Capacity Compatible 2-Level Link State Routing for Ad Hoc Networks with Mobile Clusterheads

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***Abstract*—The throughput of a mobile ad hoc network (MANET) is determined by the transceiver link capacity available at each node and the type of traffic pattern that is prevalent in the network. In order for a routing protocol to be scalable, its control overhead must not exceed transceiver link capacity. To achieve capacity compatible routing, hierarchical techniques may be employed. This paper describes how link state routing, with a single layer of hierarchy, provides sufficient scalability for MANETs where the traffic pattern consists of unicast communication between arbitrary pairs of nodes.**

I. PROBLEM FORMULATION

A mobile ad hoc network (MANET) is a best effort, multiple hop datagram-forwarding network consisting of mobile nodes interconnected by wireless links. Among the envisioned MANET scenarios is the battlefield, where there is little or no existing network infrastructure and adaptive communication between mobile nodes is required.

In this paper it is assumed that each network node is equipped with a single transceiver supporting a link capacity of C bits/second. Further, it is assumed that two nodes can communicate directly with one another if they are situated within R_{TX} meters of one another. Otherwise, one or more intermediate nodes must function as datagram forwarders to support communications. Within R_{TX} of any node, the communication channel is shared with its neighbors and channel access is governed by CSMA/CA.

The following notation and assumptions apply herein:

- $V \equiv$ Set of network nodes
- $E \equiv$ Set of bi-directional communication links
- $G \equiv (V,E)$, i.e., the graph representation of the network
- $N \equiv$ Number of network nodes = $|V|$
- $C \equiv$ Capacity of the transceiver at each node
- $R_{\text{TX}} \equiv$ Transmission range of each transceiver
- $\delta \equiv$ Average number of nodes per unit area
- $d \equiv$ Average number of neighbors per node
- $\mu \equiv$ Average node speed
- $\Gamma \equiv$ Aggregate network throughput
- $\gamma \equiv$ Average throughput available per node
- $h \equiv$ Average hop distance between a pair of communicating nodes
- $\Psi \equiv$ Aggregate (network-wide) number of control packet transmissions per second
- $\psi \equiv$ Average number of control packet transmissions per node per second

Assumptions:

a) $R_{\text{TX}} = \Theta(1)$
b) $\mu = \Theta(1)$
c) $d = \Theta(1)$
d) $\delta = \Theta(1) \Rightarrow$ Network area $A \propto N$
e) G is connected

The throughput of a network given the above characteristics is now considered. As described in [6], the feature of *spatial reuse* enables successful simultaneous packet transmission by multiple network nodes, provided the transmitter and receiver pairs are adequately spaced.

For example, supposing that communication sessions exist only between one-hop neighbors then the feature of spatial reuse facilitates $\Gamma = \Theta(N)$ and $\gamma = \Theta(1)$ when $C = \Theta(1)$. Such a traffic pattern is referred to here as ***T-1***. The feasibility of this claim can be verified by construction, for the above network conditions.

A more practical traffic pattern, and of particular interest here, is one where communication sessions are between pairs of nodes situated arbitrarily throughout the network. Such a traffic pattern is referred to here as ***T-2***. Given the above network characteristics, it has been shown in [7] that $\Gamma = \Theta(\sqrt{N})$ and $\gamma = \Theta(1/\sqrt{N})$. This is due to the fact that the benefit of spatial reuse is offset by increased average path length. That is, rather than have all communication sessions take place between one-hop neighbors, the sessions are between peer nodes via potentially multiple-hop communication paths whose average length increases with N. Specifically, it is shown in [7] that average hop count is proportional to the square root of the node count:

$$h = \Theta(\sqrt{N}) \tag{1}$$

Intuitively, since throughput is throttled by h, the result of $\gamma = \Theta(1/\sqrt{N})$ for ***T-2*** follows straightforwardly from $\gamma = \Theta(1)$ discussed earlier for the case of ***T-1*** where $h = 1$.

