Scalable Ad Hoc Routing in Large, Dense Wireless Networks Using Clustering and Landmarks

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***Abstract*— In ad hoc, multihop wireless networks the routing protocol is key to efficient operation. The design of an ad hoc routing protocol is extremely challenging because of mobility, limited power, unpredictable radio channel behavior and constrained bandwidth. As the network grows large, two additional challenges must be faced: increasing node density, and large number of nodes. High density (i.e., a large number of neighbors within radio range) leads to "superfluous" forwarding of broadcast control messages. Large network size leads to large routing tables and high control traffic O/H. The two aspects are related and they both undermine the scalability of routing protocols. In this paper, we address scalability for a specific class of routing protocols, namely, proactive link state routing protocols. Link state protocols are desirable in many applications because of low access delay, ability to include QoS criteria in path selection, support of alternate routes, etc. Yet, these protocols are most affected by density and large scale. In the paper, we propose two techniques to overcome density and large scale, namely Passive Clustering and Landmark Routing. We compare via simulation our proposed solutions to other existing scalable schemes.**

I. Introduction

Mobile Ad Hoc Networks (MANETs) are an emerging technology that allows to establish instant communication infrastructures for civilian and military applications. Target applications range 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). An ad hoc network is self-organizing and communicates mostly through multi hop wireless links. Mobility of network members, limited resources (e.g., bandwidth and energy supply) and potentially large number of mobile nodes make routing in ad hoc networks extremely challenging.

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. The on demand routing schemes (including AODV [1], DSR [2], TORA [3] and ABR [4], etc.) compute routes only when needed, without incurring the O/H if there is no data traffic. Small Query/Reply packets are used to discover (possible more than one) route to a given destination. Proactive routing schemes, such as traditional link state and distance vector routing (e.g., OSPF, RIP) compute global routes in the background using routing information updated through periodical or triggered exchanges. The benefits of proactive routing include low latency route access, alternate path support and ability to proactively monitor the quality of the (alternate) paths for effective call acceptance control. These properties make proactive schemes (in particular, Link State (LS)) desirable for applications, that include real time communications and QoS guarantees.

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Many efficient proactive routing protocols have been proposed in MANETs (DSDV[10], STAR[11], TBRPF[12], PTSP[13], WRP[14], OLSR[15], FSR [5] and LANMAR[9]).

In this paper we study approaches to scalability of proactive routing, and more specifically address link state routing schemes. Both On Demand and proactive protocols suffer from limited scalability. But, proactive schemes are most affected by large scale because of the requirement to maintain routing tables (which grow linearly with network size) and to periodically propagate routing update messages throughout the entire network. Thus, a remedy is most urgently needed for them.

In this paper, we address the scalability issue in two directions. The first direction involves "dense" ad hoc networks, where a node is within radio range of a large number of neighbors. In this case, when a node issues a control packet that must be broadcast to the entire network via "flooding" (e.g., link state update message), all the neighbors will receive and in turn forward the message. This forwarding is often "superfluous" in that only a few (say, four to six) neighbors are strictly required to forward the message so that the rest of the network receives it. Yet, superfluous forwarding can cause intolerable traffic O/H in the network and must thus be curbed. The other direction concerns large scale networks with a very large number of nodes geographically distributed over a large terrain. Large network size leads to large routing tables and high control traffic O/H. Large tables have implications in node storage and processing O/H. And traffic O/H reduces the usable network capacity. The two aspects - density and large scale - are actually related through power control. By increasing node transmit power, we can reduce the number of hops to destinations and thus reduce the "scale" factor of the network (at least in terms of hops); but we increase this way the network density. On the other hand, we may reduce power to the minimum acceptable to maintain the network connected. We would improve frequency reuse this way. But, we may end up violating the end to end delays of some applications. There are clearly complex, application dependent tradeoffs that influence the choice of power level in an ad hoc network. It is safe to say, however, that the node density or large scale problems cannot be solved by simply adjusting transmission power. Systematic approaches that are integrated with the routing algorithm must be sought.

In this paper, we propose Passive Clustering [17] to deal with node density. The clustering structure designates a subset of nodes (cluster heads and gateways) as forward routers, thus reducing broadcast flood control overhead. The advantage of using passive (instead of active) clustering is that the physical cluster structure can be built without extra control messages and it guarantees no isolated partitions of the network.

To overcome the O/H caused by large network size, we propose to use Landmark Ad Hoc Routing (LANMAR) [8], [9]. LANMAR was shown to be relatively immune from the scaling problems that plague most proactive schemes, i.e., performance degradation due to excessive routing update overhead and poor route convergence due to mobility. LANMAR relies on a local scope routing protocol for local route computation and maintenance. The original LANMAR proposal was based on Fisheye State Routing (FSR) [5]. We extend LANMAR to inter work with a variety of local scope routing protocols, thus making it a general candidate for scalability of a number of current MANET routing proposals. While the main applications discussed in the paper are based on proactive link state scheme, the results are applicable also to Distance Vector (DV) schemes (a few examples are given in the paper) as well as to On Demand schemes. In fact, On Demand schemes rely very critically on broadcast flooding (of query packets) and can thus benefit from O/H reduction in this camp.

