

Scalability Analysis of Location Management Protocols for Mobile Ad hoc Networks

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Abstract—Geography based routing in mobile ad hoc networks is an application that uses location information of nodes in a network to route data packets. Since the amount of network state information that each node needs to maintain in order to route packets is minimal, location based routing is considered scalable compared to existing routing protocols in ad hoc networks. However, geographic routing requires location management, where the locations of destination nodes need to be found before the actual routing can begin. Many location management schemes have been proposed in literature, but no prior work has quantitatively compared the scalability of these protocols with respect to increase in the number of nodes in the network. In this work, we use a theoretic framework to show the asymptotic scalability of three location management protocols. We also carry out extensive simulations to study the performance of these protocols under practical considerations. Our results indicate that all protocols perform well, with slight performance degradation with increasing network size. In particular, the Hierarchical Grid Location Management protocol (HGRID) performs the best for all practical purposes, and is a candidate for location management in a wireless network architecture.

I. INTRODUCTION

As wireless access become ubiquitous, location based services with user mobility will soon be the norm than the exception, and user location will play a key role in optimizing services for wireless customers. While such services will drive the need for better localization techniques, applications that use locations for optimal performance will require efficient location management algorithms, where user locations are kept track with minimal system overhead. We consider routing in large ad hoc networks having node membership in the order of thousands, spread over a large geographic area. Geographic routing [1],[2] has been suggested for such networks which make use of the approximate location of nodes routing data packets, where nodes are aware of their location via the use of a GPS receiver or other localization techniques [3], [4]. However, the source requires the destination node's location before it can carry out geographic routing.

Thus, location management forms an essential entity in protocols that use geographic routing, in which nodes periodically update select nodes that take on the role of a *location server* of their current location. Location servers can then be queried by source nodes in an on demand fashion for locating destination nodes. Location management usually consists of three phases: location registration (choosing location servers and updating them with location information periodically), location main-

tenance (periodic cleansing of location database for database consistency) and location discovery (querying location servers to obtain a destination's location), and the cost of location management algorithms basically depend upon the cost of the above three primitives.

Many location management protocols have been proposed in literature. Examples of these include the Grid Location Service (GLS)[5], Scalable Location Update based Routing Protocol (SLURP) [6], Scalable Location Management (SLALoM) [7], Uniform Quorum Systems [8], and Hierarchical Grid Location Management (HGRID)[9]. Except [8], all other protocols are grid based protocols, in the sense that, they divide the terrain into well numbered grids, and nodes carry out the location management primitives based on the particular grid ordering of the location management scheme. While geographic routing itself is considered scalable [10], to our knowledge, no previous study has been carried out to study the effect of location management protocols on the scalability of geographic routing in mobile ad hoc networks. Our motivation is thus two pronged – to quantitatively compare location management protocols with respect to network size, and to study how location management can affect the scalability of geographic routing. We use the notion of scalability of a protocol from [11], where a protocol is deemed to be scalable with respect a parameter if and only if an increase in that parameter does not increase the total overhead induced by the protocol faster than the network's minimum traffic load, to analyze the scalability of three location management protocols – SLURP, SLALoM and HGRID. We show that all the three protocols are asymptotically scalable with respect to increase in network size under this framework. While this is an asymptotic analysis, we carry out extensive simulations to compare the protocols, and to study the practical aspects of scalability of these protocols. In our simulations, we use a simple geographic routing scheme called *Most Forward with Fixed Radius* (MFR)[12] which uses a greedy approach to forward network packets.

The rest of this paper is organized as follows: Section II briefly describes the location management schemes under study. Section III describes the framework that we use to study the scalability of location management, and show that the protocols that we considered are indeed asymptotically scalable with network size. In Section IV, we describe our simulation environment and outline the parameters for each protocol. Section V describes our comments on the results

obtained via simulations and conclude this work in Section VI.

II. LOCATION MANAGEMENT PROTOCOLS

All the protocols that we describe in this section are grid based: in other words, given a rectangular region of area A , all protocols divide the topography into G logical unit regions (also known as *Order-1* regions) where each node is aware of the size of the topography as well as the size of an unit region. However, they differ from each other in how the logical division is used in location management.

