VERTEX-LINKED INFRASTRUCTURE FOR AD HOC NETWORKS

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Abstract - An ad hoc network is composed of geographically dispersed nodes that may move arbitrarily and communicate with each other without the support of a stationary infrastructure. Compared with a wireless network with a stationary infrastructure, such as a cellular network, an ad hoc network is inherently less efficient. Therefore, a number of proposals have been made to develop a quasi-stationary infrastructure for ad hoc networks. However, the dynamic nature of ad hoc networks makes it very costly to maintain such an infrastructure. This article proposes a Vertex-Linked Infrastructure (VLI) for ad hoc networks. This novel approach uses an easily deployable, survivable, wired infrastructure as a backbone of the ad hoc network, thus realizing the advantages of an infrastructure in wireless communications, but without the overhead due to maintaining such an infrastructure.

Keywords: vertex-linked infrastructure, ad hoc network, *military communications, routing, hierarchical network.*

1 INTRODUCTION

An ad hoc network, also known as a multi-hop packet radio network, is composed of user nodes that may move arbitrarily and communicate with each other without the support of a stationary infrastructure. Research in such networks is initiated in the Defense Advanced Research Projects Agency (DARPA) packet radio network [1]. They may be used in emergency search-and-rescue operations, battle field operations and data acquisition in inhospitable terrains.

An ad hoc network is inherently less efficient than a wireless network with an infrastructure, such as a cellular network. The size of an ad hoc network may be quite large in some applications, e.g., communications in battle fields. As there is no wired infrastructure, the relatively limited wireless bandwidth is used to find and maintain routes as well as to transmit data. As its size grows, the amount of information required to be transmitted and to be maintained by each node in an ad hoc network grows exponentially. The problem is exacerbated by topological changes. A mobile ad hoc network is an autonomous system of nodes connected by wireless links, and nodes may move randomly and organize themselves arbitrarily. The topology of the network may change rapidly and unpredictably. When the current route is unusable, a new one must be re-established. This requires the transmission of many update and control messages in the precious wireless channel. With a wired infrastructure, as mobile nodes roam around the service area and get affiliated with different backbone nodes, such control messages can be transmitted in the relatively less congested wired channels. In addition, the two-level hierarchy of a backbone network, consisting of the backbone nodes, and the local access networks, each consisting of a backbone node and its affiliated mobile users, reduces the number of update messages required in the system. This is because the update messages only need to be propagated in the backbone network, and not in each individual local access network. In Chang and Li[2], a performance comparison is made between a packet radio network with such a two-level hierarchical structure and one which is fully distributed, and it is found that in terms of end-to-end throughput, the hierarchical structure outperforms the fully distributed network in most scenarios.

This is perhaps why, when there is a choice, as in most existing commercial systems, an infrastructure is used. Thus a cellular network has an infrastructure in the form of a wired network of stationary base stations, a satellite network, in the form of stationary ground stations, and a WiFi network, in the form of stationary access points.

In some applications, such as in a battlefield, it has traditionally been thought that a stationary infrastructure is impractical. After all, the fixed base stations will be easy targets for the enemy. However, even in such cases, because of the inherent advantages of having an infrastructure, there are various proposals for quasi-stationary infrastructures. The major difficulty with such approaches, however, is with the maintenance of the infrastructure. Therefore, it is desirable to have an ad hoc network design with a stationary infrastructure, thus eliminating the overhead due to infrastructure maintenance, and yet is practical and survivable in a hostile environment such as a battlefield. In this paper, we propose the concept of a stationary, wired infrastructure

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for an ad hoc network, called the Vertex-Linked Infrastructure (VLI). An ad hoc network operating with a VLI is called a VLINET.

The rest of this paper is organized as follows. In Section 2, we describe some of the existing quasi-stationary infrastructures employed in ad hoc networks. In Section 3, we introduce VLINET. Details on network operations, and topological and reliability considerations are included. In Section 4, we discuss ways to enhance the survivability of this proposed system, and consider optical fiber as a possible transmission medium. We conclude in Section 5.

2 QUASI-STATIONARY INFRASTRUCTURES

Although it is generally believed that a stationary infrastructure is impractical in a hostile environment, due to the inherent advantages of having an infrastructure, there are various proposals for ad hoc networks with quasi-stationary infrastructures.

