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Integrated Multicast and Geocast Routing in MANETs

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***Abstract*—In this paper we present Geo-PRIME, the first integrated routing protocol for geocast and multicast traffic. Geo-PRIME uses interest-defined signaling which eliminates the distinction between traditional on-demand and proactive routing. Interest-defined signaling is based on the concept of *regions of interest* which are connected components that are used to confine signaling traffic to those regions of the network where the information is actually needed. In Geo-PRIME, the nodes that belong to a destination, either geocast or multicast, elect a node as core of the destination. Cores are in charge of initiating a distributed algorithm that establishes routing meshes that are used to transport data packets from sources to destinations. In order to reduce the protocol overhead, Geo-PRIME aggregates control information of destinations that are located in the same region of the network. Experimental results based on extensive simulations show that the proposed protocol attains similar or better data delivery, end-to-end delay, and control overhead, than traditional geocast and multicast routing protocols for MANETs such as LBM and ODMRP respectively.**

I. INTRODUCTION

Mobile Ad Hoc Networks (or MANETs) are composed of mobile computers that interact with each other by means of wireless links. MANETs nodes can be highly heterogeneous, ranging from powerful high-end computers to a variety of devices with severe restrictions in memory or processing power such as small sensors or home appliances. Due to its distributed nature, MANETs require neither a pre-installed infrastructure nor centralized administration, and are self-organizing in the sense that they are capable of adapting to very dynamic environments where nodes can join or leave the network at any time, topology changes due to node mobility and wireless channel conditions and, traffic patterns are highly variable. Potentially, MANETs can be composed of hundreds of nodes.

In this type of networks, any node can act as traffic generator, traffic destination, or router. In order to establish a data flow between a source and a set of destination nodes that cannot communicate by means of direct wireless transmissions, the routing algorithm of a MANET has to designate a set of nodes as routers for that flow. These designated routers are in charge of relaying the data packets generated by the source until they reach the intended destinations. In the context of the MANETs, this set of routers has to be dynamic in order to respond to topological, channel condition and traffic changes.

Currently, there is a growing class of mobile applications that require support for group communications where the data generated by a source has to be delivered to a group of nodes. The constituency of a group of nodes can be defined either explicitly or implicitly. For instance, a multicast group is composed by an anonymous and dynamic set of nodes who have joined the multicast group explicitly. On the other hand, a geocast group is composed by the nodes located within a given geographical region. Multicast groups are uniquely identified by a multicast address and geocast groups are identified by a set of coordinates that define a geographic region. In both cases, nodes can belong to multiple multicast and geocast groups simultaneously.

As described in Section II, up to date routing protocols for group communications have been tailored to support either multicast or geocast traffic. Therefore, in situations where the network has to transport both types of data flows, nodes have to run two different routing protocols in parallel. The latter is inefficient because the two protocols tend to interfere with each other and compete for the scarce network resources such as bandwidth, battery power and space in the data queues. Moreover, routing protocols for multicasting and geocasting are such that the network is flooded frequently with distance updates, route requests, multicast updates or geocast updates (e.g., [8], [4], [6], [11] [13], [3]) which severely reduces the scalability of the network with respect to the number of nodes and the number of concurrent data flows that is capable of transporting.

The main contribution of this paper is the introduction of the first unified framework for multicast and geocast routing in MANETs. In this new approach to routing, the same control signaling and data structures are used to support multicast and geocast routing which eliminates the need of running more than one routing protocol.

The rest of the paper is organized as follows. Section III presents Geo-PRIME, which implements our integrated routing framework. In Geo-PRIME, the routes needed to forward packets for multicast and geocast flows are established using interest-based signaling [5]. Section IV describes the results of simulation experiments used to compare the performance of Geo-PRIME with that of relevant multicast and geocast routing protocols for MANETs. We compare Geo-PRIME with ODMRP [8] to determine the effectiveness of Geo-PRIME as a multicast routing protocol and against LBM [7] to assess the effectiveness of Geo-PRIME as a geocast routing protocol. We also compare Geo-PRIME against the combined use of ODMRP and LBM to consider the case of combined multicast

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and geocast traffic. The results show that Geo-PRIME is a very efficient routing protocol for multicast and geocast traffic and that it provides substantial performance improvements over the traditional approach to supporting multicast and geocast routing independently.

II. RELATED WORK

There have been a large number of routing protocols proposed and implemented to date for MANETs. However, due to space limitations we only address a small but representative sample of them. Our summary is intended to highlight the facts that (a) existing routing protocols for MANETs support either multicast routing or geocast routing, and (b) the dissemination of signaling traffic in MANETs tend to flood the whole network too often.

A. Geocast Protocols

Geocast routing protocols for MANETs are typically classified into flooding-based and route-based (i.e., data packets are transmitted to the destination region through flooding or a variant of flooding) and route-based (i.e., routes from the source to the destination region are calculated).