The rest of the paper is organized as follows. Section II gives a brief overview of several proactive routing protocols. Section III addresses the dense network problem and gives an overview of Passive Clustering and the way it is used to assist routing protocols. Section IV addresses large scale networks and gives an overview of Landmark Ad Hoc Routing and its integration with FSR, DSDV and OLSR for in-scope routing. Section V presents simulation results evaluating and comparing the proposed schemes. Section VI concludes the paper.

II. Brief Overview of Routing Algorithms

In this section, we present a brief review of key proactive routing protocols proposed for MANETs. The protocols are either DV type or LS type of routing. The main advantages of the DV approach are small size of routing updates, simplicity and computation efficiency. However the DV scheme suffers from slow convergence and tendency of creating routing loops. In LS algorithms, global network topology information is maintained in all routers. Convergence to a new topology is faster than the DV scheme and preventing loops is easier due to the global topology knowledge. Unfortunately, excessive control overhead may be generated by link state dissemination, especially when high mobility triggers frequent updates.

The protocols reviewed here including DSDV, FSR, OLSR and LANMAR, which have been proposed for wireless mobile networks to address the looping problem of DV protocols or to reduce the control overhead of LS updates.

A. Destination-Sequenced Distance Vector (DSDV)

Destination-Sequenced Distance Vector (DSDV) [10] is a distance vector type routing scheme using Distributed Bellman-Ford algorithm. The destination sequenced sequence numbers are used to prevent the forming of routing loops. The updates generated by a node (the ”destination”) are sequentially numbered. Upon receiving an update (for a given destination), a node will accept it only if it contains a sequence number larger than the previously received updates. The control overhead generated by DVDS is generally lower than link state type protocols because it exchanges smaller distance vectors than link state updates. The DSDV protocol uses both periodic and triggered routing updates to keep routing information fresh at mobile nodes. In a mobile environment, triggered updates may generate very high routing overhead.

B. Fisheye State Routing (FSR)

Fisheye State Routing (FSR) [5], [6] is a link state type routing protocol. A node stores LS entries for every destination in the network. It periodically broadcasts the LS update relative to a destination to its neighbors with a frequency that depends on the hop distance (ie, scope) to that destination. LS updates corresponding to far away destinations are propagated with lower frequency than those for close by destinations. As a result, reduced routing packet size leads to reduction in update overhead. The accuracy of a route is achieved progressively as the data packet approaches its destination where a higher refresh rate is used.

C. Optimized Link State Routing Protocol (OLSR)

Optimized Link State Routing Protocol (OLSR) [15] is a link state routing protocol. The protocol uses multi-point relays (MPRs)[16] to reduce the number of ”superfluous” broadcast packet retransmissions and also to reduce the size of the LS update packets. A node, say node A, periodically broadcasts HELLO messages to all immediate neighbors to exchange neighborhood information (i.e., list of neighbors) and to compute the Multi-Point Relay set (MPR). From neighbor lists, node A figures out the nodes that are two hops away and computes the minimum set of one hop relay points required to reach the two-hop neighbors. Such set is the MPR set. The optimum (minimum size) MPR computation is NP complete. Efficient heuristics are used. By construction, only the relay nodes need to forward the LS updates in order to guarantee dissemination in the entire network. In a further effort to reduce routing O/H, the LS update of node A is also reduced in sizes as it includes only the neighbors that select node A as one of their MPR nodes. This leads to a reduced LS packet size and traffic O/H. The LS update size reduction, however, comes at the cost of reduced topology accuracy. In particular, only ”long” links tend to be advertised. For example, if A has a direct link to C, and A can also reach C via a close by node B, then node A will not be aware of the (short) connection existing between neighbors B and C and cannot exploit it in case of primary link (AC) failures. When the network is sparse, every neighbor of a node becomes a multi-point relay. The OLSR then reduces to a pure link state protocol.

D. Landmark Ad Hoc Routing (LANMAR)

The Landmark Ad Hoc Routing Protocol (LANMAR) [8], [9] was designed for ad hoc network that exhibit group mobility. Namely, one can identify logical subnets in which the members have a commonality of interests and are likely to move as a ”group” (e.g., a team of co-workers at a convention, a brigade or tank battalion in the battlefield). Within each such group, a landmark is elected distributedly. LANMAR uses the notion of landmarks to keep track of such logical groups. A global distance vector (landmark distance vector (LMDV)) mechanism is devised to propagate the direction to all the landmarks in the entire network. LANMAR works in symbiosis with a local scope routing scheme. Let us say, the local scope scheme of FSR. FSR maintains detailed routing information for nodes within a given scope D (i.e., FSR updates propagate only up to hop distance D). When a node needs to relay a packet to a destination within its Fisheye scope, it uses the Fisheye routing tables directly. Otherwise, the packet will be routed towards the landmark corresponding to the destination’s logical subnet, which is read from the logical address carried in the packet header. When the packet arrives within the scope of the destination, it is routed using local tables (that contain the destination explicit address), possibly, without going through the landmark.

