An Efficient Geographic Multicast Protocol for Mobile Ad Hoc Networks

Xiaojing Xiang* Xin Wang† Zehua Zhou*

*State University of New York at Buffalo, Buffalo, NY, USA
{xxiang, zzhou5}@cse.buffalo.edu

†State University of New York at Stony Brook, Stony Brook, NY, USA
xwang@ece.sunysb.edu

Abstract— **Group communications is important in supporting multimedia applications. Multicast is an efficient method in implementing the group communications. However, it is challenging to implement efficient and scalable multicast in Mobile Ad hoc Networks (MANET) due to the difficulty in group membership management and multicast packet forwarding over the dynamic topology. We propose a novel Efficient Geographic Multicast Protocol (EGMP). EGMP uses a hierarchical structure to implement scalable and efficient group membership management. And a network-range zone-based bi-directional tree is constructed to achieve a more efficient multicast delivery. The position information is used to guide the hierarchical structure building, multicast tree construction and multicast packet forwarding, which efficiently reduces the overhead for route searching and tree structure maintenance. EGMP does not depend on any specific geographic unicast routing protocol. Several methods are assumed to further make the protocol efficient, for example, introducing the concept of zone depth for building an optimal tree structure and combining the location service for group members with the hierarchical group membership management. Finally, we design a scheme to handle empty zone problem faced by most routing protocols using a zone structure.**

I. Introduction

Group communications is important in Mobile Ad Hoc Networks (MANET). Sending action direction to the soldiers in a battlefield and communications among the firemen in a disaster area are some examples of these applications. Group communications are also very important in supporting multimedia applications such as gaming and conferencing. With a one-to-many or many-to-many transmission pattern, multicast is an efficient method to realize group communications. The high dynamics of MANET, however, makes the design of routing protocols much more challenging than that of wired network.

The *conventional* MANET multicast protocols can be divided into two main categories, tree-based and mesh-based. The tree-based protocols (e.g., LAM [19], MAODV [26], AMRIS [30]) construct a tree structure for the multicast delivery, and the tree structure is known for its efficiency in utilizing the network resource optimally. However, maintaining tree structure in these conventional protocols is very difficult, and the tree connection is easy to be broken and the transmission is not reliable. The mesh-based protocols (e.g., FGMP [9], Core-Assisted Mesh protocol [15], ODMRP [16]) are proposed to enhance the robustness by providing redundant paths between the source and destination pairs at the cost of higher forwarding overhead. Furthermore, these conventional multicast protocols generally do not have good scalability due to the overhead for route searching, group membership management, and tree/mesh structure creation and maintenance over the dynamic topology of MANET.

For MANET unicast routing, geographic routing protocols [3] [6] [21] [12] [5] [13] have been proposed in recent years for more scalable and robust forwarding. The protocol proposed in [21] with the algorithm described earlier in [6] achieves a fully "stateless" routing. They assume mobile nodes are aware of their own positions through certain positioning system (e.g., GPS), and a source can obtain the destination's position through some kind of location service [14] [17]. An intermediate node makes forwarding decisions based on the destination's position which is inserted in the packet header by the source and its one-hop neighbors' positions learnt through periodic beaconing among one-hop neighbors [21]. By default, the packets are greedily forwarded to the neighbor that allows for the greatest geographic progress to the destination. When no such neighbor exists, perimeter (face) forwarding [6] [21] is used to recover from the local void, in which the packets traverse the face of the planarized local topology subgraph by applying the right-hand rule until greedy forwarding can be resumed. Since the forwarding decisions are only based on the local topology, geographic routings are more scalable and robust in a dynamic environment.

Similarly, to reduce the topology maintenance overhead in multicasting, an option is to make use of the position information. But there are many challenges to implement an efficient and scalable geographic multicast scheme in MANET. For example, in unicast geographic routing, destination's position is carried in the packet header to guide packet forwarding. But in multicast routing, the destination is a group of members. Putting all the members' addresses and positions into the packet header is a direct and easy way, but this is only applicable for the small group case [4] [8] [24]. Besides scalable packet forwarding, a scalable geographic multicast protocol also needs to efficiently manage the membership of a possible large group, obtain the members' positions and forward packets to the members distributed in a possible large network terrain. These are ignored in the above protocols.

We propose an efficient geographic multicast protocol (EGMP). EGMP can scale to large group size and network size and can efficiently implement multicasting delivery and group membership management. EGMP uses a hierarchical structure to achieve scalability. The network terrain is divided into geographical non-overlapping square zones, and a leader is elected in each zone to take charge of the local group membership management. A zone-based bi-directional multicast tree is built in the network range to connect those zones having group members, and such tree-structure can utilize the network resource efficiently.

Our contributions in this work include:

1) We design a scheme to build and maintain the intrazone and interzone topology for supporting scalable and efficient multicast forwarding.
2) We make use of the position information to implement hierarchical group membership management, and combine location service with the hierarchical membership management to avoid network-range location searches for the group members, which is scalable and efficient. With location guidance and our efficient membership management structure, a node can join or leave a group more quickly.
3) With nodes self-organizing into zones, a zone-based bi-directional tree is built in MANET environment. Based on geographic routing, the maintenance of the tree is simplified and the transmission is more robust in dynamic environment.
4) We introduce an important concept *zone depth*, which reflects the relationship between a member zone and the zone where the root of the tree exists. The zone depth is efficient in guiding the tree branch building and tree structure maintenance, especially in the presence of node mobility.
5) We also design a scheme to handle the empty zone problem, a challenging problem in designing a zone-based protocol. In EGMP, whenever an on-tree zone becomes empty, the tree structure is adjusted accordingly to keep the tree connected.

