Location Management for Hierarchically Organized Mobile Ad hoc Networks

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***Abstract*—A geography-based grid location service (GLS), proposed elsewhere, has resulted in a scalable location management service for mobile ad hoc networks (MANETs) where packet forwarding decisions are based on geographic position. A similarly scalable location management strategy has been devised for MANETs that employ hierarchical link state routing. Both approaches employ hierarchical principles to facilitate scalability. However, currently proposed approaches for hierarchical link state routing rely on a designated subset of nodes for location management. Such nodes represent potential sites of hot spot contention.**

In this paper, it is proposed that by applying the distributed database selection technique of GLS, a hierarchical location management scheme may be realized for MANETs based on link state routing that equitably distributes location server functionality among network nodes. Second, it is shown that location registration overhead per node for hierarchical location management is only *logarithmic* in the node count.

I. INTRODUCTION

A mobile ad hoc network (MANET) is a best effort, multiple hop datagram-forwarding network consisting of mobile nodes interconnected by wireless links. Due to the dynamic network topology and typically scarce wireless link capacity, routing in MANETs is arguably more difficult than in networks with a wired infrastructure such as the Internet.

It is assumed here that the physical topology of the MANET is flat. However, there are numerous means by which addressing or location hierarchy can be applied to a network. These approaches hide topology detail through address or location aggregation, at the network layer. Such aggregation is referred to here as *network layer hierarchy* (NLH).

Among the protocols that incorporate NLH include the grid location service (GLS) of [1] for geography-based routing, the two-level virtual subnet structure of [5], the landmark-based routing protocol of [7] and the multiple level clustered hierarchies of [8], [9] and [13]. In each of these protocols, NLH reduces routing table size and/or control message overhead.

Despite the potential benefits of NLH, a number of challenges exist in MANET location management. First, the mobility aspect of MANETs means that nodes may frequently change their address/location in lower levels of the NLH. Second, the structure of the NLH may itself be dynamic. Third, because of the homogeneity of flat physical topologies, it may not be possible for a small subset of nodes to perform a large share of location management functionality. The focus here is on fair distribution of management functionality and assessing communication overhead due to location registration events that occur as a result of individual node mobility.

The remainder of this paper is organized as follows. In Section II the network framework under consideration is described. In Section III, existing location management schemes are considered. Section IV proposes an adaptation of the distributed database principle of GLS to hierarchical link state routing protocols, known here as *virtual hierarchy location management* (VHLM). Section V provides an analytical assessment of *location registration* overhead due to hierarchical location management. Section VI concludes this paper.

II. NETWORK FRAMEWORK

The underlying physical topology of a MANET is represented here by an undirected graph, $G = (V,E)$, where V is the set of nodes and E is the set of bi-directional links. It is assumed that, at any time, nodes are situated throughout a fixed size area proportional to $|V|$ in accordance with a two-dimensional uniform random variable distribution. For the purpose of analyzing the frequency of location update events, the random waypoint model for node mobility, employed in [10], with zero pause time is assumed here.

Each node is equipped with a single network interface card (NIC) having a transmission radius of R_{TX} m. If the distance separating a pair of nodes is less than R_{TX}, then a bi-directional link exists between them and they are considered to be neighbors of one another. Otherwise, the nodes are not connected. Each NIC employs carrier sense multiple access with collision avoidance so that each node operates in a shared *broadcast* media with its neighbors.

The scalability of a routing protocol may be assessed in terms of a number of distinct criteria. Among these include scalability with respect to increasing node count ($|V|$), increasing average node density and increasing average node speed. In order to isolate the performance of a location management strategy with respect to increasing $|V|$, it is assumed that average node density and average node speed are held constant.

Lastly, it is shown in [3] that the average hop count (h) on the shortest path between an arbitrary pair of nodes in a two-

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dimensional network is $\Theta\left(\sqrt{|V|}\right)$. As noted in [14], to maintain connectivity in random graphs, R_{TX} must be $\Theta\left(\sqrt{\log|V|}\right)$. Thus, for random graphs h is actually $\Theta\left(\sqrt{|V|/\log|V|}\right)$. However, the $\log|V|$ term that appears in the expression for h will be ignored here for the sake of simplicity and compactness of notation and the $\Theta\left(\sqrt{|V|}\right)$ result given in [3] is employed, instead.

