 30 m/s.

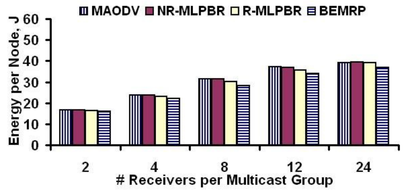

Figure 9.3: 25 nodes, 50 m/s.

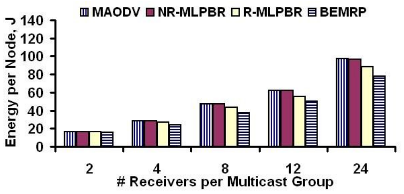

Figure 9.4: 50 nodes, 10 m/s.

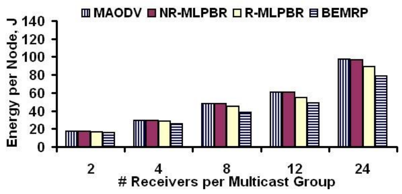

Figure 9.5: 50 nodes, 30 m/s.

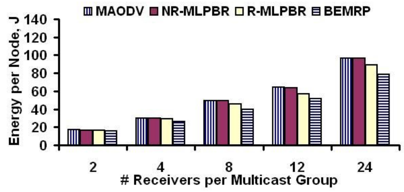

Figure 9.6: 50 nodes, 50 m/s.

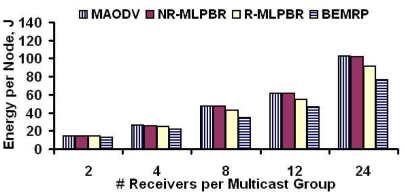

Figure 9.7: 75 nodes, 10 m/s.

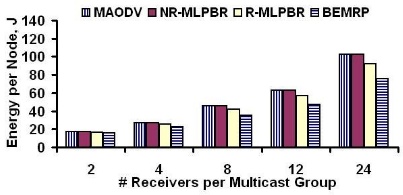

Figure 9.8: 75 nodes, 30 m/s.

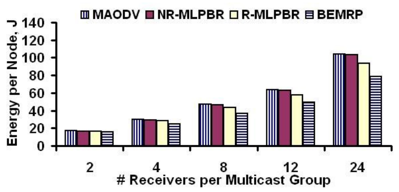

Figure 9.9: 75 nodes, 50 m/s.

Figure 9: Average Energy Consumed per Node (Tree Discovery Procedure: DMEF).

25 to 50 nodes and from 25 to 75 nodes, the energy consumed per node decreases. For multicast group sizes of 8, 12 and 24, as we increase the network density from 25 nodes to 50 nodes, the increase in the energy consumed per node for MAODV, NR-MLPBR, R-MLPBR and BEMRP is by factors of 54%-157%, 53%-156%, 48%-136% and 38%-118% respectively. As we increase the network density from 25 nodes to 75 nodes, the increase in the energy consumed per node for MAODV, NR-MLPBR, R-MLPBR and BEMRP is by factors of 49%-173%, 47%-172%, 42%-146% and 27%-114% respectively. MAODV and NR-MLPBR incur a relatively larger energy consumed per node at high network densities due to the nature of these multicast routing protocols to discover trees with minimum hop count. R-MLPBR and BEMRP discover trees with reduced number of links and hence incur relatively lower energy consumed per node at high network density. For a given network density, the energy consumed per node due to flooding can be as large as 5%-16%, 12%-23% and 22%-37% more than that incurred using DMEF in the presence of low, medium and high node mobility respectively.

- *Impact of Multicast Group Size*: As we increase the multicast group size from 2 to 24, the energy consumed per node for MAODV and NR-MLPBR increases by a factor of 2.2 to 2.4, 5.6 to 5.8 and 6.0 to 7.1 for low, medium and high density networks respectively. In the case of BEMRP and R-MLPBR, as we increase the multicast group size from 2 to 24, the energy consumed per node increases by a factor of 2.2 to 2.4, 4.9 to 5.4 and 4.8 to 6.4 in networks of low, medium and high density respectively. The increase in the energy consumed per node is below linear. Hence, all the four multicast routing protocols are scalable with respect to the increase in multicast group size.