The most representative flooding-based protocol is LBM [7] which can operate in two modes. In the first mode, the protocol designates a forwarding zone which is defined as the minimum rectangle that contains the source node and the destination geocast region. In this mode, data packets are simply flooded along the forwarding zone. In the second mode, data packets are relayed only if they were received from a node which is located farther away from the intended destination region. The main disadvantages of LBM are the facts that forwarding zones can be arbitrary large, even spanning the whole network, and that in cases where the network is not isotropic LBM can fail to find routes from source to destination even if they actually exists. In Geogrid [9], the network is divided into a set of geographic regions and a representative node is chosen in each region. Then, the protocol operates similar to LBM and data packets are relayed from all the representative nodes which are located within a forwarding zone defined as the smallest rectangle that contains the source and the intended geocast destination.

There are several route-based geocast protocols reported in the literature. In [3], the authors propose flooding forwarding zones (conical shaped, rectangular shaped, and the whole network) with control signaling that used for establishing routing meshes connecting sources with destinations. These meshes are composed by reverse routes that are established when JOIN-TABLE packets are unicast routed from the destination to the source. Similarly to LBM, when the network is not isotropic this approach can fail to find routes even if they actually exists. GZHLS [12] is a link state protocol that divides the network into non-overlapping geographical regions and then uses link-state information to compute routes between representative nodes located at each region. Data packets are unicast routed to the representative nodes of the relevant geographical regions and then they are routed using a greedy strategy that simply select as next hop a node that is closer to the destination.

B. Multicast Protocols

Multicast routing protocols can be classified based on the type of routing structure they construct and maintain; namely, tree-based and mesh-based protocols. A tree-based multicast routing protocol constructs either a shared multicast routing tree or multiple multicast trees to deliver data packets to the nodes that belong to the multicast group. Several tree-based multicast routing protocols have been reported in the past. For example, the multicast ad hoc on-demand distance vector protocol (MAODV) [11] maintains a shared tree for each multicast group consisting of receivers and relays. Sources acquire routes to multicast groups on-demand in a way similar to the ad hoc on-demand distance vector protocol (AODV) [10].

Unlike tree-based protocols that maintain tree-like routing structures, mesh-based protocols simply compute connected components that contain sources and receivers. Two basic approaches of mesh-based multicast routing are characterized by the On-Demand Multicast Routing Protocol (ODMRP) [8], and the Protocol for Unified Multicasting through Announcements (PUMA) [13].

In ODMRP [8], group membership and multicast routes are established and updated by the sources on-demand. Each multicast source broadcasts Join Query (JQ) packets periodically, and these are disseminated to the entire network to establish and refresh group membership information. When a JQ packet reaches a multicast receiver, the latter creates and broadcasts a Join Reply (JR) to its neighbors stating a list of one or more forwarding nodes. A node receiving a JR listing it as part of forwarding groups forwards the JR stating its own list of forwarding nodes. Several extensions to ODMRP have been proposed to reduce the signaling overhead it incurs, however, the salient feature of ODMRP and its extensions is that multiple nodes produce some flooding for each group.

PUMA [13] uses a receiver-initiated approach in which receivers join a multicast group using the address of a core that is broadcast to the network proactively. If a node requires transmitting packets to a multicast group, it has to direct them to the core of that group. The limitation of PUMA is that all nodes must receive periodic signaling packets regarding each multicast group, regardless of the interest nodes may have in the group.

III. GEO-PRIME

A. Overview

Geo-PRIME establishes and maintains a routing mesh for each active destination, namely, for each multicast group or geocast region with active sources and at least one receiver (group member). The first source that becomes active for a given destination sends its first data packet piggybacked in a *mesh request* (MR) packet that is flooded up to a horizon threshold that is defined by the user. Upon reception of an MR, the members of the intended destination become active and start the process of establishing and maintaining a routing mesh spanning the active sources and the nodes that belong to the destination. The nodes that belong to the destination (also referred as group members) participate in a distributed election algorithm to elect the core for their group. Core nodes periodically generate *mesh announcement* (MA) packets with monotonically increasing sequence numbers for as long as there is at least one active source interested in them. When no active sources are detected for a destination, the core of the destination stops generating MAs, which causes the routing information corresponding to the mesh of the destination to be deleted.

To confine control traffic to those portions of the network that need the information, a region of interest is defined for an established mesh. The region of interest of a destination is a connected component of the network spanning all the receivers that compose the destination, the interested active sources and a set of relay nodes needed to connect them. The frequency with which MAs for a given destination are sent within its region of interest is much higher than the frequency with which MAs are sent outside of it.

In order to integrate the signaling for multicast and geocast routing, a destination D is treated as a connected *destination-mesh* (DM_D), which contains multicast group members or nodes inside a geocast region, and a set of nodes needed to keep them connected.

For the remaining of this paper, we assume that all the nodes in the network are capable of knowing their current positions, either through GPS or any other positioning system.

