A Density and Mobility Aware Energy-Efficient Broadcast Route Discovery Strategy for Mobile Ad hoc Networks

Dr. Natarajan Meghanathan

Jackson State University, Jackson, MS 39217

Summary
We propose a novel network density and mobility aware energy-efficient broadcast route discovery strategy (called DMEF) to determine stable routes in mobile ad hoc networks (MANETs). During the on-demand route discovery process, each node dynamically chooses its own broadcast transmission range for the Route-Request message depending on the perceived number of neighbor nodes in its default maximum transmission range and the node's own mobility values during the time of broadcast. A node surrounded by more neighbors advertises itself only to a limited set of nearby neighbors and a node surrounded by few neighbors advertises itself to a maximum of its neighbors. Similarly, a slow-moving node advertises itself to a majority of its neighbors so that links formed using this node can be more stable. A fast-moving node advertises itself only to the neighbors closer to it. Simulation results indicate that DMEF is very effective, vis-à-vis flooding, in reducing the number of broadcast route discoveries by determining routes with a longer lifetime and as well as in reducing the energy consumed per route discovery. DMEF does not require any changes in the packet headers and can be used with any MANET routing protocol that has been proposed in the literature.

Key words:
Route discovery, Flooding, Energy efficiency, Stable routes, Mobile ad hoc networks

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 and reactive. Proactive routing protocols require the nodes to periodically exchange the table updates to pre-determine routes between any pair of source-destination nodes. Reactive (on-demand) routing protocols determine routes only when a route is required from a source to a destination. In dynamically changing environments, typical of MANETs, reactive routing protocols incur lower control overhead to discover routes compared to the proactive routing protocols [1]. In this paper, we work only with the on-demand reactive routing protocols.

Flooding is the default route discovery approach for on-demand MANET routing protocols. 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 neighbors. Neighbor 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 neighborhood, at least 39% of the neighborhood would have seen it already and on the average only 41% of the additional area could be covered with a rebroadcast [2]. In this paper, we propose a novel density and mobility aware energy-efficient broadcast strategy called DMEF that attempts to reduce the energy consumed due to broadcast route discoveries by letting a node to broadcast only within a limited neighborhood. The neighborhood size to which a node advertises itself as part of the route discovery process is decided by the number of neighbors surrounding the node and the mobility of the node. The neighborhood 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 incurred using flooding.

The rest of the paper is organized as follows: Section 2 describes the proposed DMEF strategy in detail. Section 3 discusses related work and the advantages of DMEF.

Section 4 discusses the simulation environment and presents simulation results illustrating the effectiveness of DMEF. Section 5 concludes the paper. Note that, throughout this paper, the terms 'path' and 'route', '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 neighborhood" of each other. Each node broadcasts periodically a beacon message in its complete neighborhood. 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 neighborhood.

2.2 Basic Idea

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 neighbors 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 that is surrounded by more neighbors in the complete neighborhood should broadcast the RREQ message only within a smaller neighborhood 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 neighbors in the complete neighborhood should broadcast the RREQ message to a larger neighborhood (but still contained within the complete neighborhood) so that a majority of the nodes in the complete neighborhood 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 takes the following approach: A node that is highly mobile makes itself available only to a smaller neighborhood around itself, whereas a node that is less mobile makes itself available over a larger neighborhood (but still contained within the complete neighborhood). The reasoning is that links involving a slow moving node will exist for a long time. Hence, it is better for a slow moving node to advertise itself to a larger neighborhood 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 neighbors that are closer to it. Hence, it is worth to let a fast moving node advertise only to its nearby neighbors.

2.3 DMEF Mathematical Model

DMEF effectively uses the knowledge of neighborhood 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:

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

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:

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

In practice, the value of parameter α has to be sufficiently larger than the value obtained from (2), so that the RREQ message reaches neighbors 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 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 neighborhood 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 neighborhood and node velocity.