4.6 Energy throughput

For each of the multicast routing protocols and for a given network density and node mobility, the energy throughput decreases with increase in the multicast group size. This can be attributed to the need to spend more energy to deliver a given multicast packet to more receivers vis-à-vis few receivers. For a given network density and multicast group size, the energy throughput of a multicast routing protocol decreases slightly as the node velocity is increased from low to moderate and high. For a given multicast group size and node mobility, the energy throughput of a multicast routing protocol decreases with increase in network density. This can be attributed to the involvement of several nodes (for larger network density) in distributing the offered traffic load to the multicast group. For a given simulation condition, the energy throughput of BEMRP is slightly larger than that of the other multicast routing protocols. This can be attributed to the lower energy consumed per node (and less number of links) for BEMRP.

Performance with Flooding as the Tree Discovery Strategy

- *Impact of Node Mobility*: As we increase the node mobility, the energy throughput for a multicast protocol reduces as large as by 8%-12%, 12%-17% and 24%-26% in low, moderate and high density networks respectively. For a given network density,

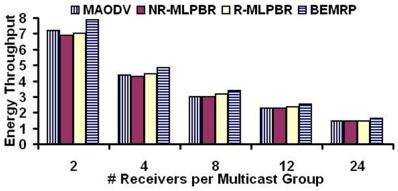

Figure 10.1: 25 nodes, 10 m/s.

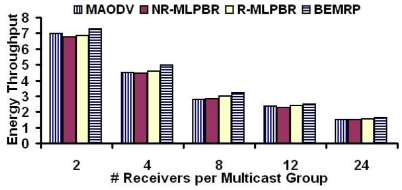

Figure 10.2: 25 nodes, 30 m/s.

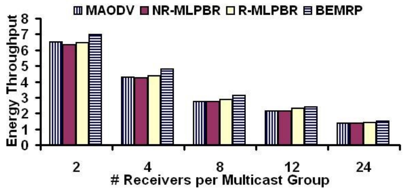

Figure 10.3: 25 nodes, 50 m/s.

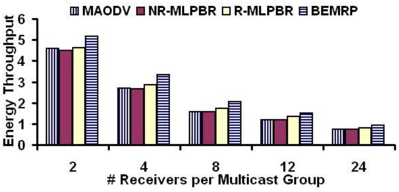

Figure 10.4: 50 nodes, 10 m/s.

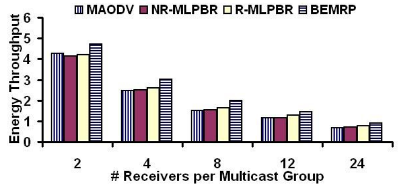

Figure 10.5: 50 nodes, 30 m/s.

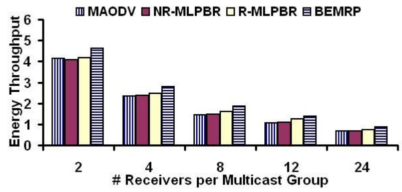

Figure 10.6: 50 nodes, 50 m/s.

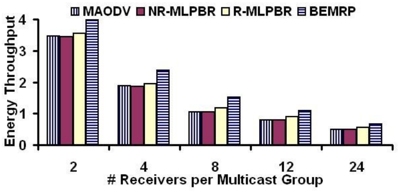

Figure 10.7: 75 nodes, 10 m/s.

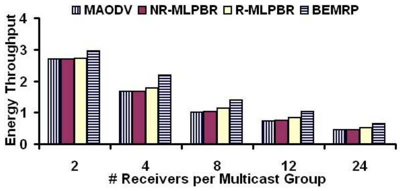

Figure 10.8: 75 nodes, 30 m/s.

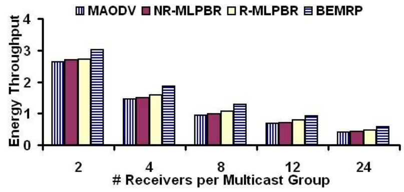

Figure 10.9: 75 nodes, 50 m/s.

Figure 10: Energy Throughput: # Packets Delivered per Joule (Tree Discovery Procedure: Flooding).

the reduction in the energy throughput with increase in node mobility is due to the relatively larger amount of energy spent for broadcast tree discoveries.

- *Impact of Network Density*: The decrease in energy throughput with increase in network density is more for MAODV and NR-MLPBR, relatively lower for R-MLPBR and is the least for BEMRP. At network density of 50 nodes, the energy throughput of MAODV and NR-MLPBR is 45%-64% and that of R-MLPBR and BEMRP is 50%-65% of that observed at network density of 25 nodes. At network density of 75 nodes, the energy through of MAODV, NR-MLPBR, R-MLPBR and BEMRP is 29%-48%, 30%-50%, 33%-50% and 38%-50% of that observed at network density of 25 nodes.
- *Impact of Multicast Group Size*: As the multicast group size is increased from 2 to 4, the energy throughput of the multicast routing protocols decreased by 30%-40%, 36%-40% and 24%-45% in networks of low, moderate and high density respectively. As the multicast group size is increased from 2 to 24, the energy throughput of the multicast routing protocols decreased by about 78%, 83% and 85% in networks of low, moderate and high density respectively.