We organize the rest of this article as follows. In Section II, we discuss some related work on MANET multicast protocols. The detailed description of the EGMP protocol is give in Section III. Section IV shows the simulation results of the EGMP protocol. Section V concludes this paper and presents the future work.

II. Related Work

In this section we discuss the conventional multicast protocols and the geographic multicast algorithms for MANET.

The conventional topology-based multicast protocols include tree-based protocols (e.g., [19] [26] [30]) and mesh-based protocols (e.g., [9] [15] [16]). The conventional multicast protocols are usually composed of the following three components and generally they can not scale to large network size. 1) Group membership management. The group membership changes frequently as each node may join or leave a multicast group randomly, and the management becomes harder for a large group. 2) Creation and maintenance of a tree- or mesh-based multicast structure. In these protocols, the structures are based on some non-geographic mechanisms, which makes the tree-based structure not so robust, while the mesh-based ones achieve the robustness at the cost of inefficiently utilizing network resource. Also the non-geographic routing mechanisms prohibit these protocols from scaling to a large network size. 3) Multicast packet forwarding. The multicast packets are forwarded along the pre-built tree or mesh structure, but the pre-built paths are vulnerable to be broken over the dynamic topology, especially in a large network with potentially longer paths.

Besides the three components included in the conventional multicast protocols, a geographic multicast protocol also needs location service to obtain the members' positions. The geographic multicast protocols presented in [4], [8] and [24] need to put the information of all the group members into the packet header, which creates a lot of overhead for a large group, so they are only applicable for the small group case. Also, they rely on some network-range location service to search for positions of all the group members, which will add more overhead. Transier et al. [28] made an effort to improve the scalability of geographic protocol with group size. However, as it requires periodic local-range and network-range membership flooding, significant control overhead will be generated when the network range increases, which makes the membership management not efficient. Our protocol has assumed a different scheme with no periodic network-range flooding, so that our protocol is not only scalable but also efficient in membership management.

III. Efficient Geographic Multicast Protocol

In this section, we will describe the EGMP protocol in details. We first give an overview of the protocol in Section III-A, and then introduce the notations and definitions used in our protocol in Section III-B. In Section III-C we present the zone structure building process and the zone-supported geographic routing strategy. Finally, in Section III-D and Section III-E we introduce the processes for the multicast tree creation, maintenance and the multicast packet delivery.

A. Protocol Overview

EGMP uses a two-tier structure. The whole network is divided into square zones. In each zone, a leader is elected and serves as a representative of its local zone on the upper tier. The leader collects the local zone's group membership information and represents its associated zone to join or leave the multicast sessions as required. As a result, a network-range core-zone-based multicast tree is built on the upper tier to connect the member zones. The source sends the multicast packets directly onto the tree. And then the multicast packets will flow along the multicast tree at the upper tier. When an on-tree zone leader receives the packets, it will send the multicast packets to the group members in its local zone.

To implement this two-tier structure, we need to address a number of issues. For example, how to build the zone structure? How to elect the zone leader and handle its mobility? A zone may become empty due to the node movements, and how to keep the tree connected when an on-tree zone becomes empty? A member node may move from one zone to another, how to reduce the packet loss during mobility? In the following sections, we will give the answers to these questions. In EGMP, we assume every node is aware of its own position through some positioning system (e.g., GPS). The forwarding of data packets and most control messages is based on the geographic unicast routing protocols [6] [21] as mentioned in Section I.

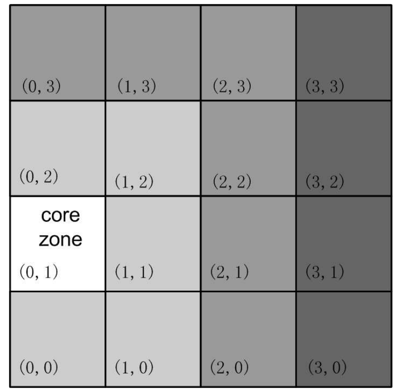

Fig. 1. Zone depth in the multicast session.

B. Notations and Definitions

pos: A mobile node's position coordinates (x, y).

zone: The network terrain is divided into square zones as shown in Fig. 1.

r_{zone}: Zone size. The length of a side of the zone square. In our zone structure, the intrazone nodes can communicate directly with each other without the need of any intermediate relays, so that $zone\_size \leq \frac{r}{\sqrt{2}}$, where r is the mobile nodes' transmission range.

zone ID: The identification of a zone. A node can calculate its zone ID (a, b) from its pos (x, y) as: $a = [\frac{x-x_0}{r_{zone}}]$ and $b = [\frac{y-y_0}{r_{zone}}]$, where (x_0, y_0) is the position of the virtual origin, which is set at the network initial stage as one of the network parameters. For simplicity, we assume all the zone IDs are positive.

zone center: For a zone with ID (a,b), the position of its center (x_{center}, y_{center}) can be calculated as: $x_{center} = x_0 + (a+0.5) \times r_{zone}$, $y_{center} = y_0 + (b+0.5) \times r_{zone}$. A packet destined to a zone will be forwarded towards the center of the zone.

zLD: Zone leader. A zLD is elected in each zone for managing the local zone group membership and taking part in the upper tier multicast routing.

tZone: The zones on the multicast tree. The tZones are responsible for the multicast packet forwarding. A tZone may have group members or not.

core zone: The core zone is the root of the multicast tree.

zone depth: For each multicast session, a zone's depth reflects its distance to core zone. For a zone with ID (a, b), its depth is $depth = \max(|a_0 - a|, |b_0 - b|)$, where (a_0, b_0) is core-zone ID. For example, in Fig. 1, for the five zones surrounding the core zone, $depth = 1$. And the outer six zones have $depth$ as two. The depth of core zone is zero.

zNode: Zone node, a node located in the same zone as the node being mentioned.