B. Mesh Activation and Deactivation

Geo-PRIME activates meshes only for those destinations for which there is interest. Meshes are activated using mesh-activation requests (MR), which make receivers change their state from inactive to active and to start the mesh creation and maintenance process. A mesh-activation request (MR_D^S) generated by source S for destination D and transmitted by node B is a seven-tuple of the form:

$$(\; type, \; horizon, \; persistent, \; id^S, \; d_S^B, \; id^D, \; sn^S \;)$$

where $type$ states the type of message, $horizon$ is an application-defined threshold used to limit the dissemination of the MR, $persistent \in \{true, false\}$ is a flag that indicates the persistence of the interest, id^S is the sender's identifier, d_S^B is B's hop distance to the sender S, id^D is the destination's identifier, and sn^S is a sequence number.

Upon reception of an MR, a node determines whether it is an intended destination of the MR. If it is not, it simple looks in its data cache for a pair of the form *(sender id, packet id)*. If the pair is not in the cache and if the horizon value has not been reached, the MR is relayed, otherwise it is dropped.

C. Mesh Establishment and Maintenance

A *mesh announcements*(MA_D^{*B}) transmitted by node B for destination D is a nine-tuple of the form:

$$(id^{*B}, \; core_D^{*B}, \; sn_D^{*B}, \; d_D^{*B}, \; mm_D^{*B}, \; next_D^{*B}, \; dc_D^{*B}, \; cc_D^{*B}, \; position_D^{*B})$$

where id^{*B} is the identifier of node B, $core_D^{*B}$ is the identifier of the core of the destination D, sn_D^{*B} is the largest sequence number known by B for destination D, d_D^{*B} is the hop-distance of node B to the core of D. mm_D^{*B} is a flag that indicates if B is a mesh member, a receiver, both, or a regular node. $next_D^{*B}$ is the identifier of the preferred next hop of node B towards the core of D. For the case of geocast destinations, dc_D^{*B} is the euclidean distance from D's core to the center of the geocast region D, cc_D^{*B} is the number of geocast regions that contain the region D and $position_D^{*B}$ is the position of the geocast region D codified as the coordinates of the bottom-left and upper-right corners of a rectangular geographic area.

For a given destination D, nodes maintain a neighborhood list L_D that stores an ordered set composed of the MAs that the node has recently received from each of its neighbors regarding that destination. An MA received from neighbor B that is already stored in L_D is denoted by MA_D^B (with the $*$ dropped).

Each MA stored in L_D is augmented with a time stamp (ts) obtained from the local clock. Announcements are ordered using a strict total order relation $\prec$, which is defined as follows:

$$MA_D^B \prec MA_D^A \Leftrightarrow (sn_D^B < sn_D^A) \;\vee\; (sn_D^B = sn_D^A \wedge d_D^B > d_D^A) \vee (sn_D^B = sn_D^A \wedge d_D^B = d_D^A \wedge id^B < id^A) \quad (1)$$

In addition to L_D, a node x keeps track of the core of the destination ($core_D^x$), the largest sequence number known for the destination (sn_D^x), its current distance to the core of the destination (d_D^x), its *feasible distance* to the core of the destination (fd_D^x), its preferred next hop towards the core ($next_D^x$) and its mesh membership status flag (mm_D^x). If D is a geocast destination, x also keeps track of the euclidean distance from the core of D to the center of the geocast region (dc_D^x), the location of the geocast destination ($position_D^x$), the location of a geocast region (if it exists) which is completely contained within region D and is the region that is completely contained within the largest number of other geocast regions ($interior_D^x$), a counter that indicates the total number of geocast regions that completely contain destination D (cc_D^x), and a counter that indicates the total number of geocast regions that completely contain destination $interior_D^x$ ($cc\_interior_D^x$). The last three elements are used to perform state aggregation as described in Section III-E.

The initial value of the routing state is as follows: $L_D \leftarrow \emptyset, core_D^x \leftarrow next_D^x \leftarrow nil, cc\_interior_D^x \leftarrow cc_D^x \leftarrow sn_D^x \leftarrow 0, d_D^x \leftarrow fd_D^x \leftarrow \infty$, $interior_D^x \leftarrow position_D^x$, and $mm_D^x \leftarrow REG$ (regular node).

D. Core Election

Upon reception of an MR, a group receiver first determines whether it has recently received an MA from the core of the group, and no further action in this regard is needed if that is the case. Otherwise, the receiver considers itself the core of the group and starts transmitting MAs stating itself as the core of the group. Nodes propagate MAs based on the best MA they receive. When an MA advertising a better core is received, then the new core is adopted and a new MA advertising the new core information is transmitted. For multicast case, an

