CERIAS Tech Report 2001-01

Achieving Flexibility and Scalability: A New Architecture for Wireless Network

Yi Lu, Bharat Bhargava
Center for Education and Research in
Information Assurance and Security
&
Department of Computer Science, Purdue University
West Lafayette, IN 47907

Achieving Flexibility and Scalability: A New Architecture for Wireless Network*

Yi Lu Bharat Bhargava
Center For Education and Research in Information Assurance and Security
and
Department of Computer Sciences
Purdue University
West Lafayette, IN, U.S.A

Abstract *We present a Hierarchical Hybrid Network architecture for wireless networks. In such a network, mobile nodes are hierarchically organized into groups. Different groups can have different routing protocols. Mobile nodes communicate with nodes outside their groups through the group agents. The groups are highly autonomous. This architecture is flexible and scalable. We conduct experiments to compare the new architecture with Ad Hoc networks. The new architecture has a more stable topology and higher throughput when the number of mobile nodes is large. The objective of our research is to set up a survivable, secure mobile wireless network.*

Keywords: wireless, mobile, Ad Hoc, hierarchical

1 Introduction

Wireless networking provides users with network resources and connectivity irrespective of their locations. The applications of wireless networking are in nation security operations, rescue missions, and military communications. One key feature of wireless networking is *flexibility*. The users can take advantage of wireless connections with few limitations. Another feature is *scalability,* which implies that the performance of a network doesn't decrease with the growth of the number of users in the network. For instance, in a battlefield, a wireless network should cover hundreds even thousands soldiers.

1.1 Current Wireless Networks

There are two classifications of wireless networks [13]. One of them relies on some preexisting fixed infrastructure, such as wireless LANs and cellular wireless networks. This kind of wireless networks assume the presence of stationary base stations [1]. Base stations are connected through wired lines to form a fixed backbone. Each base station serves a geographical area called *cell*. Many mobile hosts (*MH*s) may be present in a cell. A mobile host can communicate with other nodes in the system only through the base station of the cell in which it is present. The communication link between a mobile host and the base station is wireless. Mobile hosts can move from one cell to another during a communication session and keep the connection "on the move".

A representative of the other class is Ad Hoc networks. In an Ad Hoc network, there is no fixed infrastructure such as base stations or mobile switching centers. Nodes of an ad-hoc network are mobile hosts with similar transmission power and computation capabilities. MHs that are within each other's radio range communicate directly via wireless links. Otherwise, they communicate through multi-hop routing (other mobile nodes forward message as routers) [2]. The location of a mobile host must be identified before a call to the mobile host can be established.

Infrastructure-based wireless networks are scalable [13]. Take the cellular wireless network as an example. A cellular phone user can connect to the network at any time in any place within a cell. If the cell can accommodate more users, this user will be connected without an affect on other users in the same cell. But such networks provide less flexibility because of their fixed base stations. When two users are out of the service area, even if they are not far away from each other, they cannot talk with their cellular phones.

*This research is supported by CERIAS and NSF grants CCR-9901712 and CCR-0001788. This paper is published in International Conference on Internet Computing (IC'2001), Las Vegas, June 2001.

Due to high flexibility, Ad Hoc networks are important in environments where wireless access to a wired backbone is either inefficient or impossible. But Ad Hoc networks have their weaknesses. One basic assumption for Ad Hoc networks is that all the network nodes have equal capabilities (all nodes are equipped with identical communication devices and are capable of performing functions from a common set of networking services) [4], which does not always hold in reality. Another drawback is the lack of scalability. The performance of an Ad Hoc network falls as the number of users increases.

1.2 Related Work

Many researchers are working on Ad Hoc networks. They improved the performance of Ad Hoc networks by designing new routing protocols [4] and adding new services [7][8].

1.3 Our Work

We think the weakness of an Ad Hoc network is inherited from its architecture. We designed a new wireless network architecture called Hierarchical Hybrid Network to achieve scalability as well as flexibility. The organization of the rest of the paper is as follows. Section 2 gives an overview of the design considerations of wireless network architecture. Section 3 presents the new architecture and discusses features of the architecture. In section 4, some experiments and the discussion of the results are provided. Section 5 discusses the research that will be done next. Section 6 summarizes the paper.

