Multiple-Landmark Routing for Large Groups in Ad Hoc Networks

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Abstract—**A typical scenario in Mobile Ad Hoc Networks (MANET) consists of nodes having functional and motorial affinities (e.g., tanks in the same battalion). In order to achieve scalability for such a network having a large scale, we introduce, in this paper, a novel "Multiple-Landmark" Ad Hoc Routing protocol (M-LANMAR). The protocol is an "implicit", flexible hierarchical routing scheme following the traditional hierarchical method for handling scalability in large, wired networks. M-LANMAR features dynamic distributed election of multiple landmarks (with scope constraints) and destination discovery within each group using landmark forwarding mesh or multicast fabric techniques plus route caching. The scalability is achieved through efficiently handling the group motion patterns, namely, the truncation of local routing tables and the "summarization" of routing information to remote groups of nodes. Different from the previous proposed Landmark Ad Hoc Routing (LANMAR), M-LANMAR allows separate maintenance/optimization of user group size and local routing scope, leading to unrestricted group size regardless of local routing scope. The simulation results not only show election stability of the multiple landmarks but also confirm the good scalability properties of M-LANMAR in general ad hoc network infrastructures (networks that are large in size and/or that contain large logical groups).**

I. Introduction

An "ad hoc" network is a self-configuring wireless network designed for applications ranging from collaborative, distributed mobile computing (sensors, conferences, conventions) to disaster recovery (such as fire, flood, earthquake), law enforcement (crowd control, search and rescue) and tactical communications (digital battlefields). The characteristics of ad hoc networks (dynamic topology, limited bandwidth, unreliable transmissions, limited energy supply, etc.) make routing algorithm design particularly challenging, especially if the network grows to thousands of nodes, as is often the case in sensor networks and in battlefield scenarios.

So far, a considerable body of literature has addressed research on routing in mobile ad hoc networks including a new generation of On-Demand ad hoc routing schemes and efficient proactive routing protocols. In particular, "implicit", flexible hierarchical routing schemes (can be either on-demand or proactive), which follow the traditional method of handling scalability in large, wired networks, i.e., hierarchical routing, have been proposed for MANET. The implicit hierarchical schemes have a hierarchical flavor and enjoy some of the scalability properties without suffering from the address maintenance overhead of traditional hierarchical schemes. Examples include Zone Routing (with detailed routing within "zones" and on-demand routing across zones) [10]; Fisheye routing (a Link State routing protocol with progressively decreasing frequency of routing updates for remote destinations) [2]; and, geo-routing (where a "hierarchical" direction to a destination is inferred from the geographical coordinates) [9]. Also to the implicit hierarchical category belongs Landmark Ad Hoc Routing [7], [8] (using group ID, which is assigned according to nodes' affinities in motion, for routes to far away nodes).

The particular scenario in which large scale (both in terrain size and in number of nodes) ad hoc wireless networks with collections of nodes having functional and motorial affinities (e.g., tanks in the same battalion) is the motivation of the research presented in this paper. The previous work in Landmark Ad Hoc Routing (LANMAR) has attempted to address the problem of scalability by utilizing the group motion pattern. LANMAR identifies logical subnets in which the members have a commonality of interests and are likely to move as a "group". A "landmark" is dynamically elected in each logical subnet and directs packets to its group. However, when a logical subnet grows large in size or acquires an arbitrary, irregular shape, the local routing scope of the landmark may not cover all the nodes in the group. The nodes which are uncovered are treated through registration (to the landmark of its subnet) and packet redirection (from the landmark), in a way similar to mobile IP registration in which mobile nodes register with the Home Agent. Thus, the landmark forwards the packet to the intended destination. The scheme works well in small/moderate group sizes. However, too many drifters will increase the routing overhead and lead to performance degradation, which unfortunately might be the norm for the research subject. The problem suggests that the previous single landmark per group scheme is inefficient for general network structures with arbitrary group dynamics.

In this paper, we propose a routing scheme ("Multiple-Landmark" Ad Hoc Routing) using multiple landmarks in each logical group. While retaining the efficiency in dealing with group motions (as exhibited in the previously proposed LANMAR), our scheme allows unrestricted group size regardless of local routing scope, enabling full coverage from the union of multiple landmarks' scopes. Overhead from using multiple landmarks is minimized as only one landmark of each group is propagated over the entire network (as LANMAR does).