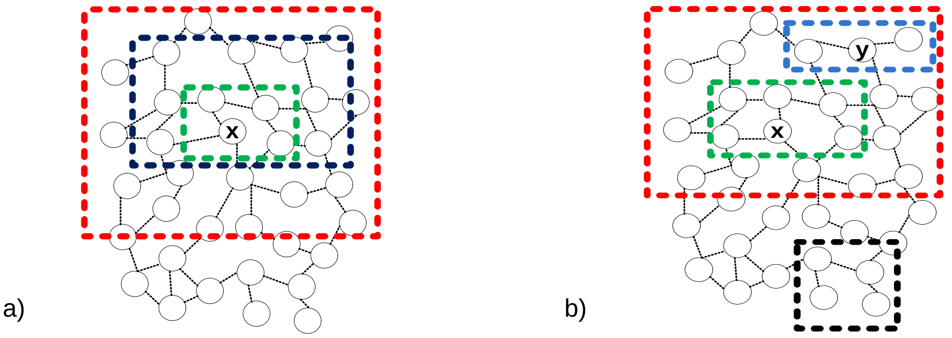

Fig. 1. Scenarios with multiple active geocast regions. (a) A region is completely contained within other two regions. In this case, the three regions can share a single core. (b) Two geocast regions are contained within a third region but they do not overlap. In this case, only one of the inner regions will share a core with the largest region.

MA with a larger core id is considered better than one with a smaller core id. For geocast case, the best MA is the one generated by the node reporting the largest number of geocast regions that contain such node. If only a single geocast region is known, the MA reporting the smallest distance to the center of the geocast region is preferred. In the geocast case, node ids are used to break ties.

Therefore, if a node x receives an MA advertising a multicast core with a larger identifier ($core^{*B}_D > core^x_D$), or a geocast core such that $(dc^{*B}_D < dc^x_D) \vee (dc^{*B}_D = dc^x_D \wedge core^{*B}_D > core^x_D)$, then L_D is set to $\{MA^{*B}_D\}$, $core^x_D$ is set to $core^{*B}_D$ dc^x_D is set to dc^{*B}_D, and the other parameters are set as follows: fd^x_D to d^{*B}_D, d^x_D to $d^{*B}_D + lc^x_B, sn^x_D$ to sn^{*B}_D, and $next^x_D$ to id^B.

E. Geocast State Aggregation

In the case where a geographical region is completely contained within another region, nodes perform routing state aggregation. For instance, Fig. 1(a) shows a region (defined by rectangles with dotted lines) that contains two other regions. In this case, instead of electing a core for each region, it is possible elect a single core for the three regions with the corresponding savings in control overhead. In Fig. 1(a), node x will be elected as the core of the three regions because it is located inside of the three regions and it is also the node that is closer to the centroid of the smallest region. For the case of Fig. 1(b), two geocast regions are contained within a third region but they do not overlap. In this case, only one of the inner regions will share a core with the largest region. Since nodes located inside the smallest regions report the same number of overlapping regions (two in this case) the node that is closer to the centroid of largest region is selected. Therefore, node x will act as the core of the largest region and the small region that is closer to the centroid and node y will be elected as the core of the small region that contains it.

To make this possible, nodes need to know the number of geocast regions that contain them. Then, if the node x receives an MA^{B*}_G from neighbor B for destination G, and there is some destination D stored in x such that $position^x_D$ is inside $position^{*B}_G$, then x increases by one the value of cc^x_D (in order to avoid counting multiple times, node x stores the information about which region is contained in another, and also, it updates this information as the destinations are activated or deactivated). Then, if x knows about more than one active destination, it adopts the core published in MA^{B*}_G if it has information about destination D such that Eq. 2 holds.

$$\begin{aligned}
&is\_this\_region\_inside\ (\ position^{*B}_G, position^x_D) \quad \wedge \\
&(\ (cc\_interior^x_D\ <\ cc^{*B}_G) \vee (cc\_interior^x_D =\ cc^{*B}_G\ \wedge \\
&d\ (position^{*B}_G,\ position^x_D) < d(interior^x_D, position^x_D)) \\
&\vee\ \ (cc\_interior^x_D\ \ = cc^{*B}_G \wedge d(position^{*B}_G, position^x_D) \\
&= d(interior^x_D, position^x_D) \wedge dc(core^{*B}_G) < dc(core^x_D)) \\
&\vee\ (\ cc\_interior^x_D\ =\ cc^{*B}_G \wedge d(position^{*B}_G, position^x_D) \\
&= d(interior^x_D, position^x_D) \wedge\ dc(core^{*B}_G) = dc(core^x_D) \\
&\wedge core^x_D < core^{*B}_G))
\end{aligned} \tag{2}$$

where $is\_this\_region\_inside$ $(position^{*B}_G,\ position^x_D)$ is true when $position^{*B}_G$ is inside $position^x_D$, otherwise is false. $d\ (position^{*B}_G,\ position^x_D)$ is the euclidean distance between the centroid of $position^{*B}_G$ and the centroid of $position^x_D$, and $dc(core^x_D)$ is the euclidean distance from x to the centroid of D.

If some destination D in x meets equation 2, then x updates its routing state as follows: $interior^x_D \leftarrow position^{*B}_G, cc\_interior^x_D \leftarrow cc^{*B}_G, L_D \leftarrow \{MA^{*B}_G\}$, $core^x_D \leftarrow core^{*B}_G$, $dc^x_D \leftarrow dc^{*B}_G, fd^x_D \leftarrow d^{*B}_G$, $d^x_D \leftarrow d^{*B}_G + lc^x_B$, $sn^x_D \leftarrow sn^{*B}_G$, and $next^x_D \leftarrow id^G$.

