A HYBRID FORWARDING APPROACH FOR THE MESH-BASED GEOCAST ROUTING PROTOCOL IN AN AD HOC NETWORK

by
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ABSTRACT

An ad hoc network is a multi-hop wireless network, which has no fixed infrastructure, that is formed dynamically by the mobile nodes. Typical application areas of an ad hoc network include rescue sites, battlefields or disaster scenarios.

In an ad hoc network, the ability to send a message to a group of users, based solely on their geographic location, is called geocast communication. Geocast communication is a variant of multicast communication. There are two categories of multicast protocols proposed for geocast communication: tree-based and mesh-based protocols. Previous studies showed that a mesh-based routing protocol is more robust against frequent topology changes than a tree-based routing protocol. This thesis focuses on the improvement of a geocast routing protocol, i.e., the mesh-based geocast routing protocol.

To reduce the size of the forwarding zone, the mesh-based geocast routing protocol defined several individual forwarding approaches (FAs) to transfer control and data packets. We propose a new FA, the HYBRID FA, which combines the individual FAs by having an FA chosen dynamically (based on the network environment) in real time. Our simulation results show that our HYBRID FA significantly improves the transmission reliability without a significant increase in control overhead.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

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CHAPTER 1

INTRODUCTION

An ad hoc network is formally called a Mobile Ad hoc NETwork (MANET). A MANET consists of mobile nodes and has no fixed infrastructure. Thus, nodes join and leave the network randomly. An ad hoc network is formed dynamically compared with conventional wired networks and wireless networks, the latter of which relies on a central base station. A MANET is also called a decentralized network, as every node performs the functions of both host and router.

The MANET technology has been developing for more than 20 years. Its original funding principally came from the U. S. Government (Joseph et al, 1999). The initial sponsors include the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR).

Due to the fast development of microcomputer chips and other telecommunication equipment, many portable computer-based devices now exist in our everyday lives. For example, laptops, Personal Digital Assistants (PDA) and cellular phones are so popular and convenient that people, even in developing countries, use them extensively for both their personal and business activities. Since portable devices form the mobile nodes in a MANET, these recent advances make an ad hoc network possible and practical.

Due to the features of an ad hoc network's mobile node, a MANET has several salient characteristics (Joseph et al, 1999), which conventional wired networks and common wireless networks do not have. These features include:

- dynamic topologies,
- bandwidth-constrained and variable capacity links,
- power-constrained operation, and
- limited physical security.

The above are both constraints and challenges for developing a MANET. From the viewpoint of routing protocol design, each mobile node's mobility helps create an extremely dynamic topology. Improving the accuracy of data transfer as well as keeping the network overhead low is two of the biggest challenges for MANET research groups.

There are numerous scenarios in which the established conventional network facilities cannot be used by mobile devices desiring communication. For example, in rescue or emergency operations, if a natural or environmental disaster has demolished the previous infrastructure, people need rapid installation of a communication infrastructure. Another example is with commercial projects. There is a need for simple installation of a communication infrastructure for commercial gatherings such as conferences, exhibitions, workshops and meetings.

This thesis concerns geocast communication in an ad hoc network. Geocast communication refers to sending data packets to a specific geographic area in a network. For example, in a natural disaster rescue scenario, we may want to send an alert message to “south of Washington street in Golden”. The goal of the geocast routing protocol is to have all mobile nodes within the specified area receive the alert message. As illustrated in the above example, geocast communication uses location information to route packets. Location information can be provided by many sources, e.g., the Global Positioning System (GPS) (National Air and Space Museum, 2000). In this thesis, it is assumed that every mobile node knows its own geographical location.

Within the area of developing more efficient protocols for geocast communication, this thesis focuses on the improvement of a “mesh-based” geocast protocol in an ad hoc network. The rest of this thesis is organized as follows: geocast communication is introduced in detail in Chapter 2, a new protocol is discussed in Chapter 3, simulation work to compare the new geocast routing protocol with previous geocast routing protocols is described in Chapter 4, simulation results and analysis are given in Chapter 5, and conclusions and future work is included in Chapter 6.

CHAPTER 2

GEOCAST ROUTING PROTOCOLS FOR MANETS

Wide deployment of GPS will make a users' location information as common as the date is today (Navas, et al, 1997). Geocast communication is one of the example applications related to location information. It is a variant of multicast transmission. In geocast communication for an ad hoc network, a message is sent to a group of mobile nodes within a particular geographical region, i.e., the geocast region. In multicast communication for an ad hoc network, a message is sent to a group of mobile nodes that join a group explicitly. In other words, a multicast group is composed of several group members who join the group in order to hear the multicast communication. While a multicast group member may exist anywhere in the MANET, a geocast group member is defined by its geographical location. As mentioned in Chapter 1, this thesis assumes every mobile node knows its location. In this chapter, a detailed examination of geocast routing protocols is offered: addressing the physical location in network systems is introduced in Section 2.1, routing protocols using location information are described in Section 2.2, and a mesh-based geocast routing protocol for an ad hoc network is specified in Section 2.3.

2.1 Geocast – geographic addressing and routing

In (Navas, et al, 1997), the authors designed both the geographic addressing models and geographically routing methods for a wired network. “The main purpose is to integrate the concept of physical location into the current design of the Internet which relies on logical addressing” (Navas, et al, 1997).

In order to address a geographic destination, the following closed geometric units are used:

- point,
- circle (center point, radius), and
- polygon (point(1), point(2), …, point(n-1), point(n), point(1)).

Point and polygon are the units used in our simulations to represent a mobile node’s location and a geocast region, respectively. Specifically, a rectangle represents the geocast region and a point represents a geographical location (see Section 4.3).

Examples of representing locations with points follows:

> Two-dimensional GPS positioning offers latitude and longitude information as a two dimensional vector, <latitude, longitude>, where longitude ranges from –180 (west) to 180 (east), and latitude ranges from –90 (south) to 90 (north).
>
> Thus < 40.48640, -74.45513 > is an example of the GPS coordinates for the town of New Brunswick, New Jersey, U.S.A (Navas, et al, 1997).

Three methods are detailed in Navas and Imielinski’s paper for achieving geographically-routed messages: a geographically-aware router solution, a multicast solution, and a Domain Name Service (DNS) solution (Navas, et al, 1997). In particular, the authors describe a geographically-aware router solution which uses the polygonal geographic destination information in the message header for routing. This is similar to the geocast header used in our simulations (see Section 4.2).

2.2 Location-aided routing protocols

To accomplish the goal of geocast communication, a geocast routing protocol must use location information. Currently, there are four proposed protocols that use location information for routing unicast packets in a MANET.

Distance Routing Effect Algorithm for Mobility (DREAM) is one of the unicast routing protocols that uses location information to route packets in an ad hoc network (Basagni, et al, 1998). In DREAM, the source node uses its location table to construct a circle centered on the last known location of the destination node. The radius of the circle is determined by the knowledge of the velocity of the destination node, perhaps using a probability distribution for the destination node's velocity. The source node defines a request zone as the area enclosed by an angle whose vertex is the source node and whose sides are tangent to the circle believed to contain the destination node (see Figure 2.1). The source node then sends its packets to all one-hop neighbors in the request zone. In other words, packets are forwarded in the request zone instead of in the entire ad hoc network. Each of these neighbors computes a new request zone based on the neighbors' location tables and then forwards the packet accordingly.