The rest of the paper is organized as follows. First, we give an overview of our Multiple-Landmark Ad Hoc Routing scheme in Section II. Then in Section III and Section IV, we describe respectively an algorithm for electing multiple landmarks and a scheme for routing using the multiple landmarks and route caches. Section V gives a discussion of possible solutions from LANMAR and a comparison with our scheme. Experimental results contrasting our multiple-landmark routing to the previous single-landmark scheme are presented in Section VI. Section VII concludes the paper.

II. Overview of Multiple-Landmark Ad Hoc Routing

Multiple-Landmark Ad Hoc Routing (M-LANMAR) uses the concept of the implicit two-tier logical hierarchy. That is, nodes moving in a similar pattern are designated as part of the same subnet. This logical grouping is reflected in the IP like address $< GroupID, HostID >$. The protocol is supported by two complementary, cooperating routing schemes: (a) a high level, "long haul" routing scheme that directs packets to their landmarks (e.g., DSDV [5]) and; (b) a short range (scope), "myopic" routing scheme (e.g., Link State, or Distance Vector) that finds direct routes to destinations.

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In addition, M-LANMAR dynamically elects multiple landmarks in each subnet and re-elects them when topology changes. Each landmark has direct routing information for nodes within its scope. The union of the multiple landmarks' ranges covers the entire group. Routes to the landmarks are propagated to all the network nodes using the "long haul" distance vector mechanism. Local topology information is maintained using Fisheye State Routing (FSR) operating up to only a few hop distances. Thus, in M-LANMAR each node has detailed topology information about nodes within its scope and has a distance and routing vector to all landmarks either of its own subnet or of the closest landmark of other subnets.

A data packet directing to an in-scope destination is routed using local tables. Otherwise, if a data packet is sent to a destination outside of a node's scope, it is directed towards the closest landmark corresponding to the destination's logical subnet (reflected in $GroupID$ in the packet header). When the data packet reaches the destination subnet, either the destination is directly found in some nodes' local routing tables or the packet is forwarded by that group's landmarks. For the latter case, eventually, in one landmark's neighborhood, the local routing tables will pick up the $HostID$ entry and route the packet directly to the host. Route cache is built up for later delivery. Detailed descriptions of the election algorithm and data forwarding scheme are given in later sections.

M-LANMAR reduces the control overhead largely through the truncation (i.e., scoping) of local routing tables and the "summarization" of routing information to remote groups of nodes. The features in turn reduce storage, processing and link transmission overhead and thus greatly improve routing scalability in large, mobile ad hoc networks.

III. Election of Multiple Landmarks

The process of electing multiple landmarks is coupled with the landmark routing procedure. The landmark election algorithm assigns an election weight to each participating node. The election weight of a node is defined as the number of nodes in the same logical group within its local scope. The weights of landmarks are associated with the landmarks and propagated using the distance vector landmark update messages (denoted as LMDV). With periodic LMDV broadcasts, the latest election results are propagated. This way, the election process is completely distributed and goes on in the background all the time. For multiple groups, the election of each logical group's landmarks is performed independently and simultaneously. At a steady state, landmarks from different groups propagate their presence to all other nodes in the network.

The election decision is made locally based on the following rule: the node with the largest weight will be the elected landmark for the scope. Each node participates in election with its weight. The election procedure consists of two components: Claim (nodes check their qualifications to become landmarks) and Compete (peer landmarks in the same group challenge each other when they are within each other's scope.)

Each node performs the Claim component periodically or when the following events happen: a neighbor changes (is inserted or deleted) or an old landmark times out. In this component, each node computes its election weight. It becomes a landmark candidate if the weight is larger than or equal to a threshold T, i.e., T is the minimum practical size for a grouping. Otherwise, it remains as an ordinary (non-landmark) node. A landmark may also disqualify itself when its weight is less than T. Then another node in its group within its scope will take over. A candidate landmark directly proclaims itself as a landmark if there is no landmark within its scope. Otherwise, the candidate must win the competition against other existing landmarks within its local scope.

The Compete component is performed at some landmark nodes when a landmark node detects that other landmarks exist in its scope after receiving a landmark update message. The winner of the competition remains as a landmark and the "defeated" one stops including itself in LMDV updates. Since all nodes carry out the same procedure, only one node is elected in the scope and the algorithm converges by definition. Because the competition to decide who will be elected is carried out only among landmarks within the same scope and only by landmark nodes, other nodes simply record/update their LMDV table based on received routing update messages.

