Providing Robust and Scalable Packet Transmission in Dynamic Environment

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***Abstract*— The Mobile ad-hoc networks have become very popular because of their universal usage. In recent years very attractive and big challenges in designing a Robust and Scalable Multicasting Routing Protocol in MANET due to the difficulty in maintenance of multicast structure over the dynamic network topology for a large group size or network size. In this paper we propose a Robust and Scalable Geographic Multicast Protocol (RSGM). The RSGM protocol no need have maintained state information for robust and scalable packet transmission in dynamic environment. The without state virtual-tree-based structures considerably reduce the tree management overhead, support more efficient transmissions. The RSGM protocol to avoid periodic flooding of the source information throughout the network, an well-organized source tracking mechanism is designed.**

***Index Terms* — Multicast routing, geographic multicast, mobile computing, wireless networks, mobile ad hoc networks, geographic routing.**

1. INTRODUCTION

In recent years Mobile ad hoc networks became a very popular subject for research. MANET, wireless devices could self- configure and form a network with a random topology. Such a network may operate in a standalone fashion, or may be connected to the larger Internet. The network's topology may change fast and unpredictably. Multicast is a fundamental service for supporting information interactions and collaborative task execution among a group of users and enabling cluster-based computer system design in a distributed environment. Even though it is important to support multicast in a MANET, it is required by military and emergency applications, there is a big challenge to design a robust and scalable multicast routing protocol in the dynamic environment.

A lot of hard works have been made to develop multicast protocols for Mobile Ad-hoc networks. These include conventional mesh-based protocols and tree based protocols. The mesh-based protocols (e.g., FGMP [4], Core-Assisted Mesh protocol [11], and ODMRP [12]) are proposed to enhance the robustness with the use of redundant paths between the source and the set of multicast group members, which incurs a higher forwarding overhead. The tree-based protocols (e.g., LAM [13], MAODV, AMRIS, and MZRP) construct a tree structure for well-organized multicast packet delivery, and the tree structure is known for its efficiency in utilizing network resources. However, it is very complicated to maintain the tree structure in mobile ad hoc networks, and the tree connection is easy to break and the communication is not reliable.

In order to support more consistent and scalable communications, it is significant to reduce the states to be maintained by the network, and make the routing not significantly impacted by topology changes. Recently, several location based multicast protocols have been proposed [16], [17], for MANET. These protocols assume that mobile nodes are aware of their own positions through certain positioning system (e.g., GPS), and make use of geographic routing to transmit packets along the multicast trees.

In this paper, we propose a Robust and Scalable Geographic Multicast protocol (RSGM). The RSGM protocol is designed to be trouble-free; thus, it can operate more efficiently and reliably. Its can scale to a large group size and network size and provide robust multicast packet transmissions in a dynamic mobile ad hoc network environment. We introduce several virtual architectures for more robust and scalable membership management and packet forwarding in the presence of high network dynamics due to unstable wireless channels and frequent node movements.

2. RELATED WORK

In this section, we first summarize the basic procedures assumed in conventional multicast protocols, and then discuss a few geographic multicast algorithms proposed in the literature.

A topology-based multicast protocol generally has the following tow inherent Components that make them difficult to scale:

- Group membership management. The group membership changes frequently as each node may join or leave a multicast group randomly, and the management becomes harder as the group size or network size increases.

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The geographic multicast protocols presented in [16], [17], and need to put the information of the entire tree or all the destinations into packet headers, which would create a big header overhead when the group size is large and constrain these protocols to be used only for small groups. In DSM [16], each node floods its location in the network. A source constructs a Steiner tree and encodes the multicast tree into each packet, and delivers the packet by using source routing.

The HRPM [6] and Scalable Position-Based Multicast protocol (SPBM) are more related to our work, as the two share the essence as RSGM in improving the scalability of location-based multicast by using hierarchical group management. HRPM decompose a huge group into a hierarchy of recursively organized manageable-sized subgroups, and uses distributed geographic hashing to construct and maintain such a hierarchy. Although it is interesting to apply hashing to find the rendezvous point (RP) for the network to store and retrieve state information, the hashed location is obtained with the assumption of the network size, which is difficult for a dynamic network. Also, as the hashed location is virtual, it is possible that the nodes could not find the (consistent) RP.

RSGM uses more efficient zone-based structure to allow nodes to quickly join and leave the group. Additionally, RSGM introduces Source Home to facilitate quick source discovery and avoid network-wide flooding of source information. As RSGM does not use any periodic network-wide flooding and uses stateless virtual-tree-based structures for control and data transmissions, RSGM can be scalable to both the group size and the network size.