Performance with DMEF as the Tree Discovery Strategy

- *Impact of Node Mobility*: As we increase the node mobility from low to moderate and high, the energy throughput for a multicast routing protocol reduces as large as by 7%-8%, 8%-12% and 16%-17% in networks of low, moderate and high density respectively. The relatively higher energy throughput while using DMEF can be attributed to the tendency of the broadcast strategy to involve only relatively slow moving nodes to be part of the trees. As a result, less energy consumed for broadcast tree discoveries.
- *Impact of Network Density*: The decrease in energy throughput with increase in network density is more for MAODV and NR-MLPBR, relatively lower for R-MLPBR and is the least for BEMRP. At network density of 50 nodes, the energy throughput of MAODV, NR-MLPBR, R-MLPBR and BEMRP is 48%-63%, 47%-63%, 52%-64% and 58%-69% of that observed at network density of 25 nodes. At

network density of 75 nodes, the energy through of MAODV, NR-MLPBR, R-MLPBR and BEMRP is 32%-47%, 32%-48%, 36%-48% and 42%-50% of that observed at network density of 25 nodes.

- *Impact of Multicast Group Size*: As the multicast group size is increased from 2 to 4, the energy throughput of the multicast routing protocols decreased by 36%-44%, 35%-45% and 30%-47% in networks of low, moderate and high density respectively. As the multicast group size is increased from 2 to 24, the energy throughput of the multicast routing protocols decreased by about 80%, 84% and 84% in networks of low, moderate and high density respectively.

4.7 Energy consumed per tree discovery

For a given broadcast strategy, the energy consumed per tree discovery is the same for all of the four multicast

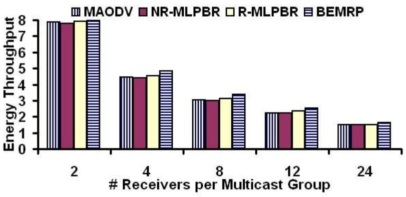

Figure 11.1: 25 nodes, 10 m/s.

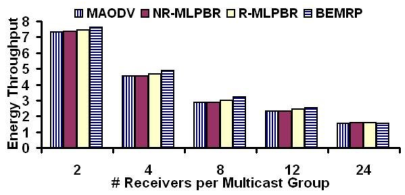

Figure 11.2: 25 nodes, 30 m/s.

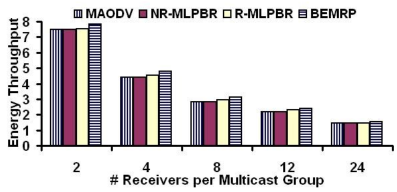

Figure 11.3: 25 nodes, 50 m/s.

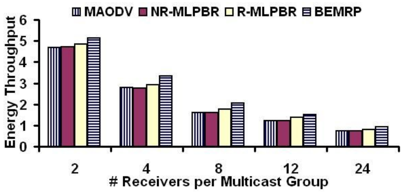

Figure 11.4: 50 nodes, 10 m/s.

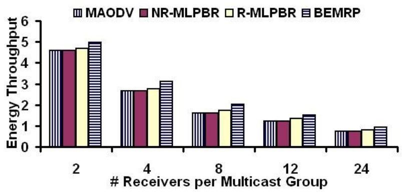

Figure 11.5: 50 nodes, 30 m/s.

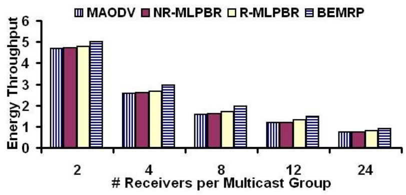

Figure 11.6: 50 nodes, 50 m/s.

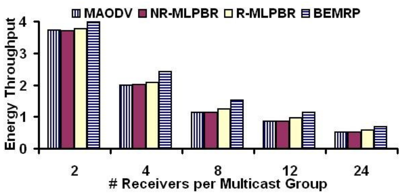

Figure 11.7: 75 nodes, 10 m/s.