A. Scalable Update Based Routing Protocol (SLURP)

In SLURP, each mobile selects exactly one unit region as its *home region* by using a mapping function f , which uniquely (and randomly) maps its address to the selected home region. The mapping function allows any node to discover another node's home region simply by knowing its address.

Location Management in SLURP: All mobile nodes which are present in the home region R_u of node u act as location servers for u and keep an entry for u in their location database. When u moves across two unit regions G_i and $G_{i'}$, it does the following:

- u updates its home region R_u of the movement by a location update.
- u also requests nodes in $G_{i'}$ about the location information it has to keep for nodes that had selected $G_{i'}$ as a home region.

A home region is updated by sending a location update packet to the region, and the first location server to obtain the packet would carry out a broadcast in the region to update all location servers in that region of the movement of u .

Discovering a node's location: A source node v that wishes to communicate with u can now use f to identify R_u , and sends a location query packet towards R_u to obtain the current location of u . The first location server to receive the query for u responds with the current location of u . As soon as v receives this response, data packets are routed to this approximate location using the geographic routing algorithm.

B. Scalable Location Management (SLALoM)

SLALoM combines K^2 Order-1 regions to form Order-2 regions. Each node selects a *home region* in each Order-2 region via f that maps roughly the same number of nodes to each Order-1 region in an Order-2 region. Hence, every node has $O(\frac{A}{K^2})$ home regions in A (note that since the original square cannot be perfectly tiled with Order-2 regions, it is possible that some nodes may not have home regions in the Order-2 regions adjacent to the boundary of A). Also, if a node u is present in an Order-1 region R_i , which lies in an Order-2 region Q_i , then all home regions of u that lie in or adjacent to Q_i are considered *near* home regions, while the rest are considered *far* home regions.

Location Management in SLALoM: When u moves across two Order-1 regions R_i and $R_{i'}$, it does the following:

- If R_i and $R_{i'}$ are in the same Order-2 region Q_i , u informs all its near home regions of the movement, by a partial location update.
- If R_i is in Q_i , and $R_{i'}$ is in a different Order-2 region $Q_{i'}$, u updates all home regions of the movement by a full location update.
- u also requests nodes in $R_{i'}$ about the location information it has to keep for nodes that had selected $R_{i'}$ as a home region.

A single home region update in SLALoM is similar to II-A. Multiple home regions are informed by location updates that traverse a multicast tree such that each update traverses a distance K between two home regions. The length of such a tree is then $O(\frac{A}{K})$. Thus it is relatively easy to understand that all home regions know that u is in $Q_{i'}$. In addition, all near home regions know that u is in $R_{i'}$.

Discovering a node's location: A node v wishing to communicate to another node u sends a query packet to the closest home region of u . If the home region is a near home region, a response is generated, by the location server that gets the query, with u 's exact location. If the home region is a far home region, v forwards its message to the closest near home region of u , and the location server that receives this message then forwards it to the exact location of u .

C. Hierarchical Grid Location Management (HGRID)

HGRID defines a hierarchy of K levels ($L_1 \dots L_k$) on the unit grid regions. Each L_{i+1} quadrant is composed of four L_i quadrants. At each level, the leader selection is as follows: for level i ($1 \leq i \leq k-1$), the top rightmost L_{i-1} leader is the i^{th} hierarchical leader of the bottom left L_i grid, top leftmost L_{i-1} leader the hierarchical leader of the bottom right L_i grid, bottom rightmost L_{i-1} leader the hierarchical leader of the top left L_i grid and the bottom leftmost L_{i-1} leader is the hierarchical leader of the top right L_i grid. The top of the hierarchy, (L_k), is defined by the four L_{k-1} grids. A node which is physically located in an i^{th} hierarchical grid is responsible for the duty of an i^{th} hierarchical location server.