3. ROBUST AND SCALABLE GEOGRAPHIC MULTICAST PROTOCOL

In this section, we describe the RSGM protocol in details.

RSGM supports a two-tier membership management and forwarding structure. At the lower tier, a zone structure is built based on position information and a leader is elected on demand when a zone has group members. If a leader is unaware of the position or addresses of the source, it could obtain the information from the Source Home. With the knowledge of the member zones, a source forwards data packets to the zones that have group members along the virtual tree rooted at the source. After the packets arrive at a member zone, the leader of the zone will further forward the packets to the local members in the zone along the virtual tree rooted at the leader.

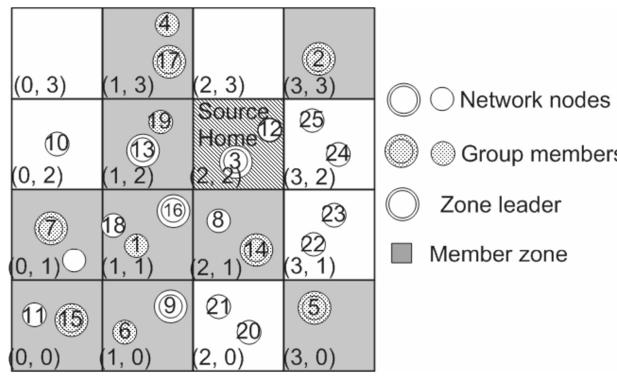

Fig. 1. A reference zone structure used in RSGM.

The scheme for virtual tree construction without the need of storing and tracking tree-state information, and the reliable transmissions of control and multicast data packets without resorting to an external location server.

For presentational convenience, we will first introduce the assumption made and the terminologies to be used in the rest of the paper. We assume that every node is aware of its own position (e.g., through GPS or some indoor localization technique). The forwarding of data packets and most control messages is based on a geographic unicast routing protocol. In our performance study, we implemented GPSR [14] as an underlying unicast protocol to support the packet transmissions. The protocol, however, does not depend on a specific geographic unicast routing protocol.

3.1 ZONE CONSTRUCTION AND MAINTENANCE

In RSGM, the zone structure is virtual and calculated based on a reference point. Therefore, the construction of zone structure does not depend on the shape of the network region, and it is very simple to locate and maintain a zone.

3.1.1 Zone Construction

Virtual zones are used as references for the nodes to find their zone positions in the network domain. The zone is set relative to a virtual origin located at (x_0, y_0) which is set at the network initialization stage as one of the network parameters. The length of a side of the zone square is defined as zone size. Each zone is identified by a zone ID (zID). A node can calculate its zID (a, b) from its pos (x, y) as follows:

$$\begin{cases} a = \dfrac{x - x_0}{zone\_size} \\ b = \dfrac{y - y_0}{zone\_size} \end{cases}$$

For simplicity, we assume the entire zone IDs is positive. A zone ID will help locate a zone, and a packet destined to a zone will be forwarded toward its center. The center position (x_c, y_c) of a zone with zID (a,b) can be calculated as:

$$\begin{cases} x_{center} = x_0 + (a + 0.5)\ X\ zone\_size. \\ y_{center} = y_0 + (b + 0.5)\ X\ zone\_size. \end{cases}$$

3.1.2 On-Demand Leader Election

A leader will be elected in a zone only when the zone has group members in it to avoid unnecessary management overhead. When a multicast group member M just moves into a new zone, if the zone leader (zLdr) is unknown, Mqueries the neighbor node in the zone for the leader. When failing to get the leader information, Mwill announce itself as a leader by flooding a LEADER message into the zone. In the case that two leaders exist in a zone, e.g., due to the slight time difference of leader queries and announcements, the one with the larger ID will win and be selected as the leader. A zone leader floods a LEADER in its zone every time interval Intvalrefresh to announce its leadership until the zone no longer has any members. If no LEADER message is received within the interval 2 Interval refresh, a member node will wait for a random period and then announce itself as the zone leader when no other node announces the leadership.

3.2 Group Membership Management

The group membership is managed at two tiers. RSGM takes advantage of the virtual-zone-based structure to efficiently track the group membership and member positions. 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.

