Location Aware One-to-Many Communication in Mobile Multi-Hop Wireless Networks*

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Abstract – This paper presents a uniform solution for multipoint communication in mobile multi-hop wireless networks, spanning the full range of problems from routing to broadcast. Each node is aware of its own location and through a dissemination mechanism, becomes aware of the location of all other nodes in the network. Thus when a node has a packet to transmit, it is able to locally compute a "snapshot" of the network topology. A tree that describes the paths to follow to reach the destinations of the multipoint communication is then locally computed on the resulting snapshot. The tree obtained is optimally encoded by its unique *Prüfer sequence*, included in the packet header, and then the paths traversed hop-by-hop as in any source routing technique. All the local computations are efficient, being executed in polynomial time. Our uniform solution to multipoint communication has been simulated in mobile multi-hop wireless networks with up to 60 nodes, showing a success rate of over 95% for routing and multicast. Furthermore, compared to flooding, our solution achieves improvements of up to 50% on multicast completion delay.

I. INTRODUCTION

In general, *multipoint* communication includes all forms of communication with multiple participants. In this paper, we restrict our attention to that of a single source node but do not limit the number of destinations. That is, we consider one-to-k communication where $1 \leq k \leq n$ and where n is the number of nodes in the network. The problems of routing, multicast, and broadcast correspond to the cases where $k = 1$, $1 < k < n$, and $k = n$, respectively. Rather than treating each of these three problems separately, we provide a uniform way to approach multipoint communication in mobile multi-hop wireless networks.

Mobile multi-hop wireless radio networks (also called *ad hoc* networks) are networks that have no fixed infrastructure such as base stations. Since all the radio nodes are mobile, the nodes rely on each other to forward packets to destinations not directly in their transmission range. While the primary use of ad hoc networks is in military applications, these networks are being considered to extend the range of commercial wired and cellular networks in the event of network failure or unavailability since they can be deployed quickly.

Since all nodes are mobile, this provides a major challenge to multipoint communication protocols to constantly adapt to the changes caused by node movement. As well, the transmission bandwidth is a limited resource and protocols must utilize bandwidth as effectively as possible.

Generally, the existing routing protocols in ad hoc networks can be classified as either *proactive* or *reactive.* A proactive protocol continuously maintains routes, thus when a packet arrives at a source, the route to the destination is already available and can be followed immediately. Most proactive routing protocols are based on shortest path algorithms that have been adapted to the mobile environment [4, 14, 11]. In contrast, a reactive protocol does not maintain routes. Instead, a *route discovery* phase precedes the transmission of a packet [9, 13] in an "on demand" fashion. The main tradeoffs between these approaches is in how long the source must wait before using a route and the bandwidth to obtain or maintain the route.

Many existing protocols for multicast are based on *multicast routing trees* [6, 5, 15]. These solutions, as well as the denser "multicast mesh" solution [7], rely on the existence and correct operation of either an ad hoc routing protocol or a protocol to build and maintain a hierarchical organization in the network. Thus, the correctness and performance of existing multicast protocols depends on the correctness and performance of the underlying protocols.

Perhaps the simplest way to implement broadcast in a multi-hop wireless network is to use flooding. The flooding is controlled by keeping a hop count, initialized to the network diameter, in the packet. If the hop count is positive, the count is decremented and the packet transmitted, otherwise the packet is discarded. Another method keeps track of the identifiers of broadcast packets and only retransmits packets having new identifiers.

Here we present a uniform solution to multipoint communication for mobile multi-hop wireless networks which does not assume any routing protocol as a basis,

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nor does it build or maintain any underlying routing structure. Our solution is based on the expectation that nodes of ad hoc networks are location aware. The commercial proliferation of low cost positioning system devices, such as Global Positioning System (GPS) receivers, make this expectation reasonable. We thus assume that a node is equipped with a GPS receiver, through which it can compute its three-dimensional position, velocity and time.