III. Dense Networks and Passive Clustering

Passive Clustering (PC) is a cluster formation protocol [17]. The goal of a clustering protocol in general is to partition the network into clusters such that a Clusterhead is elected in each cluster; each cluster member is within radio reach of the Clusterhead and two Clusterheads cannot hear each other. Nodes being members of two or more clusters are called Gateways, as they serve as conduits between clusters. Passive Clustering differs from traditional clustering schemes in that it does not use dedicated, protocol specific control packets or signals. Instead, it opportunistically exploits the neighborhood information carried in the MAC layer header of data/routing packets. Only two extra bits in the MAC header are required to carry a node's cluster state and to support the clustering protocol. The cluster infrastructure is "soft state" and can be constructed as a by-product of any kind of packet exchange. Thus, after nodes start exchanging routing information, the clusterheads (CHs) and gateways (GWs) are established and form a covering set of the entire network. Moreover, the Passive Clustering protocol can dynamically reconfigure clusters in the face of mobility and topology changes.

Only gateways and cluster heads act as broadcast forwarders, i.e., participate in the propagation of routing control/update messages. In a dense network, this dramatically reduces the broadcast O/H. Passive Clustering guarantees that if the original topology was connected, the clustered topology consisting only of clusterheads and gateways is also connected [17]. Thus, the propagation of broadcast messages on the clustered topology guarantees dissemination to the entire network.

Passive Clustering was initially designed for on-demand protocols to reduce the flood-search overhead. As it can construct cluster infrastructure without extra control packets, we have chosen it to further reduce transmission overhead for proactive routing. In fact, as proactive protocols frequently broadcast routing updates, the clustering structure can be easily built up as a byproduct.

In routing protocols like FSR and LANMAR, only CHs and GWs participate in routing updates transmissions. In fact, a variant of FSR (FSR+PC) uses CHs and GWs for propagation. Moreover, nodes that are not CHs and GWs (Ordinary nodes) only broadcast HELLO messages to announce themselves to neighboring CHs and GWs. In LANMAR, the LMDV updates are also propagated only by CHs and GWs. Note however that the paths on the clustered infrastructure are not necessarily min-hop paths. This is irrelevant for broadcast flooding (where the main concern is O/H reduction). In Distance Vector protocols such as LMDV the path saved in the routing table is the min-hop dissemination path. Thus, a slight degradation in hop length can be expected when updates are disseminated on the clustered infrastructure.

It is interesting at this point to compare the Passive Clustering approach with the OLSR approach to high nodal density. There is similarity in the two schemes. One advantage of the MPR reduction scheme used by OLSR is that it tends to find shorter (i.e., lower hop) paths because of the two-hop optimization. One drawback is the amount of traffic O/H (neighbor list) and processing required for such computation. Thus, the MPR computation latency would not be suitable for on demand routing support (which is not our goal here anyway). However, the traffic O/H does impact the efficiency in proactive routing protocols. One additional improvement introduced by OLSR is the LS update reduction to reflect only the MPR set. As we commented earlier, such reduction leads however to a loss of accuracy in connectivity among nodes 2-hops away and beyond. A similar reduction could easily be carried out also with passive clustering. Namely, the LS reflects only the links between an arbitrary node and the gateways/clusterheads. Naturally, in this case as in the OLSR case, the information about "short" links would be lost. At this time, we have not yet pursued this Link State reduction with FSR.

IV. Large networks and Landmark Aggregated Routing

LANMAR combined with a local routing algorithm reduces both routing table size and control overhead effectively through the truncated local routing table and the "summarized" routing information for remote groups of nodes. It thus greatly improves routing scalability to large, mobile ad hoc networks. The two routing components reveal different control overhead behaviors as a function of network size and density. The LMDV table only keeps a vector of the landmark nodes. The size of LMDV, i.e., the number of groups, depends on the average number of nodes in a group (denoted n'). If N is the total number of nodes in the network, the number of groups is N/n' and the size is $O(N/n')$. For battlefield applications, where group sizes are in the order of hundreds, the LMDV size grows slowly.

The local in-scope routing component FSR is more prone to the increase of network size, particularly, the growth within the scope. That is, when node density increases, the in-scope entries also increase despite of hop limitation. For instance, the size of the FSR topology table is in 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. Thus, table size grows more than linearly with density due to the increase of both n and m. The shared channel is then occupied mostly by the routing packets and collisions are increased. LANMAR with FSR (LANMAR-FSR) will thus perform poorly in high node density.

LANMAR can adopt many proactive routing protocols for in-scope routing. In the sequel we discuss the integration of DSDV and OLSR as in-scope routing algorithm respectively in an attempt to alleviate the overhead of local routing when density is high, while at the same time improving the large network scalability of such protocols.