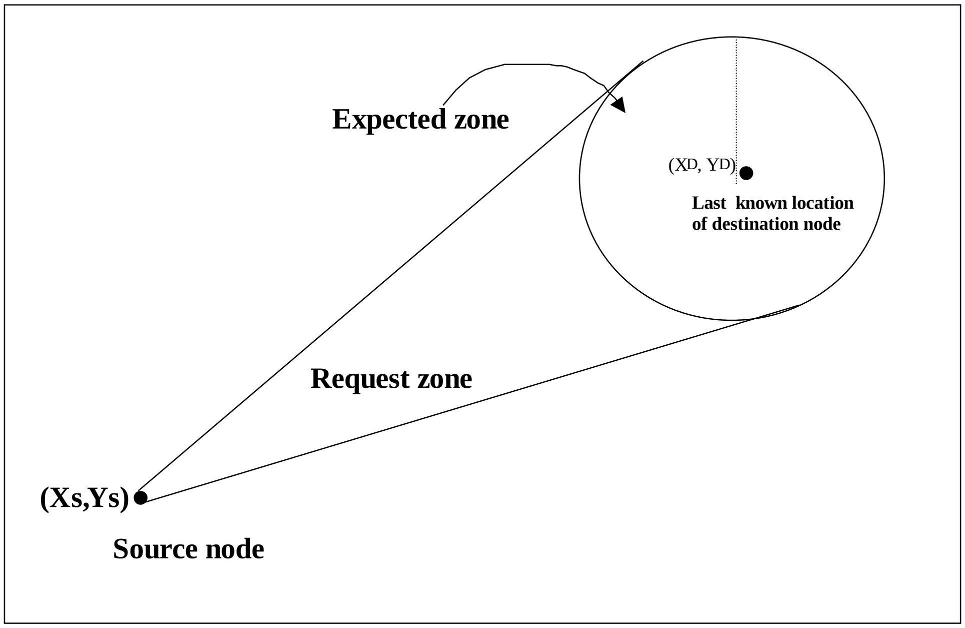

Figure 2.1: Request zone in DREAM.

The Location Assisted Routing (LAR) protocol (Ko et al, 1998) is another a unicast routing protocol that uses location information to route packets in an ad hoc network. LAR is similar to DREAM in that the expected zone for the destination node is a circle formed around the last known location of the destination. LAR is also similar to DREAM in use of a request zone, instead of the whole network, to forward packets.

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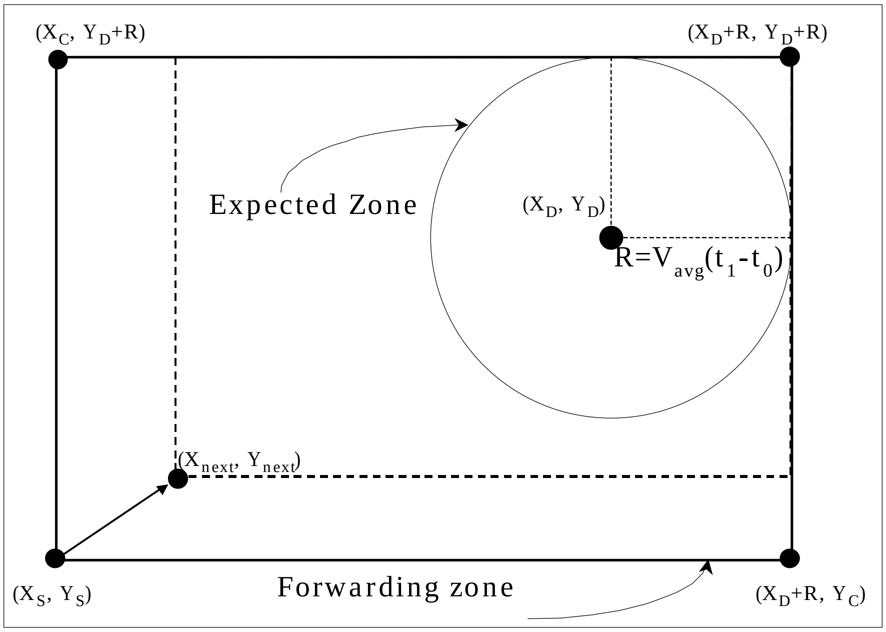

Figure 2.2 Forwarding zone formed in algorithm 1 of LAR.

However, LAR uses a different method than DREAM to define the forwarding zone (known as the request zone in DREAM). In LAR, two algorithms are proposed to define the forwarding zone. The first algorithm is similar to that of DREAM, except the forwarding zone is defined as a rectangle instead of an angle (see Figure 2.2). In the second algorithm, a node decides whether to forward a packet by comparing its distance and its neighbor’s distance (i.e., the neighbor that sent the node the packet) to the center of the expected zone. If the node is closer to the destination than its neighbor, it will forward the packet; otherwise, it drops the packet because its neighbor is closer than the node to the expected zone.

Recently, two more unicast routing protocols that use location information to route packets in an ad hoc network have been proposed. The first is called Greedy Perimeter Stateless Routing (GPSR) (Karp, et al, 2000). GPSR uses the positions of neighbors and a packet’s destination to make packet-forwarding decisions via two algorithms. In the greedy forwarding algorithm, a packet is unicast to the neighbor that is closest to the destination. The perimeter forwarding algorithm is used when greedy forwarding fails. Perimeter forwarding is used to forward packets around a “void” (i.e., no neighbors are closer to the destination) in the network.

The last unicast routing protocol proposed that uses location information to route packets in an ad hoc network is the Geographical Routing Algorithm (GRA) (Jain, et al, 2001). Similar to GPSR, GRA uses a greedy forwarding algorithm until a packet becomes stuck (i.e., no neighbors are closer to the destination). In this situation, GRA uses a route discovery algorithm to locate a route to the destination.

The authors of LAR have developed two protocols for geocast communication in an ad hoc network. In the first protocol, which is called the Location-Based Multicast Algorithm (LBM), LAR is extended to provide geocast communication (Ko, et al, 1999). The proposed protocol limits the forwarding of a multicast packet to the forwarding zone in LAR, which results in lower message deliver overhead compared to flooding the multicast packet.

In the second protocol, a unicast routing protocol called the Temporally Ordered Routing Algorithm (TORA), which was developed by Park and Corson (Park, et al, 1997), is extended to provide geocast communication (Ko, et al, 2000). This new protocol is called Geo-TORA. We refer interested readers to (Ko, et al, 2000).

2.3 Mesh-based multicast routing protocols

Since geocast communication is similar to multicast communication from the view point of having group recipients, we introduce multicast communication and how multicast routing protocols handle the mobility of mobile nodes in an ad hoc network. When an application needs to send the same information to more than one destination, multicasting is often used; multicasting is more advantageous than multiple unicasts in terms of the communication costs. A multicast group is a collection of hosts that register to receive the multicast communication.

There are two main categories of multicast protocols developed for static networks: source tree-based approaches (Deering, et al, 1993) and core-based approaches (Ballardie, et al, 1993). However, both types of multicast protocols suffer from weak performance due to the frequent tree maintenance cost and resource-constraints of mobile nodes in an ad hoc network environment.

Recently, mesh-based approaches have been developed in order to avoid the problems of using source tree-based and core-based multicasting protocols in a MANET (Lee, et al, 1999, and Garcia-Luna-Aceves, et al, 1999). A mesh is a subset of the network topology that provides multiple paths between multicast senders and receivers. Redundancy in the paths helps keep routes between senders and receivers, even if a mobile node in the mesh moves.

In the On-Demand Multicast Routing Protocol (ODMRP) (Lee, et al, 1999 and Chiang, et al, 1998), the multicast protocol is a mesh-based approach rather than the traditional tree-based approach. There are two phases in ODMRP: request phase and reply phase. While the multicast source has packets to send, it floods a periodic JOIN-REQUEST (JR) packet (the request phase) throughout the ad hoc network. When a node receives a non-duplicate JR packet, it stores the upstream node ID (i.e., the ID of the neighbor that transmitted the packet) and rebroadcasts the packet to its neighbors. If a JR packet reaches a multicast receiver, the receiver updates its member table and broadcasts a JOIN TABLE (JT) packet to its neighbors (the reply phase). The receiver augments the JT packets with the ID of the neighbor that transmitted the JR packet. If a node that is not a multicast receiver receives a JT packet with it's ID as the upstream node, it knows it has become a part of the forwarding group (FG). The node then rebroadcasts the JT packet with its stored upstream node ID. A mesh is formed as the JT packets are received by the source. Since multiple JT packets may be transmitted by the multicast receivers, multiple paths are created between the source of the JR packet and the multicast receivers. Simulation results illustrate a mesh maintains connectivity of the multicast group more effectively than a tree in times of high mobility. FG nodes cache messages so duplicate JT packets are not transmitted. Figure 2.3 provides an example of ODMRP (Lee, et al, 1999).