When making the winning decision among competing nodes, the largest weight rule is followed. In case of a tie, the node with the lowest ID wins. To alleviate the possible oscillation of landmarks in a mobile situation, we use hysteresis in the replacement of an existing landmark. I.e., the existing in-scope landmark is replaced by a coming landmark only if its weight is, say, less than 1/2 of the weight of the candidate. Once ousted, the old leader needs full weight superiority to be reinstated.

Within a larger (than local scope) group terrain, the election algorithm will elect multiple landmarks. Given the threshold condition, it can not be guaranteed that the union of the scopes of all elected landmarks of a particular group will cover all group members. Nodes not within any landmark's scope become drifters and must register with the closest landmark. The difference to the previous LANMAR is that M-LANMAR can always keep the portion of uncovered nodes small (as shown in Table II) or none.

Table I and II give the number of landmarks elected and their coverage in a network with 100 nodes. The 100 nodes belong to two logical groups. Each group is uniformly distributed in a 500m X 1000m field. Nodes have transmission range 175m and the local scope is 2 hops. The experiment was run in a static network to simplify our discussion. (Results when nodes are mobile will be shown in Section VI). The tables show the experiment results with increasing threshold T. T starts from 1, which means, every node is qualified to be a landmark. When T increases, the elected number of landmarks decreases (Table I). This is because the number of qualified nodes is reduced. The trend can be verified from Table II, where the average number of members covered by a landmark increases when T increases, meaning that fewer elected landmarks are closer to the geographical center of the group and thus each covers more members. The percentage of total coverage is also reported in Table II. As predicted, higher threshold leads to loss of coverage. For example, when T = 20, the coverage drops to 84 percent in group B. Since the main goal of multiple landmark election is to cover the maximum number of members with the minimum number of landmarks, selecting a reasonable threshold is important. The table suggests that threshold T = 8 is the best choice for this particular example.

TABLE I

Number of Elected Landmarks

Threshold T	num of elected LMs		
	Total	Group A	Group B
1	11	4	7
8	8	4	4
15	5	3	2
20	4	2	2

TABLE II

Coverage of Elected Landmarks

Threshold T	avg members		coverage	
	Group A	Group B	Group A	Group B
1	19	12.9	100%	100%
8	19.8	16	100%	98%
15	22	22.5	100%	80%
20	28.5	23.5	92%	84%

IV. Routing Using Multiple Landmarks

A. Landmark Route Maintenance

In M-LANMAR, each node maintains a landmark distance vector (denoted as LMDV). The LMDV stores the multiple landmarks of its own logical group and one closest landmark of every other group. This information is propagated periodically. Each particular landmark entry is associated with an incremental sequence number ([5]) to ensure loop-free operations and fast propagation of link failures or landmark failures, i.e., at the corresponding landmark, the sequence number is increased by 2 for normal operations or by 1 for an infinity cost (landmark defeated); or at any nodes, it is increased by 1 for an infinity cost (link failure).

Upon receiving an LMDV update message, non-landmark nodes simply record its own group's landmarks and update the entries of other groups with that group's closest landmark. A non-landmark node may also proclaim itself as a landmark, and compete with landmarks already existing in its scope. Landmark nodes engage in the same type of ”bookkeeping” as non-landmark nodes, recording its own groups' landmarks and updating the entries of other groups with that group's closest landmark. But if it detects other landmarks existing in its scope from an arriving message, it competes against them. The outcome of the competition is recorded in LMDV accordingly and will be broadcast in the next message exchange. A defeated landmark's entry will be denoted with an infinity cost and an increased sequence number to invalidate its entries in the LMDVs of other nodes. A landmark entry will also be timed out if it is not heard from for a certain period. Thus, each node always has fresh routes to different landmarks.

B. Packet Forwarding Using Multiple Landmarks

As mentioned in Section II, M-LANMAR utilizes a local routing table for close destinations and a landmark distance vector for remote ones. In this section we elaborate the procedure used by the multiple landmarks of a remote group to forward packets to a destination in the group.