Location Management in HGRID: When u moves across two Order-1 regions R_i and $R_{i'}$, the following take place:

- If the movement is within the region under the same L_1 leader, u sends a location update to L_1 . Otherwise, u additionally sends an update to its previous L_1 grid indicating its departure.
- At each level i , the update from u is processed by the location server that first receives the update, and broadcasts the message in the grid. Further, if the movement specified in the update requires the next hierarchical server to be notified, it forwards the packet to that grid.
- When an update reaches a L_{k-1} leader, the node receiving the packet first carries out a local broadcast protocol to make all the L_{k-1} leader databases consistent.

Discovering a node's location: To discover a node u 's location, v sends a query packet to u 's L_1 leader. If u and v are in the same L_i^{th} grid, the query has to be forwarded until it reaches an L_i^{th} server (in the worst case), before a

location reply can sent back. Since the location databases in the upper levels of the hierarchy carry the approximate location information of nodes, location replies from these servers return the address of the server who has more accurate information of u .

III. SCALABILITY ANALYSIS

In this section, we analyze the scalability of the above protocols with respect to increasing network size. We borrow the notion of scalability from [11], where the scalability of a protocol is defined as the ability of a protocol to support the continuous increase of its network parameters without degrading the the network performance. For clarity, we briefly describe the main contribution of [11]:

- The *minimum traffic load* of a network is the minimum amount of bandwidth required to forward packets over the shortest paths available, assuming all the nodes have a priori full topology information
- If $Tr(\lambda_1, \lambda_2, \dots)$ be the minimum traffic load experienced by a network under parameters λ_1, λ_2 etc., then the network scalability factor Ψ_{λ_i} with respect to parameter λ_i is defined to be

$$\Psi_{\lambda_i} = \lim_{\lambda_i \rightarrow \infty} \frac{\log Tr(\lambda_1, \lambda_2, \dots)}{\log \lambda_i}$$

- If $X_{ov}(\lambda_1, \lambda_2, \dots)$ be the total overhead due to protocol X under parameters λ_1, λ_2 etc., then the protocol scalability factor $\rho_{\lambda_i}^X$ of protocol X with respect to parameter λ_i is defined to be

$$\rho_{\lambda_i}^X = \lim_{\lambda_i \rightarrow \infty} \frac{\log X_{ov}(\lambda_1, \lambda_2, \dots)}{\log \lambda_i}$$

- A protocol X is said to be scalable with respect to parameter λ_i if and only if, as λ_i increases, the total overhead induced by such protocol does not increase faster than the network's minimum traffic load. i.e,

$$\rho_{\lambda_i}^X \leq \Psi_{\lambda_i}$$

Since the per node degree and the node density per unit area remains constant with network size for the class of networks that we consider, we can readily compute the minimum traffic load of the network. If there are N nodes in the network, and each node generates λ_t bits per second and the average path length increases as \sqrt{N} hops, then $Tr(\lambda_t, N) = \theta(\lambda_t N^{1.5})$. This expression assumes that there is an ideal location management protocol from which the source obtains the destination node's location, as well as a perfect geographic routing algorithm that routes the packets in the best possible manner, given the locations of intermediate nodes. Thus $\Psi_N = 1.5$.

For the protocols described in II, the overhead in location management consists of location updating (LU), maintenance (LM) and discovery(LD). Hence, ρ_N^X should be ≤ 1.5 for each overhead induced by each routing protocol in order to be deemed scalable for geographic routing.

A. Scalability of SLURP

On average, a node's home region is located at a distance of $O(\sqrt{N})$ from the current location of the node. Hence, it takes $O(\frac{\sqrt{N}}{z})$ transmissions for a location update to reach a node's home region, where z is the average distance traversed by a transmission, given a node density γ and transmission range r ($z \leq r$). If the rate at which a node crosses unit regions is $\frac{v}{d}$, where v is the average velocity with which nodes move, and d is the side of an unit region, then the total location update overhead in SLURP is $O(\frac{vN\sqrt{N}}{dz})$ packets/sec. For each new session, a location discovery packet is sent by the source to the destination's home region, and on average, the update traverses a distance of $O(\sqrt{N})$. Thus, the total overhead for location discovery is $O(\frac{\lambda_s N \sqrt{N}}{z})$ packets/sec, where λ_s is the rate at which new sessions arrive at each node from the transport layer. Since each node does a constant number of operations as part of maintenance on entering a new grid, the total location maintenance overhead is $O(\frac{vN}{d})$ packets/sec.