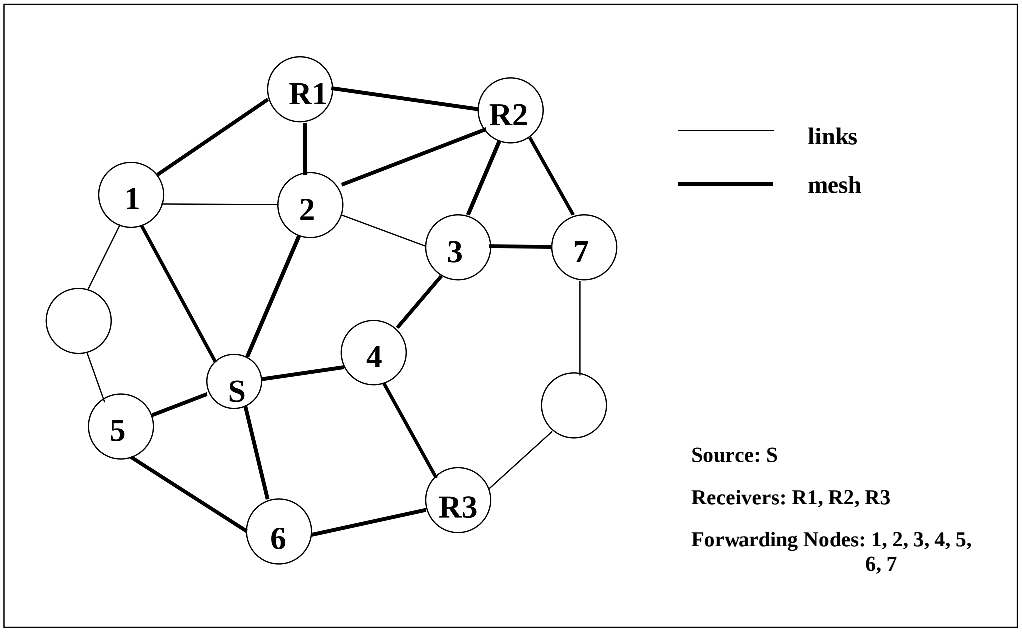

Figure 2.3: A mesh formed in ODMRP.

The Core-Assisted Mesh Protocol (CAMP) is another proposal for multicast communication in an ad hoc network that extends the connectivity of trees into meshes (Madruga, et al, 1999). Similar to ODMRP, CAMP has both a request phase and a reply phase. However, in CAMP, “cores are used to limit the control traffic needed for receivers to join multicast groups” (Madruga, et al, 1999). Each multicast communication may have multiple cores. In fact, a core does not need to be part of the mesh to aid the multicast group. If a node is able to use the core to join the group, then control overhead to process the join is reduced. However, a node can still join a group without using a core.

Compared with tree-based multicast routing protocols, both ODMRP and CAMP provide redundant paths from multicast sources to multicast receivers. Since a change in the network topology has less effect on multiple paths, a mesh-based multicast protocol can work more efficiently in an ad hoc network. A mesh is used in our geocast protocol to establish multiple paths between each source node and the geocast region (see Chapter 3 for details).

Combining the ideas of previously developed location-aided routing protocols (Section 2.2) and mesh-based multicast routing protocols (Section 2.3) for an ad hoc network, Boleng, et al, developed a mesh-based geocast routing protocol for an ad hoc network (Boleng, et al, 2001 and B. Williams, et al, 2001). In Section 2.4, the protocol is specified in detail.

2.4 A mesh-based geocast routing protocol

In Section 2.3, we discuss protocols developed for multicast communication in an ad hoc network environment; as mentioned, a meshed-based protocol is superior since it provides redundant paths between each source node and the geocast region. In other words, a mesh-based protocol is much more efficient than other protocols in reducing the fragile tree problem in a dynamically changing topology (M. Gerla, et al, 1999). Boleng, et al, give further explanation for using a mesh in their protocol as follows (Boleng, et al, 2001):

> Since the group members in a geocast communication are, by definition, in close proximity to each other, it is less costly to provide redundant paths from a source to a geocast region than it is to provide redundant paths from a source to a multicast group of nodes that may not be in close proximity to each other.

In Section 2.4.1 and 2.4.2, we give details on how this mesh-based geocast protocol functions. In Section 2.4.3, we present data from the performance evaluation of the protocol.

2.4.1 Mesh construction between a source and the geocast region

In the mesh-based geocast protocol from (Boleng, et al, 2001), a JOIN-DEMAND (JD) packet is periodically sent by a source node when the source node has information to send to the geocast region. A JD packet has the same function as the JR packet in ODMRP and CAMP; however, a different name delineates that all mobile nodes (MNs) in the geocast region *must* join the geocast group. The protocol uses an implicitly defined geocast group (defined by the geocast region) and ensures that all reachable MNs in the geocast region receive each geocast packet transmitted.

A JD packet is forwarded until it reaches a node within the geocast region. The node within the geocast region, i.e., a geocast group member, responds to the JD packet by sending a JT packet to the source node along the reverse path. The JT packets establish paths in the mesh between the source node and the geocast region. The data packets are then routed by the paths in the mesh.

2.4.2 Constructing a forwarding zone

There are three different forwarding approaches (FAs) to forward the JD packets to the geocast region. In the first FA, the JD packets are flooded throughout the ad hoc network. This FA, which is similar to flooding the JR packets in ODMRP, is called FLOOD. An example of a mesh created by the FLOOD FA is illustrated in Figure 2.4.

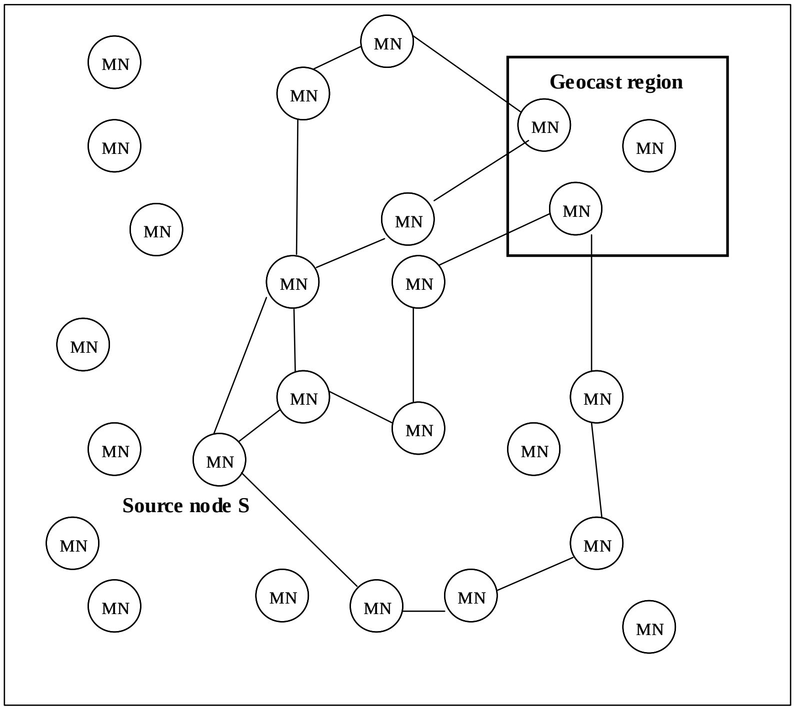

Figure 2.4: Mesh created by FLOOD FA (Boleng, et. al, 2001).

In the second and third FAs, a concept similar to DREAM and LAR’s first algorithm, which are discussed in Section 2.2, is used. That is, a forwarding zone is defined to reduce the area to forward the JD packets. In other words, only the mobile nodes within the forwarding zone will forward the JD packets. The second and third forwarding approaches are called BOX and CONE FAs, respectively.