A data packet directing to a remote destination initially aims at the closest landmark of the destination group (recall that for a remote group, the closest landmark is kept in LMDV). If on the way to the closest landmark or in the landmark's local routing tables, a local route to the destination is found, the packet is forwarded directly. Otherwise, the closest landmark (to the packet source) initiates a ”broadcast” to all landmarks in the destination group (called ”landmark mesh” forwarding). The landmark mesh forwarding procedure can be carried out in many different ways. We present here a solution based on point to point tunnels (which was actually implemented in our simulator). More elaborate techniques can use multicast in sending the packet to all the landmarks of a destination group in order to improve efficiency when logical groups grow large and broadcast functionality is required anywhere within a group (e.g., for service discovery). In this procedure, the original packet is encapsulated in a single multicast envelope, instead of in multiple unicast envelopes.

The tunnel based landmark mesh forwarding works as follows. The initiating landmark (call it Initial Forwarder (IF)) encapsulates the original data packet within another IP header. The encapsulated packet is copied and one copy is addressed and sent to each landmark in the group (i.e., multiple unicasts). During the dissemination, intermediate non-landmark nodes transparently forward the encapsulated packet. Once it arrives at the destination (the endpoint of the tunnel), it is decapsulated. The original destination is then obtained and is searched for in the local tables. If the destination is found, the original packet is delivered towards it; if not, the packet is dropped. The endpoint of the tunnel that successfully finds a route to the original destination is called End Forwarder (EF). It is possible that two or more tunnels could deliver duplicate packets to the same destination. The duplicates are filtered out using a conventional detection mechanism (e.g., sequence number) at the application level.

Repeated use of mesh tunneling implies high overhead. In a connection supporting a file transfer, for example, it would be desirable to avoid ”multiple unicasts” after the first packet. To overcome this problem, route caching is used after the first delivery. Taking the advantage of existing routing tables and encapsulation, our cache scheme records only the EF at the IF node for a particular source-destination communication pair. After successfully delivered the first packet of a connection, the EF sends a Route Cache Request (RCR) to the IF (the start point of the tunnel). When the IF receives this request, it caches the EF as a route to the original destination and forwards future data packets to such a destination directly to the EF. Cached entries are eventually timed out if no more data packets arrive at the IF. When there is more than one EF sending RCR to the IF, the IF will choose a route at a minimum distance, or choose a route randomly in order to balance the load. After the IF sends an encapsulated packet, the packet is forwarded to the EF by intermediate nodes according to their LMDV/local tables. In a mobile environment, using the current routing tables enables fast adaptation to topology change and new routes. When the EF can no longer find the original destination in its local routing table, Explicit Route Cache Cancel (RCC) message is issued to the IF to tear down the existing cache. Both RCR and RCC are sent as a unicast packet.

V. Discussions

Given the precarious nature of network connectivity and node health in typical ad hoc network scenarios, dynamic landmark election enables both LANMAR and M-LANMAR to function in a mobile ad hoc network. The LANMAR protocol elects only one landmark with maximum weight for each logical group. As the group size may be larger than the local scope of the landmark or may acquire an arbitrary, irregular shape, (which is most likely to occur in military applications), those ”out of scope” members are required to register themselves with the landmark as ”drifters” (recall from Section I). For the situation, a brute force solution is to increase the local routing scope. The enlarged scope will cover more nodes and eventually eliminate most drifters. However, an increase in scope increases the local routing table and link overhead. For example, in the ”local” FSR link state protocol, each destination within the scope has a link state entry in the routing table. The size of the table is on the order of $O(nm)$, where n is the number of nodes in the scope and m is the average number of neighbors per node. The increase in scope size thus generates increased link and storage overhead and degrades the performance. This leads to a dilemma of selecting the local routing scope. A small scope keeps routing tables small, but leads, in large groups, to ”drifter” node inefficiencies. A large scope covers large groups efficiently, but leads to high local routing overhead.

The M-LANMAR solution we propose in this paper allows us to ”decouple” the two constraints and to separately maintain/optimize local scope and user group size, which in turn leads to a more flexible and robust routing protocol for large scale mobile ad hoc networks.