Let *maxNeighb_lowDensity*, *maxNeighb_modDensity* represent the maximum number of neighbors a node should have in order to conclude that the complete neighborhood density of the node is low and moderate respectively. If a node has more than *maxNeighb_modDensity* number of neighbors, then the node is said to exist in a complete neighborhood of high density. Let *lowDensity_α*, *modDensity_α* and *highDensity_α* represent the values of *α* to be chosen by a node for complete neighborhoods 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 neighbors in the complete neighborhood 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 neighborhood 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 neighborhood

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 ($v_u^t \le maxVel\_lowMobility$)
$\beta_u^t \leftarrow lowMobility\_\beta$
else if ($v_u^t \le maxVel\_moderateMobility$)
$\beta_u^t \leftarrow moderateMobility\_\beta$
else
$\beta_u^t \leftarrow highMobility\_\beta$

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

if ($|Neighbors_u^t| \le maxNeighb\_lowDensity$)
$\alpha_u^t \leftarrow$ Maximum ($minimum\_\alpha_u^t$, *lowDensity_α*)
else if ($|Neighbors_u^t| \le maxNeighb\_modDensity$)
$\alpha_u^t \leftarrow$ Maximum ($minimum\_\alpha_u^t$, *modDensity_α*)
else
$\alpha_u^t \leftarrow$ Maximum ($minimum\_\alpha_u^t$, *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 Related Work

We surveyed the literature for different broadcast route discovery strategies that have been proposed to reduce the route discovery overhead and we describe below the strategies relevant to the research conducted in this paper. In Section 3.3, we qualitatively analyze the advantages of our DMEF broadcast strategy compared to the broadcast strategies described below in Sections 3.1 and 3.2.

3.1 Reliable Route Selection (RRS) Algorithm

In [3], the authors proposed a Reliable Route Selection (referred to as RRS) algorithm based on Global Positioning System (GPS) [4]. 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 neighbor nodes lying in its stable zone and maintain unstable links with the neighbor 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 speed of the node. The status zone is a circular region (with its own center) inscribed inside the circular region formed by the transmission range of the node. The center of the status zone need not be the center 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 center 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 neighborhood 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.

3.2 Efficient Broadcast Route Discovery Strategies

In [2], 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 neighbor-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 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 neighbors. 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 that would be 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) **Neighbor-knowledge based method:** This method requires nodes to maintain a list of 1-hop neighbors and 2-hop neighbors, learnt via periodic beacon exchange. Using these lists, a node calculates the set (of the smallest possible size) of 1-hop neighbors required to reach all the 2-hop neighbors. The minimum set of 1-hop neighbors that will cover all of the 2-hop neighbors is called the Multi Point Relays (MPRs).

3.3 Advantages of DMEF and Differences with Related Work

Our DMEF route discovery 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 for its normal functionality.
- 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 with any MANET routing protocol without requiring any change in the routing protocol.
- In RRS, a node lying in the stable zone of the transmitter of the RREQ rebroadcasts the message in its complete neighborhood. However, it is only the recipient nodes lying in the stable zone of the transmitter that rebroadcast the RREQ. Hence, RRS is not energy-efficient. On the other hand, in DMEF, the transmission range for broadcast at a node is dynamically and locally determined using the node's velocity and neighborhood density values 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 of the node R. The value of δ has to be iteratively reduced by trial and error method 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 neighborhood, compared to the source of the broadcast process.

- The network density does not influence the stable zone radius selected by RRS. As a result, in RRS, the number of nodes retransmitting the RREQ message in a neighborhood 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 3.2 are summarized as follows:

- The probability-based 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 [5] on the impact of these broadcast strategies on the stability and hop count of the DSR routes indicates that the hop count of the paths can be far more than the minimum hop count 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-based and area-based methods require careful selection of the threshold counter and area of coverage 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 process. DMEF does not depend on any location-aware services for its operation and the structure of the RREQ message for a routing protocol need not be changed.