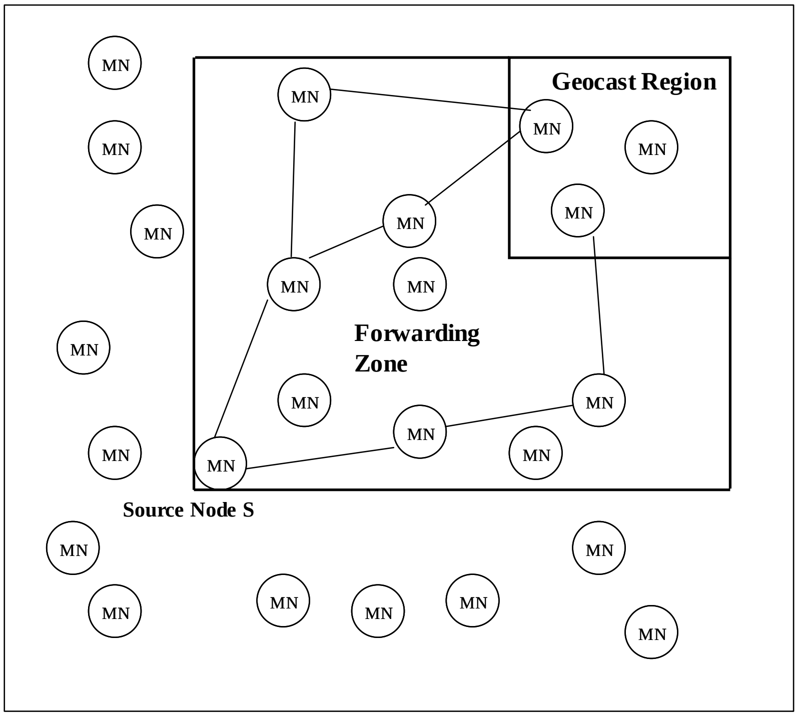

Figure 2.5: Mesh created by BOX FA (Boleng, et al, 2000).

Figure 2.5 illustrates a mesh created by the BOX FA. The BOX FA uses a method to define the forwarding zone similar to the LAR's first algorithm. Specifically, a rectangle containing the source node and the geocast region is defined such that the source node and geocast region are located at opposite ends of the rectangle. The forwarding zone of the BOX FA is much smaller than the forwarding zone in the FLOOD FA.

Figure 2.6 illustrates a mesh created by the CONE FA. Compared to the BOX FA, the CONE FA restrains the size of the forwarding zone even further. The source node is at the vertex of the cone and the geocast region is located at the opposite end of the cone. Using the CONE FA, packets are only forwarded in the direction of the geocast region.

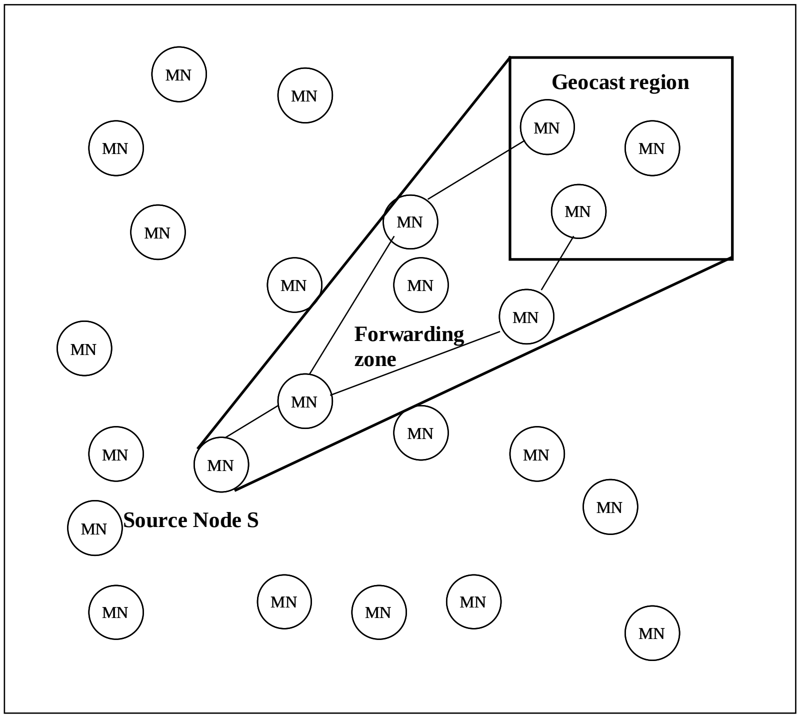

Figure 2.6: Mesh created by CONE FA (Boleng, et. al, 2000).

2.4.3 Performance evaluation

In (Boleng, et al, 2001), the mesh-based geocast protocol, using the FLOOD, BOX and CONE FAs, is evaluated. The following metrics are used for the performance evaluation: protocol overhead, network-wide data load, end-to-end delay, and goodput ratio. The protocol overhead counts the total number of control packets transmitted by the mobile nodes in the network. Similarly, the network-wide data load counts the total number of data packets transmitted by the mobile nodes in the network. This metric represents the density of the mesh established by the mesh-based geocast protocol. The end-to-end delay, as one common delay metric, measures the average time a data packet takes to travel from a source node to the geocast region. The goodput ratio is the number of bytes received by the geocast group members over the number of bytes sent by the geocast source nodes. It is assumed that once one of the mobile nodes in the geocast group receives a data packet, all reachable mobile nodes in the geocast group receive the data packet. The goodput ratio therefore represents the accuracy of transmission by the geocast protocol.

A series of simulation experiments have been executed to observe the performance of the mesh-based geocast routing protocol (Boleng, et al, 2001). The average speed of mobile nodes is varied between 0, 5, 10, 15 and 20 meters per second. The random waypoint mobility model (Broch, et al, 1998) is used to define the movement of mobiles nodes during the simulation period.

Figure 2.7 illustrates the total control packets transmitted as speed increases. As shown, the FLOOD FA transmits the largest number of control packets among the three FAs. The BOX FA transmits the second highest number of control packets, and the CONE FA transmits the smallest number of control packets in the network. As the average speed of mobile nodes is increased, the total number of control packets transmitted is reduced for all three FAs.

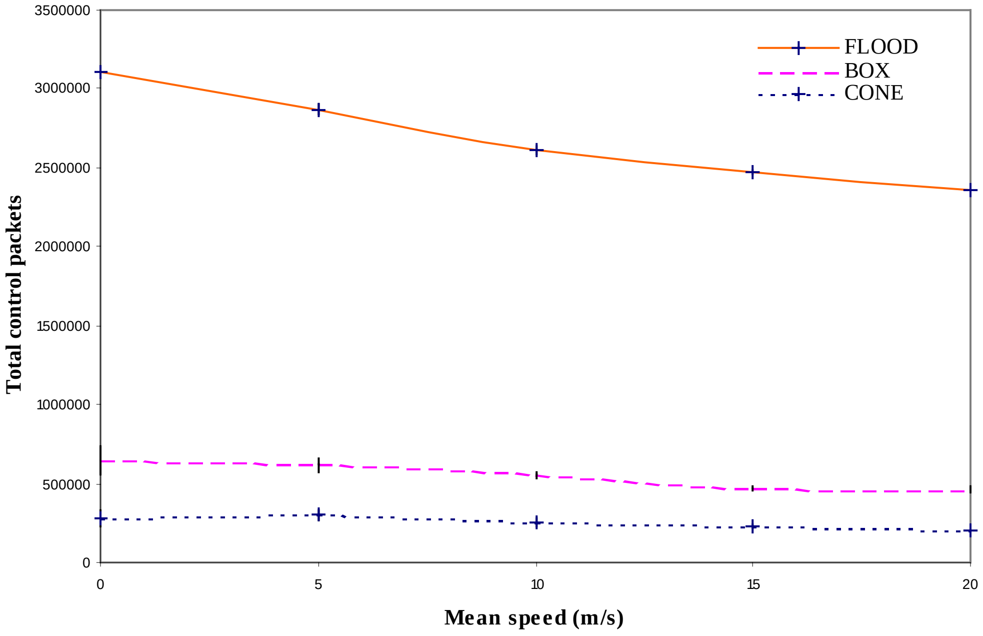

Figure 2.7: Total number of control packets transmitted as a function of mobility speed (Boleng, et al, 2001).

The performance evaluation in (Boleng, et al, 2001) shows a decrease in network-wide data load, end-to-end delay and goodput ratio as speed increases. Figure 2.8 quantifies the result for goodput ratio. As illustrated, the FLOOD FA has the highest goodput ratio, the BOX FA has the second highest goodput ratio and the CONE FA has the lowest goodput ratio.