C. Zone Structure Building and Geographic Routing

In this section, we first describe the zone construction process, including the intrazone and interzone topology building and zLD election. We then introduce the zone-supported geographic unicast routing which will be used in our protocol.

1) Intrazone and interzone topology building: In the underneath geographic unicast routing protocols, nodes periodically broadcast a BEACON message to distribute a node's position. We insert in the BEACON message a flag indicating whether the sender is zLD to ease leader election. Since $r_{zone} <= \frac{r}{\sqrt{2}}$, the broadcasting will cover the whole local zone. To reduce the beaconing overhead, we enhance the fixed-interval beaconing mechanism in the underneath unicasting protocol to a more flexible one. A non-leader node will send a beacon only when its moving distance from last beaconing is larger than or equal to D_{beacon}, or the time interval from last beaconing is longer than or equal to $Intval_{max}$, or it moves to a new zone. A zLD is forced to send out a beacon every period of $Intval_{min}$ to announce its leadership role.

On receiving a beacon from a neighbor, a node puts the node ID, pos and $flag$ contained in the message into its zone table. Table I shows an example of the zone table. The zone ID of the sending node can be calculated from its pos. An entry will be removed if not refreshed within a period $Timeout_{ZT}$ or the corresponding neighbor is detected unreachable by the MAC layer protocol.

Table I shows the zone table of node 18 in Fig. 3. Node 18 is in zone (1, 1). It can receive beacons from its zLD node 16. Also it can hear the beacons from its one-hop neighbors node 7, node 1 and node 13, which are in zone (1, 0), (2, 0) and (2, 1) respectively.

TABLE I
THE ZONE TABLE OF NODE 18

nodeID	Position	flag	zone ID
16	(x_{16}, y_{16})	1	(1, 1)
7	(x_7, y_7)	1	(1, 0)
1	(x_1, y_1)	0	(2, 0)
13	(x_{13}, y_{13})	1	(2, 1)

2) Zone leader election: A zLD is elected through the leader election process. When a node appears in the network, it sends out a beacon announcing its existence. And then it waits for a $Intval_{min}$ period for the beacons from other nodes. Every $Intval_{min}$ a node will check its zone table and decide its zLD under different cases: 1) The zone table contains no other zNodes, it will announce itself as zLD. 2) All the zNodes' flags are unset, that means no zNode has announced the leadership role. If the node is closer to the zone center than other zNodes, it will announce its leadership role through beacon message. 3) More than one zNodes have their flags set, the one with the highest node ID is elected. If the node's own flag is set before the checking, but another node wins as zLD, the node will deliver its multicast table to the elected zLD. 4) Just one flag is set for one of its zone nodes, the node with flag set is zLD.

3) Zone-supported geographic unicast routing: Nodes from the same zone are within each other's transmission range and are aware of each other's location. Transmission between nodes in different zones, however, often needs intermediate nodes to relay the packets. In EGMP, the network-tier forwarding of the control messages and data packets is through the underneath geographic unicast routing. However, in the geographic unicast routing, location service is required for the source to get the destination node's position, which will add extra overhead. In EGMP, to avoid the network-range location service, we combine the location service with our hierarchical zone structure. At the network tier, the packet is forwarded to the center of the destination zone without the need of any specific node's position. Only when the packet reaches the destination zone, it will be forwarded to a specific node or broadcasted depending on the message type. And for the intrazone communications, only one transmission is required as all the nodes are within each other's transmission range.

However, since we use the destined zone's center to estimate the destination node's position, such inaccurate destination position may misguide the geographic forwarding and result in forwarding failure. For example, in Fig. 3, when node 16 sends a packet to zone (1, 0), if node 7 is the only node in zone (1, 0) and node 18 is the one closest to the center of zone (1, 0), by using the underlying geographic unicast protocol (for example, GPSR [21]), the packet will be forwarded to node 18 greedily. But the greedy mode will fail at node 18 as it cannot find a neighbor closer to the destination position (the center of zone (1, 0)). So the perimeter mode is used to continue the forwarding. But it still cannot guarantee the packet arriving at node 7 with the inaccurate destination position. Such problem is neglected by the previous geographic protocols using an area as a destination.

To avoid this problem, when the underlying geographic forwarding fails, EGMP will retry to forward the packet using the *zone forwarding mode*. Only when the zone mode also fails, the packet will be dropped. The zone mode will search for a path based on the zone table, as the zone table can reflect the local zone topology more accurately. In the zone mode, an intermediate node will check the zone IDs listed in the zone ID column of the zone table, and pick a zone closest to the destination zone and closer than its zone. If such a zone exists, the node will forward the packet to the corresponding neighboring node. To find a closer zone, the node can calculate the dis values of its zone and the zones in the zone list using $dis_{(a,b)} = (a - a_{dst})^2 + (b - b_{dst})^2$, where ($a_{dst}$, b_{dst}) is the destination zone ID. A zone with a smaller dis value is closer to the destination zone. In the above example, if the underlying geographic unicast forwarding fails at node 18, it will try to continue the forwarding using zone mode. It checks its zone table (Table I), and since the dis value of zone (1, 0) to destination zone (1, 0) is zero, the packet is forwarded to node 7 in zone (1, 0). To avoid any possible routing loop, a node will only forward a packet which is received for the first time.

D. Multicast Tree Construction and Packet Delivery

In this section, we will present the multicast tree creation and maintenance schemes, and describe the multicast packet delivery strategy. And in the following description, except when explicitly indicated, we use G, S and M respectively to represent a multicast group, a source of G and a member of G.