4 Simulations

The effectiveness of the DMEF strategy has been studied through simulations conducted using a MANET discrete-event simulation software developed by us in Java. We use the well-known minimum-hop based Dynamic Source Routing (DSR) protocol [6] and the recently proposed Location-Prediction Based Routing (LPBR) protocol [7] to reduce the number of global broadcast route discoveries, as the routing protocols that use DMEF as their route discovery strategy. The benchmark used for DMEF evaluation is the performance of DSR and LPBR with flooding as the route discovery strategy. The network dimensions are: 1000m x 1000m. The maximum transmission range of a node is 250m. Network density is varied by conducting simulations with 25 (low density), 50 (moderate density) and 75 (high density) nodes. The mobility model used is the Random Waypoint model [8] according to which the velocity of each node is uniformly randomly distributed in the range [$v_{min} \ldots v_{max}$]. The value of v_{min} is 0 m/s and the value of v_{max} is 10, 30 and 50 m/s representing average node velocities of 5 (low mobility), 15 (moderate mobility) and 25 m/s (high mobility) respectively. The traffic model used is the constant bit rate (CBR) model with a data packet of size 512 bytes sent every 0.25 seconds. There are 15 source-destination (*s-d*) pairs. The transmission energy is 1.4 W and the reception energy is 1 W [9]. Network bandwidth is 2 Mbps. The Medium Access Control (MAC) layer model followed is the IEEE 802.11 Distributed Coordinated Function (DCF) model [10]. The DMEF parameter values are given in Table 1. Total simulation time is 1000 seconds.

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

4.1 Dynamic Source Routing (DSR) Protocol

The unique feature of DSR [6] is source routing: data packets carry information about the route from the source to the destination in the packet header. As a result, intermediate nodes do not need to store up-to-date routing information in their forwarding tables. Route discovery is by means of the broadcast query-reply cycle. A source node *s* wishing to send a data packet to a destination *d*, broadcasts a RREQ packet throughout the network. The RREQ packet reaching a node contains the list of intermediate nodes through which it has propagated from the source node. After receiving the first RREQ packet, the destination node waits for a short time period for any more RREQ packets, then chooses a path with the minimum hop count and sends a RREP along the selected path. If any RREQ is received along a path whose hop count is lower than the one on which the RREP was sent, another RREP would be sent on the latest minimum hop path discovered. To minimize the route acquisition delay, DSR lets intermediate nodes to promiscuously listen to the channel, store the learnt routes (from the RREQ and data packets) in a route cache and use these cached route information to send the RREP back to the source. We do not use this feature as promiscuous listening dominates the energy consumed at each node and DSR could still effectively function without promiscuous listening and route caching. Also, in networks of high node mobility, cached routes are more likely to become stale, by the time they are used.

4.2 Location Prediction Based Routing (LPBR) Protocol

LPBR [7] simultaneously minimizes the number of flooding based route discoveries and the hop count of the paths for a source-destination session. During a regular flooding-based route discovery, LPBR collects the location and mobility information of the nodes in the network and stores the collected information at the destination node of the route search process. When the minimum-hop route discovered through the flooding fails, the destination node attempts to predict the current location of each node using the location and mobility information collected during the latest flooding-based route discovery. A minimum hop path Dijkstra algorithm [11] is run on the locally predicted global topology. If the predicted minimum hop route exists in reality, no expensive flooding-based route discovery is needed and the source continues to send data packets on the discovered route; otherwise, the source initiates another flooding-based route discovery.

4.3 Performance Metrics

The performance metrics studied are as follows:

- *Total Energy Lost per Route Discovery*: This is the average of the total energy consumed for the global broadcast based route discovery attempts. This includes the sum of the energy consumed to transmit (broadcast) a RREQ packet to all the nodes in the neighborhood and to receive the RREQ packet sent by each node in the neighborhood, summed over all the nodes.
- *Percentage of Total Energy Spent for Route Discovery*: This is the ratio of the total energy spent for route discovery to the sum of the energy spent across all the nodes in the network.
- *Hop Count per Path*: This is the average hop count per path, time-averaged over all the *s-d* sessions. For example, if we have been using two paths P1 of hop count 3 and P2 of hop count 5 for 10 and 20 seconds respectively, then the time-averaged hop count of P1 and P2 is (3*10+5*20)/30 = 4.33 and not 4.
- *Time between Route Discoveries*: This is the average of the time between two successive global broadcast based route discovery attempts. Larger the time between two successive route discoveries, lower will be the control overhead.
- *End-to-End Delay per Data Packet*: This is the average of the delay incurred by the data packets that originate at the source and delivered at the destination. The delay incurred by a data packet includes all the possible delays: the buffering delay due to the route acquisition latency, the queuing delay at the interface queue to access the medium, the transmission delay, propagation delay, and the retransmission delays due to the MAC layer collisions.
- *Packet Delivery Ratio*: This is the ratio of the data packets delivered to the destination to the data packets originated at the source, computed over all the *s-d* sessions.
- *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.