Clearly, in order to maintain $\gamma = \Theta(1)$ for the case of ***T-2***, $C = \Theta(\sqrt{N})$. Further, the per node overhead of the network routing protocol must not exceed C. That is, in order for a

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routing protocol to be *capacity compatible*, the following relationship between C and ψ must be met:

$$C = \Theta\left(\sqrt{N}\right) \Rightarrow \psi = \mathrm{O}\left(\sqrt{N}\right) \qquad (2)$$

For networks where traffic pattern ***T-2*** represents the dominant form of communications, it is crucial (from a capacity compatibility standpoint) to implement a routing protocol that satisfies (2). The proposal of such a protocol based on *link state routing* (LSR) is the purpose of this paper. The proposed protocol, here forward known as *two-level link state routing* (2-LLSR), achieves the scalability criterion of (2) by employing a layer of hierarchical organization.

As an aside, it is discussed in [2] that in order for random networks to be connected with increasing N, it is required that $\delta = \Theta(\log N)$. This implies that for ***T-2***, $h = \Theta\left(\sqrt{N/\log N}\right)$, $\Gamma = \Theta\left(\sqrt{N/\log N}\right)$ and $\gamma = \Theta\left(1/\sqrt{N \cdot \log N}\right)$. However, for this paper, the $\log N$ term is ignored to simplify notation.

II. Overview Of 2-LLSR

To achieve scalability, nodes running 2-LLSR organize themselves into $\Theta\left(N^{\beta}\right)$ clusters, $0 < \beta < 1$. The creation of clusters can be done in one of two ways:

i. Nodes affiliate themselves with one of $\Theta\left(N^{\beta}\right)$ uniformly spaced, *stationary* beacon nodes.

ii. Nodes affiliate themselves with one of $\Theta\left(N^{\beta}\right)$ designated clusterheads or *leader nodes* that are mobile, as per Fig. 1.

In this paper, the deployment of (*ii*) is discussed. Analysis of (*i*) is provided in [15].

Leader-based cluster affiliation (*ii*) consists of nodes affiliating themselves with the nearest leader node (in terms of hop count). A *Hello protocol* is assumed to be in operation for nodes to discover and maintain adjacencies and to help facilitate cluster affiliation. Each Hello packet contains a list of neighbors and also the hop count to the nearest leader node. When a node is equidistant from a pair of leader nodes, it randomly picks one with which to affiliate itself.

N_1 is defined as the number of leader nodes (and clusters) and corresponds to level-1 in the hierarchy (i.e., the cluster level). As shown in Fig. 1, $N_1 = 10 = \sqrt{100} = \sqrt{N}$. Level-0 is the node level of the hierarchy and thus $N_0 = N$. Level-2 corresponds to the network itself and $N_2 = 1$. Lastly, c_1 is defined as the average node count per cluster while c_0 is number of nodes per node (i.e., $c_0 = 1$) and c_2 is number of nodes in the network (i.e., $c_2 = N$):

$$c_k = N/N_k \text{ where } k \in \{0,1,2\} \Rightarrow c_1 = N/N_1 \qquad (3)$$

Selection of $N_1 = \sqrt{N}$ for Fig. 1 was done partly for illustrative purposes so that the concept of non-overlapping clusters might be clearly seen. Although such a configuration does satisfy the capacity constraint given by (2) for traffic pattern ***T-2***, it turns out that specifying $N_1 = \Theta\left(\sqrt{N}\right)$ is actually *sub-optimal* in terms of minimizing ψ. As will be shown in Section IV, the optimal selection of N_1 for 2-LLSR is $N_1 = \Theta\left(N^{3/5}\right)$. Nevertheless, setting $N_1 = \Theta\left(\sqrt{N}\right)$ does have practical scalability benefits and represents a convenient configuration for illustrative purposes. Therefore, it is assumed in this section and in Section III that $N_1 = \Theta\left(\sqrt{N}\right)$. Letting $N_1 = \Theta\left(\sqrt{N}\right)$ and applying (3) yields $c_1 = \Theta\left(\sqrt{N}\right)$.