Combining the above, $\rho_N^{LU-SLURP} = 1.5$, $\rho_N^{LM-SLURP} = 1$ and $\rho_N^{LD-SLURP} = 1.5$.

B. Scalability of SLALoM

SLALoM maintains multiple home regions, and updates near home regions as long as the node movement is within the $Order - 2$ region in which it is located. Otherwise, it updates all its home regions via a multicast tree spanning $O(\frac{A}{K})$ transmissions. For an optimum value of $K = N^{\frac{1}{3}}$, the total location update overhead has been derived to be $O(\frac{vN^{\frac{4}{3}}}{dz})$ packets/sec, and the total location discovery cost to be $O(\frac{\lambda_s N^{\frac{4}{3}}}{z})$ in [7]. The total location maintenance overhead is $O(\frac{vN}{d})$ packets/sec, since the maintenance operation is same as that of II-A.

Thus, $\rho_N^{LU-SLALoM} = 1.33$, $\rho_N^{LM-SLALoM} = 1$ and $\rho_N^{LD-SLALoM} = 1.33$.

C. Scalability of HGRID

In HGRID, the server regions are clustered in such a way that localized mobility causes location updates from nodes to terminate in lower order servers. Thus, the distance traversed by a location update is proportional to the level of the hierarchical boundary crossing, and the total location update overhead has been derived to be $O(\frac{vN \log N}{dz})$ packets/sec in [9]. For location discovery, if the source-destination pair is located within the same i^{th} hierarchical grid, then the location query packet terminates at the i^{th} hierarchical server in the worst case. Thus, a location query traverses $O(\sqrt{N})$ in the worst case, and hence the total location discovery overhead is $O(\frac{\lambda_s N \sqrt{N}}{z})$ packets/sec. However, this is a loose bound, and may be improved upon. Location maintenance is similar to SLURP and SLALoM.

Thus, $\rho_N^{LU-HGRID} = 1$, $\rho_N^{LM-HGRID} = 1$ and $\rho_N^{LD-HGRID} = 1.5$.

IV. SIMULATION ENVIRONMENT

We implemented all the three protocols in Glomosim [13] as separate location management layers that operate in conjunction with IP. Data from transport is queued in a separate buffer if the location of the destination is unknown, and a location query is sent to the destination's location server. Packet lifetime in the buffer is 4 seconds, and is subsequently dropped if a location query sent out for the packet's destination fails to return the location of the destination within this lifetime. A periodic broadcast protocol enables each node to realize its local connectivity, and records it in a neighbor table to assist in geographic routing. MFR [12] was implemented as the geographic routing algorithm. Specific parameters for our simulations are listed in table I.

TABLE I
SIMULATION PARAMETERS

Simulation Time	300 sec
Simulation Area	1000x1000m - 6000x6000m
Unit Grid Size	250m
Number of Nodes	80 - 2880
Node Density	80 nodes/ km^2
Transmission Range	350m
Transmission Speed	54 Mbps
MAC Protocol	IEEE 802.11(g)
Mobility Model	Random Waypoint
Maximum Speed	10 m/sec
Minimum Speed	0 m/sec
Pause Time	0 sec
CBR connections	1000
Data Payload	512 bits
Traffic Pattern	Random
Buffer Size	1000 packets

Since the performance of SLALoM is dependant on the selection of K , we decided to vary K from 2 to 6, such that the total number of home regions per node remained the same for all scenarios. HGRID defines up to 5 hierarchical levels for the scenarios considered. The different packet types and location management overhead in bytes for all protocols are given in table II.

TABLE II
PACKET TYPES AND OVERHEAD

Packet Type	SLURP	SLALoM	HGRID
Update	33	35	34
Query	37	37	37
Response	53	53	53
Notification	33	33	33
Maintenance	33+20n	33+20n	33+20n

In order to test the network under stable conditions, we let the nodes move around for the first 150 seconds of the simulation, so that location server and database set up is initialized appropriately and the control traffic is stabilized. To test the efficiency of the protocols for location discovery as well as efficient delivery of data, we initialized 1000 CBR connections, where the source and destination nodes are chosen randomly for all the scenarios. Each connection sends

one data packet, randomly starts after 150 seconds into the simulation and terminates randomly at 250 seconds into the simulation.