VI. Performance Evaluation

A. Simulation Model

Our simulation runs on the GloMoSim simulation platform [1]. The GloMoSim library is a detailed simulation environment for wireless network systems. The MAC layer uses the default characteristics of the distributed coordination function (DCF) of IEEE 802.11 [6]. It uses Request-To-Send (RTS) and Clear-To-Send (CTS) control packets to provide virtual carrier sensing for *unicast* data packets to overcome the well-known hidden terminal problem. Each data transmission is followed by an ACK. *Broadcast* data packets are sent using CSMA/CA only. The radio model uses characteristics similar to a commercial radio interface (e.g., Lucent’s WaveLAN). The channel capacity and transmission range are 2 Mbits/sec and 175m respectively. The network traffic is generated by CBR data sessions. Each CBR sends two 128-byte data packets every second. Totally 30 source-destination pairs are spread randomly over the network. The mobility model is the *Reference Point Group Mobility* model [4]. Each node in a group has two components in its mobility vector, the individual component and the group component. The individual component is based on the *random waypoint* model [3]. The pause time is fixed to 10-second, while mobility speed for each node varies from 0 to 10 m/sec. The group component of mobility is also based on the random waypoint model.

The following metrics are used to evaluate the performance: (i) *Packet delivery fraction* – the ratio between the number of data packets received and those originated by the sources. (ii) *Control overhead* – the total control bytes transmitted by each node. Each hopwise transmission is counted as one transmission. It is measured in Kbits/sec. (iii) *Average end-to-end packet delay* – the time from when the source generates the data packet to when the destination receives it. This includes: route acquisition latency, processing delays at various layers of each node, queuing at the interface queue, retransmission delays at the MAC, propagation and transfer times.

For all routing protocols evaluated in this study the same configurations are used. Routing update interval for FSR topology table is 0.9 second and for LMDV is 0.5 second. Neighbor timeout period is 1.2 second. The timeout period for data duplicates is long enough to detect all the possible duplicates. The original LANMAR protocol is denoted as S-LANMAR in the following figures and referred to as S-LANMAR as well.

B. Simulation Results

B.1 Election in A Mobile Environment

The experiments use the same network scenario as described in Section III except that all the nodes here are mobile. The threshold T value is 8, which is chosen according to Table I. Figure 1 shows the number of landmarks elected in a mobile environment. The number is obtained at the end of the simulation. The graph shows that the number of elected landmarks increases little with increasing mobility. The graph also shows that when nodes are mobile, slightly more landmarks will be elected than when they are static. This is because the distribution of the nodes is not as uniform.

Figure 2 gives the distributions of total time duration that nodes being a landmark. The distributions are obtained from simulations in both low and high mobility. Presented results here are sorted based on all nodes’ time duration. The X axis indicates the increasing order. The figure shows that many nodes can maintain longer periods as landmarks in mobility 2 than in mobility 10. In this particular simulation scenario, the longest time a node remains a landmark at mobility 2 is 350 seconds. As the simulation time is 360 seconds, this indicates that after the warm up period, the node remains a landmark for the entire time. Meanwhile, in mobility 10, the longest time at landmark status reduces to 100 seconds. The distributions also show that only a small portion of nodes (10 percent) remains as landmarks for a substantial period of the simulation time, which provides a stable landmark structure for routing. This portion keeps almost the same even in high mobility though mobility reduces the duration of landmark status. Some portion of nodes are landmarks for zero time (never) whereas others are only landmarks for a very short period. Usually, those short-lived landmarks are nodes that claimed themselves as landmarks initially, but later lost their roles.

Figure 3 shows the dynamics of the coverage of landmarks over the two groups (A and B) of both S-LANMAR and M-LANMAR during the simulation. The mobility is 10 m/sec. The Fisheye scopes are 2 hop distances. The figure shows that S-LANMAR can not maintain high coverage due to the small scope of each group’s single landmark. Also, with S-LANMAR the coverage varies a lot through the simulation. In contrast, the M-LANMAR has smaller variation and maintains 100 percent coverage most of the time.

The results showed in these figures suggest that the multiple landmark election can stay stable in a mobile environment.