The performance results illustrated in Figures 2 through 8 are an average of simulations conducted with 5 mobility profiles for each operating condition.

4.4 Total Energy Spent Route Discovery

Performance results in figures 2.1 through 2.3 illustrate that DMEF achieves its purpose of reducing the energy spent in the network due to global broadcast route discoveries. The reduction in the energy spent for route discoveries is evident in both DSR and LPBR protocols.

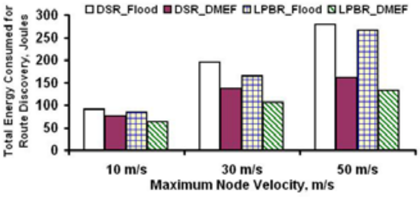

Figure 2.1: 25 Nodes

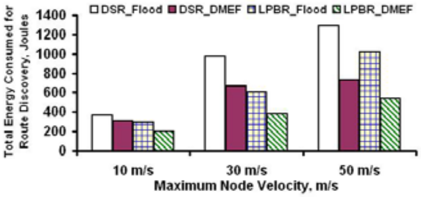

Figure 2.2: 50 Nodes

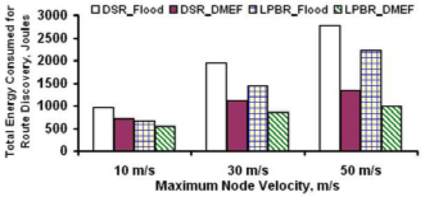

Figure 2.3: 75 Nodes

Figure 2: Total Energy Consumed for Route Discovery

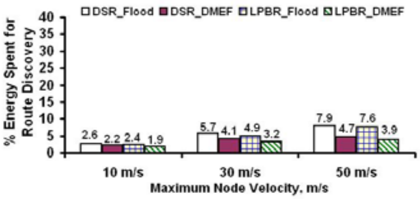

Figure 3.1: 25 Nodes

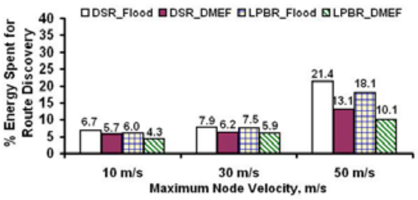

Figure 3.2: 50 Nodes

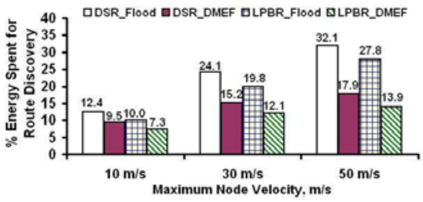

Figure 3.3: 75 Nodes

Figure 3: Percentage of Total Energy Spent for Route Discovery

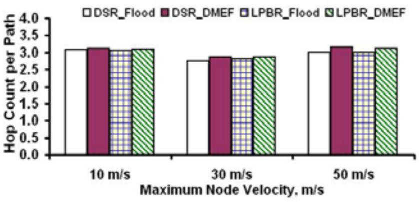

Figure 4.1: 25 Nodes

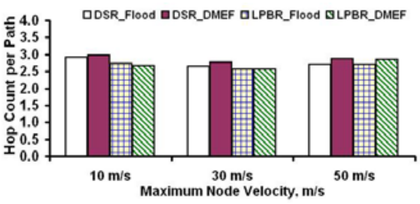

Figure 4.2: 50 Nodes

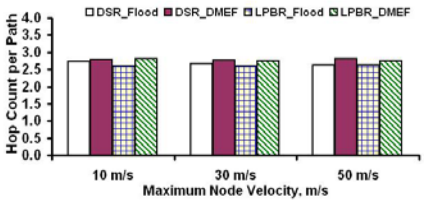

Figure 4.3: 75 Nodes

Figure 4: Average Hop Count per Path

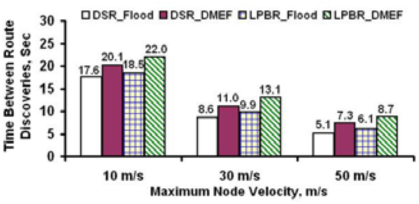

Figure 5.1: 25 Nodes

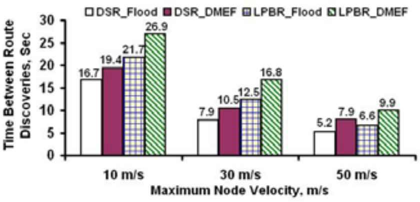

Figure 5.2: 50 Nodes

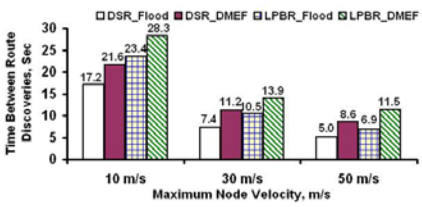

Figure 5.3: 75 Nodes

Figure 5: Time between Two Successive Route Discoveries

The reduction in the energy spent for route discoveries is also more evident as we increase the network density and/or node mobility. This illustrates the effectiveness of DMEF because the strategy aims to minimize the unnecessary rebroadcasts in a network especially when the network density is high. In high-density networks, it is enough to rebroadcast through a reduced set of nodes to find a set of paths between a source and destination rather than broadcasting through all the nodes in the network. Compared to DSR, LPBR incurs relatively lower number of global broadcast based route discoveries. In addition, DMEF helps the protocol to reduce the energy spent per broadcast based route discovery. Aided by both these factors, LPBR incurs a significantly lower energy due to route discoveries compared to DSR.

4.5 Percentage of Total Energy Spent for Route Discovery