3.2.1 Local Group Membership Management

The group membership is first aggregated in the local zone and managed by the zone leader. When joining or leaving a group, a member M sends a message REFRESH (groupIDs, posM) immediately to its zone leader to notify its membership change, where posM is its position and groupIDs are the addresses of the groups in which M is a member. M also needs to unicast a REFRESH message to its zone leader every time interval Intvalrefresh to update its position and membership information. A member record will be removed by the leader if not refreshed within 2 _ Interval refresh. When M moves to a new zone, its next periodic REFRESH will be sent to the zone leader in the new zone. It will announce itself as the leader if the new zone does not have one. The moving node will still receive the multicast data packets from the old zone before its information is timed out at the leader of the old zone, which reduces the packet loss during the moving.

3.2.2 Membership Management at the Network Level

After the membership information is aggregated in the local zone, a source only needs to track the IDs of the member zones that have group members. The leaders of the member zones are responsible for the sending of the zone membership information to the source.

Zone membership reporting by zone leaders. When a zone changes from a member zone to a nonmember zone of G or vice versa, the zone leader sends a REPORT message immediately to S to notify the change. The leader can obtain the address and position of S using methods described in Section 3.3. A zone leader needs to send REPORT every time interval Intvalzone to S to refresh its zone membership information. In the case that S is the source of more than one multicast group, instead of sending a REPORT to S for e achgroup, the leader sends one REPORT carrying all corresponding group IDs. S will remove a member-zone record if not refreshed within 2 _ Intvalzone.

Empty-zone handling. A zone may become empty when all the nodes move away. The probability that a zone is empty is approximately $P=e^{-pr2}$ when the node density is and the zone size is r. Let’s calculate the probability of zone being empty for two typical node densities and zone sizes: 1) When p=60 nodes/km^2, r=100m, P=0.55; 2) When p=20 nodes/km^2, r=400m, P=0.04. We can see that in either case, the probability of a zone being empty is not negligible. Therefore, it is critical to address the empty-zone problem.

When a member zone of G is becoming empty, the moving out zone leader will notify S immediately to stop sending packets to the empty zone. If the moving out leader fails to notify S (e.g., the leader suddenly dies), the packet

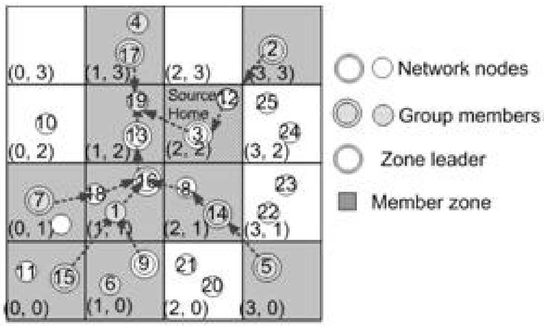

Fig. 2. The aggregation of REPORT messages and the virtual-reverse tree formulation.

Forwarded to the empty zone will finally be dropped without being delivered. The node which drops the packet will notify S to delete the zone from its zone list. A false deletion will be corrected when S receives the periodic membership reporting again from the corresponding zone. As a result, the forwarding of the REPORT messages follows a tree structure as shown in Fig. 2. The REFRESH messages sent by member nodes to the zone leader can be similarly aggregated and sent through the virtual reverse tree.

3.3 Session Initialization and Source Tracking

In order to join and leave a multicast group, the nodes in the network need to have the source information. As a source can move in a MANET, it is critical to quickly find the source when needed and efficiently track the location of the source node. RSGM incorporates mechanisms for session creation and efficient source discovery.

3.3.1 Session Initiation

A multicast session (G) is initiated and terminated by a source (S). To start a multicast session, S floods an ANNOUNCE (S, posS, groupIDs) message into the network (for reliability, promiscuous broadcasting is used in the flooding), where groupIDs are IDs of the groups (G is one of them) for which S is the source. Upon receiving this message, a node (N) interested in being the group member of G starts the joining process by unicasting to its zone leader a REFRESH message carrying the information of S. After a session begins, S can piggyback its position (posS) to the multicast packets sent out to refresh its position at the receivers. When a member M moves to a new zone, the new leader can obtain the address and position of S from M. To terminate G, S floods an ANNOUNCE message with G removed from its group ID list.

3.3.2 Source Tracking

A source may move during the session time. The forwarders and receivers of the multicast packets can obtain the position of the source that is piggybacked with the packets, while other nodes including the ones that newly join the network must resort to some explicit source location or update mechanism to get the position. The conventional scheme for resource information update is through periodic network-wide flooding of source information [12]. Straightforward ways to look for a source include flooding query messages and performing an expanding ring search. However, these methods will incur excessive control overhead and search delay.