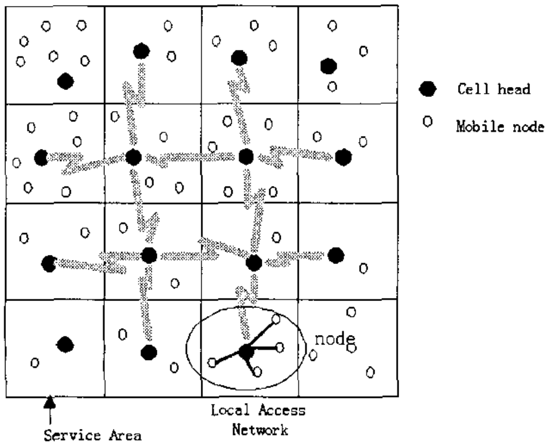

Fig. 1. Cellular Packet Radio Network.

For example, in the US High Frequency Intra-Task Force (HF-ITF) Network [3], the nodes in the network are organized into a set of clusters, each with a cluster head, and connected by a backbone network constituted from gateways and cluster heads. A distributed algorithm, called the Link Cluster Algorithm, provides the construction and maintenance of this two-level hierarchical organization. A critical assumption of this algorithm, which uses the Time Division Multiple Access (TDMA) technique to transmit control messages, is that each node must know the number of nodes in the network. This assumption may not hold in many applications. In Chang and Li[4], a Distributed Cellular Packet Radio Network (DCPRNET) is proposed. As shown in Fig. 1, the whole service area is divided into disjoint regions called cells. Each cell has a node elected as the cell head, which provides local network control functions, such as routing and flow control, to the nodes within the same cell. Each node is assumed to have Global Positioning System (GPS) capability, and with a map of the network layout, it knows which cell it is affiliated with. In other words, nodes are organized into clusters (local access networks) based on their geographical locations. The nodes will communicate with each other through the backbone network formed by the cell heads.

In Pond and Li[5,6], a hierarchical architecture for a distributed media access protocol is developed for the US Army's Enhanced Position Location and Reporting System (EPLRS)[7]. Again, the goal is to capture the advantage of reduced overhead available with a quasi-stationary infrastructure.

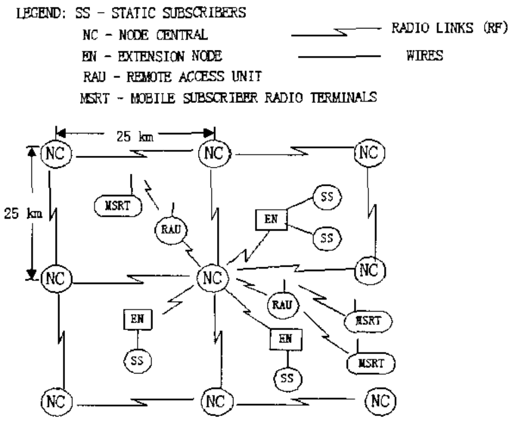

Fig. 2. The US Army Mobile Subscriber Equipment (MSE) Network.

The US Army Mobile Subscriber Equipment (MSE) Network[8], is another example. As shown in Fig. 2, MSE consists of an infrastructure with Node Centrals (NCs), Extension Nodes (ENs), and Remote Access Units (RAUs). All network elements are packaged on mobile platforms, but once deployed, will remain stationary. The EN's serve static subscribers, while the RAUs serve Mobile Subscriber Radio Terminals (MSRTs). An MSRT accesses its RAU by a radio link, from up to 15 km away. Each NC is typically connected by line-of-sight radios to four other NCs, with all the NCs located on a grid pattern with 25 km spacing. Each MSRT will be affiliated with an NC through its RAU.

Communications between two MSRTs will go over the backbone network formed by the NCs.

More recently, there have been a number of proposals to deploy a quasi-stationary backbone network in the form of Unmanned Airborne Vehicles (UAVs) above the service area. Each UAV serves as the cluster head of some nodes within its coverage area. The UAVs communicate with each other with radio links. Due to the vulnerability of the UAVs to enemy attacks, and the mobility of the mobile users, this quasi-stationary backbone infrastructure is again very costly to maintain.