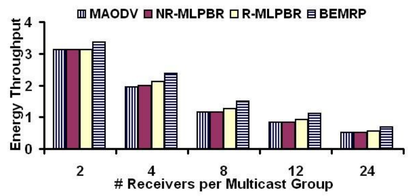

Figure 11.8: 75 nodes, 30 m/s.

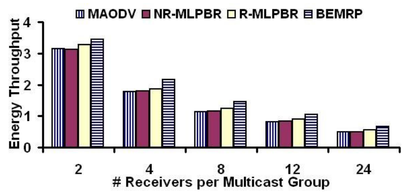

Figure 11.9: 75 nodes, 50 m/s.

Figure 11: Energy Throughput: # Packets Delivered per Joule (Tree Discovery Procedure: DMEF).

routing protocols. For both flooding and DMEF, the energy consumed increases with increase in network density, attributed to the involvement of multiple nodes in the broadcast of the MTRMs. In low-density networks, the energy consumed per tree discovery using flooding is 10-22%, 19-35% and 14-20% more than that of the energy consumed per tree discovery using DMEF in low, moderate and high node mobility conditions respectively. In moderate density networks, the energy consumed per tree discovery using flooding is about 15%, 23% and 28% more than that of the energy consumed per tree discovery using DMEF in low, moderate and high node mobility conditions respectively. In high-density networks, the energy consumed per tree discovery using flooding is about 18%, 30% and 37% more than the energy consumed per tree discovery using DMEF. As observed, DMEF performs better than flooding with increase in network density and/or node mobility.

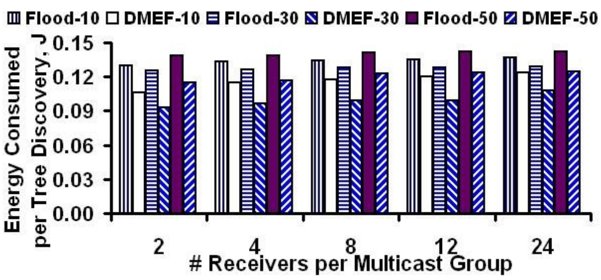

Figure 12: Energy Consumed per Broadcast Tree Discovery: Flooding vs. DMEF (25 Nodes).

For a given multicast group size, the energy consumed while using flooding in moderate (50 nodes) and high density (75 nodes) networks is respectively about 3.8 and 8 times more than that incurred in networks of low density. This indicates that as the number of nodes is increased by *x* times (*x* = 2 for moderate density and *x* = 3 for high density), the energy consumed due to flooding increases by 2^x times. In the case of DMEF, for a given multicast group size, the energy consumed in moderate density networks is about 3.7, 3.5 and 3.2 times more than that observed in low density networks for low, moderate and high node mobility conditions respectively. For a given multicast group size, the energy consumed during DMEF in high-density networks is about 7.8, 7.2 and 6.6 times more than that observed in low-density networks for low, moderate and high node mobility conditions respectively. Thus, the energy consumed while using DMEF does not increase exponentially as observed for flooding. DMEF performs appreciably well in lowering the energy consumed per tree discovery with increase in node mobility and/or increase in network density.

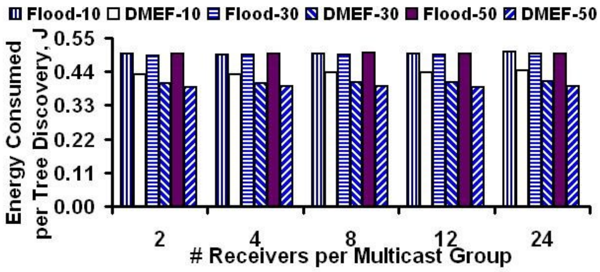

Figure 13: Energy Consumed per Broadcast Tree Discovery: Flooding vs. DMEF (50 Nodes).

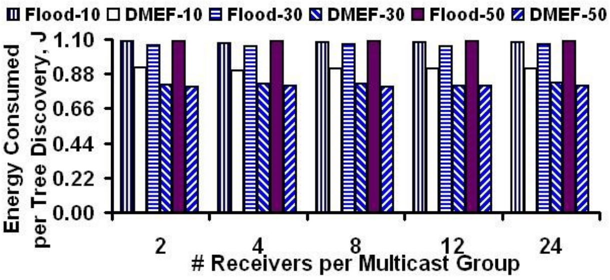

Figure 14: Energy Consumed per Broadcast Tree Discovery: Flooding vs. DMEF (75 Nodes).