All the network nodes will record the zone ID and sequence number of the Source Home. Later, multicast sources will share the elected Source Home and all the nodes in the Source Home will maintain the addresses and IDs of the sources. Whenever a source moves to a new zone, it unicasts a REGISTER (zIDnew) message to the Source Home. When the message reaches the Source Home, the first node receiving it floods the message into the Source Home so that all the nodes learn which zone the source is currently located in. To learn the source information which is currently maintained by the Source Home, a node just moving into the Source Home will query its neighbors in the zone. During the zone membership reporting (Section 3.2.2), a zone leader will send a REPORT message to the Source Home if it does not know the source address or the address it maintains is outdated. The first node in the Source Home that receives the REPORT and has a record of S will forward the message toward the zone where S is located. When the REPORT message arrives at the zone of S, the message will be first forwarded to the leader. As S is a member of G and needs to send REFRESH periodically to its leader, the leader has the position of S and will forward the packet to S.

If the Source Home is becoming empty, when a leaving node finds it has no neighbors in the zone, it will announce its entering zone as the new Source Home to the network, and flood into the new Source Home its source list which contains the information of the sources it currently maintains. The sequence number of the Source Home is increased by one every time the Source Home changes. Some nodes may have no information on the Source Home or hold an old zone ID due to their failure in receiving the announcement of the updated Source Home.

3.4 Multicast Packet Delivery

A source needs to send the multicast packets reliably to the group members. With the membership management, the member zones are recorded by source S, while the local group members and their positions are recorded by the zone leaders. Multicast packets will be sent along a virtual distribution tree from the source to the member zones, and then along a virtual distribution tree from the zone leader to the group members. A virtual distribution tree is formulated during transmission time and guided by the destination positions.

TABLE 1
Notations Used in the Cost Analysis

N	total number of mobile nodes with in the network
e	Zone size
r_t	Transmission range
R	network size, assuming a sequre network terrain with a side length R
v	average moving speed of the mobile nodes
G	total number of multicast groups
S	total number of sources
M_n	total number of member nodes
M_z	total number of mZones

The multicast packets are first delivered by S to member zones toward their zone centers. S sends a multicast packet to all the member zones, and to the member nodes in its own zone through the zone leader. For each destination, it decides the next hop by using the geographic forwarding strategy described in Section 1. After all the next hops are decided, S unicasts to each next-hop node a copy of the packet which carries the list of destinations that must be reached through this hop. Only one copy needs to be sent when packets for different destinations share the same nexthop node. Thus, the packets are forwarded along a tree-like path without the need of building and maintaining the tree in advance. For robust transmissions, geographic unicast is used in packet forwarding. The packets can also be sent through broadcast to further reduce forwarding bandwidth, at the cost of reliability.

When an intermediate node receives the packet, if its zone ID is not in the destination list, it will take a similar action to that of S to continue forwarding the packet. If its zone is in the list, it will replace its zone ID in the destination list with the local members if it is a zone leader, or replace the ID with the position and address of the zone leader otherwise. The intermediate node will find the nexthop node to each destination and aggregate the sending of packets that share the same next-hop node as source S does.

4. COST ANALYSES

In this section, we quantitatively analyze the per-node cost of the protocol, which is defined as the average number of control messages transmitted by each node per second. We will analyze the basic two-tier scheme, and for simplicity, in most cases, we will not consider the message aggregations; thus, the analysis result is an upper bound of the cost.

The notations to be used in this section are listed in Table 1. With a two-tier system structure, the total cost includes the cost for upper tier management and the cost for lower tier management. Before obtaining the cost of the overall protocol, we first introduce a few lemmas, and calculate the per-node control overhead for each tier.

Lemma 1. Assume that a node keeps the same moving direction in a zone. Then, the average moving distance of the mobile nodes in a zone is $\frac{\pi r}{4}$

Proof. The moving distance d of a node in a zone is the length of its moving trail in the zone square. For example, in Fig. 3, line a is such a moving trail. Suppose the angle formed by the moving trail and the bottom side of the zone square is θ. Due to the symmetry of the square, we only need to consider the case when $\theta \in (0, \frac{\pi}{4})$.

As illustrated in Fig. 3, all the possible moving trails with angle θ are located between two parallel lines b and c, where b and c are tangent to the zone with angle θ. Line l is perpendicular to b and c and intersects b at point A. a intersects l at B. If the distance between A and B is z, the length of a moving trail is decided by its angle θ and distance z. Therefore, we can calculate the average distance of a node moving in a zone as

$$d = \frac{\int_0^{\frac{\pi}{4}} \left(2\int_0^{r \sin\theta} \frac{z}{\sin\theta \cos\theta} dz + \int_{r\sin\theta}^{\frac{r}{\sqrt{2}}(\cos\theta - \sin\theta)} \frac{r}{\cos\theta} \right) d\theta}{\int_0^{\frac{\pi}{4}} \int_0^{\frac{r}{\sqrt{2}}(\cos\theta - \sin\theta)} dz\, d\theta}$$

$$= \frac{\pi r}{4}$$

The analysis result shows that when the network size and group size increase, the control overhead placed on each node by the protocol will remain relatively constant. Next, we will demonstrate the scalability of the protocol by simulation studies.