F. Processing Mesh Announcements

Upon reception of MA^{*B}_D from neighbor B for destination D, node x updates its routing information using the following procedures.

Node x accepts the MA if it contains a sequence number equal or larger than the current largest sequence number or if it is the first time that an MA is received from B (Eq. 3). The MA is dropped otherwise (Eq. 3).

$$L_D \leftarrow \begin{cases} L_D \cup \{MA^{*B}_D\} & \text{if } MA^B_D \notin L_D \\ L_D - \{MA^B_D\} \cup \{MA^{*B}_D\} & \text{if } sn^x_D \leq sn^{*B}_D \\ L_D & \text{if } sn^x_D > sn^{*B}_D \end{cases} \tag{3}$$

The feasible distance to the core of x (fd_D^x) is a non-increasing function over time that can only be reset by a change of core or by a new sequence number (Eq. 4). Feasible distances are used to select a *feasible set* of next hops towards the core of the destination.

$$fd_D^x \leftarrow \begin{cases} d_D^{*B} & \textbf{if } sn_D^{*B} > sn_D^x \\ \min\{fd_D^x, d_D^{*B}\} & \textbf{if } sn_D^{*B} = sn_D^x \\ fd_D^x & otherwise \end{cases} \tag{4}$$

The sequence number stored at node x for the core of destination D (sn_D^x) is also a strictly increasing function over time that can only be reset by a change of core (Eq. 5).

$$sn_D^x \leftarrow \max\{sn_D^x, sn_D^{*B}\} \tag{5}$$

The distance to the core of destination D of node x (d_D^x) is computed using Eq. 6 and the relation $\prec$ defined in Eq. 1. By definition, the core of the group has a 0 distance to itself and its feasible distance is always 0. In this paper, link cost (lc) always equal one.

$$d_D^x \leftarrow \begin{cases} d_D^i + lc_i^x : \max\limits_{i \in L_D : sn_D^i = sn_D^x} \{i\} & \text{if such } i \text{ exists} \\ \infty & otherwise \end{cases} \tag{6}$$

The next hop to the core of D ($next_D^x$) is also computed using Eq. 7 which is based on the relation $\prec$ defined in Eq. 1.

$$next_D^x \leftarrow \begin{cases} id^i : \max\limits_{i \in F_D^x} \{i\} & \text{if such } i \text{ exists} \\ nil & otherwise \end{cases} \tag{7}$$

where $F_D^x = \{i : i \in L_D \wedge fd_D^x = d_D^i \wedge sn_D^i = sn_D^x\}$ is the set of x's feasible neighbors for destination D.

The mesh membership flag $mm_D^x \in \{RM, MM, RCV, REG\}$ indicates whether x is a regular node (REG), a group receiver (RCV), a mesh member (MM), or both group receiver and mesh member (RM).

A node x is a mesh member if and only if:

$$\exists y \in L_D : mm_D^y \neq REG \wedge d_D^y > d_D^x \wedge \\ next_D^y \leq id^x \wedge ts_D^y + MA\_period \geq ct \tag{8}$$

where ts_D^y is the time stamp assigned to y when it was stored in L_D, ct is the current value of the clock of x, and MA_period is the value of the MA-period.

G. Transmission of Mesh Announcements

Nodes transmit MAs to inform other nodes about updates in their routing state. These updates can be originated either by internal events like a change in the group membership status that modify the value of mm_D^x, or the generation of a new sequence number; or by external events such as the reception of an MR generated by a source that has just become active or the reception of an MA_D^{*B} from a neighbor B. This way, when the core of the destination generates a new MA with a larger sequence number, the latter is disseminated along the network advertising the new sequence number (Eq. 5) and establishing next-hop pointers towards the core ($core_D$, Eq. 7).

An MA transmitted by a group member R, forces the next hop of R ($n = next_D^R$) to update its mesh membership status according to Eq. 8. If this changes the value of mm_D^n, then n transmits a new MA to advertise its new state. This way, nodes that lay in a path $p = R, n, n_1, ..., n_k, core$ with $next_D^R = n, next_D^n = n_1, ..., next_D^{n_k} = core_D$ are forced to create a *destination-mesh* which is a connected component of the network that contains all the receivers of a group and a set of nodes needed to interconnect them.

H. Regions of interest

A region of interest of a destination D is a connected component of the network that contains those nodes relevant to the dissemination of information for the flows with destination D, namely, nodes that compose the destination, senders, and relay nodes located in paths connecting the sources with the destination. Because all the nodes in the region of interest of a destination have interest in the destination, they participate proactively in the signaling needed to maintain routing information for the destination.

Accordingly, and to support a receiver-initiated method for multicast receivers to join multicast groups and to allow non-group members to send data to multicast and geocast groups, all nodes in the network receive information about the existence of the core of active groups. However, MAs are sent within a region of interest with much higher frequency than that used outside of it and in fact, this frequency decreases exponentially with respect to the distance in hops from a node to the boundary of the region of interest.