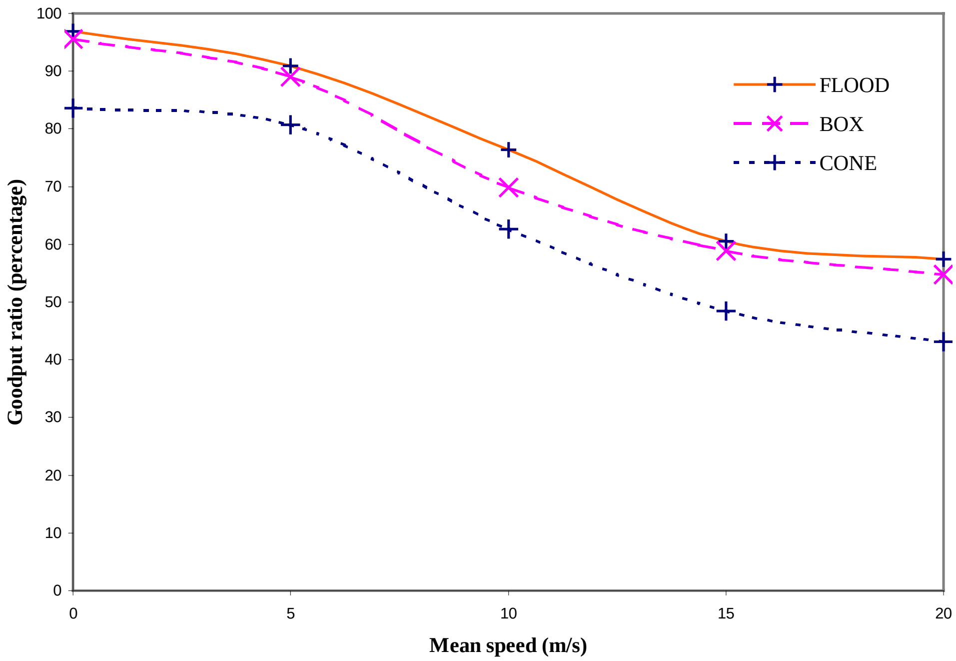

Figure 2.8: Number of data packets received over number of data packets sent (goodput ratio) as a function of mobility speed (Boleng, et al, 2001).

Comparing Figure 2.7 and Figure 2.8, Boleng et al conclude that the FLOOD FA illustrate a good performance on transmission accuracy at the expense of a lot more network overhead congestion. By reducing the forwarding zone with the BOX FA, control overhead and accuracy are reduced. The reason is straightforward. When the forwarding zone is restrained to a small area, such as with the CONE FA, there are fewer mobile nodes within the forwarding zone. Thus, only a few mobile nodes are available to forward packets which reduces control overhead. In addition, fewer forwarding mobile nodes creates a sparser mesh, which compared to a larger forwarding zone and denser mesh, reduces transmission accuracy.

In order to improve the efficiency of the mesh-based geocast routing protocol, we try to improve the method to define the forwarding zone. We also try to adapt the FA according to the current network environment. In this thesis, we made improvements to the BOX FA by defining a CORRIDOR FA. In addition, we developed a new protocol, a HYBRID FA, which combines three individual FAs. We discuss our new FAs in Chapter 3.

CHAPTER 3

THE HYBRID FORWARDING APPROACH

As discussed in Chapter 2, each of the three different FAs used in the mesh-based geocast routing protocol by (Boleng, et al, 2001) has strengths and weaknesses. For example, the CONE FA has the smallest overhead (a strength) and the smallest goodput ratio (a weakness). To improve the efficiency and performance of this mesh-based geocast routing protocol, we first present a new forwarding approach. This new FA (CORRIDOR FA) improves the BOX FA from (Boleng, et al, 2001). We then present a hybrid FA that attempts to keep the strengths of the different FAs without the weaknesses; we refer to this protocol as a mesh-based geocast routing protocol with a hybrid FA or the HYBRID FA. In Section 3.1, the CORRIDOR FA, which is used in the HYBRID FA, is described; in Section 3.2 the HYBRID FA is specified.

3.1 The CORRIDOR FA

The CORRIDOR FA is an improvement upon the BOX FA (Boleng, et. al, 2001) discussed in Chapter 2. Figure 3.1 shows two examples of the CORRIDOR forwarding zone in an ad hoc network. The CORRIDOR FA defines the forwarding zone as the area within two parallel lines convex to the geocast region. First, imagine a center point ***C*** of the geocast region, which is calculated from the coordinates of the geocast region. Then, imagine a line from the center of the source node ***S*** to ***C***. Two of the edges for the CORRIDOR forwarding zone are the two parallel lines, which are parallel to the line between ***S*** and ***C***, that cross the margins of the geocast region. The other two edges of the forwarding zone are perpendicular to the two parallel edges; one edge crosses ***S*** and the other edge crosses ***C***. Thus, these four edges form a polygon. MNs that are within both the geocast region and the CORRIDOR forwarding zone respond to packets as an MN in the geocast region.

There are eight scenarios of a source node forming a forwarding zone toward a geocast region. They are defined according to the different positions of the source node and the geocast region. Figure 3.1 illustrates two of the eight scenarios. The other six scenarios are easily deduced from these two example scenarios. Specifically, Figure 3.1a illustrates an example when the source node is to the west of the geocast region; the forwarding zone is similar when the source node is to the east, north or south of the geocast region. Figure 3.1b illustrates an example when the source node is to the southeast of the geocast region; the forwarding zone is similar when the source node is to the southwest, northwest or northeast of the geocast region. In our simulation environment, the geocast region is placed in the upper right corner of the simulation area. Thus, there are no cases in which the MNs are to the east, north, or northeast of the geocast region.

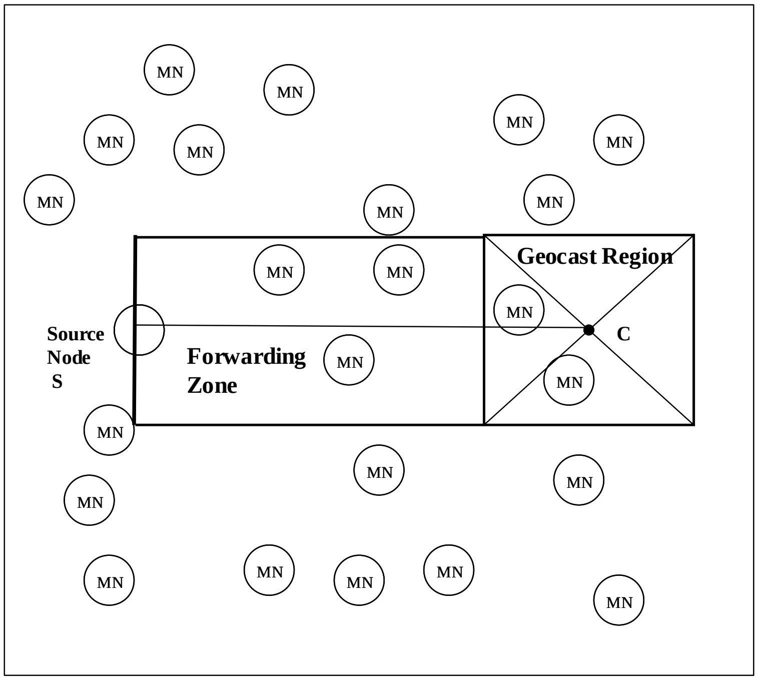

Figure 3.1 – a : Forwarding zone when source node is on the west of the geocast region.

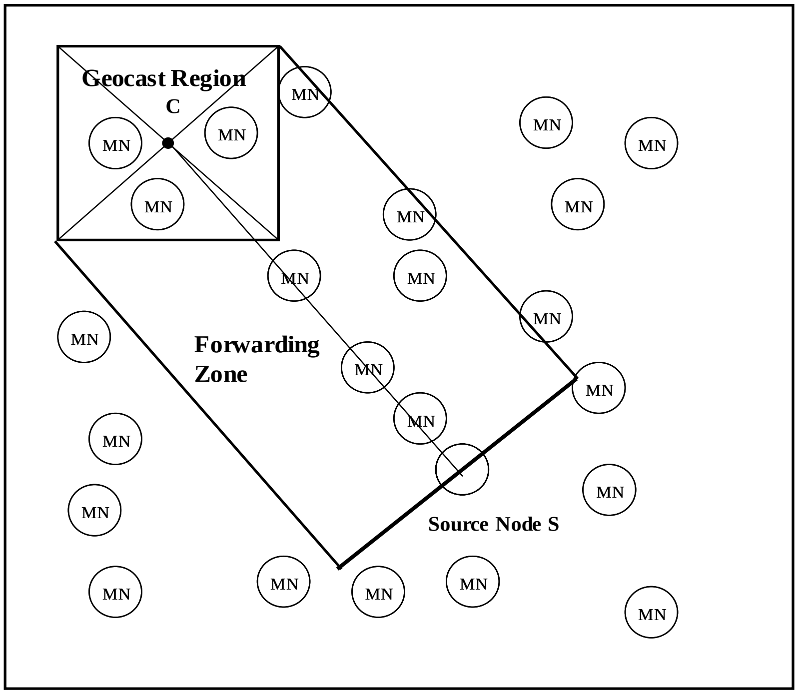

Figure 3.1 – b: Forwarding zone when source node is on the southeast of the geocast region.