1) Multicast session initiation and termination: When S wants to start a multicast session G, it will announce the existence of G by flooding a message $NEW\_SESSION(G, zoneID_S)$ into the whole network. The message carries G and the ID of the zone where S is located, which is used as the initial zone ID of the core zone for group G. When a node M receives this message and is interested in G, it will join G using the process described in the following section. Every node will keep a membership table. Table II shows one entry of the membership table of node 18 in Fig. 3. Each entry saves the information of a group that the node is a member, and the information includes the group ID, the core-zone ID and a flag isAcked indicating whether the node is on the corresponding multicast tree. A zone leader (zLD) maintains a multicast table. When a zLD receives the NEW_SESSION message, it will record the group ID and core-zone ID into its multicast table. Table III is an example of one entry in the multicast table. The table contains the group ID, core-zone ID, upstream zone ID, downstream zone list and downstream node list.

Whenever S decides to end G, it floods a message END_SESSION(G). When receiving this message, the nodes will remove all the information about G from their membership tables and multicast tables.

TABLE II
ONE ENTRY OF THE MEMBERSHIP TABLE OF NODE 18

group ID	G
core-zone ID	$(2, 2)$
isAcked	TRUE

Procedure $LeaderJoin(me, pkt)$
me: the leader itself
pkt: the JOIN_REQ message the leader received

```
BEGIN
if (pkt.srcZone == me.zoneID) then
   /* the join request is from a zNode */
   /* add the node into the downstream node list of the multicast
   table */
   AddNodetoMcastTable(pkt.groupID, pkt.nodeID);
else
   /* the join request is from another zone */
   if (d_me < d_pkt) then
      /* add this zone to the downstream zone list of the multicast
      table */
      AddZonetoMcastTable(pkt.groupID, pkt.zoneID);
   else
      ForwardPacket(pkt);
      return;
   end if
end if
if (!LookupMcastTableforCore(pkt.groupID)) then
   /* there is no core-zone information */
   SendCoreZoneRequest(pkt.groupID);
else if (!LookupMcastTableforUpstream(pkt.groupID)) then
   /* there is no upstream zone infomation */
   SendJoinRequest(pkt.groupID);
else
   SendReply;
end if
END
```

Fig. 2. The pseudocode of the leader joining procedure.

2) Multicast group joining: When a node M wants to join G, if it is a non-leader node, it sends a $JOIN\_REQ(M, zoneID_M, G)$ message to its zLD. If a zLD receives a JOIN_REQ or itself will join G, it will begin the leader joining procedure as follows. If the received JOIN_REQ comes from a member M of the same zone, the zLD adds M to the downstream node list in its multicast table. If the message is from another zone, it will compare the depth of the request zone with that of its own zone. If its depth is smaller, i.e., its zone is closer to the core zone than the request zone, it will add the request zone to its downstream zone list; otherwise, it just continues forwarding the JOIN_REQ message towards the core zone.

If new nodes or zones are added to the downstream list, the leader will check the core-zone ID and the

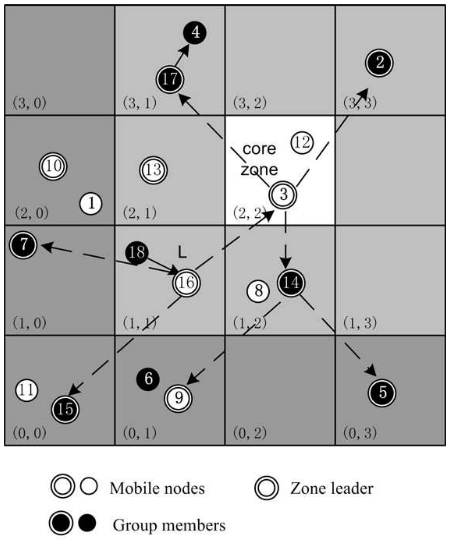

Fig. 3. Multicast session example.

upstream zone ID and take corresponding action. If it doesn't know the core zone, it starts an *expanded ring search*. When knowing the core zone, if its upstream zone ID is unset, the leader will represent its zone to send a JOIN_REQ message towards the core zone; otherwise, the leader will send back a JOIN_REPLY to the source of JOIN_REQ (which may be multiple hops away and geographic unicasting is used for this transmission). When the source of the JOIN_REQ message receives JOIN_REPLY, if it is a node, it sets the isAcked flag in its membership table and the joining procedure is finished. If the join request is from a zone, the leader of the request zone will add the upstream zone ID as the source zone ID of the JOIN_REPLY message, and then send JOIN_REPLY to unacknowledged downstream nodes or zones. The pseudocode of the leader joining procedure is given in Fig. 2.

TABLE III
THE ENTRY OF GROUP $g1$ IN THE MULTICAST TABLE OF NODE 16

group ID	G
core-zone ID	$(2, 2)$
upstream zone ID	$(2, 2)$
downstream zone list	$(1, 0)$, $(0, 0)$
downstream node list	18

An example is given in Fig. 3, in which the core zone of G is (2, 2), and the double circled nodes are zLDs. Suppose currently zone (0, 0) and (1, 1) are not on the multicast tree, and their zLDs node 15 and node 16 already know the core zone ID from the NEW_SESSION message. Now node 15 will join G. Since node 15 is zLD of zone (0, 0), it will begin the leader joining procedure. It finds the upstream zone ID is unset, and it sends a JOIN_REQ towards the core zone (2, 2). The message will reach zone (1, 1) and be intercepted by the zLD node 16. Node 16 then starts its leader joining procedure. It compares the depth of zone (0, 0) and its own zone. Since $d_{zone(0,0)} = 2$ and $d_{zone(1,1)} = 1$, $d_{zone(0,0)} > d_{zone(1,1)}$, node 16 adds the zone ID (0, 0) to its downstream zone list. Then node 16 finds the upstream zone ID is unset, so it sends a JOIN_REQ towards the core zone. This message is received by the core-zone zLD node 3, and triggers joining procedure of node 3. Node 3 adds the zone ID (1, 1) to its downstream zone list after comparing the depths. As core zone is the root of the multicast tree and no upstream zone exists, it sends back a JOIN_REPLY to zone (1, 1). On receiving this message, node 16 sets the upstream zone ID as (2, 2) and sends a JOIN_REPLY to the downstream zone (0, 0). Node 15 sets its upstream zone as (1, 1) on receiving the JOIN_REPLY and the joining process is finished. After this joining process, two multicast branches are built. One branch is between zone (2, 2) and zone (1, 1), and the other one is between zone (1, 1) and zone (0, 0).

