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A Survey of Topology Control of Multihop Wireless Networks for Energy Efficiency and Routing in AD HOC Networks

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Abstract–*An ad hoc wireless network, or simply an ad hoc network, consists of a collection of geographically distributed nodes that communicate with one other over a wireless medium. An ad hoc network differs from cellular networks in that there is no wired infrastructure and the communication capabilities of the network are limited by the battery power of the network nodes. One of the original motivations for ad hoc networks is found in military applications. We present two centralized algorithms for use in static networks, and prove their optimality. For mobile networks, we present two distributed heuristics that adaptively adjust node transmit powers in response to topological changes and attempt to maintain a connected topology using minimum power. We analyze the throughput, delay, and power consumption of our algorithms using a prototype software implementation, an emulation of a power-controllable radio, and a detailed channel model.*

Keywords*: Optimum Centralized Algorithm,Topology Control, Multihop Wireless Network*

1. INTRODUCTION

There are no wired infrastructures or cellular networks in ad hoc wireless network. In this survey, we assume that each wireless node has an omni-directional antenna and a single transmission of a node can be received by any node within its vicinity which, we assume, is a disk centered at this node. We also discuss specifically the topology control when directional antennas are used. Each mobile node has a transmission range. Node v can receive the signal from node u if node v is within the transmission range of the sender u. Otherwise, they communicate through multi-hop wireless links by using intermediate nodes to relay the message. Consequently, each node in the wireless network also acts as a router, forwarding data packets for other nodes. In addition, we assume that each node has a low-power Global Position System (GPS) receiver, which provides the position information of the node itself. If GPS is not available, the distance between neighboring nodes can be estimated on the basis of incoming signal strengths and the direction of arrival. Relative co-ordinates of neighboring nodes can be obtained by exchanging such information between neighbors.

In this paper we study the problem of assigning transmission ranges to the nodes of a multihop packet radio network so as to minimize the total power consumed under the constraint that adequate power is provided to the nodes to ensure that the network is strongly connected (i.e., each node can communicate along some path in the network to every other node). Such assignment of transmission ranges is called complete. We also consider the problem of achieving strongly connected bounded diameter networks.

For points in three dimensions we show that the problem of deciding whether a complete range assignment of a given cost exists, is NP-hard. For the same problem we give an O(n2) time approximation algorithm which provides a complete range assignment with cost within a factor of two of the minimum. The complexity of this problem in two dimensions remains open, while the approximation algorithm works in this case as well.

A packet radio network is a network where the nodes consist of radio transmitter/receiver pairs distributed over a region. Communication takes place by a node broadcasting a signal over a fixed range (the size of which is proportional to the power expended by the node's transmitter). Any receiver within the range of the transmitter can receive the signal assuming no other nodes are transmitting signals that reach the receiver simultaneously. For a message to be sent to a node outside of the range of the message originator, multiple “hops" may be required, whereby intermediate nodes pass on (re-broadcast) the message until the ultimate destination node is reached.

Such networks have applications in many situations, over many different scales, where traditional networks are too expensive or even impossible to build.

Some examples include as follows

(1) Setting up a LAN in a historic building where adding wiring would destroy or obscure valuable features of the building.

(2) Battlefield or disaster situations where temporary WANs are required but the infrastructure for a traditional network does not exist.
(3) Networks which include nodes in outer space (e.g., satellites, space stations, the moon).

Why do we need to control the topology? Simply because the wrong topology can considerably reduce the capacity,increase the end-to-end packet delay, and decrease the robustness to node failures. For instance, if the topology is too sparse, there is a danger of network partitioning and high end-to-end delays. On the other hand, if the topology is too dense, the limited spatial reuse reduces network capacity. Networks that do not employ topology control are likely to be in one of these modes for a significant fraction of their operational time, resulting in degraded performance, or even disrupted connectivity. Furthermore, transmit power control results in extending battery life of the nodes - a crucial factor for many multihop wireless networks.

A *multihop wireless network* is one in which a packet may have to traverse multiple consecutive wireless links in order to reach its destination. Over the years, this general concept has manifested itself in numerous forms under numerous names. These include *packet radio* networks, developed several decades ago for tactical military communications, and more recently, *ad **hoc*** networks, used to refer to a collection of hosts communicating over a wireless channel. Other terms include *mobile* networks Ricochet **[l]** network and the Army Near-Term Digital Radio (NTDR) [2] network are examples, respectively, of fully operational commercial and military multihop wireless networks.