2 Design Considerations

We discuss criteria that are taken into account in the design of the new architecture.

2.1 Resource Issues

In a wireless network, most mobile nodes are portable computing facilities such as PDA, GPS, notebook computer, etc., equipped with portable wireless communication devices. These computing facilities have limited system resources, like memory, software, and low computing capabilities. Lightweight batteries may power these facilities along with their communication devices. The weak power and the limited battery life will impose restrictions on the transmission range, communication activity, and computational power of the communication devices. Such mobile nodes can hardly afford the overhead of forwarding packets for other nodes.

On the other hand, there may be some workstations in wireless networks, which are powered by heavy-duty batteries, equipped with high-speed communication devices. These workstations have enough system resources and computing power to forward packets. For instance, each soldier in a battlefield may have only portable computing facilities, while each battalion can have a powerful workstation mounted on a tank. When two soldiers cannot communicate each other directly, they can communicate through the workstation.

2.2 Mobility Model Issues

Mobility models are used to analyze newly designed systems or guide the design of new architectures. Random mobility model [14] is commonly used in the study of Ad Hoc networks. According to this model, the speed and direction of the motion in the new time interval have no relation to those of the motion in the previous time interval. This model will generate unrealistic individual motion like sudden stopping or sharp turning. The motion of an individual is independent from those of other individuals.

RPGM (Reference Point Group Mobility) is another mobility model that partitions the network into several groups [5]. Each group has a logical center. The center's motion defines the motion of the entire group. Each node in a group has independent random motion in addition to the group's motion. RPGM model is closer to the real world than random mobility model, because the members among a group tend to coordinate their movements. For example, in the battlefield, soldiers in the same company usually move to the same trajectory at the same speed from the perspective of a battalion or a brigade.

2.3 Traffic Model Issues

Although the networks are designed to allow *any* two nodes to communicate, the reality is that a small percentage of nodes in a domain are communicating outside of the domain at any given time. Many (if not most) hosts never communicate outside of their domain [3]. We can assume that a large portion of the traffic will be among the nodes in the same group. This assumption is reasonable in a hierarchical organization. For example, it is much more likely that communication will take place between two soldiers in the same battalion, rather than between two soldiers in two different brigades.

3 Hierarchical Hybrid Network

Based on the discussion in the previous section, we proposed a hierarchical wireless network architecture: *Hierarchical Hybrid Network*. We call it HH network.

3.1 The Architecture

First, we introduce terms and denotations that are used in the HH network architecture.

Definition 3.1: A *group* is a set of mobile nodes, each of which MAY directly communicate with other mobile nodes in the same group. Each group has a unique group ID. A mobile node in a group is either a *member* or a *group agent* of that group. A mobile node belongs to a group if and only if it is a member or a group agent of that group.

Definition 3.2: A *Critical node* is a mobile node that is a member of a group and a group agent of another group simultaneously. Its major function is to forward packets between these two groups.

Definition 3.3: A *Non-critical node* is a mobile node that belongs to only one group.

Assumption: A mobile node can belong to at most two groups.

Definition 3.4: Group A is *above* group B if and only if a member of A is a group agent of B or there is a group C such that A is *above* C and C is *above* B. Group B is *under* Group A if and only if A is *above* B. A is also called a *upper level* group to B, B is called a *lower level* group to A. Let G be the set of all groups, then *above* is a partial order of G.

Definition 3.5: A *domain* is a group along with all the groups that are under it. The group agent of that group is called the *domain agent* of that domain. Two domains are called *peer domains* if their domain agents are members of the same group.

Definition 3.6: The *closure domain* of mobile nodes X and Y is the smallest domain that contains both X and Y.

In the HH network architecture, all the mobile nodes are partitioned into groups. To simplify the discussion, we assume that each group has at most one group agent. If we conceive of links between a group agent and the other members in the same group, the network looks like a forest as shown in Figure 1. Mobile nodes in the same dotted circle are considered in the same group. The group agent and the group members of that group are represented by different shapes. The shadowed area represents a domain consisting of three groups.