We have introduced and described the use of a dissemination mechanism specifically designed to meet the challenging system requirements of ad hoc networks in [3, 2]. Using this mechanism, a node's attributes are spread throughout the network. Thus, each node can maintain a cache of attributes keyed by node identifier for each other node in the network.

When a packet arrives at a source node S, S first constructs a graph G representing the current network topology obtained from the cached node attributes. S then *locally* computes a tree for the multipoint communication. For routing this tree is a simple path, for multicast it is a Steiner tree, and for broadcast it is a spanning tree. S then includes a coded representation of the paths (i.e., the tree) the packet is to follow as a *Prüfer sequence* [12] in the packet header, and transmits the packet using unicast to each child node. Each child node that is the root of a subtree will forward the packet to each of its children in the same manner until finally the path is exhausted. We show that each step of our multicast protocol can be solved by an efficient ($O(n^2)$) local computation.

Overall, our uniform solution to multipoint communication has the following desirable properties:

- Our solution relies on a bandwidth and energy efficient dissemination mechanism.
- Each of the three subproblems solved does not impose a significant overhead to the communication.
- Minimal overhead is associated by including the tree encoded by its unique Prüfer sequence.

The effectiveness of our unified approach to multipoint communication is demonstrated through the use of simulation. Our results show that in a multi-hop wireless network with up to 60 nodes moving at a velocity from 6 to 20 m/s, independently of the network load, that routing and multicast is successful more than 95% of the time.

The remainder of this paper is organized as follows. Section ii overviews the dissemination mechanism that allows each node to efficiently distribute its attributes. Section iii describes our uniform solution to multipoint communication, with an emphasis on the efficiency of the implementation of each of the local operations. In Section iv, the effectiveness of our uniform approach in delivering a packet to all the nodes that are the destination of the multipoint communication is shown through simulation. Finally, Section v concludes the paper.

II. ATTRIBUTE DISSEMINATION

Recall that we assume each node is equipped with a Global Positioning System (GPS) receiver which allows a node to compute its three-dimensional position (latitude, longitude, and altitude), velocity and time with high precision from signals broadcast by the GSP constellation of satellites. Thus each node is aware of its own location as well as other attributes.

Since multi-hop networks lack a fixed infrastructure, in order for each node to become aware of the location of the other nodes in the network, every node must disseminate its attributes to all other nodes. Upon reception of such an "attribute packet" from a node v_j, a node v_i updates its *cache* that stores, for each other node, v_j's most updated attributes.

The dissemination mechanism was designed to minimize bandwidth and energy usage in multi-hop wireless networks. Since the packets containing the attributes are very small (less than 20 bytes), they require very little of a node's available bandwidth and, correspondingly, energy to transmit. In addition, rather than periodically flooding the network with its attributes, the frequency a node needs to disseminate its attributes depends on its velocity. Thus, each node can locally adjust its dissemination frequency according to its mobility rate. The accuracy of our a dissemination mechanism, as well as the effectiveness in supporting routing in multi-hop wireless networks, has been studied and presented in [2, 3].

III. MULTIPOINT COMMUNICATION IN AD HOC NETWORKS

Assume that a node S needs to send a packet to a subset D of nodes of the network, $1 \leq k \leq n, k = |D|$. The node S is the *source* of the packet and the destinations are given by D.

Every time a node needs to transmit a packet to the nodes in the destination set D, it computes from its cache the graph G representing the network topology. Then, it computes *locally* on the resulting graph G, a tree of minimal cost to reach the nodes in D. Here, the cost associated with each edge in G is 1 and represents the total number of transmissions (hops) a packet takes to reach all nodes in D. Therefore, a minimum cost tree minimizes the overall transmission time, the related energy consumption and the overall bandwidth needed for the multipoint communication.