The *topology* of a multihop wireless network is the set of communication links between node pairs used explicitly or implicitly by a routing mechanism. The topology depends on .‘uncontrollable” factors such **as** node mobility, weather, interference, noise, as well as on “controllable” parameters such as transmit power and antenna direction. While considerable research has been done on *routing* **[3]** – mechanisms that efficiently react to changes in the topology due to uncontrollable factors, the area of adjusting the *controllable* parameters in order to create the desired topology has received little attention. This paper addresses the problem.

Ad hoc wireless networks consist of wireless nodes that can communicate with each other in the absence of a fixed infrastructure. Wireless nodes are battery powered and therefore have a limited operational time. Recently, the optimization of the energy utilization of wireless nodes has received significant attention. Different techniques for power management have been proposed at all layers of the network protocol stack. Power saving techniques can generally be classified into two categories: by scheduling the wireless nodes to alternate between the active and sleep mode, and by adjusting the transmission range of wireless nodes. In this paper, we deal with the second method.

2. PROBLEM STATEMENT

In this section, we develop a new representation for multihop wireless networks and define terms used in this paper. Conventionally, multihop wireless networks are represented as a. graph where two vertices have an edge if and only if the corresponding nodes can communicate. We develop a new framework chiefly because the conventional representation hides the radio parameters and propagation properties that are critical to a realistic analysis. In our representation, the entities that contribute to the ability to communicate, namely the geographical locations, the propagation characteristics, and the node transmission parameters are kept separate.

*Definition 2.1***:** A *multihop wireless network* is represented as M = (N, L), where N is a set of nodes and L : N = *(Z+,Z+***)** is a set of coordinates on the plane denoting the locations of the nodes.

*Definition 2.2***:** A *parameter vector* for a given node is represented *P = { f1,f2….fn}* where f1:N->R, is a real valued adjustable parameter.

In general, we can look at the topology control problem as one of optimizing a set of cost metrics under a given set of constraints. Examples of constraints include degree boundedness, k-connectivity for a particular value of *k*, bounded diameter, etc. Examples of cost metrics include total transmit power, maximum transmit power, maximum spreading length etc.

3. MODELING AD HOC NETWORKS

One can model an ad hoc network as a collection of points in 2-dimensional (or 3-dimensional)Euclidean space, where each point represents a network node. Each node can be characterized by its computational and communication power. The computational power of a node determines thelevel of coding and encryption that the node can perform, two key issues in wireless communication. The communication characteristics of the network are governed by the propagation characteristics of the radio channel and the environment, and the battery power and power control capabilities of the individual nodes. We now elaborate on these issues.

The radio propagation and interference models can be used to derive meaningful bounds on the capacity of ad hoc networks, given node locations and transmission power constraints. Such a model based on physical layer parameters, however, is cumbersome to use for designing and analyzing higher layer protocols. A simpler model that abstracts away the physical layer details is to represent an ad hoc network as a graph G - (V, E) in Euclidean space. The set V is the set of all nodes. We refer to G as the transmission graph. Interference can be modeled to a limited extent by the following assumption: a transmission from u to v is successful only if there is no other node ~v that has an edge to v and is simultaneously transmitting. This is essentially the model that has been used to study packet radio networks (PRNs).

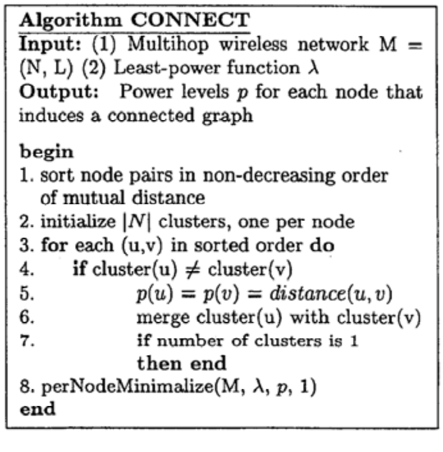
The PRN model, as described above, assumes that each node of an ad hoc network always transmits at the same transmission power. Modern mobile wireless units have the ability of adjusting their transmission power according to the transmission needs, subject to a maximum limit. Such power control reduces interference, conserves battery power of the mobile units, and hence allows for better use of the channel bandwidth. For example, if we represent the network using the transmission graph G as described in the preceding paragraph, we can have a node u successfully transmitting to v, even if there is a node w adjacent to v that is transmitting at the same time; this may happen because the received power at v of w's transmission may be much less than that of the received power at v of u's transmission, owing to different levels at which u and w are transmitting at that time.

4. STATIC NETWORK:OPTIMUM CENTRALISED

4.1 ALGORITHM

A static network affords the luxury of using a centralized or even an offline algorithm to compute the transmit power levels. The node locations, as well as the least-power function are available as input to the algorithm. We present two polynomial time algorithms, one that results in a connected network, and the other in a biconnected network.