V. SIMULATION RESULTS

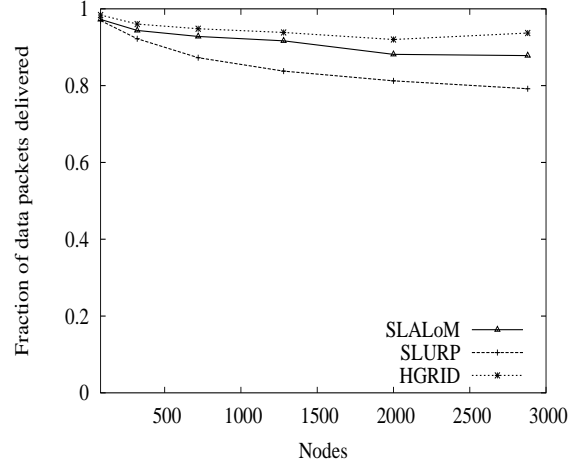


Fig. 1. Data Throughput

Figure 1 shows the fraction of data packets successfully delivered by each protocol. HGRID is able to deliver packets in more than 90% of the cases for all scenarios, and hence performs best. SLURP performs worst, with significant performance degradation for network sizes of 1500 nodes and more. The under performance of SLURP can be attributed to the higher percentage of queries that fail to return the location of the destination and higher delay of location responses. Recall that each data packet is held for only 4 seconds in the buffer, and if a query-response fails to terminate within this period, the packet is dropped. Hence, the delayed responses in SLURP are useless since the packets awaiting the destination's location would already have been discarded at the source.

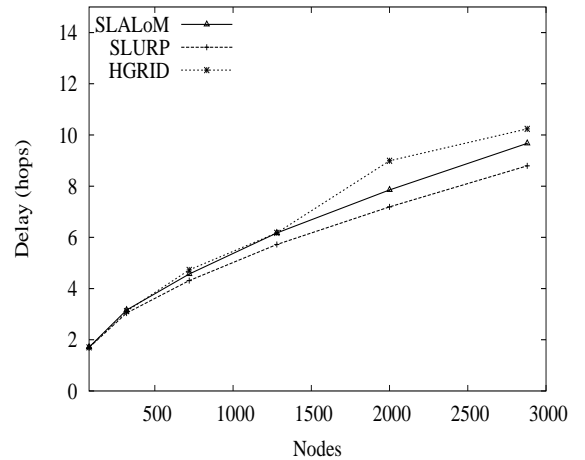


Fig. 2. Data Delay

Figure 2 shows the delay experienced by the successfully delivered data packets in number of hops (transmissions).

Since the location responses convey the exact location of the destination in SLURP, packets take the shortest path in SLURP. HGRID and SLALoM take longer paths, since on average, packets are routed to near home regions in SLALoM or hierarchical location servers having more accurate knowledge of the destination in HGRID, before being handed over to the destinations finally. However, the average delay experienced by data packets follows a different trend as shown by figure 3. Even though packets take the longest paths in HGRID, they have the lowest average delay, since the network is least congested. Since higher control overhead adversely affects data on the shared channel, a lower data delay in SLURP indicates that the network is less congested in SLURP than SLALoM, and is easily verified by figure 6.

