CAPACITY COMPATIBLE TWO-LEVEL LINK STATE ROUTING FOR MOBILE AD HOC NETWORKS

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ABSTRACT

The throughput of mobile ad hoc networks (MANETs) has been analyzed previously. A possible network traffic pattern is one where communication sessions are between pairs of nodes arbitrarily situated throughout the network. Thus, the lengthy multiple hop paths of such communication sessions constrict network throughput. However, the property of spatial reuse still allows the aggregate network throughput to scale at a rate that is proportional to the square root of the node count. On the other hand, the throughput per node scales at a rate that is inversely proportional to the square root of the node count. Therefore, to maintain throughput per node that is constant with increasing node count, transceiver link capacity must grow at a rate that is proportional to the square root of the node count. Not only must link capacity scale appropriately, but so must the control overhead incurred by network communication protocols (i.e., overhead should not grow at a rate that exceeds the growth in link capacity). This paper describes how two-level link state routing can afford such scalability. That is, by adding only a single level of hierarchy to an otherwise flat routing architecture, it is possible to implement communication protocols that enable datagram forwarding while conforming to the network capacity constraints.

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 little or no existing network infrastructure exists and adaptive communications 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 directly communicate 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 a carrier sense multiple access with collision avoidance (CSMA/CA) protocol.

To concisely describe the network scenario under consideration in this paper, the following notation and assumptions are useful:

- $V \equiv$ Set of network nodes
- $E \equiv$ Set of bi-directional communication links
- $G \equiv (V,E)$, i.e., the underlying graph representation of the network where V is the set of vertices and E is the set of bi-directional edges
- $N \equiv$ Number of network nodes = $|V|$
- $C \equiv$ Capacity of the transceiver situated at each node (bits/s)
- $R_{TX} \equiv$ Transmission range of each transceiver (m)
- $\delta \equiv$ Average number of nodes per unit area
- $d \equiv$ Average number of neighbors per node (i.e., the degree of a node)
- $\mu \equiv$ Average node speed (m/s)
- $\Gamma \equiv$ Aggregate network throughput (bits/s)
- $\gamma \equiv$ Average throughput available per node (bits/s)
- $h \equiv$ Average hop distance between a pair of 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) $R_{TX} = \Theta(1)$
b) $\mu = \Theta(1)$
c) $d = \Theta(1)$
d) $\delta = \Theta(1)$
e) G is connected

The throughput of a network given the above characteristics is now considered. As described in [1], the feature of *spatial reuse* enables successful simultaneous packet transmission by multiple network nodes, provided the transmitter and receivers pairs are adequately spaced.

For example, supposing 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 proven trivially by construction, for the above network conditions. That is, a transmitter set $X \in V$ can be assigned where members of X are spaced evenly throughout the network such that each member is separated by exactly 3 hops from another member of X in the north, south, east and west directions.

A more practical traffic pattern and of particular interest here, is one where communication sessions are between pairs of nodes arbitrarily situated throughout the network. Such a traffic pattern is referred to here as ***T-2***. Given the above network characteristics, it has been shown in [2] that $\Gamma = \Theta\left(\sqrt{N}\right)$ and $\gamma = \Theta\left(1/\sqrt{N}\right)$. 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 [2] that average hop count is proportional to the square root of the node count:

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

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

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

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

For networks where traffic pattern ***T-2*** represents the dominant form of communications, it is crucial 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 protocol proposed here, 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 [3] 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***, $R_{TX} = \Theta\left(\sqrt{\log N}\right)$, $h = \Theta\left(\sqrt{N/\log N}\right)$, $\Gamma = \Theta\left(\sqrt{N/\log N}\right)$ and $\gamma = \Theta\left(1/\sqrt{N \cdot \log N}\right)$. However, for the remainder of this paper, the $\log N$ term is ignored to simplify notation.