As observed in Figures 3.1 through 3.3, for both DSR and LPBR, the difference in the percentage of total energy spent for route discovery using flooding and DMEF increases as we increase the network density and/or node mobility. For a given node mobility, the energy savings obtained with DMEF increases with increase in network density. Similarly, for a given network density, the energy savings obtained with DMEF, relative to flooding, increases with increase in the level of node mobility. For a given network density and node mobility, the relative reduction in the percentage of total energy spent for route discoveries due to DMEF vis-à-vis flooding is almost the same for both DSR and LPBR. This illustrates that DMEF can be used for energy-efficient route discovery by any routing protocol for mobile ad hoc networks.

4.6 Average Hop Count per Path

DMEF prefers to determine long-living routes by primarily broadcasting the RREQ message through nodes that are relatively slow moving in the network. As a result, the routes determined for the DSR and LPBR protocols need not have hop count matching with that of the minimum hop count paths in the network. DMEF determines routes that have at most 8% larger hop count compared to the minimum hop routes, but the routes determined through DMEF exist for a relatively larger lifetime compared to the routes determined using flooding. For both DSR and LPBR, for a given node mobility in the network, as we increase the network density from low to moderate and to high, the average hop count per path decreases (by about 5%-15%).

4.7 Time between Successive Route Discoveries

The twin objectives of DMEF are to be energy-efficient and to determine routes that exist for a long time. DMEF accomplishes the latter objective by preferring to broadcast the RREQ messages primarily through nodes that have been moving relatively slowly in the network. As a result, the routes determined using DMEF exist for a relatively longer time in the network. The lifetime of routes determined for both DSR and LPBR protocols using DMEF as the route discovery strategy is significantly larger compared to that of the DSR and LPBR routes determined using flooding. This is because DMEF prefers to propagate RREQ packets through relatively slow moving nodes that are also close to each other. In addition, LPBR attempts to increase the time between successive global broadcast discoveries by predicting a source-destination route using the Location Update Vectors (LUVs) collected during the latest broadcast route discovery. As we increase the network density, the chances of correctly predicting at least one source-destination path in the network increases. Hence, in the case of LPBR, for a given node mobility, the time between two successive global broadcast route discoveries increases as the network density increases. For both DSR and LPBR, compared to flooding, the relative increase in the lifetime of the routes discovered using DMEF and the reduction in the frequency of DMEF route discoveries can be significantly observed with increase in network density and/or node mobility.