Once the tree is computed, a packet is processed in a manner similar to any source routing protocol. Namely, the obtained tree is included in the header of the data packet, and the packet is transmitted in a hop-by-hop manner to all and to only those nodes in the tree (provided, of course, that each of these nodes is reachable). In the rest of this section we address the three main problems that must be solved in order to implement our uniform solution to multipoint communication in multi-hop wireless networks, namely: (1) obtaining the network topology graph; (2) computing the minimum

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cost tree for the destination set; and (3) efficiently encoding the tree such that the transmission time of the packet itself is not significantly affected.

Obtaining Network Topology

The entries of a node's cache gives the attributes of node v_i at the time those measures were transmitted by v_i. In particular, from the location and the transmission radius attributes a node can compute which nodes are in the transmission range of each node in the network. Thus, the "current" network topology (where all the nodes are located, and how they are bidirectionally linked) is obtained.

In graph theoretic terms, this means that a source node S can construct from its cache an *undirected graph* $G = (V, E)$ that corresponds to the network topology, where V is the set of network nodes, $|V| = n$, and E is the set of bidirectional radio links. An edge (v_i, v_j) in E between two nodes v_i and v_j in V means that, according to the attributes stored in S's cache for v_i and v_j, the nodes v_i and v_j are in the transmission range of one another. Clearly, the construction of the network topology graph G from the cache requires time polynomial in n, the number of nodes in the network, and thus it only imposes a negligible overhead for a node.

Computing the Minimum Cost Tree

Once the source S of the multipoint communication has generated the topology graph G, a *multipoint communication tree*, i.e., a minimal set of routes to all the nodes in the destination set D, is locally computed.

If $k = |D| = 1$ then there is only a single destination in the destination set. Thus to solve the problem of routing to D we need only run a single-source shortest path algorithm (such as Dijkstra's algorithm [1]) on G with S as the source. The running time of this algorithm is $O(n^2)$ when an adjacency matrix is used to represent the graph.

In the case of $1 < k < n$, a proper subset of the nodes are in the destination set. Constructing a minimum cost multicast tree, also called a *Steiner tree*, for the nodes of a given subset in a generic network is a well known NP-hard optimization problem (see, among many others, [8]). This implies that exact algorithms for generating the tree of minimum cost to all nodes in a given subset is impractical. Therefore, a number of heuristic algorithms have been proposed that allow the construction of a Steiner tree in a time which is polynomial in $n = |V|$ and $m = |E|$. Furthermore, for many of these algorithms it is possible to prove an error ratio with respect to an optimal solution which is at most $2 - \frac{2}{|D|}$, where D is the destination set, thus guaranteeing a bounded distance from the best possible solution. (Extensive overviews of and references to these heuristics can be found in, e.g., [8, 10].)

For the case $k = n$, all nodes are in the destination set. Thus to solve the problem of broadcast we need only run a minimum cost spanning tree algorithm (such as Prim's algorithm [1] which is $O(n^2)$).

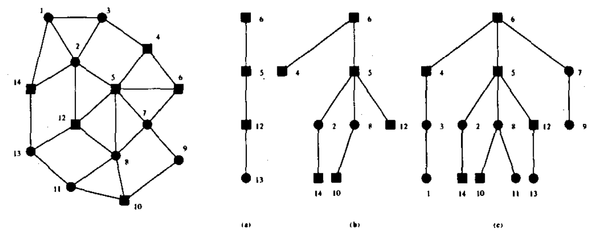

Figure 1: The network topology according node 6's cache (left); (a) the shortest path for a route to $D = \{13\}$; (b) the Steiner tree for multicast to $D = \{4, 5, 6, 10, 12, 14\}$; (c) the spanning tree for broadcast.

As an example, suppose that node 6 receives a packet to transmit, and suppose that the graph in Figure 1 is the network topology graph G that node 6 constructs from its cache. If the destination set is $D = \{13\}$, then node 6 runs a shortest path algorithm on G resulting in the path in Figure 1(a).