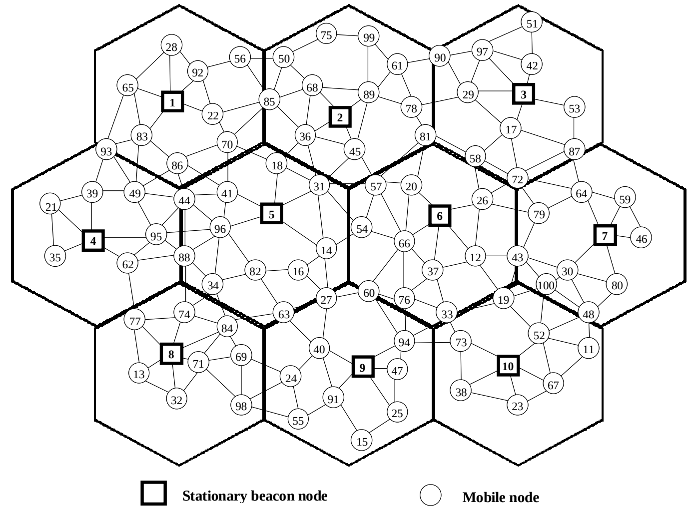

Fig. 1: Beacon-based zone formation.

OVERVIEW OF 2-LLSR

To achieve scalability, nodes running 2-LLSR organize themselves into $\sqrt{N}$ routing zones. The creation of routing zones can be done in one of two ways:

i. Nodes affiliate themselves with one of $\sqrt{N}$ uniformly spaced, stationary beacon nodes, as per Fig. 1.

ii. Nodes affiliate themselves with one of $\sqrt{N}$ designated "zone leader" nodes that are mobile.

In this paper, the deployment of (*i*) is discussed. Analysis and verification of (ii) will be provided in a sequel to this paper.

Beacon-based routing zone affiliation (*i*) consists of nodes affiliating themselves with the nearest beacon node (in terms of hop count). When a node is equidistant from a pair of beacons, it randomly picks one zone with which to affiliate itself. The underlying hexagonal tessellation shown in Fig. 1 represents only approximate routing zone boundaries. That is, the zone affiliation is based on *hop distance* to beacon nodes rather than geographic distance. For example, node 63 straddles the hexagonal boundary between zones 5 and 9. However, the beacon node for zone 5 is 3 hops distant from 63 while 63 is only 2 hops distant from the beacon nodes 8 and 9. Thus, 63 would select between zones 8 and 9 (*not* 5) for its zone affiliation.

Beacon nodes should be approximately uniformly spaced over the network area. N_B is defined as the number of beacon nodes and N_Z is defined as the average node count per routing zone. Here forward, it is assumed that

$N_B = \Theta\left(\sqrt{N}\right)$. As will be evident from the assessment of overhead, this is done to meet the scalability requirement of (2). Letting $N_B = \Theta\left(\sqrt{N}\right)$ yields:

$$N_Z = \Theta\left(\sqrt{N}\right) \tag{3}$$

Further, combining uniformly spaced beacons with (3) and Assumption (d) means that, on average, no single routing zone will have a disproportionately large or small number of nodes affiliated with it. That is, *all* zones consist of $\Theta\left(\sqrt{N}\right)$ nodes.

Within each zone, an intra-zone LSR protocol is employed to facilitate intra-zone packet forwarding. Thus, each node within a given zone knows the least hop paths to all other zone members as well as to those zone members serving as *gateway nodes* to neighboring zones. Packet forwarding between zones is based on the routing zone ID of the destination node. The topology map of routing zones is flooded once to all network nodes to support inter-zone packet forwarding. The routing zone topology map is used to determine the inter-zone path, to the zone of the destination node, with the fewest number of *inter-zone hops*. Here, an inter-zone hop refers to the crossing of a boundary between neighboring zones.

In order for a source node u to learn the routing zone location of a peer node v, a location management 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 zone location with a *home routing zone* known to all nodes. Letting $v \in V = \{1,2,\ldots,N\}$ be the node ID for an arbitrary node and $\{1,2,\ldots,N_B\}$ be the set of routing zone IDs, all nodes in the network can unambiguously determine the home routing zone of v (v_H) via the following hashing function:

$$v_H = 1 + \operatorname{mod}_{N_B}(v-1) \tag{4}$$

A zone registration packet is sent by v to v_H whenever v changes routing zone affiliation. This may be done, for example, by addressing zone v_H via a Subnet-Router anycast address as specified for IPv6 in [10]. Upon reaching a member of v_H, the Subnet-Router anycast address is accepted and the recipient node examines the contents of the datagram. Recognizing the packet as being a location registration packet, the recipient node initiates flooding of the packet within routing zone v_H. Thus, all members of a routing zone v_H serve as the home location registry of those nodes for whom v_H satisfies (4).