4.8 End-to-End Delay per Data Packet

DMEF exerts a relatively lower control overhead to determine routes compared to flooding. This is evident as DSR incurs a relatively lower end-to-end delay per data packet (refer Figure 6) when routes are determined using DMEF compared to flooding. The relative difference between the delays per data packet for DSR routes discovered using flooding and DMEF increases as we increase the node mobility and/or network density. With DSR, the route discovery overhead incurred due to relatively unstable routes discovered using flooding weighs far more than the slightly larger hop count of routes discovered using DMEF. In LPBR, there is a relatively slight reduction in the delays per data packet with DMEF in networks of high density/ high mobility. This is due to the relatively less congestion in the nodes attributed to the reduced number of route discovery attempts. In networks of low node mobility, the delay per data packet for LPBR using DMEF is sometimes observed to be slightly larger than the delays per packet obtained with flooding. This is due to the slightly larger hop count of the paths discovered in such networks and lower route discovery overhead.

4.9 Packet Delivery Ratio

Performance results in Figures 7.1 through 7.3 illustrate that the packet delivery ratio of the two routing protocols using DMEF can be lower than that obtained using flooding only by at most 3% in low-density networks. In moderate density networks, both the route discovery strategies yield almost the same packet delivery ratio. In high density networks, the packet delivery ratio of routing protocols using DMEF can be larger than that obtained using flooding by about 3%. In high-density networks, even though flooding helps to propagate the RREQ messages through several routes, the excessive overhead generated by these redundant RREQ messages block the queues of certain heavily used nodes in the network, thus leading to sometimes a relatively lower packet delivery ratio compared to DMEF. In low-density networks, DMEF could very rarely fail to determine source-destination routes, even if one exists, due to its optimization approach of trying to shrink the range of broadcast of the RREQ messages. DMEF broadcasts RREQ messages over a relatively larger transmission range in low-density networks compared to those used for high-density networks. As we increase node density, the packet delivery ratio under both flooding and DMEF approaches unity.