III. EXISTING METHODS

A. *Grid Location Service (GLS)*

The GLS, proposed in [1], represents an efficient means by which a distributed database of geographic positioning information can be created, maintained and queried. As shown in Fig. 1, GLS relies on a grid-based geographic hierarchy overlaying the network area. In this figure, a large square area divided recursively into smaller square areas. The smallest square areas, l-by-l squares, are referred to as level-1 squares. The largest square consisting of the entire network area is a level-(L+1) square and is $l\times2^L$-by-$l\times2^L$. The bold squares show the hierarchical grid areas to which a particular node v belongs for each level of the grid hierarchy.

To understand GLS, an arbitrary node v is considered. The salient features of the distributed database maintaining the geographic coordinates of v are as follows:

i. The set of nodes functioning as location servers for v are based on the relation of their node ID to v and their location in the grid hierarchy

ii. The density of database servers for v in regions near v is high and low in the regions far from v

iii. The frequency at which v updates its location to nearby database servers is high while servers situated far from v receive updates at a low frequency

Feature (i) ensures that for each grid zone a node can be selected unambiguously to function as the location server for v. The ID-based rule for selecting the server set consists of selecting the zone node $z \in Z$ whose ID minimizes the following for all nodes belonging to a level-k grid zone:

$$\mathrm{mod}_{v+|V|}\left(z+|V|\right) \tag{1}$$

The ID-based selection of the distributed location database serves two objectives. First, it provides a means for unambiguously selecting a server set and to subsequently unambiguously direct *queries* properly to the server set. Second, it tends to distribute the load of server functionality evenly throughout V as it will be typically rare that any node will satisfy (1) for a disproportionately large number of nodes. Proof that the location registration and location query procedures are performed correctly in GLS is given in [1].

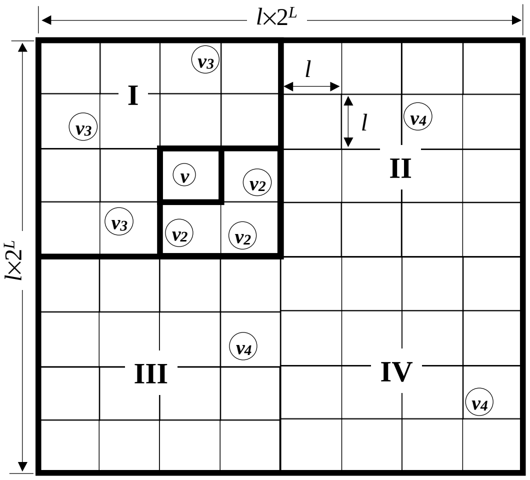

Fig. 1: Example grid-based hierarchy

The combination of features (ii) and (iii) provides favorable scalability to GLS. Intuitively, these features embody the purpose of network-layer hierarchy by effectively summarizing location detail about v in regions of the network that are far from v.

Considering further feature (iii), the GLS incorporates a form of *distance scoping* to reduce the frequency of location updates for location servers far from v. That is, to update servers in its level-2 square (v_2), v waits until it has migrated a distance d before updating the servers. Before updating level-3 servers, it v must migrate $2\times d$ from the position of its previous update. In general, v moves $2^{k-2}\times d$ before updating its level-k servers. This distance scoping measure has a beneficial effect by reducing location registration overhead.

B. *Other Methods*

A number of location management strategies have been proposed for MANETs. Among these include procedures described in [2], [4], [5] and [6].

For the sake of brevity, the approaches of [2], [4] and [5] can be summarized as scaling poorly in comparison to GLS. The reason for this is that they do not exploit hierarchy at the network layer to reduce the frequency of location registration to distant (i.e., $\Theta\left(\sqrt{|V|}\right)$ hops away) location servers. That is, *all events* triggering a location update (be it due to periodic update, or a change in cluster membership or physical subnet membership) result in updating the location management server(s).