Compared to the BOX FA, the CORRIDOR FA has more of a tendency to direct the forwarding zone toward the geocast region. Our performance evaluation (see Chapter 5) illustrates that, although the average number of hops in the forwarding zone is typically the same in the BOX and CORRIDOR FAs, the CORRIDOR FA reduces control overhead and network-wide data load. Since the forwarding zone in the CORRIDOR FA is smaller than that of the BOX FA, the mesh built in the forwarding zone is sometimes slightly less dense in the CORRIDOR FA. Thus, the goodput ratio for the CORRIDOR FA is slightly smaller than the goodput ratio for the BOX FA.

We compare the performance of the BOX and the CORRIDOR FAs under the same simulation environment (see Chapter 4). We evaluate the two FAs with the performance metrics discussed in Section 2.3. Specifically, we varied the mean mobility speed of the mobile nodes and observed the network-wide data load, protocol overhead, end-to-end delay and goodput ratio for the two FAs. We present the simulation results in Section 5.2 of Chapter 5.

Based on our simulation results, we conclude that the CORRIDOR FA is more efficient than the BOX FA. As mentioned, the CORRIDOR FA has a slightly lower transmission reliability but a significantly lower control overhead than the BOX FA. Although the CORRIDOR FA is not the perfect solution, it does improve the BOX FA. Thus, the CORRIDOR FA is one of the FAs used in our HYBRID FA.

3.2 Using the HYBRID FA in a mesh-based geocast routing protocol

The algorithm for the HYBRID FA is described in Section 3.2.1; the implementation of the HYBRID FA is specified in Section 3.2.2. We implement two versions of the HYBRID FA. One version is more active than the other in changing the FA used.

3.2.1 The HYBRID FA

When one compares the performance of the different FAs used in a mesh-based geocast routing protocol, one finds that none of them is the perfect solution to provide geocast communication. In this section, a new approach, which combines the FLOOD, CORRIDOR and CONE FAs, is presented. Since the new protocol uses multiple forwarding approaches, it is called the HYBRID FA. The goal of the HYBRID FA is to maintain the strengths of the FLOOD, CORRIDOR and CONE FAs without the weaknesses.

Instead of using only one FA for all routing purposes, the HYBRID FA has the source node choose the FA applicable to the network environment in real time. The CONE, CORRIDOR and FLOOD FAs are three candidates a source node can choose. As discussed in Section 2.3, a CONE FA has the lowest protocol overhead compared to the other FAs. However, since the CONE FA has a relatively small area to establish the mesh, the lowest goodput ratio is obtained by the CONE FA. In order to keep the network overhead as low as possible, our HYBRID FA begins using the CONE FA. If the CONE FA fails to create a mesh (i.e., no JT packet is returned within a timeout), a CORRIDOR FA is tried. If the CORRIDOR FA fails to create a mesh, the FLOOD FA is tried. If the CORRIDOR or the FLOOD FA successfully builds a mesh, the forwarding zone is reduced. Details on increasing or decreasing the size of the forwarding zone are provided below.

When a source node first receives a command to send a JD packet, the CONE FA is chosen as the first FA a source node tries to establish a mesh. A timer, the SWITCH-TIMER, defines the time period the source node has to build a mesh between itself and the geocast region. The mesh building algorithm is similar to the one used in (Boleng, et al, 2001). Specifically, a source node sends the first JD packet with a CONE FA and initializes the SWITCH-TIMER. When a node within the CONE forwarding zone receives a non-duplicate JD packet, it adds with its node ID to the JD packet in order to track the route the packet has traveled. When a node within the geocast region receives a JD packet, it creates a JT packet and sends the JT packet to the source node along the route of node IDs cached in the JD packet. When a JT packet reaches the source node, SWTICH-TIMER is cancelled and one path between the source node and the geocast region in the mesh is created.

If no JT packet arrives at the source node before SWITCH-TIMER expires, then the source node switches from the CONE FA to the CORRIDOR FA. The next JD packet is then sent with the CORRIDOR FA. If the CORRIDOR FA fails (i.e., the source node doesn’t receive a JT packet within a second SWITCH-TIMER), the next JD packet is transmitted with the FLOOD FA. If any FA builds at least one path in a mesh between the source node and the geocast region successfully (i.e., the source node receives a JT packet before SWTICH-TIMER expires), the source node reduces the forwarding zone before it sends the next JD packet. Specifically, if the CONE FA was successful, the source node will continue to use the CONE FA for the transmission of the next JD packet; if the CORRIDOR FA was successful, the source node will use the CONE FA for the transmission of the next JD packet; if the FLOOD FA was successful, the source node will use the CORRIDOR FA for the transmission of the next JD packet.

When a source node needs to send a data packet, the data packet is sent to the geocast region along the mesh paths established between the source node and the geocast region. If no such mesh exists, the data packet is dropped.

3.2.2 Implementation of two algorithms used in the HYBRID FA

To simulate the HYBRID FA, the ns-2 simulator is used (ns-2 homepage, 2000). Each MN in the simulation is augmented with a geocast agent, which provides geocast communication. For example, the geocast agent at a source node sends the JD packets. In other words, the geocast agents define the geocast communication activities of the MNs (see Chapter 4 for details).

In the HYBRID FA implementation, each geocast agent maintains two flags that represent the FAs: the “current” and “try” flags. These two flags decide which FA is to be used by the geocast agent. There are four options available to set the “current” and “try” flags: ‘C’, ‘D’, ‘F’ and ‘U’. ‘C’ represents the CONE FA, ‘D’ represents the CORRIDOR FA, ‘F’ represents the FLOOD FA, and ‘U’ indicates that no FA has been set.

Generally, the “current” flag represents the FA used by a geocast agent to send data packets; the “try” flag represents the FA used by a geocast agent to send JD packets. When a geocast agent is created, the “current” flag is set to ‘U’ and the “try” flag is set to ‘C’. Initially, if the source node tries to send a data packet, the data packet is dropped since the “current” flag is set to ‘U’; in other words, no mesh from the source node to the geocast region exists. Also, initially, if the source node transmits a JD packet, it uses the CONE FA since the “try” flag is set to ‘C’. If the JD packet succeeds, that is, a JT packet is received by the source node within SWITCH-TIMER, the geocast agent will set its “current” flag to ‘C’. The geocast agent is then able to send data packets to the geocast region. On the other hand, if the JD packet fails, that is, a JT packet is not received by the source node within SWITCH-TIMER, the geocast agent will set the “try” flag to ‘D’. Furthermore, if the JD packet fails a second time, the geocast agent will set the “try” flag to ‘F’. In other words, the forwarding zone increases if a JT packet is not received within SWITCH-TIMER. If the FLOOD FA fails, then no mesh is available and the “current” flag is set to ‘U’. Whenever a JT packet is received by the source node, the geocast agent will set the “current” flag to the FA that succeeded; in addition, the geocast agent will set the “try” flag from ‘F’ to ‘D’ or ‘D’ to ‘C’.

We simulate two algorithms for the mesh-based geocast routing protocol with the HYBRID FA. The first algorithm is called “HYBRID-Passive”. The second algorithm is called “HYBRID-Active”.

In the HYBRID-Passive FA, there is a fixed frequency to send JD packets. Specifically, a JD packet is sent every second. The SWICTH_TIMER is set to 0.2 seconds due to the average round trip time of a JD/JT packet, which is 0.16 seconds. In the HYBRID-Passive FA, a JD packet is sent every second regardless of whether a JT packet is received. Figure 3.2 illustrates the traffic pattern used in the HYBRID-Passive FA.