3 VERTEX-LINKED INFRASTRUCTURE

Given the advantages available with an infrastructure, it is natural to ask if it is possible to come up with an ad hoc network design with a wired infrastructure, and yet is practical and survivable in a hostile environment such as a battlefield. We believe the answer is "yes." In this section, we propose the concept of a stationary, wired infrastructure, called the Vertex-Linked Infrastructure (VLI). An ad hoc network operating with a VLI is called a VLINET.

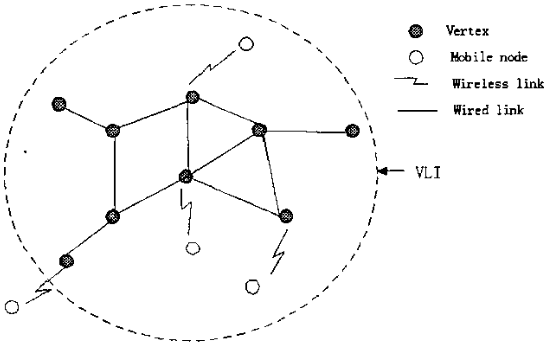

Fig. 3. The Vertex-Linked Infrastructure (VLI) Network

As shown in Fig. 3, a VLI consists of a collection of transceivers connected by wires in an arbitrary topology. In this paper, to distinguish between these transceivers, which are stationary once deployed, and the mobile users, we call the former vertices and the latter nodes. A VLI will be deployed, perhaps from the air, in the service area of interest. Mobile nodes communicate with each other through this infrastructure, in much the same way as in a cellular system. The following describes the details of the operations of a VLINET.

3.1 Network Initialization and Deployment

Since a VLI has a static topology, one can pre-determine the paths between any two vertices (transceivers) in VLI before deployment. The pre-determined paths from one vertex to all other vertices can be stored locally at each vertex. For example, we can employ a self-routing address scheme whereby the path to each destination is encoded in the destination address. For survivability, multiple addresses, each corresponding to a different path, can be encoded for each destination. More details are given in the next section on self-routing address design. Each vertex periodically broadcasts a beacon with its identity (ID). Each mobile user must first register with one of the vertices. If it receives beacons from multiple vertices, it can just pick one of them to register. Again, for survivability, we can allow a mobile to register at multiple vertices. Using the wired network, the vertices periodically send updates on mobile users registered locally to other vertices in the VLI. Thus each vertex has a complete picture of the vertex affiliation of each mobile user. Consider a mobile user A attempting to send to mobile user B. A will send the packet with B's ID to A's affiliated vertex in the VLI. This vertex looks up the affiliated vertex of B, put this vertex's address into the packet header, and send it. Due to the self-routing nature of the address, the packet will eventually arrive at the affiliated vertex of B, and subsequently delivered to B.

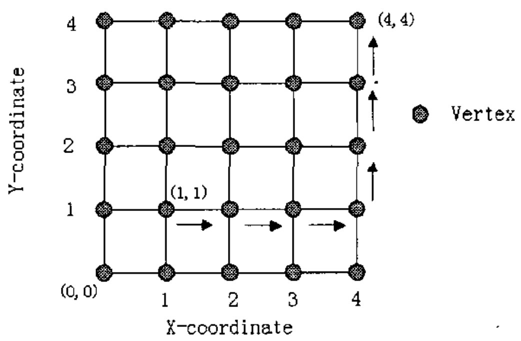

Fig. 4. A four by four grid network.

3.2 Self-routing Address Design

Various self-routing address designs have been proposed for networks with a regular structure, such as the Grid Network (GN). As shown in Fig. 4, in the GN, the vertices are laid out in a grid pattern, and each has an address equal to its (x,y) coordinates. When a packet is routed in the network, a comparison is made between the x-coordinate of the destination address and that of the local address. Depending on whether it is smaller or larger than the local address, the packet is transmitted to the next node to the west or to the east. If the x-coordinates are the same, then we compare the y-coordinates to see whether we should go north (when the destination y-coordinate is larger than the local y-coordinate) or go south (when the destination y-coordinate is smaller than the local y-coordinate). If both the x- and y-coordinates are the same, then we know we have arrived at the destination. Suppose we are at vertex (1,1) and the destination is (4,4). By doing these x- and y-coordinate comparisons at all the intermediate vertices, we will take the packet three hops east along the x-coordinate, and then three hops north along the y-coordinate. Note that if we randomize the order of comparisons, i.e., instead of always comparing the x-coordinates first, we may compare the y-coordinates first in some cases, we will be able to obtain all the possible paths between (1,1) and (4,4). A similar scheme can be developed for other topologies with regular structures, such as the Shufflenet, or a hypercube network. Recently, a self-routing scheme has also been developed for a network with an arbitrary topology [9].