If instead the destination set is $D = \{4, 5, 6, 10, 12, 14\}$ (denoted by the square vertices in G), node 6 now computes a multicast tree for G and D, rooted at 6. The algorithm selected for this example (and for the simulation in the next section) is a minimum spanning tree based heuristic that produces a multicast tree in a time proportional to $m + n \log n$ [16, 8]. Figure 1(b) shows the resulting Steiner tree. Note that a multicast tree always has group members as leaves (interior nodes may or may not be group members).

If the destination set is $D = V$, then node 6 runs a minimum spanning tree algorithm on G resulting in the spanning tree in Figure 1(c).

Optimal Coding of Trees

Once the appropriate tree has been obtained, we code the tree and include it in the header of the packet. Every tree corresponds to a unique Prüfer sequence, and every sequence can only be obtained from one tree. Any finite tree with j nodes (and therefore $j - 1$ edges) can be optimally encoded as a sequence of $j - 2$ integers (here, the node identifiers) [12]. Notice that this encoding is as efficient as specifying the longest source route needed for routing in ad hoc networks according to on-demand protocols. Thus, from the perspective of header size, our uniform solution to multipoint communication needs only as much space as an on-demand routing protocol. Encoding a tree using its Prüfer sequence induces very little overhead along with the transmission of the packet and, as in routing, it reduces with each hop subsequently taken by the packet. It can be shown that, in the worst case (a tree that spans the whole topology graph G, i.e., $j = n$), the time required to code a tree into its Prüfer sequence is $O(n^2)$.

IV. SIMULATION RESULTS

We have simulated our uniform solution to multipoint communication using a discrete-event simulator of a multi-hop wireless network implemented in C++. We counted the number of successful routings and multicasts, namely, the number of routings and multicasts that deliver the packet to all the nodes in the destination set. If any node of the destination set does not receive the packet, then the routing/multicast is considered unsuccessful.

Two scenarios were considered: $n = 30$ nodes moving in a $1000m \times 1000m$ region and $n = 60$ nodes moving in a $1000m \times 2600m$ region (the region is modeled as a grid). Node movements are discretized to grid units with a grid unit = 1 meter. Each time it moves, a node determines its direction randomly, by choosing between its current direction (with 75% probability) and uniformly among all other directions (with 25% probability). The node then moves in the chosen direction according to its current speed. When a node reaches a grid boundary, it bounces back into the region with an angle determined by the incoming direction.

Each node has a fixed transmission radius of $350m$ (we found this value results in good network connectivity, i.e., more than 95% of the time, the network is connected after topology changes). Each node is modeled by a store-and-forward queuing station characterized by parameters such as buffer space. Each link is modeled by a FCFS queue with service time as the packet transmission time characterized by a bandwidth of 1 Mbps. Control packets containing the node attributes and routing/multicast (data) packets share the same transmission channel. This implies that the accuracy of the dissemination mechanism may be affected by the network load, and that the transmission of data routings/multicasts may be slowed down by the transmission of the attributes.

Each control packet contains time-stamped, node identified, location coordinates and the current transmission radius of a node, which in the current experiments is considered the same for each node. These packets are generated every time a node moves (see [2]).

Routing packets contain a header that includes the identifier of the source node, as well as the shortest path to the destination, in addition to 1K of data. Multicast packets also contain a header that includes the identifier of the source node, the multicast group, as well as the encoded Steiner tree, in addition to 1K of data.

The following figure shows the percentage of successful routings for both scenarios, for nodes whose velocity varies from 6 to 20m/s, i.e., roughly from 20 to 70 km/h. The destination received the packet more than 98% of the time.

The following two figures show the percentage of successful multicast for the $n = 30$ node scenario, with nodes whose velocity again varies from 6 to 20m/s. For multicast group sizes between $\frac{n}{10}$ and $\frac{n}{3}$ (here only $\frac{n}{10} = 3$, $\frac{n}{6} = 5$ and $\frac{n}{3} = 10$ are plotted), all the nodes of the addressed multicast groups received the packet more than 97% of the time. Figure 3 and Figure 4 refer to the results obtained with a "low" and a "high" network loads, respectively (multicast arrivals are distributed exponentially with a mean of 250ms for "low" load, and of 10ms for "high" load).