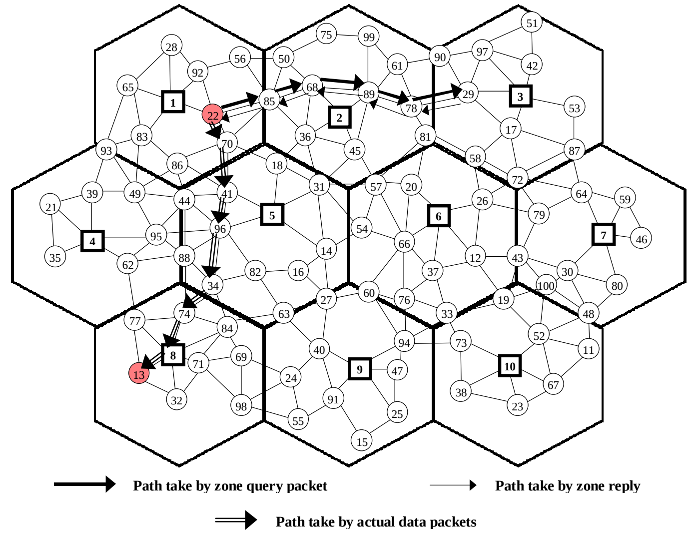

Fig. 2: Zone query example

An example of communications in a 2-LLSR network is now given, based on Fig. 2, where N =100 and N_B = 10. First, a source node u = 22 must learn the routing zone location of a destination node v = 13. If u and v are currently members of the same routing zone, then this is obtained trivially by the intra-zone LSR protocol. More likely, however, u will need to perform a zone query, as shown in Fig. 2. First, u = 22 computes v_H = 3 from (4) for v = 13. A zone query packet is forwarded to zone v_H = 3 and arrives at a member node of zone 3. There, an entry for the *current* routing zone visited by v (v_V = 8) is stored and this information is sent in a zone reply message to u.

Upon receiving the zone reply, u is able to properly address v with the concatenated hierarchical address of $v_V.v$ = 8.13. Following the implementation discussed earlier, the datagram is first addressed to zone 8 via a Subnet-Router anycast address. The address for v = 13 is entered into a Routing header extension as specified in [11]. Upon reaching a member of v_H, (node 74 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. Again, this processing is consistent with that specified for IPv6 in [11]. Forwarding of the datagram to v is then based on the intra-zone LSR protocol of zone 8.

OVERHEAD ASSESSMENT

To verify whether the beacon-based implementation of 2-LLSR satisfies (2), the *aggregate* network control packet overhead (Ψ), in terms of packet transmissions per second, is assessed. The factors already mentioned that contribute to Ψ include the intra-zone LSR protocol for the N_B zones, zone registration messaging and zone queries. Further, a Hello protocol supports intra-zone LSR and identifies gateway nodes between neighboring zones.

The Hello protocol is analyzed first. It consists of periodic messaging between neighboring nodes. By Assumption (c), therefore, per node Hello overhead, ψ_{HELLO}, is $\Theta(1)$. This yields aggregate Hello protocol overhead as follows:

$$\Psi_{HELLO} = \Theta(N) \tag{5}$$

Considering now intra-zone LSR overhead (Ψ_{LSR}), node mobility incurs link state changes at an average frequency of f_L per node. As a consequence of Assumptions (b) and (c), $f_L = \Theta(1)$. Each link state update at a node v incurs flooding, within routing zone v_V, of the updated link state packet (LSP) due to v. This results in $\Theta(N_Z) = \Theta(\sqrt{N})$ packet transmissions. Similarly each of the $N_Z = \Theta(\sqrt{N})$ nodes in v_V flood their own LSP when a link state change is detected. Thus, the aggregate LSR overhead within zone v_V is $\Theta(N)$ LSP transmissions per second. This LSP update and dissemination process occurs for all $N_B = \Theta(\sqrt{N})$ routing zones. Thus, combining $N_B = \Theta(\sqrt{N})$ with $f_L = \Theta(1)$ and (3), the aggregate intra-zone LSR protocol overhead is as follows:

$$\Psi_{LSR} = N_B \cdot N_Z \cdot N_Z \cdot f_L = \Theta\left(N^{3/2}\right) \tag{6}$$