Algorithm 1: RofI(MA)

```
if $rc \vee sd \vee mm \vee pn \vee$ it has overheard a data packet with destination $D$ $\vee$ it is located one hop away from a receiver then
else
    $r++$;
    if $r \bmod R \neq 0$ then
        return $false$;
return $true$;
```

Algorithm 1 is used to decide if a node has to relay an MA for destination D. *RofI* returns $true$ if the node is a receiver (rc), a sender (sd), a mesh member (mm), or if the node is a path node (pn). A node is a path node if, according to Eq 9, it has relayed a packet transmitted from any source to D during the last MA-period. *RofI* also returns $true$ if the node has overheard a data packet with destination D.Otherwise, *RofI* checks for the value of $r \bmod R$ and returns $true$ if it is equal to 0 and $false$ otherwise. The value of $r \bmod R$ is used to reduce the frequency with which a node located outside of the region of interest transmits MAs. The value of r is initially set to 0.

Fig. 2 presents an example of a region of interest for a multicast group. Nodes labeled p, p' and p'' are part of the region of interest, because they lay in shortest paths from the sender s to the core and have recently been used as relays.

Nodes like w are part of the region of interest because they are located one hop away from a receiver and nodes like x are part of the region of interest because they have overheard packets intended to destination D. Nodes like y receive MAs every mesh-announcement (MA-period), but they use *RofI* to choose when to forward them. For instance, if R equals 2, y would send MAs at half of the frequency used inside of the region of interest, while nodes located one hop away from the region of interest, such as z, would send MAs at one quarter of the frequency used inside the region of interest.

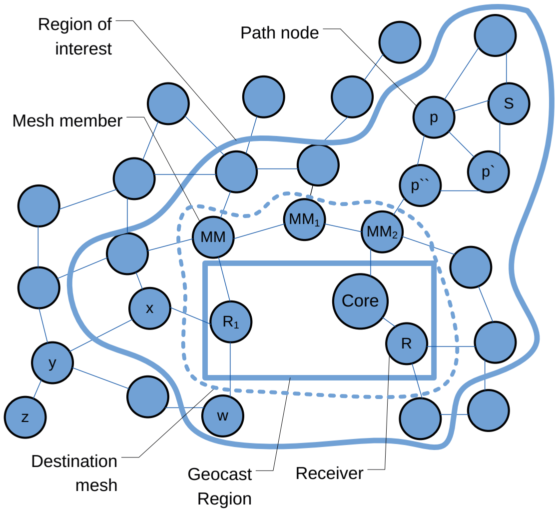

Fig. 2. Example of a region of interest.

I. Packet Forwarding and Local Repairs

When a source has data to send, it checks whether it has received an MA advertising the intended destination. If not, it broadcasts an MR as described in Section III-B. Otherwise, the sender forwards the data packet according to its routing table.

The following predicate is used by node x to decide if it has to forward a data packet to destination D received from neighbor y:

$$mm^x_D = RM \vee mm^x_D = MM \vee \exists y \in L_D : \\ d^y_D > d^x_D \wedge next^y_D \leq id^x \quad (9)$$

Eq. 9 states that node x forwards a data packet received from node y if x is part of the destination-mesh or if x was selected by the previous relay (y) as one of its next hops to the core. This way, data packets travel along directed routing meshes until they reach the destination.

Forwarders located in directed routing meshes employ the transmission of data packets by their next hops as implicit acknowledgments (ACK). If a node fails to receive three consecutive implicit ACKs from a neighbor, then it removes that node from its neighborhood list L_D and updates the value of $next^x_D$ using Eq. 7 and the value of d^x_D using Eq. 6.

As discussed in Section III-G, a change in any of these two values forces node x to transmit a new MA to advertise its new routing state and, for instance, force a newly selected next hop node to route data packets towards the destination. If the value of $next^x_D$ equals nil after removing the neighbor from L_D, then the current feasible distance fd^x_D is included in the MA (instead of the new value of the distance d^x_D). An MA with $next^{*x}_D = nil$ and $id^{*x} \neq core^{*x}_D$ is interpreted as a *neighbor request* that informs other nodes that x no longer has a route towards the destination. Upon reception of a neighbor request from x, nodes eliminate x's entry from L_D and update their routing state accordingly. Additionally, a node z also transmits an MA as a response to a neighbor request if it complies with the predicate:

$$next^z_D \neq nil \wedge (sn^z_D > sn^{*x}_D \vee sn^z_D = sn^{*x}_D \wedge d^z_D \leq d^{*x}_D) \quad (10)$$

This is because z is in fact a feasible next hop for x and can be used to reach the destination through a loop-free path.