A. *LANMAR on Top of DSDV*

DSDV has the advantage of much smaller size of routing entry for each destination than LS protocols. The modified DSDV control packets include only the destinations within the local scope and are exchanged periodically (no triggered updates). The destination-sequenced sequence numbers prevent loops. The in-scope use of the protocol renders less critical the problems of slow convergence and routing inaccuracy that plague traditional DV protocol applications. When in-scope nodes increase, the routing table increases only linearly. This variant of LANMAR is denoted as LANMAR-DSDV.

B. *LANMAR on Top of OLSR*

OLSR has the advantage of good performance in a dense network. As density increases, the number of nodes selected as MPRs increases much slower than the number of neighbors. The modifications to OLSR for LANMAR integration are straightforward. That is, each node processes OLSR table for destinations within the scope. The propagation of routing update will be cut off if it reaches the border of the sender's scope. Thus, the LANMAR on top of OLSR (LANMAR-OLSR) has the advantages that it reduces the routing overhead in dense network and it avoids the inefficiency of OLSR when network is sparse and yet the number of nodes is large.

C. *Other Scalable Solutions*

LANMAR is not the only solution to produce scalable routing schemes. An explicit hierarchical routing scheme, "Hierarchical

State Routing (HSR)," was proposed in [6], [7]. However, HSR implies the introduction of hierarchical addresses, it is very sensitive to topology changes and mobility (overhead grows quickly as mobility increases) and it requires a Domain Name Server to map the destination logical address (presumed known to the sender) to the current hierarchical address. Such mapping is not required with LANMAR. FSR provides some degree of scalability as it reduces the routing O/H per node progressively when the number of nodes increases. It does not provide, however, a reduction in routing table size. OLSR provides a reduction of routing traffic O/H and routing table size, but only if the increase in number of nodes is associated with an increase in density. In a sparse network, no scalability gain is provided by OLSR. In summary, it appears that LANMAR is the best bet for general, robust scalability.

V. Performance Evaluation

In this section, we evaluate the various approaches discussed in the previous sections through simulation. Our scenario-based evaluation is focused on two aspects - dense networks and large scale networks. Many evaluation metrics are used. Some common metrics are (i) *Control overhead* – the total **bytes** of routing control packets transmitted by a node, averaging over all the nodes. Each hop-wise transmission of a routing packet is counted as one transmission. It is measured in Kbits/sec. (ii) *Packet overhead* – the number of routing control **packets** transmitted by a node, averaging over all the nodes. Each hop-wise transmission of a routing packet is counted as one transmission. (iii) *Packet delivery fraction* – the ratio between the number of data packets received and those originated by the sources. (iv) *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, queueing at the interface queue, retransmission delays at the MAC, propagation and transfer times. (v) *Throughput* - the actual throughput achieved at destinations.

A. Simulation Model

The simulator for evaluating routing protocols was implemented within the GloMoSim library [18]. The GloMoSim library is a scalable simulation environment for wireless network systems using the parallel discrete-event simulation language PARSEC [19]. The distributed coordination function (DCF) of IEEE 802.11 is used as the MAC layer in our experiments. 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 is 2 Mbits/sec.

CBR sources are used to generate network data traffic. The source-destination pairs are spread randomly over the network. During a simulation, 30 pairs of short-lived source-destination pairs are maintained all the time. When one session closes, another pair of communication will be randomly selected. Thus the input traffic load is constantly maintained.

The simulations are conducted in an identical network scenario across all the participating protocols. Different experiments may have different network scenarios. The mobility model is the *Reference Point Group Mobility* model [20]. Each node in a group has two components in its mobility vector, the individual component and the group component. The individual component is

TABLE I
INTERVALS FOR ROUTING UPDATES

DSDV	DV Broadcast:1.5S	
FSR	Intra: 0.7S	Inter: 2.2S
OLSR	Hello: 0.9S	TC: 2.2S
LANMAR	LMDV (all variants): 0.7S	

based on the *random waypoint* model [2]. The pause time is fixed to 10-second, while mobility speed for each node varies between 0 to 10 m/sec. The group component of mobility is also based on the random waypoint model. We use a relative short pause time of 10 seconds to make the topology change more frequently to challenge the routing algorithms.

As the protocols involved have different operation mechanism, we configure the routing update rates to be as similar as possible, e.g., the frequency of LMDV update is 0.7 second. Other parameters are tuned at the scenario that has 100 nodes in 1000m X 1000m field with 150 meters transmission range and mobility fixed to 2 m/s. We tune the parameters so that the protocols produce similar delivery fraction at the above operating point. The table I gives the parameters we use for different schemes. The local routing scope is set to 2 hop distances.