Through the joining process, the group membership management is implemented in a distributed manner. An upstream zone only needs to manage its downstream zones. And the group membership management of a local zone is only taken care by the zLD.

3) Multicast group leaving: When M wants to leave G, it sends a $LEAVE(M, G)$ message to its zLD. On receiving a LEAVE, a zLD removes the source of the LEAVE message from its downstream node list or zone list. If its downstream zone list and node list of G are both empty and it is not a member of G either, the zLD sends a LEAVE(zoneID, G) to its upstream zone. Through the leave process, the unused branches are removed from the multicast tree.

4) Multicast packet delivering: In this section, we will explain how the multicast packets are forwarded to the members.

1. Packet sending from the source

In order to send the packet directly onto the multicast tree, S is required to join the multicast tree and becomes a group member. EGMP uses a bi-directional tree [2]. That means the multicast packets can flow not only from an upstream node/zone down to its downstream nodes/zones, but also from a downstream node/zone up to its upstream node/zone. In most of the core-based multicast protocols, S needs to send the packets initially to the core. For example in Fig. 3, if node 5 is a source, it needs to unicast the packets initially to the core zone (2, 2). Sending packets first to the core will introduce more delay especially when S is far away from the core.

By using a bi-directional tree, S can send the packets directly onto the tree, and avoid extra delay.

When S has data to send and it is not zLD, it decides whether it has joined the multicast tree by checking the isAcked flag in its membership table. If it is on the multicast tree, therefore its zone has joined the multicast tree, it sends the multicast packets to its zLD. When the zLD of a zone on the multicast tree (tZone) receives multicast packets, it forwards the packets to the upstream zone and all the downstream nodes and zones except the incoming one. For example, in Fig. 3, the black nodes are the member nodes of G, and the dashed lines represent the multicast tree branches. The source node 18 will send packets to G. Initially it sends the packets to its zLD node 16. Node 16 checks its multicast table, and sends the packets to its upstream zone (2, 2) and its downstream zones (1, 0) and (0, 0). Its only downstream node is node 18 which is the incoming node, so node 16 won't send the packets to it. When the packets are received by the leader node 3 of the core zone, it continues forwarding the packets to its downstream zones (3, 1), (3, 3), (1, 2) except the incoming zone (1, 1). The arrows in the figure show the direction of the packet flows.

Sometimes S is not on the multicast tree. For example, when it moves to a new zone, the isAcked flag will be unset until it finishes the rejoining to G through the new zLD. In this case, to reduce the impact of the joining latency, S will send the packets directly to the core zone until it finishes the joining process.

2. Multicast data forwarding

In our protocol, only zLD will maintain the multicast table, and the member zones normally cannot be reached within one hop. When a node N has a multicast packet to be forwarded to a list of destinations $(D_1, D_2, D_3, \ldots)$, it decides the next hop towards each destination (For a zone, its center is used) using the geographic forwarding strategy described in Section III-C.3. After deciding the next hops, N inserts the list of next hops and associated destinations in the packet header. An example list is $(N_1 : D_1, D_3; N_2 : D_2; \ldots)$ where N_1 is the next hop for the destinations D_1 and D_3, and N_2 is the next hop for D_2. And then N broadcasts the packet *Promiscuously* (for reliability and efficiency). Upon receiving the packet, a neighbor node will keep the packet if it is one of the next hops or destinations, and drop the packet otherwise. If the node is a next hop for other destinations, it will continue forwarding the packets similarly as node N.

For example, in Fig. 3, after node 3 receives the multicast packet from zone (1, 1), it will forward the packet to the downstream zones (1, 2), (3, 1) and (3, 3). It decides the next hop for each destination and inserts the list (12: (3,1),(3,3); 14: (1,2)) in the packet header. After broadcasting the packet promiscuously, its one-hop neighbors node 12, node 14 and node 8 will receive the packet. They check the next hops. Node 8 will drop this packet. Node 12 and node 14 will continue forwarding this packet. Node 12 replaces the list carried in the packet header as (17: (3,1); 2: (3,3)) and broadcasts this packet.

E. Multicast Route Maintenance and Optimization

In a dynamic network, it is critical to maintain the multicast tree structure to keep its connection, and adjust the tree structure upon topology change to optimize the multicast routing. In the zone structure, node will move between different zones and sometimes empty zones will appear, which is a key problem in a zone-based protocol. In this section, we will address these issues.

1) Moving between different zones: When a member node moves to a new zone, it must rejoin the multicast tree through the new zLD. When a zLD is moving away from its current zone, it must handover its multicast table to a new zLD, otherwise all the downstream zones and nodes will lose the connection to the multicast tree.

Whenever a node M moves into a new zone, it will rejoin G by sending a JOIN_REQ to its new zLD. During this joining process, to reduce the packet loss, whenever the node broadcasts a BEACON message to update its information to the nodes in the new zone, it also unicasts one copy of the BEACON to its old zone to update its position. Since it hasn't sent LEAVE message to the old zLD, the old zLD will unicast the multicast packet to M. When the rejoining process finishes, M will send a LEAVE message to its old zLD.