In a hierarchical hybrid network, mobile nodes that belong to the same group may communicate directly via wireless link. If they are out of each other's radio range, they take other group members (and the group agent) in the same group as internal routers to communicate. Packets sent to a mobile node in another group must and only go through one or more group agents in the closure domain of the source and the destination. It leads to the most significant characteristic of a hierarchical hybrid network: Any packet coming into or going out of a specific domain must go through the corresponding domain agent.

Figure 1 also shows how a packet is sent from a mobile node A to another mobile node B.

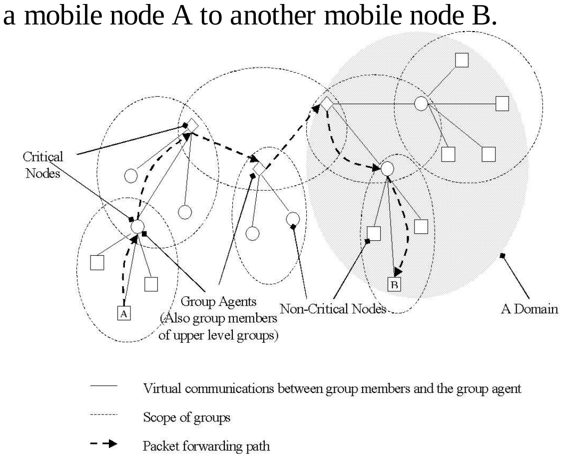

Figure 1 The Architecture

3.2 Routing in Hierarchical Hybrid Network

In HH networks, the peer domains are independent; traffic within one domain is not affected by the traffic in another domain. Thus peer domains can choose different routing schemes that are most suitable for them. That is the reason that the architecture is called “hybrid”. If different routing schemes are used, the domain agents must be able to support multiple routing schemes and the interoperation among them. A group agent must maintain the routing paths to all of its group members (if a group member can not be reached by the group agent, it is considered "out of group"). The routing paths can be set up by either path advertising or path discovering. A path advertisement is a 3-tuple <*destination*, *next-hop*, *sequence-number*>. Each mobile host maintains a sequence number for itself. This number is monotonically increasing. When a mobile host joins a group, it broadcasts a path advertisement with a new *sequence-number* and the *destination* and the *next-hop* set to itself. The following pseudo code shows how a mobile host handles a path advertisement.

if a path to the destination does not exist in the routing table
    add this path to the routing table;
    if this packet is sent by a mobile host that is in the group for which I am the group agent
        change the next-hop to my address and broadcast the advertisement to the group to which I am a member;
else if the new sequence-number is greater than the old one
    update the path;

When a mobile node forwards a packet, it checks the routing table. If the routing path to the destination exists, it forwards the packet to the next hop on the path; otherwise, it gets the routing path to its group agent and forwards the packet to the next hop on that path.

3.3 Mobility Support

A mobile system allows mobile nodes to roam within the network, and nodes' roaming is transparent to the upper level protocol such as TCP. Mobile IP [10] is the most widely used protocol to achieve network mobility. When a mobile host travels to a foreign subnet of the system, it will be assigned a "care of address", which is its temporary IP address in this subnet, by the foreign agent. Then a "tunnel" will be set up between its Home Agent and the "care of address". All the IP packets destined to the mobile host are captured by the home agent and transmitted to the "care of address". Mobile IP provides some extent of security to protect both the home and the foreign subnets. It requires the mobile host to authenticate itself with the home agent before the tunnel can be set. Nevertheless, Mobile IP is not an ideal solution for wireless networks, because the tunnel will consume unnecessary bandwidth. It is a big issue in wireless networks since bandwidth is so limited.

Ad Hoc networks use another way to provide mobility. Routing paths in an Ad Hoc network are highly dynamic. When a mobile host moves to a new point of the system, the routing path to this host changes, so that the packets destined to this host can be delivered correctly. However, this method lacks of security.

Our approach for supporting mobility in HH networks is the combination of these two schemes. The routing path to a mobile host changes when it moves to another group, but before the foreign group agent forwards packets for this host, it will authenticate the host with the home group agent. This approach can protect wireless networks against unauthorized intruders.

3.4 Features

HH networks have the following features.