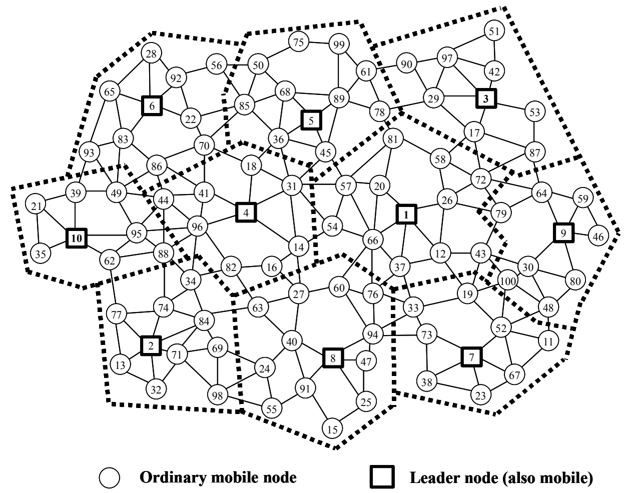

Figure 1. Clusterhead-based, or *leader*-based, cluster formation

Within each cluster, an intra-cluster LSR protocol is employed to facilitate intra-cluster packet forwarding. Thus, each node within a given cluster knows the least hop path to all other cluster members including those cluster members serving as *gateway nodes* to neighboring clusters. Packet forwarding between clusters is based on the cluster ID of the destination node. A topology map of the network clusters supports inter-cluster packet forwarding and updates to the map are flooded throughout the network. Packet forwarding to the cluster of the destination node follows the inter-cluster path with the fewest number of *inter-cluster hops*. Here, an inter-cluster hop refers to the crossing of a cluster boundary.

In order for a source node u to learn the cluster location of a peer node v, a location management (LM) strategy is required. To facilitate this, a strategy similar in concept to the home location registry (HLR) and visitor location registry (VLR) approach overviewed in [9] is employed. Each node registers its current cluster location with a *home cluster* known to all nodes. Letting $v \in V = \{1,2,\ldots,N\}$ be the node ID for an arbitrary node and $\{1,2,\ldots,N_1\}$ be the set of cluster IDs, all nodes in the network can unambiguously determine the home cluster of v, $c_{\mathrm{H}}(v)$, via the following hashing function:

$$c_{\mathrm{H}}(v) = 1 + \mathrm{mod}_{N_1}(v-1) \qquad (4)$$

A location registration (LR) packet is sent by v to the leader node of $c_{\mathrm{H}}(v)$ whenever v changes cluster affiliation.

An example of communications in a 2-LLSR network is now given, based on Fig. 2, where $N = 100$ and $N_1 = 10$. First, a source node $u = 22$ must learn the cluster location of a destination node $v = 13$. If u and v are currently members of the same cluster, then this is obtained trivially by the intra-cluster LSR protocol. More likely, however, u will need to perform a location query (LQ), as shown in Fig. 2. First, $u = 22$ computes $c_{\mathrm{H}}(v) = 3$ from (4) for $v = 13$. A LQ packet is forwarded to cluster $c_{\mathrm{H}}(v) = 3$ and arrives at the leader node of cluster 3. There, an entry for the cluster currently *visited* by v (i.e., $c_{\mathrm{V}}(v) = 2$) is stored and this information is sent in a query reply message to u.

Upon receiving the query reply, u is able to address v with the concatenated hierarchical address of $c_{\mathrm{V}}(v).v = 2.13$. Hierarchical addressing may be implemented via a Subnet-Router anycast address as specified for IPv6 in [4]. Using this approach, the datagram is first addressed to cluster 2 via a Subnet-Router anycast address. The address for $v = 13$ is entered into a Routing header extension as specified in [1]. Upon reaching a member of $c_{\mathrm{V}}(v)$, node 34 in this case, the Subnet-Router anycast address originally written in the Destination Address field of the datagram header is swapped with the address for $v = 13$ that was originally written into the Routing header extension. Forwarding of the datagram to v is then based on the intra-cluster LSR protocol of cluster 2. The addressing procedure described here applies for all unicast communications, including LR and LQ messaging.