To handle leader mobility problem, if a zLD finds its distance to the zone's border is less than a threshold D_{border} or it is already in a new zone, it assumes it is moving away from the zone it is in charge, and it starts the handover process. It checks the zNodes in the zone it is leaving from and selects the one closest to the zone center as the new zLD, then sends its multicast table to the new zLD. And the new zLD will send a BEACON announcing its leadership role immediately. Before the new zLD announces its leadership role, the old zLD may still receive packets destined to zLD as other nodes still consider it as the zLD. It will forward all these packets to the new zLD when the process is completed. If there is no other nodes in the zone and the zone will become empty, it will use the method introduced in the next section to deliver its multicast table.

2) Dealing with empty zones: A zone may become empty when all the nodes move away. Suppose the area

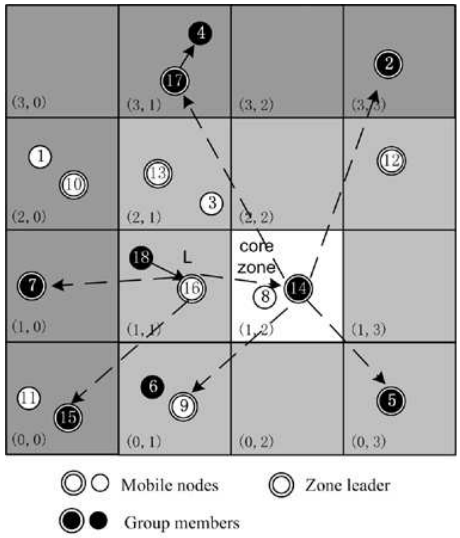

Fig. 4. An example of the core-zone switching.

of the whole network is A and the node density is d, so the total number (n) of nodes in the network is dA. Assume a node may locate at any location in the network with the same probability. Randomly picking up a zone from the network, the probability for a node to be located in the zone is $p = \frac{r_{zone}^2}{A}$. Therefore, the probability that the zone is empty is: $P = (1-p)^n$. When $A = 3000m \times 1500m$ and $r_{zone} = 150m$, $P = 0.324$ if $d = 50nodes/km^2$ and $P = 0.637$ if $d = 20nodes/km^2$. We can see the probability that a zone becomes empty is not negligible and it is critical to address the empty zone problem.

In EGMP, if a tZone becomes empty, we must adjust the multicast tree accordingly to keep the multicast tree connected. Because of the importance of the core zone, we will treat it differently. When a zLD is moving away from a non-core tZone and the zone is to be empty, it will send its multicast table to its upstream zone. The upstream zLD will then take over all its downstream zones, and delete this requesting zone from its downstream zone list. The new upstream zone needs to send JOIN_REPLY to all the new added downstream zones to notify them the change. When these downstream zones receive the JOIN_REPLY messages, they will change their upstream zone ID accordingly.

If the to-be empty zone is the core zone, since the core zone has no upstream zone, the zLD will check its connected neighboring zones and choose the one closest to the core zone as the new core zone. The zLD then forwards its multicast table to the new core zone, and floods a NEW_CORE message to announce the change. Fig. 4 shows the multicast tree after the core zone switches from zone (2, 2) to (1, 2).

3) Tree branch maintenance: To detect the broken tree branches in time, if there are no multicast packets or messages for delivering for a period of $Intval_{active}$, the zLD of a tZone will send an ACTIVE message to its downstream nodes and zones to announce the activity of the multicast branches. When a member node or a tZone fails to receive any packets or messages from its zLD or upstream zone longer than a period of $N * Intval_{active}$, it assumes that it loses the connection to the multicast tree and restarts a joining process.

4) Route Optimization: Sometimes a zLD may receive duplicate multicast packets from different upstream zones. For example, as described in Section III-E.3, after failing to receive any data packets or active messages from the upstream zone for a period, a tZone will start a rejoining process. But it is possible that the packet and message were lost due to collision, so the old upstream zone is still active after the rejoining process, and duplicate packets will be forwarded by two upstream zones to the tZone. In this case, the one closer to the core zone will be kept as the upstream zone, while the other one will be removed by sending a LEAVE message. Through this process, the multicast branch with more optimal route will be kept. If the two upstream zones have the same distances to the core zone, one of them is randomly selected.

IV. Performance Evaluation

In this section, we study the performance of EGMP.

A. Simulation Environment

We simulated EGMP protocol within the Global Mobile Simulation (GloMoSim) [29] library. The nodes are randomly distributed in the area of $3000m * 1500m$ with a default node density 50 nodes/km^2. We use IEEE 802.11 as the MAC layer protocol. The nodes move following the *random waypoint* mobility model [7]. The transmission range is 250m. Each traffic flow is sent at 8 Kbps using CBR with packet length 512 bytes, and each simulation lasts 900 simulation seconds. A simulation result is gained by averaging over several runs with different seeds. The moving pause time is set as 0 second, minimum speed is 0 km/h and the default maximum speed is 72 km/h.

B. Parameters and Metrics

Table IV lists the default parameter values used in the EGMP simulations. We studied the following metrics for the multicast performance evaluation:

1) *Packet delivery ratio*: The ratio of the number of packets received and the number of packets