- *Flexible*: No fixed infrastructure is required to set up the whole system. The topology of the system can change to fit the terrain, climatic, radio communication conditions, etc. It is highly flexible.
- *Scalable*: When a mobile node moves, the link status of its neighbors will be changed (i.e., link lost, link set up). In Ad Hoc networks, the link status changed information will be propagated to the whole system. This propagation will consume the limited bandwidth. The more mobile nodes are present in a network, the more overheads are introduced by the propagation. It results in the lack of scalability. In a HH network, a group is represented by its group agent in the *above* group. All the packets sent to the members of that group from outside are directed to the group agent. So, the movement of a member in any group only affects its peers in the same group (no propagation outside the group). Thus, scalability is achieved in HH networks.
- *Less resource requirements*: In an Ad Hoc network, every node maintains a routing table in memory that records the routing paths to all the nodes in the network. Assume the size of each entry in the routing table is 64-byte and the network has 1000 mobile nodes. The size of the routing table is about 64K bytes. In HH networks, every

mobile node only maintains the routing paths to the members in the same group. In addition, the domain agent will keep the routing information to the mobile nodes in its domain. A group may contain about ten members. So the size of the routing table of each non-critical node is only about 640 bytes.

In a hierarchical hybrid network, most packets forwarding is done by different level group agents. So the resource requirements for a non-critical host are minimized. But in Ad Hoc networks, any mobile host with poor computation capability and low radio communication band is a potential problem. Once this host is chosen to forward packets for other nodes, the performance of the whole system will suffer.

- *Highly Autonomous*: Each domain can choose different routing protocols that are suitable for their requirements and resources. For example, a network contains two domains. In one of them, nodes move slowly and most of the traffic is among a certain set of nodes, Dynamic Source Routing is used in this domain. In the other domain, the routing paths change frequently and the traffic is totally random. Destination-Sequenced Distance Vector routing algorithm can be applied in this domain.
- *Secure*: All the traffic in or out a domain must go through the domain agent. It is easy for the domain agent to enforce security checks on all the incoming and outgoing packets. Each domain may have its own domain-specific security policy. Domains with highly sensitive data may only accept packets from trustworthy nodes.

4 Experiments

Our research focuses on highly mobile environments with no stationary hosts. Ad Hoc networks are base references when evaluating HH networks in our experiments.

4.1 Experimental Environment

We use *ns2* (network simulator) to set up the experimental environment. *Ns2* currently supports Ad Hoc wireless networks and DSDV (Destination-Sequenced Distance Vector) [12], TORA (Temporally-Ordered Routing Algorithm) [9], AODV (Ad-Hoc On-Demand Distance Vector) [11], and DSR (Dynamic Source Routing) [6] routing algorithms. To carry out the experiments for HH networks, we made extensions to *ns2*. We modified the link layer implementation so that packets will carry group information. We designed a basic prototype of HH networks and implemented a hierarchical routing protocol. We added a new agent, through which mobile nodes can be organized as hierarchical groups. We implemented a tool to specify the motions of mobile nodes using RPGM model. We modified the TCPSink implementation so that the throughput can be counted.

4.2 Experiment on Link Change

In a wireless network, the frequency of the network topology changing greatly affects the performance of the system. Changes in network topology are mainly caused by link changes (link up, link down). We study the changes in the network topology by monitoring link status.

We set up an Ad Hoc network and a HH network with the same number of mobile nodes. The corresponding nodes in the two networks have the same motion behavior. These mobile nodes are divided into two groups. The experiment simulates a wireless network in a 670mx670m area. The link changes in the first 200 seconds of the simulation are recorded. We conducted the experiments as follows:

Input parameters: The number of mobile nodes in the network, the moving range of each mobile node, and the distance between the two groups.

Results: The results shown in Figure 2 indicate how the movement of the mobile nodes will affect the changes in the topology of a network.

Observations:

- The link change rate in the HH network is about half of that in the Ad Hoc network as shown Figure 2 (a).
- Figure 2 (b) and (c) show when the moving range increases or the distance between two groups decreases, the link change rate of the Ad Hoc network increases from about 300 to 600. However, link change rate of the HH network stays between 250 and 300. It shows that the interference between groups is trivial in HH networks.