5. PERFORMANCE EVALUATION

In this section, we study the performance of RSGM by simulations. We are mainly interested in the protocol's scalability and robustness in a dynamic environment.

5.1 Simulation Overview

We implemented RSGM within the Global Mobile Simulation (GloMoSim) library. We implemented the geographic unicast protocol GPSR described in [14]. In GPSR, a source can obtain the destination position through some type of location service [10], [9]. An intermediate node makes its forwarding decisions based on the destination position inserted in the packet header by the source and the positions of its one-hop neighbors learned from the periodic beaconing of the neighbors. The protocol consists of two transmission modes. In the greedy mode, a forwarding node forwards the packet to the neighbor that is closest to the destination end. When no such a neighbor exists, the node enters recover mode and assumes perimeter forwarding [14] to recover from the local void. In this case, a packet traverses the face of the planarized local topology subgraph by applying the right-hand rule until the greedy forwarding can be resumed. The implementation includes a proactive beaconing mechanism with promiscuous use of the network interface as in [14], and the beaconing interval was set as four seconds. We set RSGM's $_{Intvalrefresh}$ as four seconds and $_{Intvalzone}$ as six seconds. Except in the study of the impact of zone size, the zone size was set as 400 meters.

The simulations were run with 400 nodes randomly distributed in the area of 2,400 m ~ 2,400 m. The nodes moved following the modified random waypoint mobility model [7]. The minimum moving speed was set as one meter per second and the default maximum speed was set as 20 meters per second except when studying the effect of mobility by varying the moving speed. We set the MAC protocol and radio parameters according to the Lucent WaveLAN card, which operates at a data rate 11 Mbps and radio frequency 2.4 GHz with a nominal transmission range of 250 meters. IEEE 802.11b was used as the MAC layer protocol. Each simulation lasted 500 simulation seconds.

Each source sends CBR data packets at 8 Kbps with packet length 512 bytes. The CBR flows start at around 30 seconds so that the group membership management has time to initialize and stop at 480 seconds. The default group size was 100 members with one source per group. By default, one multicast group was simulated except when evaluating the performance of different numbers of groups in the network. A simulation result was gained by averaging over six runs with different seeds.

We are mainly interested in the protocol's scalability, robustness, and efficiency under the dynamic environment. The following metrics were studied:

1. Packet delivery ratio: The ratio of the number of packets received and the number of packets expected to be received. For the multicast packet delivery, the ratio is equal to the total number of received packets over the multiplication of the group size and the number of originated packets.
2. Normalized control overhead: The total number of control message transmissions divided by the total number of received data packets. The control messages include the control messages of RSGM and the proactive beacons in the underlying geographic unicast routing protocol. Each forwarding of the control messages was counted as one transmission.
3. Average path length: The average number of hops traversed by each delivered data packet.
4. Joining delay: The average time interval between a member joining a group and its first receiving of the data packet from that group. To obtain the joining delay, the simulations were rerun with the same settings except that all the members joined groups after the sources began sending data packets.

5.2 Simulation Results

The performance of the protocol may be impacted by many factors. We first study the impact of zone size on the performance of RSGM, and then compare the performance of ODMRP, SPBM, and RSGM with the variation of moving speed and node density. Finally, we study the scalability of the three protocols with the change of group size, the number of groups in the network, and network size.

6. CONCLUSIONS

In this paper, we have designed a robust and scalable geographic multicast protocol RSGM for MANET. In RSGM, stateless virtual transmission structures are used for simple management and robust forwarding. Both data packets and control messages are transmitted along efficient tree-like paths without the need of explicitly creating and maintaining a tree structure. Scalable membership management is achieved through a virtual-zone-based two-tier infrastructure. A Source Home is defined to track the locations and addresses of the multicast sources to avoid the periodic network-wide flooding of source information, and the location service for group members is combined with the membership management to avoid the use of an outside location server. The position information is used in RSGM to guide the zone structure building, membership management, and packet forwarding, which reduces the maintenance overhead and leads to more robust multicast forwarding when the topology changes. We have also handled the empty-zone problem which is challenging for the zone-based protocols.

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