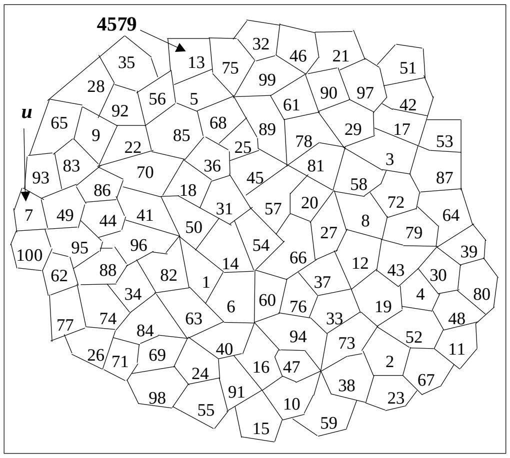

Fig. 2: Non-overlapping zones (level-1 of hierarchy)

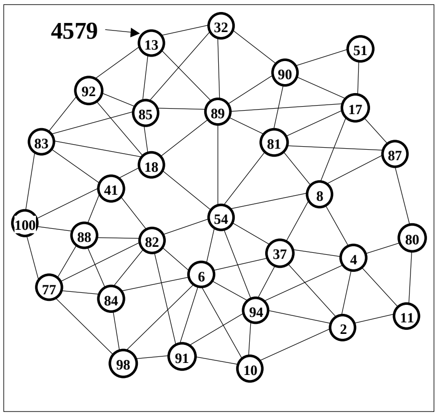

Fig. 3: Level-2 of hierarchy

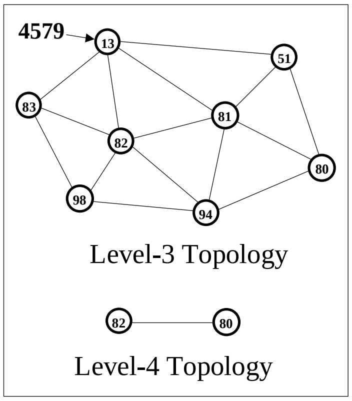

Fig. 4: Level-3 and level-4 of hierarchy (level-5 is node/area 80)

Unlike the approaches of [2], [4] and [5], the hierarchical location management protocol of [6] does exploit NLH to reduce location registration overhead. However, the method of [6] relies on a subset of elected switches to function as location managers (LMs). Further, a switch elected as a LM at a high level in the NLH must serve as the LM for a large number of nodes. In GLS, on the other hand, each node typically functions as a location server for only $\Theta(\log|V|)$ nodes. Hence, there remains a need for a link state location management strategy that is efficient *and* distributes the burden of location management equitably among all nodes.

IV. VIRTUAL HIERARCHY LOCATION MANAGEMENT

The technique of [1] to unambiguously select location servers is applied for VHLM. Considering Fig. 2, it is assumed that like the grid configuration of GLS, the network area of a link state routing environment may also be partitioned into *non-overlapping routing zones*. This can be achieved straightforwardly by pre-selecting a set of known landmark nodes about which the remaining nodes cluster by affiliating themselves with the nearest (in terms of hop count) landmark.

The underlying graph topology $G_Z = (V_Z, E_Z)$, implicit in Fig. 2, consists of each zone corresponding to a node with a link connecting it to each of its neighbor zones. It is assumed that some form of intra-area routing protocol is employed so that packets can be forwarded correctly within each zone. Lastly, G_Z must be communicated to all of V.

The routing zones serve two purposes. First, by organizing into routing zones, the detail of the network topology is summarized. Second, G_Z forms the foundation for hierarchical clustering. However, rather than forming hierarchical clusters for the purpose of hierarchical addressing or for packet forwarding, virtual hierarchies are computed, with respect to each node, for the purpose of *location server selection*. That is, once G_Z is known, location servers for any node can be unambiguously updated or queried.