IV. PERFORMANCE EVALUATION

We present simulation results comparing Geo-PRIME against ODMRP for the case of multicast traffic, against LBM for the case of geocast traffic, and against ODMRP with LBM for the case of combined multicast and geocast traffic. We use ODMRP and LBM in our experiments, because they are widely used baselines for performance comparisons of multicast and geocast routing protocols. We use packet delivery ratio, end-to-end delay, control overhead, and total overhead as our performance metrics. The control overhead is the number of control packets generated by the routing protocols and the total overhead is the number of bytes that are actually transmitted by the physical layer.

TABLE I
SIMULATION ENVIRONMENT

Total nodes	100	Node placement	Random
Simulation area	$1400 \times 1400\text{m}^2$	Simulation time	150s
MAC Protocol	802.11	Tx. rate	2000000bps
Data source	MCBR and GCBR	Pkts. per src.	1000
Mobility model	Random waypoint	Pause time	10s
		Min.-Max. Vel.	1-10m/s

The routing protocols are tested with IEEE 802.11 as the underlying MAC protocol, and all signaling packets are sent in broadcast mode. We use random waypoint as our mobility model. This model allows us to test the protocols on general situations in which each node moves independently . We used the discrete event simulator ns-2 [1] version 2.34, that provides a realistic simulation of the physical layer. We obtained the code of ODMRP from the Rice University Monarch Project [2], and for the case of LBM we implemented the first scheme presented in [7]. Each simulation was run for ten different seed values. To have meaningful comparisons, the multicast protocols use the same period of three seconds to refresh their

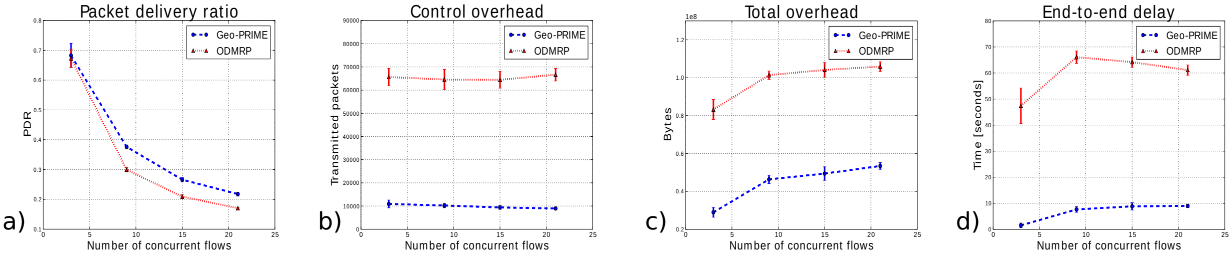

Fig. 3. Performance with increasing number of MCBR sources. (a) Delivery ratio. (b) Number of control packets generated. (c) Number of bytes generated. (d) End-to-End delay.

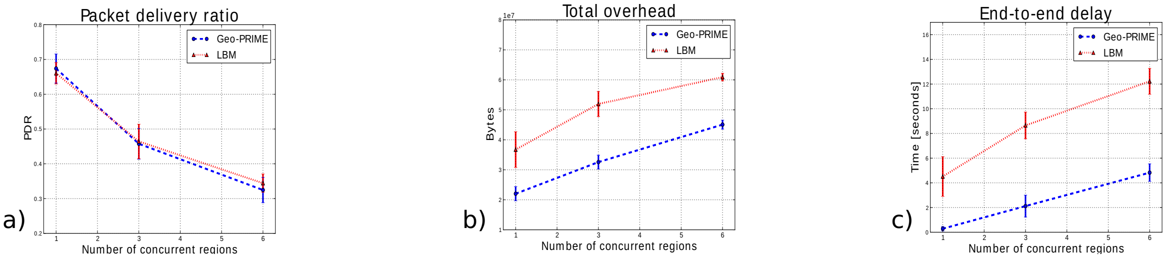

Fig. 4. Performance with increasing number of active geocast regions. (a) Delivery ratio. (b) Number of bytes generated. (c) End-to-End delay.

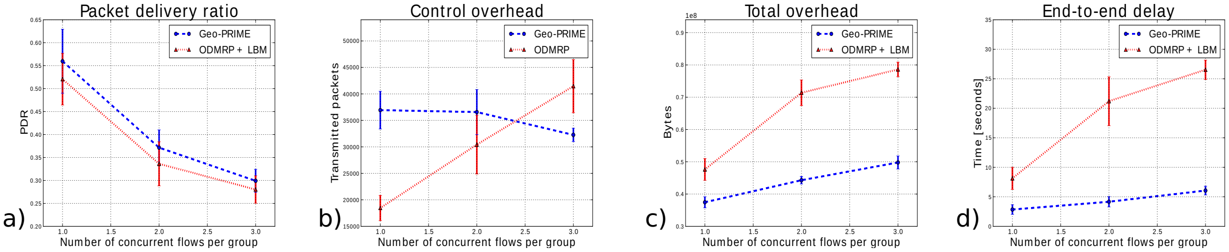

Fig. 5. Performance with combined multicast and geocast traffic. (a) Delivery ratio. (b) Number of control packets generated. (c) Number of bytes generated. (d) End-to-End delay.

routing structures (join query periods for ODMRP and MA periods for Geo-PRIME). The value of Geo-PRIME's horizon threshold was set to the same value as the TTL used in the ODMRP's Join Queries, which is the worst-case scenario for propagation of MRs in Geo-PRIME. We also assume that perfect location information is available to nodes running LBM and Geo-PRIME. Table I lists the details of the simulation environment.