B. Dense Networks

As discussed in previous section, both MPRs (in OLSR) and Passive Clustering can reduce redundant propagation of link state routing packets. We evaluate the two approaches in an experiment with increasing network density. The simulation uses 100 nodes in a 1000m X 1000m area. The transmission range increases from 150m to 400m (the average number of neighbors increases from 8 to 48 in a static grid network). As the diameter of the network reduces when the transmission range increases, FSR eventually becomes a pure link state scheme. Most of the nodes will be within its first level scope. The benefit of routing update reduction from a decreased routing update frequency thus vanishes.

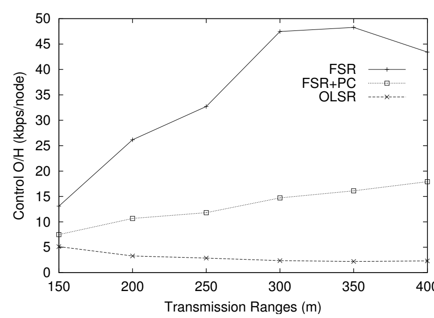

Fig. 1. Control overhead with Increasing Density

Figure 1 shows the control overhead as a function of transmission range. The increasing overhead of FSR comes from the growing packet size with increasing outgoing links at each node. The reason that the increasing trend stops when the transmission range exceeds 300m is that the large amount of control overhead congests the channel and leads to the loss of heard neighbors. When packets are too large, they are segmented to fit the MTU of the MAC layer. The figure illustrates that both FSR+PC and OLSR generates less control overhead than FSR. In FSR+PC fewer ordinary nodes transmit control packets as transmission range (i.e. density) increases. OLSR achieves less control overhead than

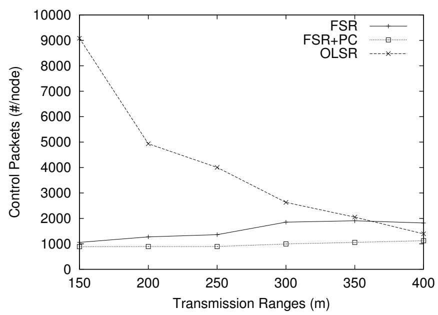

Fig. 2. Packet Overhead with Increasing Density

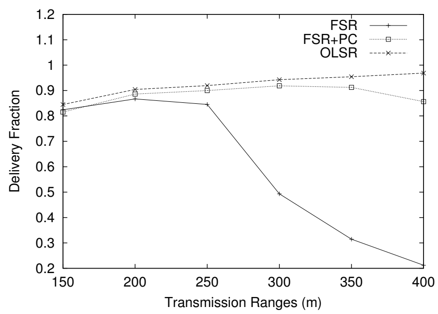

Fig. 3. Delivery Fraction with Increasing Density

FSR+PC because it reduces not only the number of transmissions, but also link state and message size.

Figure 2 gives the number of control packets emitted at each node. In contrast to the previous results, OLSR shows that a large amount of routing packets are generated, especially when the network is not dense (at this point, OLSR works similar to OSPF). The denser the network, the fewer the MPRs are selected. As only MPR nodes will relay LS update messages, the number of transmitted routing packets drops quickly. Meanwhile, FSR and FSR+PC maintain a low number of transmitted routing packets. Consistent to the previous graph, Figure 2 shows the increased number of routing packets of FSR after 300m due to the fragmentation.

Figure 3 shows the delivery fractions vs. the increasing density. Small increasing trends can be observed of all the schemes when density grows at the beginning of the curves. This is due to the fact that increasing connectivity in a mobile environment helps the establishment of routes. However, as expected, FSR degrades fast when density grows further because of the increasing control overhead. The figure also shows that FSR+PC degrades at 400m. The reason is that unlike OLSR, which calculates MPRs at each node and uses MPRs in a distributed way, the CHs and GWs in passive clustering are a common structure for all the nodes, so they are used by all the nodes. These nodes accumulate more data packets than any nodes in OLSR. Thus when network is extremely dense (48 neighbors per node with Tx = 400m!), the congestion at CHs and GWs causes packet drops.

The experiment suggests that both PC and OLSR can efficiently reduce the redundant routing packet transmission. OLSR produces higher delivery ratio than PC while it produces more control packets than PC.

C. Heavy Traffic Load

Here, we investigate the behavior of PC and OLSR for increasingly heavier loads. Assuming a constant, continuously renewed load of 30 short-lived pairs, we increase the data rate from 1 packet per second to 10 packets per second. The packet size is 512 bytes. The transmission range is 250m, corresponding to approximately 20 neighbors per node.

Figure 4 gives the throughput as a function of traffic load. The figure shows that FSR+PC saturates later than the other two protocols and achieves the highest throughput at saturation. The reason is that Passive Clustering uses very limited control overhead in achieving efficient routing, while OLSR needs HELLO messages to exchange neighbor information. The graph also shows that before the saturation point (around 1100 kbps), OLSR performs better than FSR, while after that, it produces less throughput than FSR. The reason is that the large number of control packets prevent OLSR from achieving higher throughput.