4 DISCUSSION

In this section, we explore various enhancements of the basic VLINET described above, including flood search schemes, topological considerations, survivability considerations, and the choice of the transmission medium.

4.1 Additional Routing Schemes

The basic routing scheme for VLI as described in the last section relies on the self-routing address of vertices in the VLI. Thus, once the vertex with which the destination is affiliated is found, the packet will be routed to this vertex automatically. Since each address corresponds to a fixed path, for reliability purposes, multiple redundant addresses, each encoding a different path, will be required. In the unlikely event none of these pre-selected redundant paths is available, due to excessive losses of vertices and links, it is still possible to transmit to the destination by a flooding scheme. The nice property about a flood search scheme is that if a path exists from the source to the destination, it will be found. The price to pay is the large number of redundant flood search messages. For example, the basic flooding scheme employed by MSE, or some of the modified flood search schemes described in Li and Chang[10] may be used. A flood search scheme will of course only be used as a last resort.

4.2 Topological consideration

As is described in the last section, a VLI does not have to conform to a specific topology. It may be a regular topology such as a grid, a star, or a ring, or it may be any arbitrary topology which may be most suited to the service area of interest. In fact, a customized topology may be designed to suit the terrain of the service area. For survivability considerations, it is probably best to consider those topologies with multiple redundant paths between pairs of vertices.

4.3 Survivability considerations

For survivability, and for improved data transport capacity, it is possible to deploy multiple VLINETs in the same service area. When a particular region of the service area lacks coverage, due to some vertices or links being destroyed, or due to increased data transmissions, one can rapidly deploy additional VLINETs. The network operates in pretty much the same way as described in Section 3. The only difference is when the origin and destination nodes are affiliated with different VLINETs, and there must be some way for us to bridge different VLINETs. One possibility is to allow vertices to communicate with each other over the wireless channel. Presently, they communicate with each other through the wired channels, and the more precious wireless resources are reserved for mobile users. An alternative is to deploy wireless repeaters in the system, whose sole purpose is to bridge multiple VLINETs. Thus selected vertices in each VLI will be employed as gateways for communications with other VLIs. We are effectively introducing an additional layer of hierarchy, consisiting of the gateway nodes, in the system. As described in [9], the self-routing address scheme for arbitrary topology can be easily extended to multiple hierarchies.

4.4 Transmission medium

Another important consideration is the choice of transmission media in the VLINETs. We believe a fiber-based infrastructure will be desirable. Optical communications is less susceptible to interference such as Electromagnetic Pulse (EMP) generated by the enemy. It is also possible to have all-optical infrastructure with fiber links and all-optical switches. The major limitation in optical communications is the limited optical logic processing capability. Fortunately, the self-routing address scheme developed in [9] requires only simple single-bit optical processing and can be readily implemented with existing optical logic. In addition, with the development of radio on fiber technologies, it is possible to distribute the transceivers geographically within a service area. In Li et al.[11], we have developed RaFiNet, a radio-over-fiber implementation of a VLINET.

5 CONCLUSIONS

Compared with a wireless network with a stationary infrastructure, such as a cellular network, an ad hoc network is inherently less efficient. Therefore, a number of proposals have been made to develop a quasi-stationary infrastructure for ad hoc networks. However, the dynamic nature of ad hoc networks makes it very costly to maintain such an infrastructure. This article proposes a Vertex-Linked Infrastructure (VLI) for ad hoc networks. This novel approach uses an easily deployable, survivable, wired infrastructure as a backbone of the ad hoc network, thus realizing the advantages of an infrastructure, but without the overhead due to maintaining such an infrastructure.

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