Conclusion: HH networks suffer fewer overheads introduced by topology changing than Ad Hoc networks.

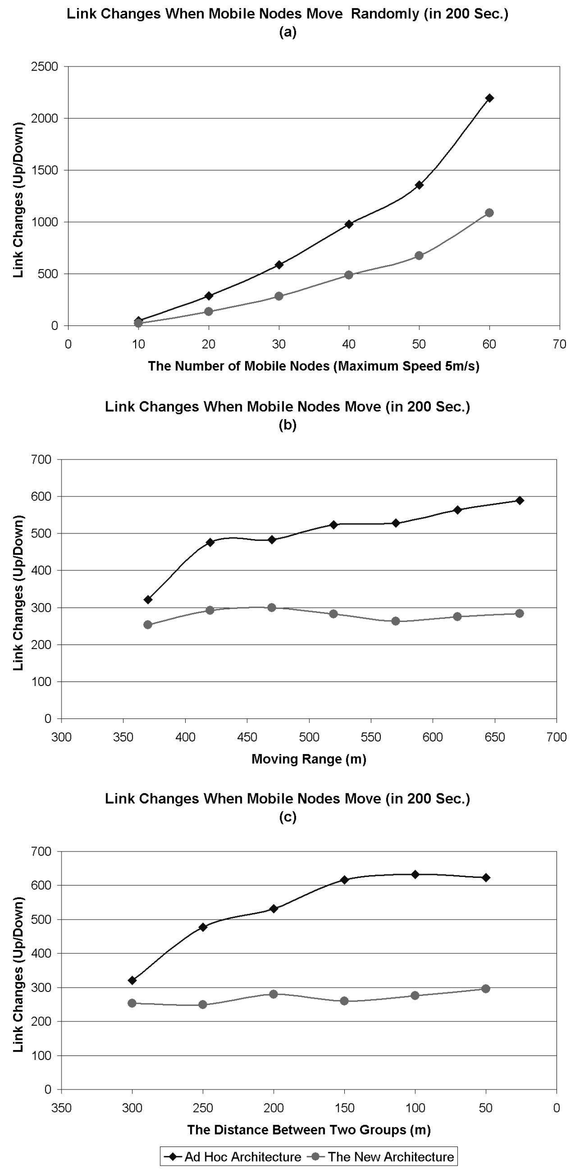

Figure 2 Results of Experiments on Link Change

4.3 Experiment on Throughput

Although the previous experiment shows that the HH network has a more stable topology when mobile nodes move, it does not mean that the HH network has a better performance in a general sense. In this experiment, we study the throughput of HH networks.

Because the movement of mobile nodes greatly affects the throughput of wireless networks, it is not proper to simply count how many packets or bytes are received when the number of mobile nodes increases. Instead, we set up an Ad Hoc network and a HH network with the same number of mobile nodes. The two networks have the same motion behavior and the same connection pattern (the same TCP connections). We count the bytes received in each network respectively, and then take the throughput of the Ad Hoc network as a reference to measure the throughput of the HH network. We repeat the experiment several times and use statistical method to analyze the throughput.

This experiment simulates a wireless network in a 1200mx1200m area. Mobile nodes are moving at maximum speed 3m/s. The mobile nodes in the HH network are organized as groups, each of which has 10 nodes. The throughput in the first 200 seconds of the simulation is monitored.

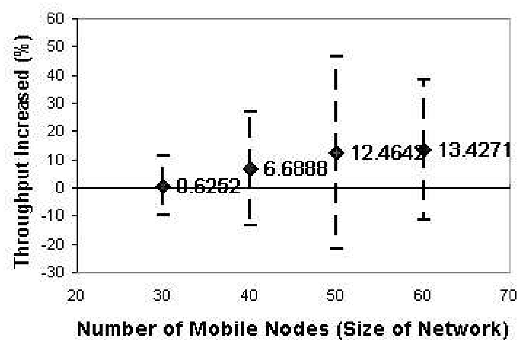

Figure 3 Throughput Comparisons

Input parameter: The number of mobile nodes.
Results: Figure 3 is a visual view of the result. The dots show the average increments of the throughput, comparing the HH network with the Ad Hoc network. The dotted lines indicate the average of the absolute deviations.
Conclusion: This experiment shows that the HH network has better throughput than the Ad Hoc network when the network size grows.