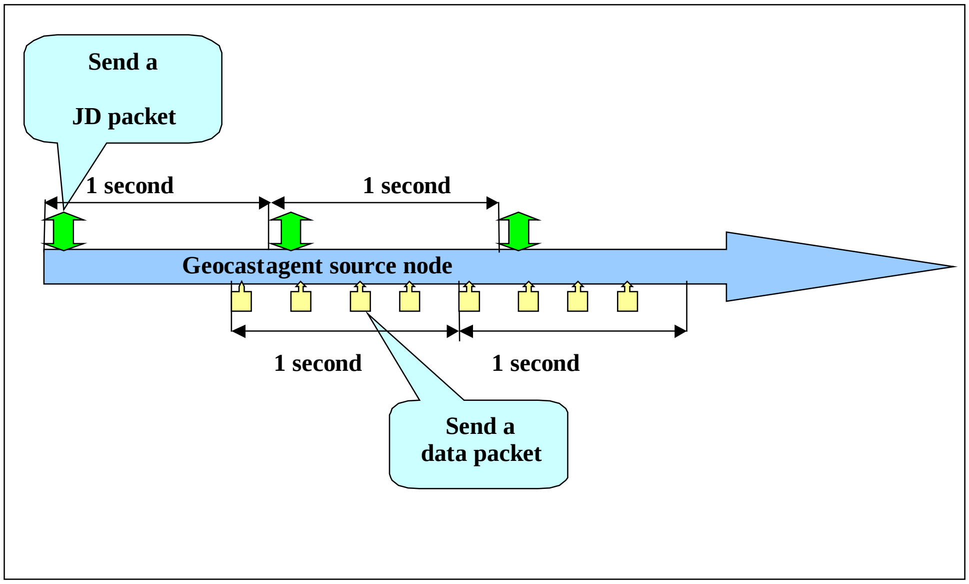

Figure 3.2: Traffic pattern in HYBRID-Passive FA.

In the HYBRID-Active FA, there is both a fixed frequency to send JD packets and a mechanism to send JD packets dynamically. Figure 3.3 sketches the traffic pattern in the HYBRID-Active FA. Similar to the HYBRID-Passive FA, the HYBRID-Active FA sets the fixed frequency for sending a JD packet to one per second and sets SWITCH-TIMER to 0.2 seconds. If a JD packet succeeds, i.e., a JT packet is received by the source node within SWITCH-TIMER, the flags are updated and the next JD packet is scheduled for one second after the previous JD packet transmission. However, if a JD packet fails, i.e., the SWITCH-TIMER expires, then the flags are updated and a new JD packet is transmitted immediately. As described above, this new JD packet will traverse a larger forwarding zone. The geocast agent will repeat the above process until a JT packet is returned. Thus, a geocast agent using the HYBRID-Active FA tries to build a mesh in a more active manner than in the HYBRID-Passive FA.

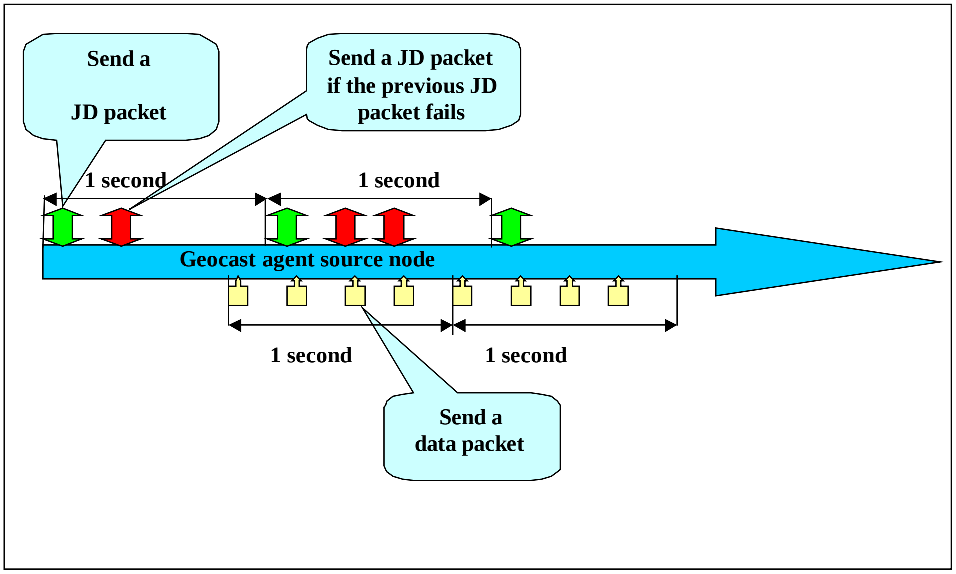

Figure 3.3: Traffic pattern in the HYBRID-Active FA.

Both the HYBRID-Active and HYBRID-Passive FAs are simulated. Chapter 5 presents the simulation results. We also present a comparison of the two HYBRID FAs with two FAs described in (Boleng, et al, 2001), as well as with the CORRIDOR FA described in Section 3.1. In Chapter 4, an introduction to the simulator and the simulation environment are provided.

CHAPTER 4

SIMULATION

In order to evaluate the performance of our various FAs in the mesh-based geocast routing protocol, we execute a series of simulation trials. In this chapter, we introduce the simulator, we illustrate the design of the simulation and we describe the simulation environment.

4.1 The ns-2 simulator

The ns (network simulator) simulator is a discrete event simulator targeted at networking research (ns homepage, 2001). This simulator provides substantial support for simulating both network layer (routing) protocols and transport layer protocols (e.g., the Transmission Control Protocol or TCP). In ns, protocols can be simulated over a wired or wireless (local and satellite) network.

Version 2 is the most recent version of ns (ns-2). The simulator was originally developed by the University of California at Berkeley and the VINT project (Fall, et al, 1997); the simulator was recently extended to provide simulation support for ad hoc networks by Carnegie Mellon University (CMU Monarch Project homepage, 1999). The ns-2 simulator has several features that make it suitable for our simulations. For example, the ns-2 simulator supports the following features:

- a network environment for ad hoc networks,
- routing along multiple paths,
- wireless channel modules (e.g., 802.11), and
- mobile hosts for wireless cellular networks.

There are two programming languages used in the implementation of the ns-2 simulator: C++ and a script language (Tools Command Language or Tcl). C++ and Tcl are combined together to define the activity of the simulator (ns-2 homepage, 2001). C++ is used to process each packet of a flow; Tcl is used for setup, simulation environment configuration and "one-time" features such as setting the FA of the current simulation or specifying the location of the static node.

4.2 Implementation of the mesh-based geocast routing protocol in ns-2

The ns-2 implementation of the mesh-based geocast routing protocol was originally developed by Brad Williams. This implementation included the FLOOD, BOX and CONE FAs. Our improvement is based on his work. Using this code, we implemented the CORRIDOR, HYBRID-Passive and HYBRID-Active FAs. Our code is available at (Toilers homepage, 2001).

The following discussion introduces the ns-2 code. The activities of the geocast agent are implemented in the "Agent" class of the ns-2 simulator. When a packet is created at the source node, a geocast header is added by the geocast agent in addition to the common header in every packet. There are three pieces of information maintained in the geocast header: a geocast field, a forwarding field and the geocast region's coordinates. The geocast field indicates the category of the packet, e.g. a JD packet, a JT packet, a data packet or an undefined packet. The forwarding field indicates the FA to transmit the current packet. In our simulations, this field indicates that the FA is either the FLOOD, CORRIDOR, or CONE FA. The geocast header also maintains the geocast region's coordinates by specifying the two end points of the diagonal in the geocast region.

Each geocast agent maintains several tables to cache routing related information, e.g., a received packet ID table and a sent packet ID table. Each geocast agent also maintains a flag to indicate whether the MN is a member of a mesh. Based on the packet's header and information stored in the geocast agent, the packet is transmitted from the source node to the geocast region. Mechanisms in the code exist to avoid transmitting duplicate packets and looping.