B.2 Comparison of M-LANMAR and S-LANMAR

As mentioned earlier, LANMAR is faced with the dilemma of scope and drifters, when group size distribution is arbitrary. This

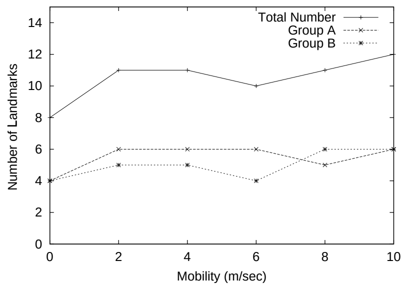

Fig. 1. Number of elected landmarks

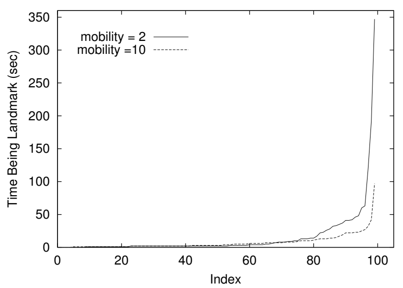

Fig. 2. Distribution of Time Period Being a Landmark

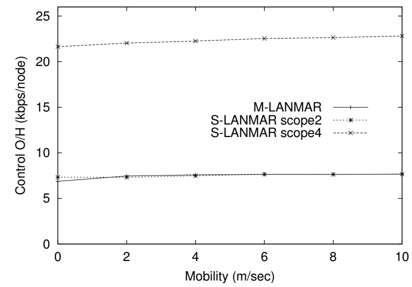

Fig. 4. Control overhead: M-LANMAR vs. S-LANMAR

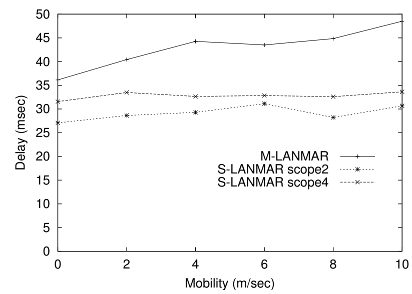

Fig. 5. End-to-end delay: M-LANMAR vs. S-LANMAR

experiment examines the problem and shows the effectiveness of M-LANMAR. The experiment uses 256 nodes with two logical groups. Each group occupies an area of $1600m \times 800m$. The M-LANMAR uses a 2 hop distance scope. The original LANMAR (denoted as S-LANMAR) uses 2 and 4 hop distances respectively. With scope 2, the landmarks can only cover a small part of the group, while with scope 4 in S-LANMAR, the landmarks can cover a larger part of the group members.

Figure 4 shows the control overhead as a function of mobility. The figure shows that S-LANMAR entails much higher control overhead with scope 4 than the other two. The high overhead is generated by the large local topology table that contains the nodes within 4 hop range. Meantime, M-LANMAR shows similar control overhead as S-LANMAR in scope 2. There are two reasons. First, both schemes have the same scope for local topology table. The second reason is that in this particular scenario, the total amount of the multiple landmark information balances the total drifter information. In M-LANMAR, one group's multiple landmarks are included in all members' LMDVs, while in S-LANMAR each drifter's routing entries exist on the nodes along the path to the landmark. The

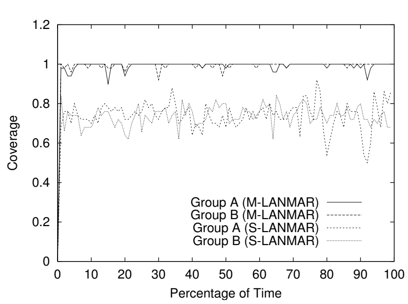

Fig. 3. Coverage of Landmarks

figure also shows that mobility has little influence on control overhead as expected.

The average end-to-end delay is presented in Figure 5 as a function of mobility. The S-LANMAR scope4 shows longer average end-to-end delay than S-LANMAR scope2 due to the high control overhead. The figure also shows that the M-LANMAR generates longer delay than S-LANMAR. The reason is that when using multiple landmarks, some of the routing paths may be longer than those using a single landmark. For example, let us consider the case where the source and the destination of a flow belong to different groups; and the destination is a drifter when using S-LANMAR schemes, while a landmark mesh forwarding is needed to reach the destination when using M-LANMAR. In S-LANMAR, the data packets will first hit the landmark of the destination group and then go towards the drifter directly. On the other hand, in the M-LANMAR case, the data packets are encapsulated while the mesh sends them directly to the multiple landmarks. Rerouting at intermediate nodes is not possible because the destination is invisible to them. Thus the data packets may miss a possible shortcut and be forwarded to the tunnel endpoint on a longer path. The figure also shows that M-LANMAR increases end-to-end packet delay when mobility increases. This is due in part to the longer paths described above and in part to M-LANMAR's ability to deliver more longer path packets than S-LANMAR. This can be confirmed in Figure 6 where M-LANMAR renders a slower degradation rate of delivery ratio than S-LANMAR as mobility increases.