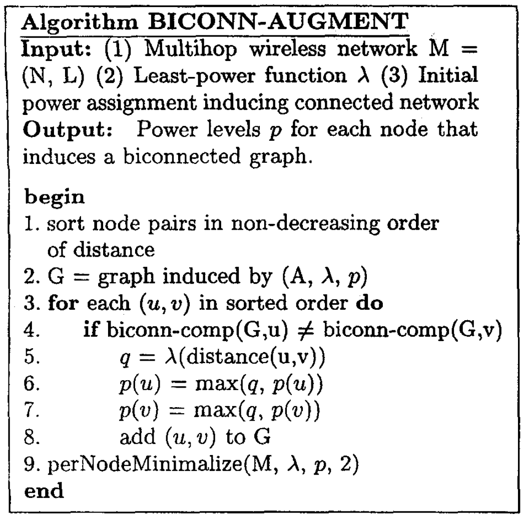
Algorithm CONNECT is given formally in the box below. It is a simple “greedy” algorithm, similar to the minimum cost spanning tree algorithm. It works by iteratively merging connected components until there is just one. Initially, each node is its own component. Node pairs are selected in non-decreasing order of their mutual distance. If the nodes are in different components, then the transmit power of each is increased to be able to just reach the other. This is done until the network is connected. The description assumes for simplicity that network connectivity can be achieved without exceeding the maximum.possible transmission powers. However, the algorithm can be easily modified to return a failure indication if this is not true.



Algorithm CONNECT
Input: (1) Multihop wireless network M = (N, L) (2) Least-power function λ
Output: Power levels p for each node that induces a connected graph

```
begin
sort node pairs in non-decreasing order
  of mutual distance
initialize $|N|$ clusters, one per node
for each (u,v) in sorted order do
    if cluster(u) $\neq$ cluster(v)
        $p(u) = p(v) = distance(u, v)$
        merge cluster(u) with cluster(v)
        if number of clusters is 1
        then end
perNodeMinimalize(M, $\lambda$, $p$, 1)
end
```

The augmentation of a connected network to a Bi-connected network is done using Algorithm BICONN-AUGMENT. Once again, it is a greedy technique. We first identify the biconnected components in the graph induced by the power assignment from algorithm CONNECT. This is done using a standard method based on depth-first search. Then, node pairs are selected in non-decreasing order of their mutual distance and joined only if they are in different biconnected components. This is continued until the network is biconnected.

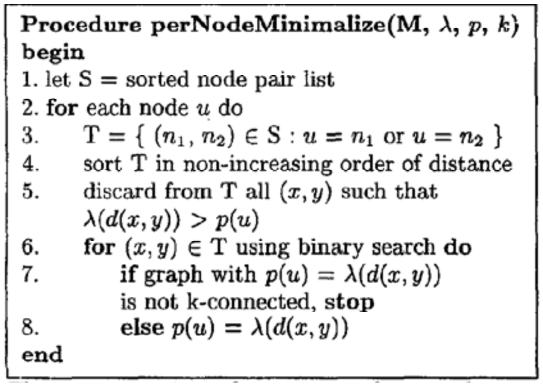


Algorithm BICONN-AUGMENT
Input: (1) Multihop wireless network M = (N, L) (2) Least-power function λ (3) Initial power assignment inducing connected network
Output: Power levels p for each node that induces a biconnected graph.

```
begin
sort node pairs in non-decreasing order
  of distance
G = graph induced by (A, $\lambda$, $p$)
for each $(u, v)$ in sorted order do
    if biconn-comp(G,u) $\neq$ biconn-comp(G,v)
        $q = \lambda$(distance(u,v))
        $p(u) = \max(q, p(u))$
        $p(v) = \max(q, p(v))$
        add $(u, v)$ to G
perNodeMinimalize(M, $\lambda$, $p$, 2)
end
```

A post-processing phase similar to that of Algorithm

CONNECT ensures per-node minimality. In this case, the solution may not be per-node minimal even in the absence of side-effect edges. Nonetheless, the same “fix” works, whatever the cause.