A. *Performance with Multicast Traffic*

We first focus on an experiment in which a single multicast group is present and the number of concurrent active senders increases. Each sender transmits 10 packets of 256 bytes per second and the group is composed of 20 nodes. Sources are not group members. The results are presented in Figs. 3(a-d).

As shown in Fig. 3(b), the number of control packets generated by Geo-PRIME is considerably less than those generated by ODMRP. This is due to the use of regions of interest in Geo-PRIME, which limit the exchange of control traffic only to those portions of the network where it is necessary, whereas ODMRP periodically floods the entire network with ”Join Request” packets generated by each source. Also, in Fig. 3(d) is shown that the Geo-PRIME's end-to-end delay is much smaller than that of ODMRP's. Since both protocols establishes minimum hop routes to the destinations, this reduction in delay is mainly due to the reduced amount of control packets exchanged by Geo-PRIME. Since the transmission medium has a limited capacity, and control packets have higher priority than data packets, in protocols like ODMRP (with a large control overhead) data packets are delayed in the transmission queues until the control packets have been transmitted. Geo-PRIME makes a much more efficient use of network resources than ODMRP, this is confirmed in Figs. 3(b,c), which respectively show the number of control packets and bytes transmitted, which are much smaller in the case of Geo-PRIME. These results are particularly positive if we look at Fig. 3(a) which shows that the number of data packets delivered by Geo-PRIME is similar or better than that of ODMRP.

B. *Performance with Geocast Traffic*

For this set of experiments, we used six geocast regions of different sizes and locations in a simulation area of 1400m x

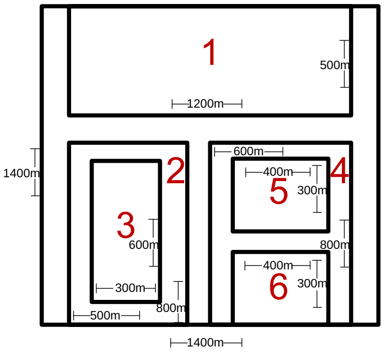

Fig. 6. Scenario with multiple geocast regions.

1400m. The dimensions and positions of the different regions are shown in Fig. 6. Each geocast destination has three active sources that were selected at random. The number of geocast regions increases according to the numbering of Fig. 6. The results are shown in Figs. 4(a-c).

Although Geo-PRIME generates control traffic and LBM does not, we can observe in Fig. 4(c) that Geo-PRIME incurs in shorter delays. This is because the total overhead induced by LBM is higher than that of Geo-PRIME (Fig. 4(b)). This tends to congest the data queues which increases the delays experienced by the data packets. Geo-PRIME is more efficient than LBM because the routing structures established by Geo-PRIME are composed of shortest paths which tend to be much smaller than the forwarding regions established by LBM. These results allow us to highlight the performance benefits achieved by restricting the dissemination of information to the regions of interest. The latter favors the spatial reuse of resources such as bandwidth and space in the data queues. From Fig. 4(a) we can notice that the delivery ratio attained by the two protocols is equivalent. From these results we can conclude that the extra redundancy used by LBM when flooding its forwarding regions does not provide any performance gain.

C. *Performance with Combined Multicast and Geocast Traffic*

In this set of experiments we evaluate the performance of the protocols when increasing the number of sources per group in a scenario composed of six geocast regions located as described in Fig. 6 and a multicast group of 20 nodes. The results are shown in Figs. 5(a-d). As it can be seen in the figures, Geo-PRIME consistently outperforms ODMRP and LBM, by delivering more data packets (Fig. 5(a)) with less delay (Fig. 5(d)) while incurring in far less control (Fig. 5(b)) and total overhead (Fig. 5(c)). These results show that having a single protocol that supports the two types of flows is much more efficient than having two independent protocols running in parallel that interfere each other and compete for the scarce network resources.

V. CONCLUSIONS

We introduced Geo-PRIME, the first routing protocol for MANETs that supports multicast and geocast data flows. Geo-PRIME uses the concept of regions of interest and state aggregation to reduce the amount of overhead induced by the protocol. The establishment of regions of interest is beneficial to the scalability of the network because promotes the spatial reuse of network resources such as bandwidth, clock cycles, energy and space in the data queues. The results of a series of simulation experiments illustrate that Geo-PRIME attains similar or higher delivery ratios than ODMRP for multicast traffic, LBM for geocast traffic, and ODMRP+LBM for multicast and geocast combined traffic. At the same time, Geo-PRIME induces much less communication overhead and attains lower delays than the other routing protocols. Based on these experimental results we have shown that the approach of having a unified protocol that supports different types of data flows has many advantages over the traditional approach that require running a set of independent specialized protocols.

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