The virtual hierarchy for a node v is computed via recursive application of a variation of the ID-based distributed clustering algorithm (DCA) described in [16]. As an example of hierarchical clustering for location server selection, node 4579, shown in routing zone 13 of Fig. 2, is considered. To establish clustering priority it is assumed that node $v = 4579$ is mapped to a modulo-$|V_Z|$ arithmetic value v' = 79 as follows:

$$v' = \mathrm{mod}_{|V_Z|}(v) \qquad (2)$$

The prioritization rule for clusterhead selection in VHLM is similar to that of GLS. That is, the routing zone that has the highest priority is the one with the smallest ID that is larger than v'. In this case ($v' = 79$), the zone with highest clusterhead priority would be 80, followed by 81, etc..

Applying the DCA to the underlying G_Z of Fig. 2, a set of clusterheads is computed that serve as the nodes in the next level of the virtual hierarchy (level-2), as shown in Fig. 3. Applying the DCA recursively to the topology of Fig. 3 yields level-3 and level-4 topologies as shown in Fig. 4. The level-5 (top level) topology consists of a single area: 80.

Upon completion of the clustering procedure v knows precisely to which routing areas it must send location registration updates and when. For example, when leaving a routing zone (level-1) v updates its level-2 server area. In this case, routing zone 13. When leaving a level-2 area, v updates its level-3 server area (again, 13). When leaving a level-3 area, v updates zone 82, its level-4 server area. Similarly, any peer node u that wishes to initiate a communication session with v computes the virtual hierarchy for v. For example, if u were located in routing zone 7, it would first send a query to zone 100 (level-2). The query would then be forwarded to 83 (level-3). When the query is forwarded to 82, the level-4 server for v, there will be a node in that area with knowledge that the level-3 server for v is situated in zone 13. The query is forwarded to a node (probably, *v* itself) in 13, which also happens to function as the level-2 server for *v*. This node returns a reply to *u* with the information that *v* is situated in zone 13. Had the level-4 query failed, it would have been forwarded to zone 80 (level-5 and top level) where level-4 location data for 4579 is maintained.

The meaning of "updating a server area" has intentionally been left vague. However, one possible implementation is for intra-area routing to forward location registration packets to the routing area node that minimizes (1).

The presentation here of VHLM with a two-level NLH consisting of non-overlapping routing zones is done primarily for convenience. Adaptation of VHLM to routing protocols with multiple level NLHs such as HSR of [9,11] is possible, as well. Although extending VHLM from a 2-level NLH to a *k*-level NLH ($k \le L = \Theta(\log|V|)$) is fairly straightforward, a detailed discussion of the extension is omitted here. Essentially, the only difference from the two-level case is that VHLM uses a variation of some hashing function to equitably distribute location data among the *k* levels of NLH and the *L*–*k* levels of virtual hierarchy. Otherwise, it is very similar to the procedure presented here, already.

V. REGISTRATION OVERHEAD ASSESSMENT

The communication overhead due to location registration for hierarchical location management is now assessed. First, it is noted that in the GLS of [1] there are three location servers for each level of the grid hierarchy and 1 for each level of the hierarchy in VHLM. However, whether the number of location management servers at each level is 3 or 1 or some other small constant does not impact a scalability assessment, as long as this number is Θ(1). Thus, this scaling constant is ignored in the ensuing analysis.

Considering level-0 servers, these are just the individual nodes themselves and, obviously, no update or registration is required. Considering level-1 servers, these are the nodes belonging to the same level-1 area as a node *v*. However, it is assumed that some form of proactive routing allows each node to know the identity of its level-1 area peers. Thus, no level-1 server update is required. Considering now level-2 servers, these servers require updates whenever a node changes level-1 areas. Since proactive routing exists only within level-1 areas, a node must send a location update message to its level-2 servers whenever it changes level-1 areas. Letting $f_k \equiv$ average frequency at which nodes change their level-*k* zone, $h_k \equiv$ average distance (in hops) between nodes of a level-*k* zone, the registration overhead incurred by nodes migrating from their level-*k* zones (Ψ_k) is as follows:

$$\Psi_k = |V| \cdot f_k \cdot h_{k+1}, \qquad k \in \{1,2,...,L\} \tag{3}$$

Again level-(L+1) is simply the entire network and, therefore, $h_{L+1} = \Theta\left(\sqrt{|V|}\right)$. Also, as a reminder, the level-(k+1) hop distance (h_{k+1}) appearing in (3) is due to the fact that when a node migrates to a new level-*k* zone, it must notify its level-(k+1) location management server. The baseline average hop cost (when k = 1), therefore, corresponds to $h_2 = \Theta(1)$, the average hop distance between nodes in a level-2 cluster. Summing over all $k \in \{1,2,\ldots,L\}$ yields the *aggregate* registration overhead (Ψ):

$$\Psi = \sum_{k=1}^{L} \Psi_k = |V| \cdot \sum_{k=1}^{L} f_k \cdot h_{k+1} \tag{4}$$