III. Operational Issues

A couple of operational issues merit further discussion. First, the reaction by 2-LLSR to the failure of a leader node is considered. When leader node failure is detected, cluster members initiate flooding of a leader failure message. Leader nodes then initiate cluster advertisements, which allow members of the failed cluster to join one of the neighboring clusters. As members of the failed cluster are assimilated, the cluster neighbor lists of affected clusters are propagated throughout the network as new inter-cluster links are formed. This ensures that all nodes have an updated cluster topology map of the network. Despite the additional complexity required to adapt to leader failures, such events do not impact the *scalability* of 2-LLSR provided the total number of leader failures that occur over the lifetime of the network is Θ(1).

Second, as an implementation option, the function of HLR may be distributed uniformly among all nodes. The concept of equitable LM functionality was originally proposed in [8] for the Grid Location Service and may be applied here, as well. That is, just as a hashing function (4) is used to determine which cluster serves as the HLR for v, another hashing function may be defined to unambiguously select from one of the members of $c_{\mathrm{H}}(v)$. Thus, HLR functionality is distributed equitably among all network nodes rather than being concentrated at leader nodes, i.e., each node serves as the HLR for Θ(1) other nodes. A benefit of implementing such an option is that leader nodes need not process all of the LM data. Of course, by sharing HLR functionality among all nodes increases the complexity of the LM strategy, as there is then *handoff* of LM data when nodes change cluster membership. However, as will be shown, the overhead of such an option conforms to the requirement of (2).

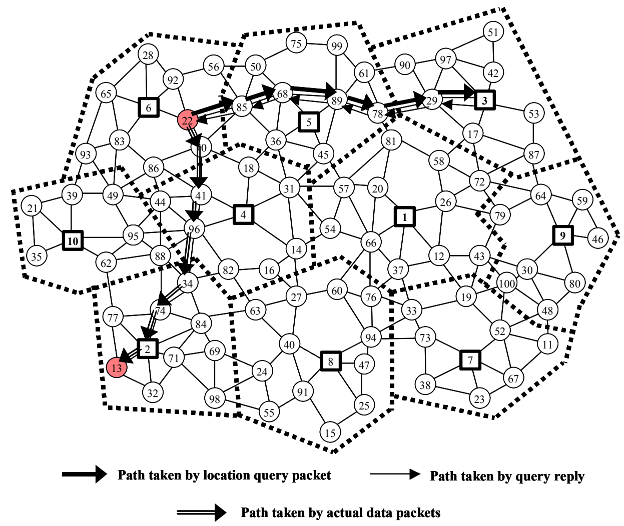

Figure 2. Location query example

IV. Overhead Assessment

Based on the earlier description of 2-LLSR, the following factors contribute to control overhead:

- *Hello* protocol (ψ_{HELLO})
- *Link state routing* (ψ_{LSR})
- *Acquisition* of intra-cluster topology data when a node migrates from one cluster to another (ψ_{ACQ})
- Location *registration* (ψ_{REG})
- *Handoff* of location management data (ψ_{HANDOFF})
- Location *query* (ψ_{QRY})

A. Hello Protocol

The Hello protocol is analyzed first. It consists of periodic messaging between neighboring nodes. By Assumptions (a) and (b), the frequency of Hello messaging (per neighbor pair) need only be Θ(1). Combining this with Assumption (c), therefore, Hello overhead $\psi_{\mathrm{HELLO}} = \Theta(1)$ per node.

B. Link State Routing

Link state routing (LSR) is applied within each cluster and for inter-cluster packet forwarding. Each node-level (i.e., level-0) link state change triggers the flooding of a level-0 link state packet (LSP) to all members of the affected cluster. LSPs are also disseminated for the cluster topology. That is, whenever a cluster neighbor link is created or deleted, a level-

1 LSP is flooded to all network nodes. The aggregate LSR overhead (Ψ_{LSR}), therefore, is due to the combined effects of level-0 (node level) and level-1 (cluster level) link state changes.