Procedure perNodeMinimalize(M, λ, p, k)

```
begin
let S = sorted node pair list
for each node $u$ do
    T = { $(n_1, n_2) \in$ S : $u = n_1$ or $u = n_2$ }
    sort T in non-increasing order of distance
    discard from T all $(x, y)$ such that
    $\lambda(d(x, y)) > p(u)$
    for $(x, y) \in$ T using binary search do
        if graph with $p(u) = \lambda(d(x, y))$
        is not k-connected, stop
        else $p(u) = \lambda(d(x, y))$
end
```

We note that, in practice, the per-node-minimality postprocessing phases for both CONNECT and BICONN-AUGMENT may be ignored. The few extra edges it introduces may be seen as an advantage. Indeed, if one were to build a biconnected network from scratch (that is, execute BICONN-AUGMENT immediately after CONNECT), there is no reason to make the connected graph per-node minimal. In our implementation, we have omitted per-node minimalization.

5. TOPOLOGY CONTROL IN MULTIHOP WIRELESS NETWORK

The absence of a central infrastructure implies that an ad hoc network does not have an associated fixed topology. Indeed, an important task of an ad hoc network consisting of geographically dispersed nodes is to determine an appropriate topology over which high-level routing protocols are implemented. In this section, we consider topology control, the problem of determining an appropriate topology in an ad hoc network. Let V denote the collection of nodes and let G denote the graph on V in which there is an edge from node u to node v if and only if u can directly reach v. Let T denote the topology returned by the topology control algorithm. The quality of the topology T can be evaluated according to several criteria including connectivity, energy-efficiency, throughput, and robustness to mobility. In the remainder of this section, we elaborate on these measures.

We consider a wireless ad hoc network consisting of a set V of n wireless nodes distributed in a two-dimensional plane. By a proper scaling, we assume that all nodes have the maximum transmission range equal to one unit. These wireless nodes dene a unit disk graph UDG(V) in which there is an edge between two nodes if and only if their Euclidean distance is at most one. In this survey, we concentrate on how to apply some structural properties of a point set for wireless networks as we treat wireless devices as two-dimensional points.

5.1 Connectivity and Energy-Efficiency

Perhaps, the most basic requirement of a topology is that it be connected. More precisely, we require that any two nodes that are connected in G also connected in T. Since the topology T forms the underlying network for routing protocols, it is also desirable that there exist energy-efficient paths between potential source-destination pairs. One notion of energy-efficiency is the *energy stretch factor*.

We would like to provide connectivity and energy-efficiency using a "simple" topology that is "easy" to maintain. While there is no single way to formalize "simplicity" and "maintainability", some objective measures that influence these subjective goals are the size of the topology in terms of the number of edges in T and the maximum degree of any node in T.

Connectivity, degree and size are network design measures common to both wired and wireless settings. Analogous to the notion of energy stretch factor is that of *distance stretch factor* (or simply the stretch factor) in fixed-connection networks, where the distance between two nodes is the length of the shortest path between the two nodes. The problem of designing topologies with low stretch factors has been extensively studied by network designers.

What distinguishes the topology control problem in the mobile ad hoc setting from traditional network design is that we need to determine the topology in a completely distributed environment. A number of distributed topology control algorithms have been proposed recently.These algorithms draw upon computational geometry techniques that define connected topologies on points in Euclidean space. The techniques, and the topologies obtained, vary in the degree of simplicity, the quality of the topology, and their suitability for distributed implementation. We now review some well-studied geometric structures and their associated topology control algorithms.

5.2 Throughput

In addition to connectivity and energy-efficiency, we would like to have a topology with high capacity or throughput; that is, it must be feasible to route "about as much traffic" in the topology as any other topology, satisfying the desired constraints. Depending on the network characteristics that are being studied and the traffic patterns being considered, one can formalize the notion of throughput of an ad hoc network in different ways.

Gupta and Kumar analyze the throughput of ad hoc networks under both the physical and protocol models of interference ,They define the throughput in terms of terms of a bit-distance product.

Suppose we say that the network transports one *bit-meter* when one bit has been transported a distance of one meter. Then, the throughput of a network can be measured in terms of the number of bit-meters that are transported per second. It is for n identical nodes randomly located in a disk of unit area, each node using a fixed transmission range, the throughput achievable for each source for a randomly selected destination.

The throughput-competitiveness of a topology depends on, among other factors, the level of interference inherent to the topology. Define the *interference number* of an edge e in T to be the maximum number of other edges in T that interfere with e, in the sense. Define the interference number of the topology to be the maximum interference number of an edge in T. A plausible goal then is to seek a topology with a small interference number. The particular interference number achievable, however, depends on the relative positions of the ad hoc network nodes and their transmission radii. This leads to the following open problem in network design: Given a collection of ad hoc network nodes, design a connected topology that minimizes the interference number. It seems unlikely that the preceding optimization problem can be solved effectively by a local algorithm; nevertheless, a centralized algorithm for the problem may be of theoretical interest.