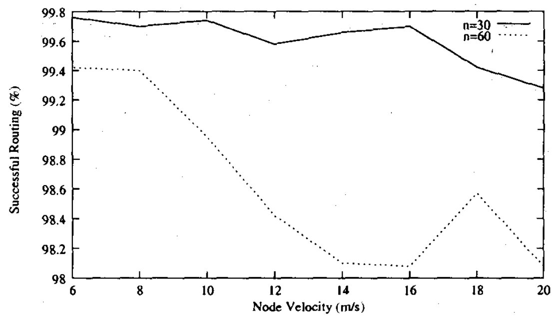

Figure 2: Average percentage of successful routings.

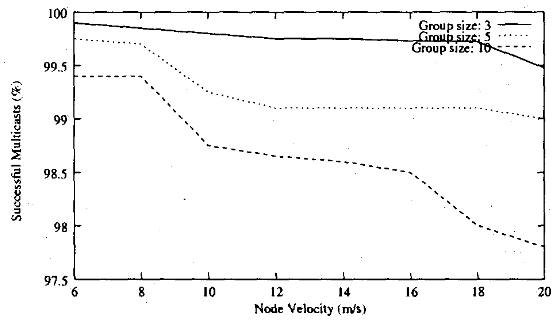

Figure 3: Average percentage of successful multicasts in networks with "low" load.

Furthermore, of the unsuccessful multicasts, more than 85% of the nodes received the packet. Thus, even though the multicast packet failed to reach all the nodes in the destination set, less than 15% did not receive it.

In our multicast scenarios, we have found that the average length of the Prüfer sequence of the multicast trees is less than 10 bytes, which implies a negligible increase of the packet transmission time with respect to the transmission time of packets multicast through global flooding (these packets need to carry along with the data only the source node and the multicast group identifiers).

Compared with global flooding, the simplest multicast protocol that, as in our approach, does not assume the construction and maintenance of any underlying network structure, results show that our solution improves on the average delay of (successful) multicast completion up to 50%. All the simulations run for a time long enough to achieve a confidence level of 95% with a precision within 5%.

V. CONCLUSIONS

In this paper we present a uniform solution to the three problems in multipoint communication in multi-hop wireless networks: routing, multicast, and broadcast. Our solution does not assume, construct or main-

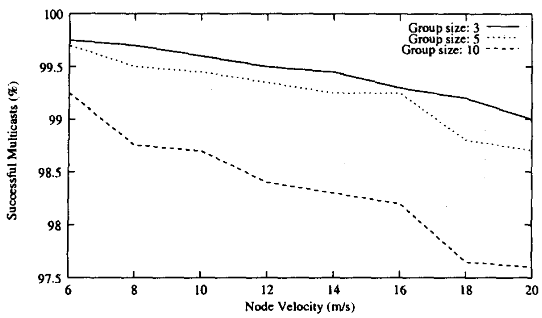

Figure 4: Average percentage of successful multicasts in networks with "high" load.

tain any network structure, nor does it use a multi-hop wireless routing or clustering protocol as a basis. Thus, node and network resources can be entirely used for the transmission of the multipoint packets.

Nodes become location aware through the efficient dissemination of node attributes, which include each node's location as obtained by a positioning device such as a GPS receiver. When a packet arrives at the source, it computes according to the cached node attributes, a tree that reaches all nodes in the destination set of the multipoint communication. The resulting tree is then optimally encoded locally and transmitted along with the packet extending the length of the packet header by no more than multi-hop wireless source routing. The time complexity of all the local operations is shown to be $O(n^2)$, where n is the number of nodes in the network. Finally, for networks with up to $n = 60$, simulation results show that our solution delivers the packet to the destination in more than 95% of the cases.

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