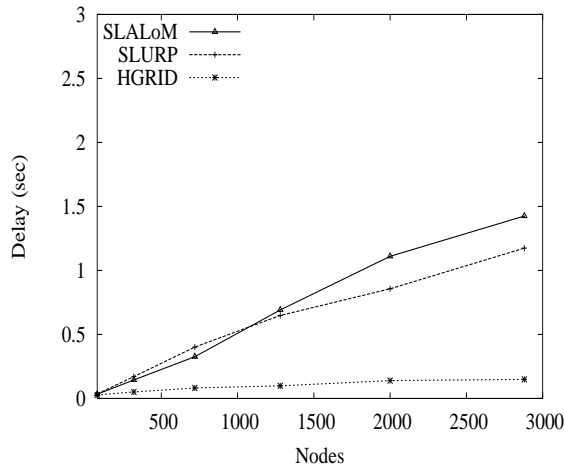


Fig. 3. Data Delay

Figures 4 and 5 show the query success probability and the average delay for location discovery for the three protocols. All protocols perform well, with more than 90% of the queries returning the location of the queried destination. Packets can be dropped due to two reasons in our simulations – *geographical holes* [2] and IEEE802.11 induced congestion. Since the home region of an arbitrary node is located furthest from an enquirer in SLURP (since home regions are chosen randomly, there is no guarantee that the region is actually close to the enquirer) compared to the other protocols, the location discovery takes longest to complete in SLURP. Also, since the home region is located further, this increases the dropping probability of a query or response packet, and thus decreases the query success probability. SLALoM has the closest home region for any node for the scenarios considered, and has the lowest delay for location discovery. However, high network congestion due to the higher control overhead causes additional packet drops in SLALoM, and thus has lower query success probability than HGRID.

Figure 6 shows the average control overhead for all the protocols. With the number of CBR sessions being low, most of the signalling overhead is due to update traffic. As indicated by the analysis, HGRID has the least control overhead, since the update overhead increases only logarithmically with the

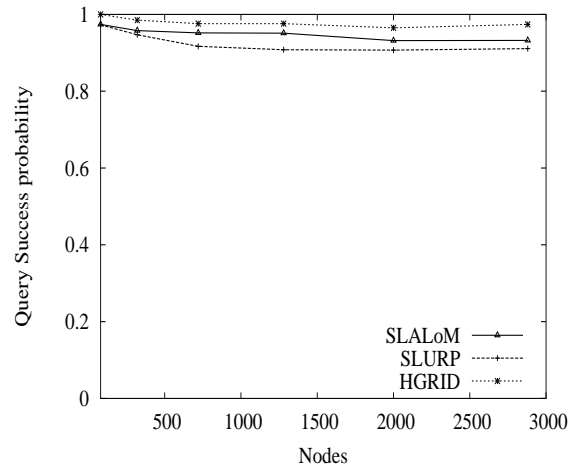


Fig. 4. Query Success Probability

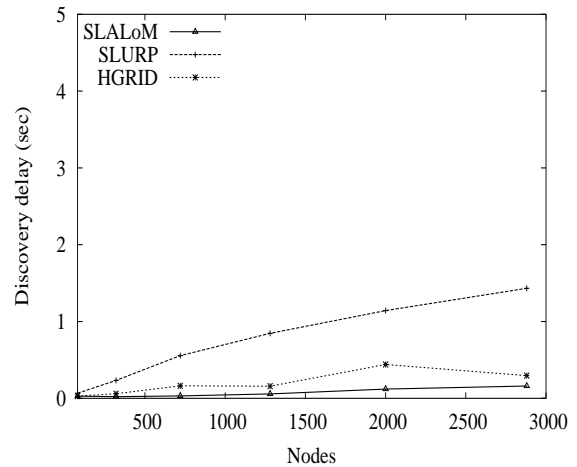


Fig. 5. Discovery Delay

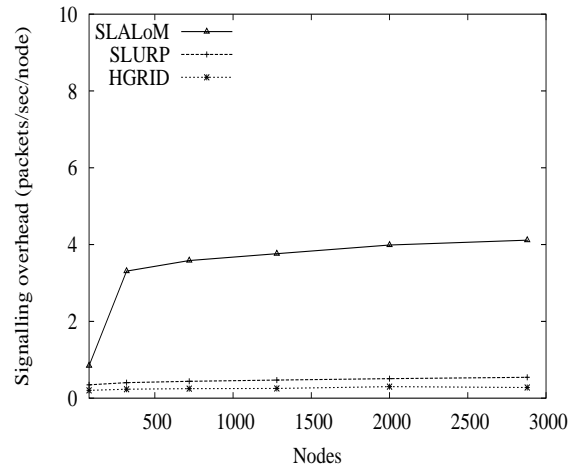


Fig. 6. Control overhead

number of nodes. For practical scenarios such as the ones considered in our simulations, SLURP performs better than SLALoM with respect to control overhead. Also, SLURP per-