Level-k link state changes occur at a frequency of $f_{k,LS}$ per level-k link. $f_{k,LS}$ is a proportional to node mobility μ. Further, $f_{k,LS}$ is inversely proportional to the square root of the average neighborhood area for a node (A_0) when $k = 0$ or the average area for a cluster (A_1) when $k = 1$. This is because the Euclidean distance a node (or cluster) must migrate to create a link with a 2-hop neighbor or break a link with a 1-hop neighbor is proportional to the square root of its neighborhood (or cluster) area. The neighborhood area for a single node is proportional to R_{TX}^2 while the average cluster area depends on R_{TX}^2, c_1 and δ. Applying Assumption (a) for A_0, and applying Assumptions (a) and (d) for A_1 yields:

$$A_0 = \Theta\left(R_{TX}^2\right) = \Theta(1) = \Theta(c_0) \tag{5a}$$

$$A_1 = \Theta\left(\frac{c_1 \cdot R_{TX}^2}{\delta}\right) = \Theta(c_1) \tag{5b}$$

Applying (5) and Assumption (b), $f_{k,LS}$ is expressed as follows:

$$f_{k,LS} = \Theta\left(\mu/\sqrt{A_k}\right) = \Theta\left(1/\sqrt{c_k}\right) \tag{6}$$

Considering now Ψ_{LSR}, $d_0 \equiv d$ and d_1 is defined as the number of level-1 links per cluster ($d_1 = \Theta(1)$ by Assumption (d)). Thus, there are N_1 clusters each consisting of $\Theta(d_0 \cdot N_0/N_1)$ level-0 links and the network consisting of $\Theta(d_1 \cdot N_1/N_2)$ level-1 links. A new LSP is originated with average frequency $f_{k,LS}$ per level-k link. A level-0 LSP is flooded to each of the $\Theta(c_1)$ members of the affected cluster while a level-1 LSP is flooded to all $N = c_2$ nodes. Applying (3), (6) and $d_k = \Theta(1)$, Ψ_{LSR} is, therefore:

$$\Psi_{LSR} = \sum_{k=0}^{1} N_{k+1} \cdot \Theta\left(d_k \cdot \frac{N_k}{N_{k+1}}\right) \cdot f_{k,LS} \cdot c_{k+1} \tag{7a}$$

$$\Rightarrow \Psi_{LSR} = \sum_{k=0}^{1} \frac{N}{c_{k+1}} \cdot \Theta\left(\frac{c_{k+1}}{c_k}\right) \cdot c_k^{-1/2} \cdot c_{k+1} \tag{7b}$$

$$\Rightarrow \Psi_{LSR} = \Theta\left(N \cdot \left[\frac{c_1}{c_0^{3/2}} + \frac{c_2}{c_1^{3/2}}\right]\right) \tag{7c}$$

$$\Rightarrow \Psi_{LSR} = \Theta\left(N \cdot \left[c_1 + \frac{N}{c_1^{3/2}}\right]\right) \tag{7d}$$

Dividing (7d) by N yields the average per node LSR overhead:

$$\psi_{LSR} = \Theta\left(c_1 + \frac{N}{c_1^{3/2}}\right) \tag{8}$$

From (8) it is evident that ψ_{LSR} depends on the cluster size. Applying the example of Section II where $c_1 = \Theta\left(\sqrt{N}\right)$, $\psi_{LSR} = \Theta\left(\sqrt{N}\right)$. Minimizing (8) is with respect to c_1 yields $c_1 = \Theta\left(N^{2/5}\right)$. Substituting $c_1 = \Theta\left(N^{2/5}\right)$ into (8) yields the minimum LSR overhead $\psi_{LSR}^{\min} = \Theta\left(N^{2/5}\right)$. Lastly, it is shown in the Appendix, that the formation of unequal sized clusters due to the random position of leader nodes, does not impact (8).