Figure 5 gives the delivery fraction as a function of load. Consistent with Figure 4, Figure 5 shows that the three protocols descend with increasing load. Particularly, FSR+PC begins to degrade sharply at a heavier load than FSR and OLSR. While the delivery fraction of the three protocols differs at the low end of the traffic load (which is consistent with Figure 3, at transmission range 250m), this does not influence the decreasing trend.

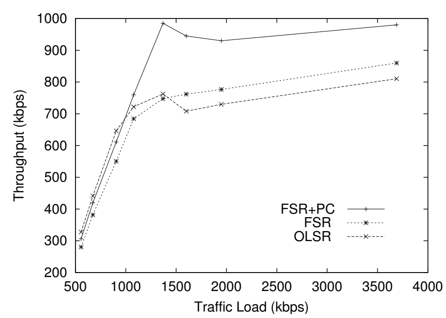

Fig. 4. Throughput with Increasing Load

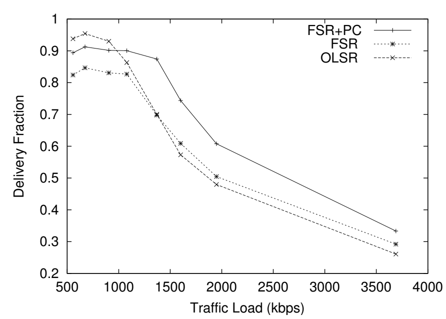

Fig. 5. Delivery Fraction with Increasing Load

D. Increasing Density by Increasing Number of Nodes

We study here the network scenario where within a fix-sized field, the number of nodes are increasing. All the nodes are only transmitting at a certain power, i.e., 175m. Thus, increasing the number is identical to increasing the density while keeping the diameter of the network unchanged. This situation will be realistic in a conference or convention environment. Our field is 1000m X 1000m. There are four logical groups initially visiting the area. The number of nodes increases from 100 to 500 hundreds, which implies that the average number of neighbors per node increases from 9 to 40 if the network is a static grid. We present here the performance of FSR, FSR+PC, LANMAR-FSR and LANMAR-FSR+PC.

Figure 6 gives the delivery fraction of the four schemes. FSR degrades fast due to the growing size of LS update packets. Though FSR progressively reduces the frequency of updates, this reduction is only marginal and cannot compensate for the excessive control overhead caused by the increase in both the number of nodes and the number of neighbors. The figure clearly shows that the Passive Clustering (FSR+PC) slows down the degradation trend of FSR. Even better does LANMAR-FSR, by using aggregated routing for logical groups. Finally, when using Passive Clustering for landmark routing (LANMAR-FSR+PC), we have the slowest decreasing trend when the network grows both in density and numbers.

Figure 7 gives the control overhead as a function of the increasing number of nodes and density. It shows that FSR generates a large amount of control overhead, and eventually neighbors are missed due to channel congestion, thus causing a drop in control overhead. The control overhead of the other three schemes increases much slower than FSR, which is consistent with the performance of delivery fraction in Figure 6. LANMAR-FSR+PC generates the lowest control O/H and increases the slowest due to smaller routing tables and less transmissions.

The experiment suggests that in general, Passive Clustering improves the performance of the routing protocols in dense network; and landmark routing provides scalability to large number of nodes.

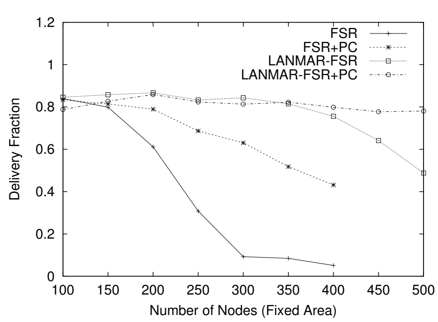

Fig. 6. Delivery Fraction

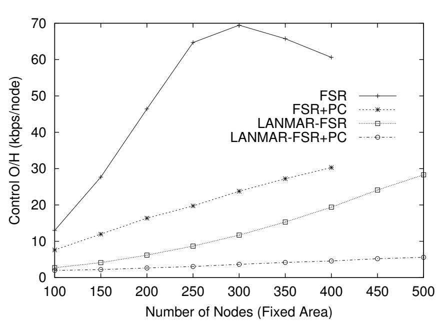

Fig. 7. Control Overhead

E. Large Networks

In this experiment, we show that with landmark routing, large scale networks with group motion affinity can achieve high performance. The scenarios we use are based on fixed density. When the number of nodes increases, the area increases accordingly. Meanwhile the number of logical groups also increases in order to keep group size relatively small. This situation is very likely to occur in a military application. We test the variants of landmark routing described in previous sections. They are, LANMAR-DSDV, LANMAR-FSR and LANMAR-OLSR. As a comparison, original protocols are tested using the same configuration as their landmark counterparts. For the original protocols, the data points stop at 400 nodes. Because, after considering the computation cost and the performance at the point (low delivery fractions of DSDV and FSR in Figure 8 and large delay of OLSR in Figure 9), we believe further executions are not necessary.