forms best when one considers the overhead in bytes instead of number of packets. With the packet overhead being nearly equal for all the protocols, the higher overhead for HGRID and SLALoM can be explained by the overhead incurred in location maintenance. The average number of location entries that have to be transmitted is more for SLALoM and HGRID (see figure 8), resulting in additional bytes being transmitted in these two protocols. Finally, figure 8 shows the increase in

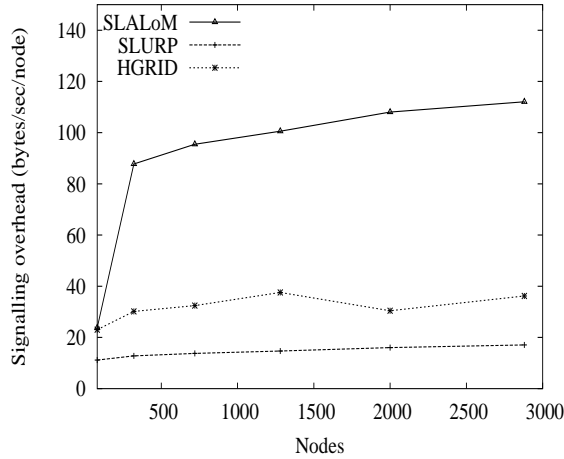


Fig. 7. Control overhead

location database size of each protocol with increase in number of nodes. SLURP has minimal memory requirements, since each node can choose any unit region randomly from the available set of Order-1 region as its home region. In SLALoM, the set of available Order-1 region is restricted to only K^2 . While lower order servers have a few location entries, the higher order servers have to retain location information about almost all nodes in HGRID. However, the average of these grows only slightly with the increase in network size. Thus, all protocols are scalable, with the database size being nearly constant or increasing marginally with network size.

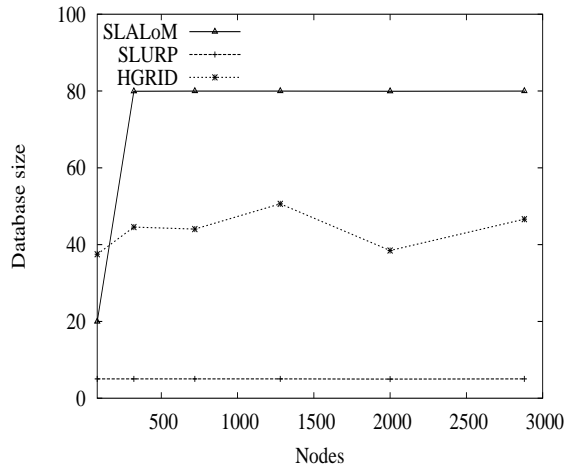


Fig. 8. Database size

VI. CONCLUSION

As wireless devices become more capable, location will play a key role in the services offered to customers. While this necessitates inexpensive solutions for efficient location tracking, managing these locations with minimal overhead in systems that use location for optimizing services will become equally important. While many efficient location management schemes have been proposed in literature, there has not been a comprehensive study to quantitatively compare these solutions. We use the framework from [11] to analyze the scalability of three grid based protocols, and show that all the protocols are asymptotically scalable with respect to network size. We also implemented the protocols in Glomosim, and carried out extensive simulations to study the performance of these protocols for practical scenarios that could not be incorporated into the theoretical framework. Our results indicate that all protocols perform well, and only affect the performance of geographic routing minimally. In particular, the Hierarchical Grid Location Management protocol (HGRID) performs the best for all practical purposes. While the network size has to be asymptotically large for SLALoM to perform better than SLURP, this may not be realizable in practise for most applications envisaged for mobile ad hoc networks. We also note that key considerations for designing an efficient location management protocol are low control overhead, close servers in proximity and quick location discovery.

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