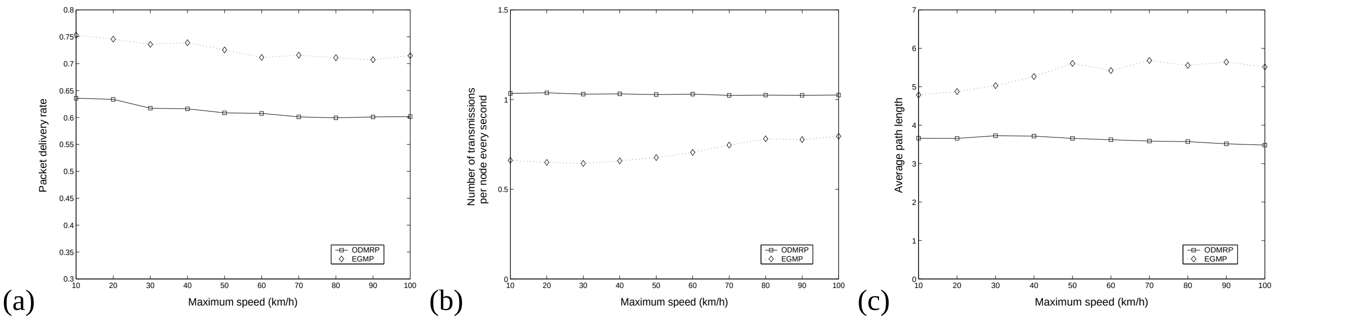

Fig. 5. EGMP performance with different moving speed (2 groups, 44 members per group): (a) packet delivery ratio; (b) average number of transmissions per node every second; (c) average path length.

expected to be received. So for the multicast packet delivery, the ratio is the total number of received packets over the multiplication of the group size and the number of originated packets.

2) *Number of transmissions per node every second*: The average number of transmissions of the multicast packets including the data packets and control messages per node every second during the multicast session. This metric studies the efficiency of the protocol including the efficiency for the data delivery and the efficiency for the multicast structure building and maintenance.
3) *Average path length*: The average number of hops traversed by each delivered data packet..
4) *Joining delay*: The time interval between the first JOIN_REQ sent out and the JOIN_REPLY received.

TABLE IV
THE PARAMETER VALUES FOR EGMP SIMULATIONS

Parameter name	**Value**	**Appeared section**
r_{zone}	150m	Section III-B
$Intval_{min}$	0.5 sec	Section III-C.1
$Intval_{max}$	4 sec	Section III-C.1
$Intval_{active}$	2 sec	Section III-E.3
$Timeout_{ZT}$	4.5 sec	Section III-C.1
D_{beacon}	50m	Section III-C.1
D_{border}	5m	Section III-E.1
N	2	Section III-E.3

C. Protocol Performance

In this section, we evaluate the performance of EGMP with different node densities, moving speeds and group sizes. As far as we know there is no other comprehensive geographic multicast protocol available now. Since every part of multicast protocol including the membership management, tree/mesh construction, multicast packet forwarding and the location service for a geographic protocol will impact the multicast protocol performance, for the performance references, the simulation results of ODMRP is shown. ODMRP is a mesh-based, on-demand multicast protocol. According to the result of [22], ODMRP performs the best in the MANET multicast protocols referred.

1) Effect of moving speed: We first study the multicast performance with different maximum moving speed from 10 km/h to 100 km/h. In these simulations, 80 nodes join two multicast groups. Each group has 44 members and one source.

From Fig. 5(a), EGMP improves the delivery ratio by nearly twenty percent compared with ODMRP. The simulation results of ODMRP are worse than those in [22] because we use a larger network size. The higher delivery ratio of EGMP is due to its geographic routing mechanism, which can adjust more quickly to the topology change and is more suited to the dynamic environment of MANET. Although the mesh structure used in ODMRP is more robust than tree structure, the mesh structure is built through some kind of back learning, and more easily becomes invalidated due to the node movements.

In EGMP, when the moving speed increases, to keep the multicast tree connected, more control messages will be generated. For example, the zLD changes will become more frequent and more frequent node movements

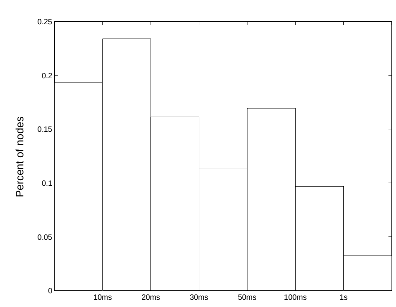

Fig. 6. Distribution of joining delay.

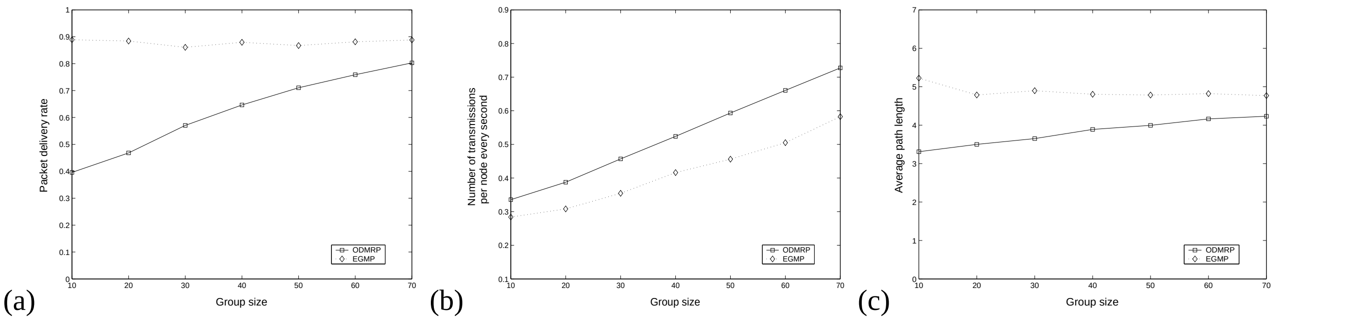

Fig. 7. EGMP performance with different group size: (a) packet delivery ratio; (b) average number of transmissions per node every second; (c) average path length.