Now, $|Z_k|$ is defined as the average size, in terms of level-0 node count, of a level-*k* zone. Using the results of [3] for average path length, this means that $h_k = \Theta\left(\sqrt{Z_k}\right)$. Further, A_k is defined as the average geographic area of a level-*k* zone. Since the average node density is assumed constant, $A_k = \Theta(|Z_k|)$. Noting that the larger the geographical area, the longer the Euclidean distance required for a node with average speed $\mu = \Theta(1)$ to leave a particular area, it is evident that:

$$f_k = \Theta\left(\mu / \sqrt{A_k}\right) = \Theta\left(\frac{1}{\sqrt{A_k}}\right) = \Theta\left(\frac{1}{\sqrt{|Z_k|}}\right) \tag{5}$$

Lastly, α_k is defined as the average arity of a level-*k* zone, $k \in \{1,2,\ldots,L+1\}$. That is, the number of level-(k–1) zones comprising a level-*k* zone. Using α_{k+1} allows h_{k+1} to be expressed in terms of $|Z_k|$:

$$h_{k+1} = \Theta\left(\sqrt{\alpha_{k+1} \cdot |Z_k|}\right) \tag{6}$$

By recursively employing a clustering procedure such as those of [12], [15] and [16] to form an *L*-level hierarchy, the average arity of level-2 zones and higher is Θ(1). Combining this fact with (5) and (6), (4) can be modified as follows:

$$\Psi = |V| \cdot \sum_{k=1}^{L} \Theta\left(\frac{1}{\sqrt{Z_k}}\right) \cdot \Theta\left(\sqrt{\alpha_{k+1} \cdot |Z_k|}\right) \tag{7a}$$

$$\rightarrow \Psi = |V| \cdot \sum_{k=1}^{L} \Theta\left(\frac{1}{\sqrt{Z_k}}\right) \cdot \Theta\left(\sqrt{|Z_k|}\right) \tag{7b}$$

$$\rightarrow \Psi = |V| \cdot \sum_{k=1}^{L} \Theta(1) = |V| \cdot L = \Theta(|V| \cdot \log|V|) \tag{7c}$$

Dividing (7c) by |*V*| yields registration overhead of $\psi = \Theta\left(\log|V|\right)$ packet transmissions *per node* per second.

VI. CONTRIBUTIONS AND CONCLUSIONS

In this paper, location management in MANETs has been considered. Of the current approaches, GLS of [1] and the hierarchical location management of [6] are the most scalable. However, unlike GLS, the method of [6] results in a subset of switches performing a large share of the location management functionality. An important contribution of this paper has been to show that location registration overhead due to hierarchical location management is $\Theta\left(\log|V|\right)$ packet transmissions per node per second.

To achieve location management that is competitive with that available for geography-based routing, virtual hierarchical location management (VHLM) is proposed here. It borrows the concept of ID-based server selection that is employed by GLS. VHLM then exploits *link state* hierarchy (as opposed to geographical hierarchy in GLS) to minimize the frequency of routing zone registration updates to its more distant location servers. The net result is that VHLM also achieves $\Theta\left(\log|V|\right)$ location registration overhead and it also distributes the burden of location management service equitably among network nodes. Further, the concept of VHLM may be adapted to routing protocols based on multiple level NLH such as HSR.

Of course, location registration is not the only source of overhead incurred by location management. There are also handoff and location query overheads. Further, additional overhead occurs for hierarchical link state routing when the clustered hierarchy reorganizes. However, this effect can be eliminated by forming stable, non-overlapping routing zones about a set of fixed-position beacon nodes.

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