C. *Acquiring Cluster Topology Data*

The overhead of acquiring the intra-cluster topology data when nodes change cluster membership depends on the average frequency at which each non-leader node migrates from one cluster to another (f_{MIG}) and the average number of level-0 links per cluster. f_{MIG} is proportional μ and inversely proportional to $\sqrt{A_1}$. Applying (5b) with Assumption (b):

$$f_{MIG} = \Theta\left(\mu/\sqrt{A_1}\right) = \Theta\left(1/\sqrt{c_1}\right) \tag{9}$$

The intra-cluster topology data will be typically acquired from a one-hop neighbor of the new cluster so the number of packet transmissions required per datagram transferred is $\Theta(1)$. The average number of level-0 links per cluster is $\Theta(d_0 \cdot N_0/N_1)$. Applying (3), (9) and Assumption (c), the aggregate topology acquisition overhead is as follows:

$$\Psi_{ACQ} = \Theta(N) \cdot f_{MIG} \cdot \Theta\left(d_0 \cdot \frac{N_0}{N_1}\right) \tag{10a}$$

$$\Rightarrow \Psi_{ACQ} = \Theta(N) \cdot \Theta\left(c_1^{-1/2}\right) \cdot \Theta(c_1) \tag{10b}$$

$$\Rightarrow \Psi_{ACQ} = \Theta\left(N \cdot \sqrt{c_1}\right) \tag{10c}$$

Dividing (10c) by N yields the per node acquisition overhead:

$$\Rightarrow \psi_{ACQ} = \Theta\left(\sqrt{c_1}\right) \tag{11}$$

Comparing (8) with (11), $\psi_{LSR} > \psi_{ACQ}$ for large N.

D. *Location Registration*

To assess the overhead due to location registration (LR), it is recalled that non-leader nodes migrate from one cluster to another with frequency f_{MIG} given by (9). Each migration event triggers a LR update which consists of sending a LR packet from a node v to its HLR cluster. As given by (1) the average number of hops between an arbitrary node and its HLR is $h_{REG} = \Theta\left(\sqrt{N}\right)$. Therefore, combining h_{REG} and (9) with the fact that f_{MIG} applies for $\Theta(N)$ nodes yields:

$$\Psi_{REG} = \Theta(N) \cdot f_{MIG} \cdot h_{REG} = \Theta\left(N^{3/2}/\sqrt{c_1}\right) \tag{12}$$

$$\Rightarrow \psi_{REG} = \Theta\left(\sqrt{N/c_1}\right) \tag{13}$$

Of particular interest here is ψ_{REG} for the case where $N_1 = c_1 = \Theta(\sqrt{N})$ as given in the example implementation of Section II and for the case where $N_1 = \Theta(N^{3/5}) \Leftrightarrow c_1 = \Theta(N^{2/5})$ to minimize ψ_{LSR} as derived in Section IV-B. Applying (13), when $N_1 = c_1 = \Theta(\sqrt{N})$ $\Rightarrow \psi_{\mathrm{REG}} = \Theta(N^{1/4})$ and when $c_1 = \Theta(N^{2/5})$ $\Rightarrow \psi_{\mathrm{REG}} = \Theta(N^{3/10})$. In either case, $\psi_{\mathrm{LSR}} > \psi_{\mathrm{REG}}$ for large N.

E. Location Query

It is assumed that new communication sessions are initiated at some frequency that is Θ(1) per node. Assuming traffic pattern ***T-2***, the *fraction* of communication sessions that are between nodes *not* belonging to the same cluster approaches 1, asymptotically. Thus, the frequency of LQs (f_{Q}) is also Θ(1) per node. The average hop distance h_{Q} each LQ must traverse is given by (1). Combining $h_{\mathrm{Q}} = \Theta(\sqrt{N})$ with the fact that there are N nodes initiating queries with frequency $f_{\mathrm{Q}} = \Theta(1)$ yields the following:

$$\Psi_{\mathrm{QUERY}} = \Psi_{\mathrm{REPLY}} = N \cdot f_{\mathrm{Q}} \cdot h = \Theta(N^{3/2}) \tag{14}$$

$$\Rightarrow \psi_{\mathrm{QUERY}} = \psi_{\mathrm{REPLY}} = \Theta(\sqrt{N}) \tag{15}$$