To assess the overhead due to zone registration, f_R is defined as the *frequency per node* at which zone registration events occur and A_Z is defined as the average area per routing zone. By (3) and Assumption (d), $A_Z = \Theta(N_Z) = \Theta(\sqrt{N})$. Since f_R is depends on the rate at which nodes migrate from one routing zone to another, f_R can be expressed simply as a function μ and A_Z. Combining Assumption (b) with $A = \Theta(\sqrt{N})$ yields:

$$f_R = \Theta\left(\frac{\mu}{\sqrt{A_Z}}\right) = \Theta\left(\frac{1}{\sqrt{N}}\right) \tag{7}$$

Each zone registration update consists of sending a registration packet from a node v to its home routing zone v_H. As given by (1) the average number of hops between an arbitrary pair of nodes is $h = \Theta(\sqrt{N})$. The zone registration packet is then flooded among the $\Theta(N_Z) = \Theta(\sqrt{N})$ nodes of v_H. Therefore, combining (1), (3) and (7) with the fact that f_R applies for all N nodes yields an expression for Ψ_{REG}:

$$\Psi_{REG} = N \cdot f_R \cdot h \cdot N_Z = \Theta\left(N^{3/2}\right) \tag{8}$$

Next, assuming new communication sessions are initiated at some frequency that is $\Theta(1)$ per node and the amount of data to be transported per communication session is also $\Theta(1)$, then the frequency of zone queries (f_Q) is also $\Theta(1)$ per node. This is consistent with the fact that $C = \Theta(\sqrt{N})$ in order to maintain $\gamma = \Theta(1)$. Combining (1) with the fact that there are N nodes network initiating queries, on average, with some frequency $f_Q = \Theta(1)$ yields the following:

$$\Psi_{QUERY} = \Psi_{REPLY} = N \cdot f_Q \cdot h = \Theta\left(N^{3/2}\right) \tag{9}$$

Combining (5), (6), (8) and (9) yields $\Psi = \Theta\left(N^{3/2}\right)$. Dividing Ψ by N yields $\psi = \Theta(\sqrt{N})$, as required by (2). Lastly, the *size* of all control packets is only $\Theta(1)$.

RELATED WORK

The Zone Routing Protocol (ZRP) proposed in [4] 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 node count, 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 location management scheme.

In [7] and [8], 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 [6], 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 $\Theta\left(\sqrt{N}\right)$ 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 virtual subnet concept of [5] 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 is not realistic as $N \rightarrow \infty$ given Assumption (d).

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 $\Theta(1)$ throughput per node (γ), the link capacity available to each network node must grow at a rate that is proportional to the square root of the node count.

A scalable two-level link state routing (2-LLSR) protocol has been proposed here whose control overhead satisfies the capacity constraint given by (2). This is an important contribution because satisfying (2) means that the link capacity (C) available to network nodes need only grow at a rate that is proportional to the square root of the node count in order to maintain $\gamma = \Theta(1)$. In contrast, a flat LSR implementation (i.e., one-level LSR) would require $C = \Theta(N)$. 2-LLSR is unique in that, unlike other two-level routing approaches, it does not require nodes to be equipped with GPS receivers, or have favorably correlated mobility patterns, or employ distance vector routing or have variable power transmitters.

In this paper, 2-LLSR is described and assessed based on routing zones formed about evenly spaced stationary beacon nodes. However, it is possible also for zones to be formed about a designated subset of mobile nodes. Like beacon-based zone affiliation, zone affiliation is based on the minimum hop distance to a zone leader. Verification that the leader-based implementation of 2-LLSR also satisfies (2) is to be reported in a sequel to this paper.

Of course, there may be other traffic patterns of interest besides ***T-1*** and ***T-2***, as discussed here. For example, communications may be *hierarchically* organized. That is, although an arbitrary node u may potentially communicate with any other node in the network (as in ***T-2*** and unlike ***T-1***), u may be more likely to communicate with a node v if v is nearby (unlike ***T-2*** and more like ***T-1***). Conversely, in this scenario, u is progressively less likely to communicate with v as the hop distance to v increases. Such a traffic pattern would impose a requirement on C that is less severe than that demanded by ***T-2*** yet not trivial as for ***T-1***, i.e., $\Theta(1) < C < \Theta\left(\sqrt{N}\right)$. Although such a traffic pattern reduces the requirement on C, compared with that of ***T-2***, it would also demand that an L-level ($L \geq 3$) routing protocol be deployed in order for control overhead not to exceed C. Evaluation of routing protocols with more than two levels is outside the scope of this paper.

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