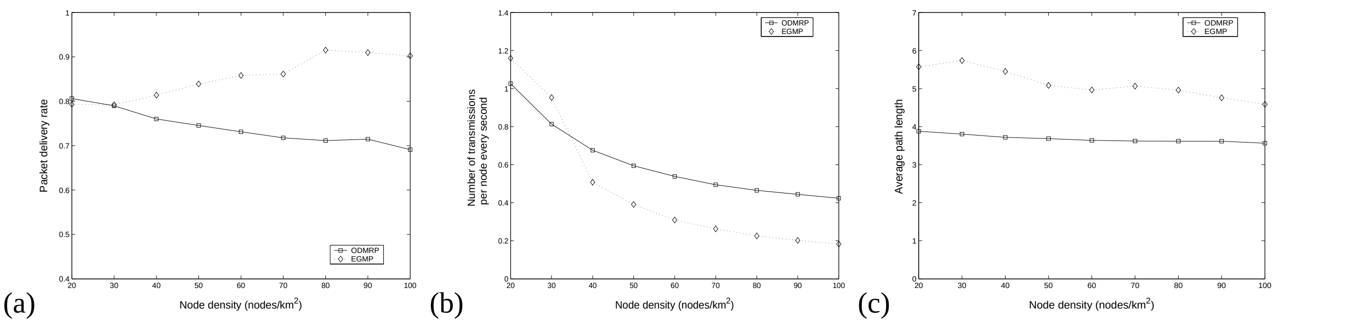

Fig. 8. EGMP performance with different node density (1 group, 50 members): (a) packet delivery ratio; (b) average number of transmissions per node every second; (c) average path length.

between zones will trigger more rejoining processes. Fig. 5(b) shows an increased transmission load with higher moving speed. But the tree structure can utilize the network resources more efficiently than mesh structure, as the mesh structure has redundant multicast packet forwarding, and has higher transmission overhead.

The average path length of EGMP is seen from Fig. 5(c) about two hops longer than ODMRP. This is due to the feature of core-zone-based tree structure and the hierarchical forwarding. The multicast packet is sent first to the zLD and then forwarded to the local members. This packet forwarding will generally introduce one more hop. And the core-based tree structure will generate some non-shortest paths between the receivers and sources. The extra hops will lead to higher transmission overhead and compromise the advantage of EGMP. While in ODMRP, the packet flows along the shortest path from the sources to the receivers, so the path has less hops.

Next we study the average joining delay of the group members. In ODMRP, there is no active joining process for the group members. The source sends out a Join REQUEST periodically to refresh the mesh structure. If the nodes want to join a group, they need to wait for the next mesh refreshing period to join the mesh structure. In the ODMRP code implemented in GlomoSim library, this refreshing interval is set as 3 seconds. Fig. 6 shows the distribution of joining delays of EGMP when the moving speed is 50 km/h. Nearly 90% of nodes can join the group within 100 msec. Due to the distributed membership management and the distributed tree structure of EGMP, the group members can join the multicast group more quickly than the centralized protocols in which the group members are managed only by the source.

2) Effect of group size: Next we evaluate the performance of EGMP with different group sizes. A multicast group is simulated with group size varied from 10 members to 70 members. One source keeps sending CBR flows to the group.

Fig. 7 demonstrates the delivery ratio, transmission load and average path length under different group sizes. From the figures, with different group sizes, the delivery ratio of EGMP keeps at more than 85%. When the group size is 10, the difference between the delivery ratio of EGMP and ODMRP is nearly 50%. When the group size increases, ODMRP makes more successful deliveries. Because when more nodes join the multicast group, the mesh structure used in ODMRP has more redundancy and will provide more robust delivery. While the tree structure shows a more stable performance with the different group sizes. The transmission loads of both two protocols increase with larger group size since more control messages will be generated for group membership management and more data forwarding are required for the larger group. The path length of EGMP keeps at around average 4.8 hops with different group sizes.

3) Effect of node density: Geographic routing is sensitive to the node density and performs better in a dense network. And node density is closely related to the performance of zone-based protocols. When the node density is low, more empty zones will appear, which will negatively affect the zone structure performance. In EGMP, the empty zone problem is considered and a scheme is designed to handle this problem. Hence we also study the impact of node density on the performance.

As expected, EGMP performs better with higher node density as shown in Fig. 8. Even when the node density is as low as 20 nodes/km^2, the performance of EGMP is comparable to ODMRP. When the node density increases, the performance of EGMP becomes better due to the more stable zone structure. When the node density is higher than 80 nodes/km^2, the increase of delivery ratio becomes slower. At high density the collisions among neighboring nodes will increase and cause more packet loss. Since part of the EGMP transmission load is generated from the zone structure maintenance which is not included in ODMRP, when the node density increases, this part of transmission load decreases with the more stable zone structure. So in Fig. 8(b), the transmission load of EGMP decreases much faster than ODMRP as the node density increases. From Fig. 8(c), the average path length tends to be shorter with higher node density. According to the feature of geographic routing, when the node density is lower, there is less chance for an intermediate node to find a neighbor closer to the destination. The perimeter forwarding mode [21] has to be adopted to traverse the local maximum, which will introduce more hops. While with higher node density, more forwarding are greedy which results in fewer hops.

V. Conclusions and Future Work

We have designed an efficient and robust geographic multicast protocol for MANET in this paper. This protocol uses a zone structure to achieve scalability, and relies on underneath geographic unicast routing for reliable packet transmissions. We build a zone-based bi-directional multicast tree at the upper tier to achieve more efficient multicast membership management and delivery, and use a zone structure at the lower tier to realize the local membership management. We also develop a scheme to handle the empty zone problem which is challenging for the zone-based protocols. The position information is used in the protocol to guide the zone structure building, multicast tree construction and multicast packet forwarding. As compared to traditional multicast protocols, our scheme allows the use of location information to reduce the overhead in tree structure maintenance and can adapt to the topology change more quickly. Simulation results show our protocol can achieve higher packet delivery ratio in a large-scale network. In future work, we are going to enhance our protocol without the help of core zone, to achieve more optimal routing and lower control overhead.

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