5 Survey of MANET broadcast route discovery strategies

We surveyed the literature for different broadcast route discovery strategies proposed to reduce the route discovery overhead and we describe below the strategies relevant to the research conducted in this paper. In Section 5.3, we qualitatively analyse the advantages of our DMEF broadcast strategy compared to the broadcast strategies described below in Sections 5.1 and 5.2.

5.1 Reliable route selection (RRS) Algorithm

In [20], the authors proposed a Reliable Route Selection (referred to as RRS) algorithm based on Global Positioning System (GPS) [8]. The RRS algorithm divides the circular area formed by the transmission range of a node into two zones: stable zone and caution zone. A node is said to maintain stable links with the neighbour nodes in its stable zone and maintain unstable links with the neighbour nodes lying in its caution zone. If R is the transmission range of a node, then the radius of the stable zone is defined as $r = R\text{-}\delta S$ where S is the velocity of the node. The status zone is a circular region (with its own centre) inscribed inside the circular region formed by the transmission range of the node. The centre of the status zone need not be the centre of the circular region forming the transmission range of the node, but always lies in the direction of movement of the node.

RRS works as follows: The Route-Request (RREQ) message of a broadcast route discovery process includes the co-ordinates representing the current position of the transmitter of the RREQ message, the co-ordinates representing the centre of the stable zone of the transmitter, the value of parameter δ to be used by an intermediate node and the stable zone radius of the transmitter of the message. The source node of the route discovery process broadcasts the RREQ message in the complete neighbourhood formed by the transmission range R. The RRS-related fields are set to initial values corresponding to the source node. An intermediate node receiving the RREQ message broadcasts the message further, only if the node lies in the stable zone of the transmitter. If a route discovery attempt based on a set value of δ is unsuccessful, the source node decrements the value of δ and launches another global broadcast based route discovery. This process is continued (i.e., the value of δ decremented and global broadcast reinitiated) until the source finds a path to the destination. If the source cannot find a route to the destination even while conducting route discovery with δ set to zero, then the source declares that the destination is not connected to it.

5.2 Probability, counter, area and neighbour-knowledge based methods

In [15], the authors propose several broadcast route discovery strategies that could reduce the number of retransmitting nodes of a broadcast message. These strategies can be grouped into four families: probability-based, counter-based, area-based and neighbour-knowledge based methods:

(i) **Probability-based method:** When a node receives a broadcast message for the first time, the node rebroadcasts the message with a certain probability. If the message received is already seen, then the node drops the message irrespective of whether or not the node retransmitted the message when it received the message for the first time.

(ii) **Counter-based method:** When a node receives a broadcast message for the first time, it waits for a certain time before retransmitting the message. During this broadcast-wait-time, the node maintains a counter to keep track of the number of redundant broadcast messages received from some of its other neighbours. If this counter value exceeds a threshold within the broadcast-wait-time, then the node decides to drop the message. Otherwise, the node retransmits the message.

(iii) **Area-based method:** A broadcasting node includes its location information in the message header. The receiver node calculates the additional coverage area obtained if the message were to be rebroadcast. If the additional coverage area is less than a threshold value, all future receptions of the same message will be dropped. Otherwise, the node starts a broadcast-wait-timer. Redundant broadcast messages received during this broadcast-wait-time are also cached. After the timer expires, the node considers all the cached messages and recalculates the additional coverage area if it were to rebroadcast the particular message. If the additional obtainable coverage area is less than a threshold value, the cached messages are dropped. Otherwise, the message is rebroadcast.

(iv) **Neighbour-knowledge based method:** This method requires nodes to maintain a list of 1-hop neighbours and 2-hop neighbours, learnt via periodic beacon exchange. Using these lists, a node calculates the smallest set of 1-hop neighbours required to reach all the 2-hop neighbours. The minimum set of 1-hop neighbours that will cover all of the 2-hop neighbours is called the Multi Point Relays (MPRs).