DSDV routing algorithm is used in the Ad Hoc network, because it is used as the routing protocol within a single group in our hierarchical routing algorithm.

In addition, the group agents have packet queues of length 60, and other nodes have packet queues of length 20 (it illustrates that group agents have more system resources). The corresponding nodes in the Ad Hoc network have the same settings.

5 Future Work

Although the existing routing protocols for Ad Hoc networks, such as DSDV, TORA, DSR and AODV can be modified and used in HH networks, they are not designed to take advantages of hierarchical architecture. We plan to design and implement a hierarchical routing protocol that supports different within-group routing algorithms in a uniform framework.

Survivability and secure communications are essential in mobile wireless networks. We proposed two fault-tolerant authentication schemes. The Hierarchical Authentication Scheme [1] can be seamlessly integrated with the new wireless network architecture. Further study will focuses on how the Virtual Home Agent Scheme can contribute to improve the survivability of hierarchical hybrid networks under hostile attacks.

6 Conclusions

In this paper, we discussed a new wireless network architecture *Hierarchical Hybrid Network* for achieving flexibility and scalability. In a HH network, mobile nodes are organized as hierarchical groups. Mobile nodes communicate with nodes in other groups through their group agents. We implemented a prototype and conducted experiments to compare HH networks with Ad Hoc networks. The results of the first experiment show that the HH network has lower link change (link up/down) rates when mobile nodes move. In the second experiment, when the number of mobile nodes is 30, the throughputs of the HH and the Ad Hoc network are almost the same, but when the number of mobile nodes increases to 60, the throughput of the HH network is about 13% higher than that of the Ad Hoc network.

References

[1] B. Bhargava, S. Kamisetty, and S. Madria. Fault-tolerant authentication in mobile computing. In *Proc. of Intl. Conf. on Internet Computing (IC'2000)*, pp 176-185, Jun. 2000

[2] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. *The fourth Annual ACM/IEEE Intl. Conf. on Mobile Computing and Networking*, pp 85-97, Oct. 1998

[3] K. B. Egevang, C. Communications, and P. Francis. The IP network address translator (NAT). *RFC 1631*, May 1994

[4] Z. J. Haas and M. R. Pearlman. Providing Ad-Hoc connectivity with reconfigurable wireless networks. *Ad Hoc Networks*, 2000

[5] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang. A group mobility model for Ad Hoc wireless networks. In *Proc. of the 2nd ACM Intl. Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, pp 53-60, 1999

[6] D. B. Johnson and D. A. Maltz. Dynamic source routing in Ad Hoc wireless networks. *Mobile Computing*, pp 153-181, 1996

[7] J. Li, J. Jannotti, D. S. J. D. Gouto, D. R. Karger, and R. Morris. A scalable location service for geographic Ad Hoc routing. In *Proc. of the 6th Annual Intl. Conf. On Mobile Computing and Networking*, pp 120-130, Aug. 2000

[8] B. Liang and Z. J. Haas. Virtual backbone generation and maintenance in Ad Hoc network mobility management. *IEEE INFOCOM'2000*, Mar. 2000

[9] V. D. Park and M. S. Corson. A highly adaptive distributed routing algorithm for mobile wireless networks. In *Proc. of INFOCOM'97*, pp 1405-1413, Apr. 1997

[10] C. Perkins. IP mobility support. *RFC 2002*, Oct. 1996

[11] C. Perkins. Ad Hoc on demand distance vector (aodv) routing. *IETF Internet draft*, 1997

[12] C. E. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers. In *Proc. of the SIGCOMM'94 Conf. on Communications Architectures, Protocols and Applications*, pp 234-244, Aug. 1994

[13] U. Varshney and R. Vetter. Emerging mobile and wireless networks. *Communications of the ACM*, 43:73-81, 2000

[14] M. M. Zonoozi and P. Dassanayake. User mobility modeling and characterization of mobility patterns. *IEEE Journal on Selected Areas in Communications*, pp 1239-1252, Sep. 1997