F. Handoff

The option of distributing HLR functionality equitably among all network nodes (rather than concentrating it at leader nodes) is considered now. For this option, when migrating from cluster x_1 to x_2, a migrating node v will not only register its new location with its HLR, but also participate in the handoff of LM data. That is, when leaving x_1, v redistributes its $e_{\mathrm{HLR}} = \Theta(1)$ HLR entries to members of x_1 (based on some hashing function) and acquires Θ(1) HLR entries from x_2. To quantify the aggregate handoff overhead, it is recalled that each (non-leader) node migrates between clusters at an average frequency f_{MIG}. Applying the concept of (1) the average hop distance for handoff messaging (h_{HANDOFF}) is given simply by $h_{\mathrm{HANDOFF}} = \Theta(\sqrt{c_1})$. Combining h_{HANDOFF} with (9) and the fact that there are Θ(N) non-leader nodes each with Θ(1) HLR entries yields:

$$\Psi_{\mathrm{HANDOFF}} = \Theta(N) \cdot f_{\mathrm{MIG}} \cdot e_{\mathrm{HLR}} \cdot h_{\mathrm{HANDOFF}} = \Theta(N) \tag{16}$$

$$\Rightarrow \psi_{\mathrm{HANDOFF}} = \Theta(1) \tag{17}$$

Clearly, the handoff overhead due to implementing LM where the HLR is distributed equitably among all nodes does *not* adversely impact the scalability of 2-LLSR.

G. Total Overhead

The total communication overhead incurred by 2-LLSR is obtained by summing ψ_{HELLO}, (8), (11), (13) (15) and (17). Clearly, the overheads due to LSR (ψ_{LSR}) and LQ messaging (ψ_{QUERY}) asymptotically dominate the other factors. By employing $N_1 = \Theta(N^{3/5})$ leader nodes (i.e., $c_1 = \Theta(N^{2/5})$) LSR overhead may be reduced to as little as $\psi_{\mathrm{LSR}}^{\min} = \Theta(N^{2/5})$. Thus, for traffic pattern ***T-2***, $\psi = \psi_{\mathrm{QUERY}} = \Theta(\sqrt{N})$. Lastly, the *size* of all control packets is Θ(1).

V. Related Work

The Zone Routing Protocol (ZRP) of [3] attempts to trade off the effects of proactive and reactive routing overheads. That is, when node mobility is low, large proactive routing zones are employed and small proactive routing zones are employed when node mobility is high. Unlike 2-LLSR, however, ZRP is a non-hierarchical routing protocol. The sizing of routing zones in ZRP is to respond to mobility conditions rather than increasing node count. Thus, ZRP does not address scalability with respect to increasing N, but rather, is designed to be responsive to mobility conditions. Further, unlike 2-LLSR, ZRP employs a controlled network-wide flood search to learn routes to destination nodes outside of a source node's routing zone whereas 2-LLSR employs a LM scheme.

In [5] and [16], scalable two-level routing protocols are proposed that satisfy (2). However, these approaches require nodes to be equipped with global positioning system (GPS) receivers. 2-LLSR operates without the aid of GPS data.

The Landmark Ad hoc Routing (LANMAR) protocol, proposed in [11], achieves scalable routing but assumes groups or subnets of nodes to follow favorably correlated mobility patterns. When the mobility patterns of nodes are uncorrelated, LANMAR resorts to a form of mobility management similar to that described in [12] for Mobile IP. By employing $\Theta(\sqrt{N})$ landmark nodes that essentially function as landmarks or home agents, it is possible for LANMAR to satisfy (2). Unlike 2-LLSR, however, LANMAR applies routing based on a *distance vector* approach to forward datagrams toward a landmark node.

The Hazy Sighted Link State (HSLS) routing protocol described in [13] also achieves scalable routing but does so via a heuristic similar to the fisheye scoping heuristic proposed in [10]. That is, the effective rate at which link state information is exchanged between a pair of nodes decreases as the hop count separating the node pair increases. By selecting an appropriate exchange rate as a function of hop distance, it is shown in [13] that (2) may be satisfied.