Figure 6 gives the delivery fraction as a function of mobility. The figure shows that the M-LANMAR performs better than S-LANMARs. Both S-LANMARs can not deliver as much data traffic as M-LANAMR. The reason is that the uncovered "drifter" nodes degrade its performance because the DSDV scheme for drifters can not adjust well to long routing paths entailed in a mobile situation [3]. This is the same reason that the data delivery ratio of

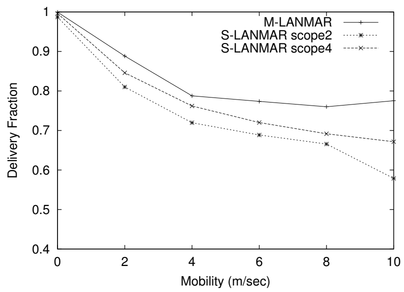

Fig. 6. Delivery fraction: M-LANMAR vs. S-LANMAR

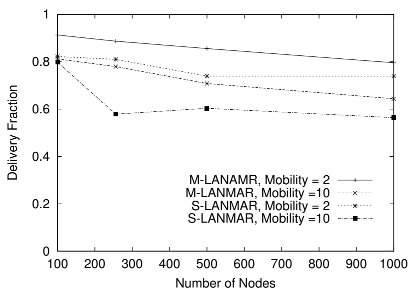

Fig. 7. Delivery fraction: various network sizes

S-LANMAR with scope 2 is lower than that in S-LANMAR with scope 4. Again, the figure shows that mobility uniformly degrades the performance of all the protocols.

B.3 Scalable to Large Group and Network Size

In this experiment, we exploit the capacity of M-LANMAR by increasing network sizes and group sizes. We vary the network size to be 100, 256, 500 and 1000 nodes with 2, 2, 4 and 8 logical groups respectively. Accordingly, one group in each network has approximately 50, 128, 125 and 125 nodes. The simulation area is proportional to the network size while keeping the same density. The fisheye scope is 2 hop distances. Both M-LANMAR and S-LANMAR are tested in the scenarios in the presence of low and high mobility.

Figure 7 shows the delivery fractions as a function of the increasing network size for all these scenarios. Both low and high mobility situations are presented in the figure for S-LANMAR and M-LANMAR. When network size increases the delivery fraction slowly decreases because longer paths across the network are more vulnerable to mobility. The figure shows that, in each mobility case, M-LANMAR has a higher delivery fraction than S-LANMAR when group and network size increases.

Figure 8 reports the delay as a function of increasing network size. Delay increases when network size increases due to longer paths between source-destination pairs. When network size is smaller, the delay is shorter. The figure shows that M-LANMAR has a longer delay than S-LANMAR, which has been observed in Figure 5 and can be explained for the same reason. The figure also shows that high mobility causes even longer delay.

VII. Conclusions

In this paper we have presented the Multiple-Landmark Ad Hoc Routing protocol. The protocol overcomes the limitation of the earlier single landmark per group scheme (LANMAR) by using dynamically elected multiple landmarks in each group to efficiently cover all group members. The multiple-landmark scheme also allows us to decouple the constraints of local scope and user group size and to maintain/optimize them separately. The decoupling enables unrestricted group size regardless of routing scope. Thus M-LANMAR can operate even when a logical subnet grows large in size or acquires an arbitrary, irregular shape. The routing algorithm that exploits the multiple landmarks mesh uses tunnels between landmarks and route caches to forward data packets to their final destinations. The simulation experiments show that M-LANMAR effectively improves the performance of general ad hoc network infrastructures over LANMAR. In particular, most nodes in the group are covered by the landmarks, so that the "drifter" problem, which affected the previous version of LANMAR, is greatly reduced. Results with 100, 256, 500 and 1000 nodes show that M-LANMAR can scale to large logical groups and to large ad hoc networks.

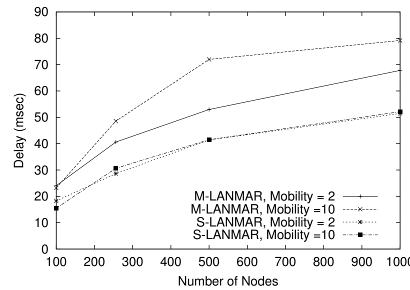

Fig. 8. End-to-end delay: various network sizes

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