Figure 8 shows the delivery fraction of the schemes. FSR and DSDV decrease fast when network size increases. The reasons are the large LS packets and the slow convergence in the mobile environment. Both LANMAR-FSR and LANMAR-DSDV show great improvement from the original ones. LANMAR-FSR and LANMAR-DSDV decrease very slowly when network size increases. As the network is in a low density (average 9 neighbors), LANMAR-FSR does not suffer from the local routing overhead problem. The figure also shows that LANMAR-DSDV performs better than LANMAR-FSR due to the smaller local routing packets (DV) than the LS packets of FSR. OLSR degrades slower than FSR and DSDV because mobility triggers routing update which makes the routing in large network more accurate. Thus the improvement of LANMAR-OLSR in delivery ratio is not as large as LANMAR-FSR and LANMAR-DSDV.

Figure 9 shows the end-to-end packet delay of the schemes. OLSR shows fast increase in packet end-to-end delay. The reason is that when there is a large amount of control packets contenting for channel usage, the data packets have to backoff a lot for a free slot. FSR usually has large routing packets but fewer control packets than OLSR, so the delay is shorter than OLSR. Comparing to the original routing schemes, their LANMAR variants show very slow increase of delay which is mainly due to the increase in hop distances when network size grows.

Figure 10 shows packet overhead. While most of the schemes keep at a low level, OLSR sends huge amount of routing packets when the network grows large. With the low density in this experiment, OLSR losses its advantage in reducing packet redundant transmissions (please referring back to Figure 2, where network density increases). Thus the number of routing packets increase quickly when network size grows. The LANMAR-OLSR routing, with the LS updates of OLSR only propagated within the local scope, generates far less control packets than OLSR and the number of control packets does not increase with the network size.

Figure 11 reports the local storage used for the routing tables. All the variants of LANMAR show great savings in table storage. LANMAR-DSDV has the smallest storage size as expected. LANMAR-FSR and LANMAR-OLSR use almost identical storage because both protocols have full topology information of the local routing area (recall that 2-hop scope is used). The storage of LANMAR protocols hardly increases when network size grows due to the very slow increase of number of landmarks while the table storage used in DSDV, FSR and OLSR grows very fast. The small size of routing tables results in low link overhead of LANMAR protocols.

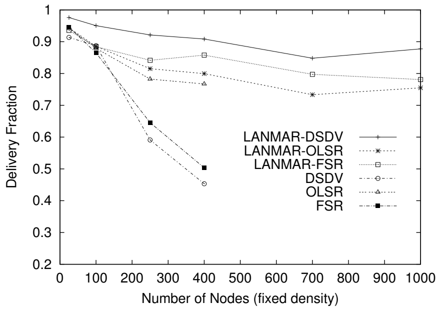

Fig. 8. Delivery Fraction When Network Grows

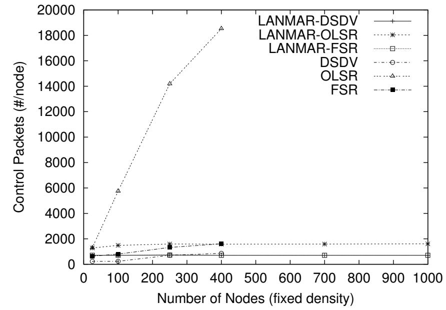

Fig. 10. Packet Overhead When Network Grows

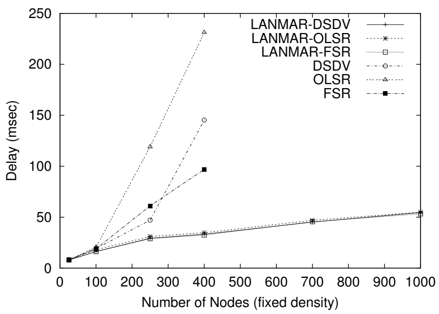

Fig. 9. Delay When Network Grows

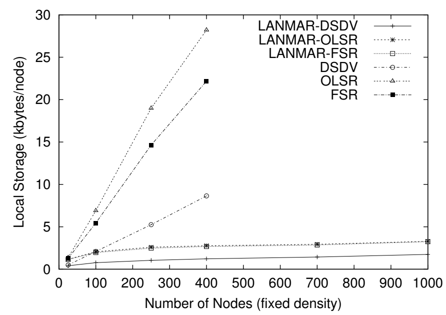

Fig. 11. Table Sizes When Network Grows

VI. Conclusions

In this paper we presented our study for scalability of proactive routing schemes (in particular, LS protocols) in dense and large scale ad hoc networks. We have shown the study of using Passive Clustering in reducing routing overhead caused by high nodal density. Also, we have proposed the Landmark scheme routing as the framework for scalable ad hoc routing. In particular, LANMAR-DSDV reduces the size of control packets required for local accurate routing (comparing to link-state type routing FSR), and LANMAR-OLSR reduces the control overhead by only selecting a subset of the neighbors for topology construction. The latter approach shows great gains when the network is dense. The simulation results indeed show that LANMAR provides a flexible routing framework for scalable routing over mobile ad hoc networks while preserving all the benefits introduced by the associated local scope routing scheme.