5.3 Advantages of DMEF and differences with related work

The DMEF strategy is very effective in discovering relatively long-living routes in an energy-efficient manner and differs from the RRS algorithm in the following ways:

- RRS is highly dependent on location-service schemes like GPS, while DMEF is not dependent on any location-service scheme.
- RRS requires the RREQ message header to be changed while DMEF does not require any change in the structure of the RREQ messages used for broadcasting. DMEF can be thus used without requiring any change in a MANET routing protocol.
- In RRS, a node lying in the stable zone of the transmitter of the RREQ rebroadcasts the message in its complete neighbourhood. However, it is only the recipient nodes in the stable zone of the transmitter that rebroadcast the RREQ. Hence, RRS is not energy-efficient. In DMEF, the transmission range for broadcast at a node is dynamically and locally determined using the node's velocity and neighbourhood density and is usually considerably less than the maximum transmission range.
- RRS does not properly handle the scenario where the value of $\delta * S$ exceeds the transmission range, R, of the node. The value of δ has to be iteratively reduced (by trial and error) to determine the connectivity between the source and destination nodes. DMEF is better than RRS because it requires only one broadcast route discovery attempt from the source to determine a route to the destination if the two nodes are indeed connected. The values of the DMEF parameters are dynamically determined at each node by the nodes themselves because a node knows better about its own velocity and neighbourhood, compared to the source of the broadcast process.
- The network density does not influence the stable zone radius selected by RRS. In RRS, the number of nodes retransmitting the RREQ message in a neighbourhood increases significantly as the network density is increased. DMEF is quite effective in reducing the number of nodes retransmitting the RREQ message in high-density networks.

The advantages of the DMEF scheme when compared with the broadcast route discovery strategies discussed in Section 5.2 are summarized as follows:

- The probability and MPR-based methods do not guarantee that the broadcast message will be routed on a path with the minimum hop count or close to the minimum hop count. Previous research [13] on the impact of these broadcast strategies on the stability and hop count of DSR routes indicates that the hop count of the paths can be far more than the minimum and the routes have a smaller lifetime than the paths discovered using flooding. The probability-based method cannot always guarantee that the RREQ message gets delivered to the destination. Also, with increase in network density, the number of nodes retransmitting the message increases for both the probability-based and MPR-based methods.

  DMEF determines paths with hop count being close to that of the minimum hop count paths and such paths have a relatively larger lifetime compared to those discovered using flooding. DMEF almost always guarantees that a source-destination route is discovered if there is at least one such route in the underlying network. DMEF effectively controls the RREQ message retransmission overhead as the network density increases.
- The counter and area-based methods require careful selection of the threshold values for their proper functioning. Each node has to wait for a broadcast-wait-time before retransmitting the message. This can introduce significant route acquisition delays. The area-based method also requires the nodes to be location-aware and include the location information in the broadcast messages.

With DMEF, there is no waiting time at a node to rebroadcast a received RREQ message, if the message has been received for the first time during a particular route discovery. DMEF does not depend on any location-aware services for its operation and the structure of the RREQ message need not be changed.

5.4 Other relevant optimizations for multicast routing overhead

In addition to the methods described in Sections 5.1 and 5.2, some of the other optimizations that have been proposed in the MANET literature include: (i) A Swarm Intelligence based multicast routing protocol for ad hoc networks (MANHSI) has been proposed in [1]; (ii) In [19], the authors propose an independent tree ad hoc multicast routing (ITAMAR) framework that includes a number of heuristics to compute a set of alternate trees to improve the mean time between interruptions in multicast communication, achieved with a small increase in the route discovery overhead; and (iii) A virtual overlay mesh of unicast paths has been proposed for efficient discovery of multicast routes in [7].

6 Conclusions and future work

Simulations have been conducted with both flooding and DMEF as the broadcast tree discovery strategies. DMEF helps the multicast routing protocols to discover stable trees and at the same time does not increase the source-receiver hop count appreciably. Hence, the energy consumed per node with DMEF is lower than that incurred with flooding. With the use of DMEF as the tree discovery strategy, the performance of NR-MLPBR and R-MLPBR with respect to the time between successive tree discoveries and energy consumed per node actually improved relatively more than that observed for BEMRP and MAODV. This can be attributed to the effective path prediction of the two multicast extensions, an idea inherited from LPBR, and complemented by DMEF. Thus, DMEF has been demonstrated to be an effective broadcast strategy to discover multicast trees. In a related work [12], we have also demonstrated the effectiveness of DMEF to discover node-disjoint multi-path routes for MANETs. Thus, DMEF is an effective broadcast strategy to discover stable unicast, multicast and multi-path routes for MANETs with relatively lower energy consumption than the default flooding approach.

The related work listed in Sections 5.1 and 5.4 require the strategies to be embedded into the design of the protocols and require changes built-in to the route discovery procedure of the protocols. Ours is the first such effort to study the impact of protocol-independent broadcast strategies (like DMEF and flooding) on the performance of multicast routing protocols. In future, we will evaluate the impact of the probability, counter, area and neighbour-knowledge based methods on the performance of the multicast routing protocols.

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