5.3 Robustness to Mobility

An additional challenge in the design of distributed topology control algorithms is to ensure some degree of robustness to the mobility of nodes. One measure of robustness of the topology is given by the maximum number of nodes that need to change their topology information as a result of a movement of a node. This number, which may be referred to as the *adaptability* of the topology control algorithm, depends on the size of the transmission neighborhood of the mobile node u, and the relative location of the nodes. The topology control algorithms based on proximity graphs all have low adaptability, since a change in a node location will only require the nodes in its neighborhood (both old and new) to recompute their edges in the topology. The topology of is more complex since it relies on a hierarchical clustering of the nodes. Under certain assumptions about the distribution of points on the plane, however, they have shown that the number of nodes that need to be updated due to a change in the underlying transmission graph is proportional to the number of nodes in the immediate neighborhood of the mobile node, the update time per node being a constant. Other than maintaining the topology, mobility also entails changes in the routing paths.

6. ROUTING METHOD

In the previous section, we considered the design of topologies that have certain desirable properties in terms of connectivity, energy-efficiency, and throughput. We now consider the design of routing schemes that harness these properties. We note that while the presentation in this article follows the approach of separating the network design and routing scheme design components, the two components are closely intertwined. The choice of the particular topology control algorithm may have a strong impact on the choice of the routing scheme. Since the topology is constantly changing, the routing scheme has to be robust to changes in topology.

How do we analyze the efficiency of an ad hoc network routing protocol? One framework is to analyze the cost of individual routing requests using the measures namely, stretch and power stretch. Also relevant are the measures of adaptability and the memory overhead. The memory overhead is simply the size in bits of all the data structures used by the routing protocol.

6.1 Localized Routing

The geometric nature of the multi-hop ad-hoc wireless networks allows a promising idea: localized routing protocols. A routing protocol is localized if the decision to which node to forward a packet is based only on:

1 The information in the header of the packet. This information includes the source and the destination of the packet, but more data could be included, provided that its total length is bounded.

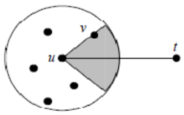
2 The local information gathered by the node from a small neighborhood. This information includes the set of 1-hop neighbors of the node, but a larger neighborhood set could be used provided it can be collected efficiently.

Randomization is also used in designing the protocols. A routing is said to be memory-less if the decision to which node to forward a packet is solely based on the destination, current node and its neighbors within some constant hops.

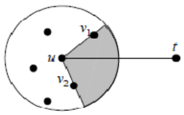
6.2 Localized Routing Protocols

We summarize some localized routing protocols proposed in the networking and computational geometry literature.

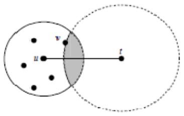
The following routing algorithms on the graphs were proposed recently



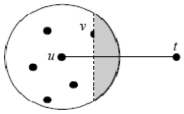
Compass



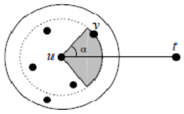
Random Compass



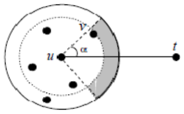
Greedy



Most Forwarding



Nearest Neighbor



Farthest Neighbor

Compass Routing: Let t be the destination node. Current node u finds the next relay node v such that the angle vut is the smallest among all neighbors of u in a given topology.

Random Compass Routing: Let u be the current node and t be the destination node. Let v1 be the node on the above of line ut such that angle v1ut is the smallest among all such neighbors of u. Similarly, we define v2 to be nodes below line ut that minimizes the angle v2ut. Then node u randomly choose v1 or v2 to forward the packet.

Greedy Routing: Let t be the destination node. Current node u finds the next relay node v such that the distance vt is the smallest among all neighbors of u in a given topology.

Most Forwarding Routing (MFR): Current node u finds the next relay node v such that v0t is the smallest among all neighbors of u in a given topology, where v0 is the projection of v on segment ut.

Nearest Neighbor Routing (NN): Given a parameter angle , node u finds the nearest node v as forwarding node among all neighbors of u in a given topology such that angle vut lessthan or equal to alpha.

Farthest Neighbor Routing (FN): Given a parameter angle , node u finds the farthest node v as forwarding node among all neighbors of u in a given topology such that angle vut lessthan or equal to alpha.

7. CONCLUSION

Wireless ad hoc networks has attracted considerable attentions recently due to its potential wide applications in various areas and moreover, the ubiquitous computing. In this survey, we present an overview of the recent progress of topology control and localized routing in wireless ad hoc networks. Nevertheless, there are still many excellent results that are not covered in this survey due to space limit.

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