References

[1] C.E. Perkins and E.M. Royer, “Ad-Hoc On-Demand Distance Vector Routing,” in *Proceedings of IEEE WMCSA’99*, New Orleans, LA, Feb. 1999, pp. 90-100.

[2] D. B. Johnson and D. A. Maltz. “Dynamic Source Routing in Ad Hoc Wireless Networks”, In *Mobile Computing*, edited by T. Imielinski and H. Korth, Section 5, Kluwer Publishing Company, 1996, pp. 153-181.

[3] V.D. Park and M.S. Corson, “A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks,” in *Proceedings of IEEE INFOCOM’97*, Kobe, Japan, Apr. 1997, pp. 1405-1413.

[4] C.-K. Toh, “Associativity-Based Routing For Ad Hoc Mobile Networks,” *Wireless Personal Communications Journal*, Special Issue on Mobile Networking and Computing Systems, Kluwer Academic Publishers, vol. 4, no. 2, Mar. 1997, pp. 103-139.

[5] G. Pei, M. Gerla, and T.-W. Chen, ”Fisheye State Routing: A Routing Scheme for Ad Hoc Wireless Networks”,in *Proceedings of ICC 2000*, New Orleans, LA, Jun. 2000.

[6] A. Iwata, C.-C. Chiang, G. Pei, M. Gerla, and T.-W. Chen. “Scalable Routing Strategies for Ad-hoc Wireless Networks”, In *IEEE Journal on Selected Areas in Communications*, Aug. 1999, pp. 1369-1379.

[7] G. Pei, M. Gerla, X. Hong, and C.-C. Chiang. A wireless hierarchical routing protocol with group mobility. In *Proceedings of IEEE WCNC’99*, Sep 1999.

[8] G. Pei, M. Gerla and X. Hong, ”LANMAR: Landmark Routing for Large Scale Wireless Ad Hoc Networks with Group Mobility,” in *Proceedings of IEEE/ACM MobiHOC 2000*, Boston, MA, Aug. 2000, pp. 11-18.

[9] M. Gerla, X. Hong, G. Pei, ”Landmark Routing for Large Ad Hoc Wireless Networks”, in *Proceedings of IEEE GLOBECOM 2000*, San Francisco, CA, Nov. 2000.

[10] C.E. Perkins and P. Bhagwat, “Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers,” in *Proceedings of ACM SIGCOMM’94*, London, UK, Sep. 1994, pp. 234-244.

[11] J.J Garcia-Luna-Aceves and M. Spohn. “Efficient Routing in Packet-Radio Networks Using Link-State Information”. in *Proc. IEEE WCNC ’99*, September 1999.

[12] B. Bellur and R. G. Ogier, “A Reliable, Efficient Topology Broadcast Protocol for Dynamic Networks”. in *Proc. IEEE INFOCOM ’99*, New York, March 1999.

[13] R. G. Ogier, “Efficient Routing Protocols for Packet-Radio Networks Based on Tree Sharing”. in *Proc. Sixth IEEE Intl. Workshop on Mobile Multimedia Communications (MOMUC’99)*, November 1999.

[14] S. Murthy and J.J. Garcia-Luna-Aceves, “An Efficient Routing Protocol for Wireless Networks,” *ACM/Baltzer Mobile Networks and Applications*, vol. 1, no. 2, Oct. 1996, pp. 183-197.

[15] P. Jacquet, P. Muhlethaler, A. Qayyum, A. Laouiti, L. Viennot and T. Clausen, ”Optimized Link State Routing Protocol”, *draft-ietf-manet-olsr-03.txt*, Internet Draft, IETF MANET Working Group, Nov. 2000.

[16] A. Qayyum, L. Viennot, A. Laouiti. “Multipoint relaying: An efficient technique for flooding in mobile wireless networks”. *INRIA research report RR-3898*, 2000

[17] M. Gerla, T.J. Kwon and G. Pei “On Demand Routing in Large Ad Hoc Wireless Networks with Passive Clustering”, *Proceedings of IEEE WCNC 2000*, Chicago, IL, Sep. 2000.

[18] M. Takai, L. Bajaj, R, Ahuja, R. Bagrodia and M. Gerla. “GloMoSim: A Scalable Network Simulation Environment”, *Technical report 990027*, UCLA, Computer Science Department, 1999.

[19] R. Bagrodia, R. Meyer, M. Takai, Y. Chen, X. Zeng, J. Martin, and H.Y. Song. “PARSEC: A Parallel Simulation Environment for Complex Systems”, *IEEE Computer*, vol. 31, no. 10, Oct. 1998, pp.77-85.

[20] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang, “A Group Mobility Model for Ad Hoc Wireless Networks,” in *Proceedings of ACM/IEEE MSWiM’99*, Seattle, WA, Aug. 1999, pp.53-60.