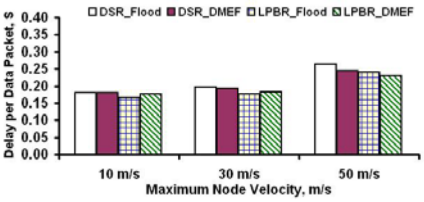

Figure 6.1: 25 Nodes

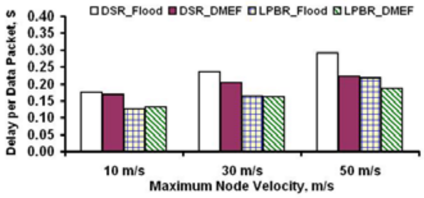

Figure 6.2: 50 Nodes

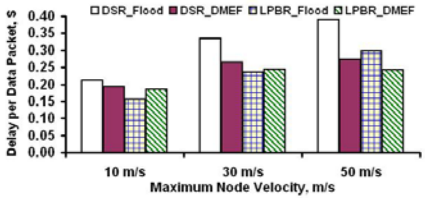

Figure 6.3: 75 Nodes

Figure 6: Average End-to-End Delay per Data Packet Delivered

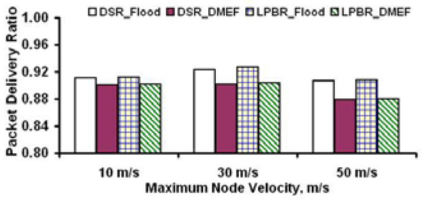

Figure 7.1: 25 Nodes

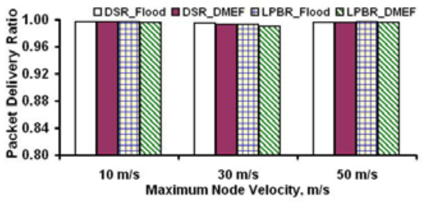

Figure 7.2: 50 Nodes

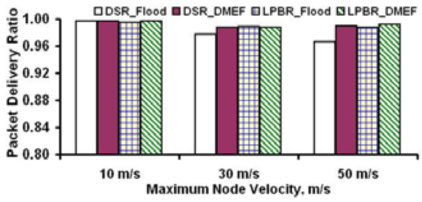

Figure 7.3: 75 Nodes

Figure 7: Packet Delivery Ratio

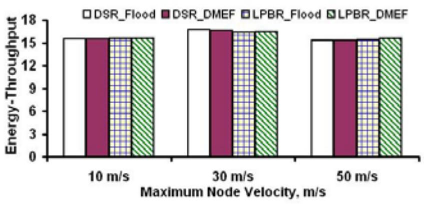

Figure 8.1: 25 Nodes

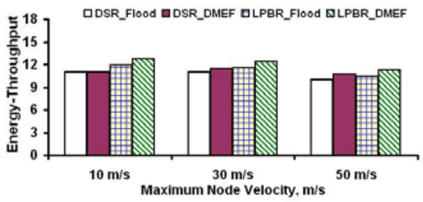

Figure 8.2: 50 Nodes

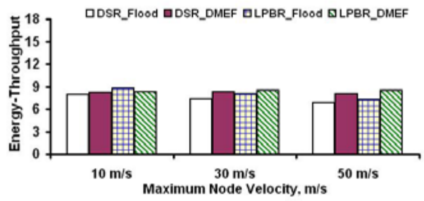

Figure 8.3: 75 Nodes

Figure 8: Energy-Throughput

4.10 Energy Throughput

For a given offered data traffic load, larger the energy throughput, the smaller the amount of energy spent in delivering the data packets to the destination. Notice that in our simulations, the number of source-destination sessions is always fixed at 15, i.e., the offered data traffic load is fixed. Based on Figures 7 and 8, we observe that with increase in the network density, the packet delivery ratio approaches unity, but the energy throughput decreases. This is because more nodes participate and spend their energy in moderate and high-density networks to route a given offered data traffic load. Note that energy consumption is in the form of direct transmissions and receptions of the intermediate nodes on a path and indirect receptions at the neighboring nodes of the intermediate nodes on a path. As we increase the network density as well as the level of node mobility, the energy throughput obtained with both DSR and LPBR using DMEF is larger than that obtained using flooding as the route discovery strategy. In low and moderate density networks and low and moderate levels of node mobility, the energy throughput for both DSR and LPBR are almost the same while using both DMEF and flooding for route discoveries.

5 Conclusions

The high level contribution of this paper is the design and development of a novel network density and node mobility aware, energy-efficient route discovery strategy called DMEF for mobile ad hoc networks. The twin objectives of DMEF are to increase the time between successive global broadcast route discoveries and reduce the energy consumption during such global broadcast discoveries vis-à-vis flooding. Each node operates with a maximum transmission range and periodically broadcasts beacons to the neighborhood covered (called the complete neighborhood) within this range. DMEF permits each node to dynamically adjust the transmission range to broadcast the Route-Request (RREQ) messages of the route discovery process. A node that is surrounded by more neighbors advertises itself only to a limited set of nearby neighbors and a node that is surrounded by few neighbors will advertise itself to a maximum of those neighbors. Similarly, a node that is slow-moving advertises itself to a majority of its neighbors so that links formed using this node can be more stable. A node that has been fast-moving advertises itself only to the neighbors closer to it. The neighborhood dynamically chosen for a RREQ broadcast is always contained within the complete neighborhood defined by the maximum transmission range of the node.

The effectiveness of DMEF has been studied through simulations with the well-known Dynamic Source Routing (DSR) protocol and the recently proposed Location Prediction Based Routing (LPBR) protocol. The benchmark used for the evaluation purposes is the commonly used flooding based global broadcast route discoveries. Simulation results indicate that DMEF is very effective in reducing the total energy spent per route discovery attempt for both DSR and LPBR. In addition, for both DSR and LPBR, DMEF reduces the number of global broadcast route discoveries by determining routes with longer lifetime, reduces the percentage of total energy spent for route discoveries, reduces the end-to-end delay per data packet and increases the energy throughput. The increase in the hop count of DSR and LPBR routes compared to that discovered using flooding is at most 8%. We conjecture that DMEF can be similarly very effective with respect to all of the other currently existing on-demand MANET routing protocols, none of which can simultaneously minimize the number of route discoveries as well as the hop count of the paths. DMEF can be used with these MANET routing protocols to discover long-living stable paths with hop count close to that of the minimum hop paths and at the same time incur less control message and energy overhead.

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Dr. Natarajan Meghanathan is an Assistant Professor of Computer Science at Jackson State University, USA. He received his MS and PhD in Computer Science form Auburn University and The University of Texas at Dallas respectively. Dr. Meghanathan's main area of research is ad hoc networks. He has more than 45 peer-reviewed publications in leading international journals and conferences in this area. He serves as the editor of a number of international journals and also in the program committee of several leading international conferences in the area of networks.