The virtual subnet concept of [14] achieves some scalability advantages over a flat routing protocol. This approach assumes that transceivers are capable of varying their transmitter power to reach all nodes. Such a requirement, however, is not realistic given Assumption (d).

VI. Contributions And Discussion

This paper considers routing in MANETs where communication sessions are between arbitrary pairs of network nodes (i.e., traffic pattern ***T-2***). In order to maintain Θ(1) throughput per node for ***T-2***, the link capacity (*C*) available to each network node must grow at a rate that is proportional to the square root of the node count.

A *capacity compatible* two-level link state routing (2-LLSR) protocol has been proposed here whose control overhead (ψ) satisfies the capacity constraint given by (2). This is an important contribution because satisfying (2) means that accommodating ψ requires only that $C = \Theta\left(\sqrt{N}\right)$. In contrast, a flat LSR implementation would require $C = \Theta(N)$.

A detailed assessment of 2-LLSR overhead is undertaken herein. An interesting finding is that the number of clusters that minimizes overhead is $N_1 = \Theta\left(N^{3/5}\right)$ with average cluster size $c_1 = \Theta\left(N^{2/5}\right)$. When $c_1 = \Theta\left(N^{2/5}\right)$, overhead is actually dominated by LQ overhead for traffic pattern ***T-2***. This is a useful result as it means that 2-LLSR overhead is not only capacity compatible but also has a modest scaling constant that is approximately equal to f_Q, the frequency of location queries (i.e., frequency at which communication sessions are initiated and deleted). Presumably, f_Q is small compared with the number of datagrams originated per communication session so that ψ occupies a small fraction of *C*.

Of course, there may be other traffic patterns of interest besides ***T-1*** and ***T-2***, as discussed here. Communications may also be *hierarchically* organized such that although an arbitrary node *u* may potentially communicate with any other node in the network, *u* may be more likely to communicate with a node *v* if *v* is nearby. For example, if a hierarchical traffic pattern facilitates $h = \Theta\left(N^{1/3}\right)$, then $C = \Theta\left(N^{1/3}\right)$ is sufficient. Although such a traffic pattern reduces the requirement on *C*, compared with that of ***T-2***, it would also demand that an *L*-level ($L > 2$) routing protocol be deployed in order for control overhead not to exceed *C*. Evaluation of routing protocols with $L > 2$ is outside the scope of this paper.

Appendix

Since the per cluster LSR overhead is *quadratic* in the cluster size, it raises the issue of whether disproportionately large clusters will incur ψ_{LSR} that exceeds the result of (8). This Appendix reports simulations, which demonstrate that although the cluster size may exceed c_1 for some clusters, the result of (8) still holds.

Fig. 3 shows the average ratio (r_N) of actual LSR overhead (based on actual cluster sizes) to the aggregate LSR overhead, $N^{3/2}$, that would occur if all clusters consist of exactly $\sqrt{N}$ nodes. The simulation scenarios consisted of $N = 100$, 400, 900, 1600 and 2500 nodes. For each scenario, 200 random, independent simulation trials were conducted.

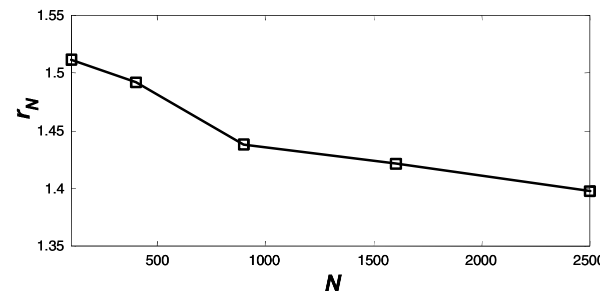

Figure 3. Assessing the effect of unequal cluster sizes

Clearly, r_N can be easily bounded by a constant for values of $N \geq 100$, i.e., $r_N = \Theta(1)$. Thus, the effect of unequal cluster sizes impacts (8) by only a scaling constant.

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