For our HYBRID FA, every geocast agent maintains two flags (see Section 3.2). These two flags are used by the geocast agents to switch FAs. In addition, a timer (SWITCH-TIMER) is initialized when the source node transmits a JD packet. Due to the average round-trip time of a JD/JT packet, i.e., 0.16 seconds, we initialize the SWITCH-TIMER to 0.2 seconds. When a JT packet arrives at the source node, SWITCH-TIMER is canceled; if no JT packet arrives within SWITCH-TIMER seconds, i.e., within 0.2 seconds, then the geocast agent switches to a larger FA (see Section 3.2). Since the timer's activity is a part of each geocast agent, we implemented the timer in C++ (Toilers homepage, 2001).

4.3 Our simulation environment

We simulate the various FAs in a 300 × 600 meters area; in other words, our simulation area is a two dimensional (2D) rectangle. The position of each MN is represented in a 2D grid; the X-axis value is chosen from the range of (0, 300) and the Y-axis value is chosen from the range of (0, 600). The geocast region is 100 × 100 meters; this square area is placed in the upper right corner of the simulation area. We simulate 50 MNs moving within the simulation area; each of these MNs moves according to the random waypoint model (Broch, et al, 1998). In the random waypoint model, an MN is assigned a destination. The MN then moves to the destination at a given mean speed. Once the destination is reached, the MN stops for a given pause time. The MN then chooses another random destination for the MN's next movement. We evaluate each FA with the following mean mobility speeds: 1 m/s, 5 m/s, 10 m/s, 15 m/s and 20 m/s. The standard deviation of each mean mobility speed is ±10%. We set the mean pause time in each simulation trial to 10 seconds; the standard deviation of the mean pause time is also ±10%. The transmission range of each mobile node is 100 meters. The total simulation time period of each simulation lasts more than 1000 seconds. Table 4.1 summarizes our simulation parameters.

Table 4.1: Simulation parameters.

Parameter	**Value**
Number of Mobile Nodes (***n***)	50
Simulation Area (***w*** × ***h***)	300 × 600 meters
Transmission Range (***r***)	100 meters
Pause Time	10 seconds ± 10%
Speed (distribute uniformly with ± 10%)	1 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s
Simulation Time	1000 seconds

From the simulation parameters in Table 4.1, we calculate a set of derived simulation parameters that also exist in our simulation environment. As shown in Table 4.1, ***n*** represents the number of MNs in our simulation, ***w*** and ***h*** represent the width and height of the simulation area respectively, and ***r*** represents the transmission range of each MN. There are four derived simulation parameters derived from ***n***, ***w***, ***h*** and ***r***. They are the node density, coverage area per node, average neighbor count and network diameter. We obtain these derived simulation parameters by the following equations.

Node Density represents the density of MNs in the simulation area.

$$Node\ Density = \frac{n}{w \times h}$$

Coverage Area per Node represents the average area each node covers with its transmission range.

$$\mathit{Coverage\ Area\ per\ Node} = \frac{\pi \times r^2}{w \times h}$$

Average Neighbor Count represents the average number of neighbors each MN has. We calculate the average neighbor count without consideration of edge effect (i.e., if an MN moves to the edge of the simulation area, there are less neighbors than when it is near the center of the simulation area).

$$\mathit{Average\ Neighbor\ Count} = \pi \times r^2 \times \mathit{NodeDensity} - 1$$

Network Diameter represents the maximum number of hops a packet can travel from a source node to the destination geocast region.

$$\mathit{Network\ Diameter} = \frac{\sqrt{w^2 + h^2}}{r}$$

We list the derived simulation parameters for our simulation in Table 4.2.

Table 4.2: Derived simulation parameters.

Parameter	**Value**
Node Density	1/3600
Coverage Area per Node	17.4%
Average Neighbor Count	6.7
Network Diameter	6.7 hops

We place one static node in each simulation at location (250,550) in the simulation area. This location represents the center of the geocast region. Placing one node in the geocast region ensures that at least one node exists to receive the control and data packets transmitted to the geocast region. In other words, we should not reduce the data packet delivery ratio of our routing protocol if no MN exists in the geocast region. Figure 4.1 provides an example scenario of the simulation environment used to evaluate our mesh-based geocast routing protocol.

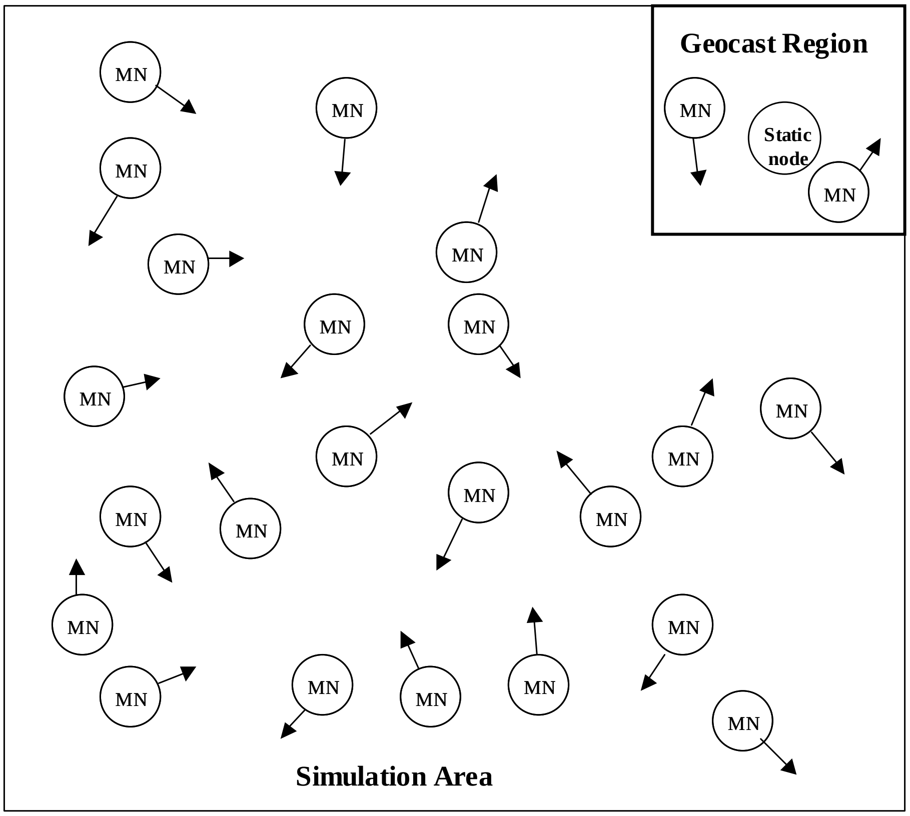

Figure 4.1: A typical simulation area.

In each simulation trial, one geocast source node generates four constant bit rate (CBR) data packets per second. The packet size of each data packet is 64 kilobytes. In all FAs, the geocast source also transmits JD packets on a fixed frequency of one per second. In addition, the HYBRID-Active FA may also transmit a JD packet at every 0.2 seconds. To avoid network congestion caused by sending JD and data packets at the same time, there is a 0.875 seconds delay to send the first data packet after sending the first JD packet (see Figure 3.3 for an example of the traffic pattern).

Tables 4.1 and 4.2 illustrate that our simulation environment stresses the simulated network in each simulation trial. Stressing the network in simulations ensures that a protocol is evaluated thoroughly. We present the simulation results from our simulation in Chapter 5.

CHAPTER 5

SIMULATION RESULTS

In this chapter, simulation results on evaluating the mesh-based geocast routing protocol with various FAs are provided. Specifically, we first compare the CORRIDOR FA with the BOX FA; we then compare the HYBRID FA with the FLOOD, CORRIDOR, and CONE FAs. Lastly, we evaluate two versions of the HYBRID FA: HYBRID-Passive FA and HYBRID-Active FA. The performance metrics are specified in Section 5.1; we present the simulation results and analysis in Section 5.2.

5.1 Performance metrics

To compare the performance of the HYBRID FA with the FLOOD and CONE FAs developed by Boleng, et al., and the CORRIDOR FA developed herein, we evaluate the four performance metrics used in (Boleng, et al, 2001): protocol overhead, network-wide data load, end-to-end delay and goodput ratio.

The protocol overhead is calculated by adding one for each hop in the network a control packet takes; the protocol overhead represents the number of control packets created by the protocol to build and maintain the mesh. The simulation calculates the network-wide data load by counting the total number of data packets transmitted in the network (i.e., adding one for each hop in the network a data packet takes). Since there is a fixed number of data packets generated by the geocast agent (see Chapter 4), the network-wide data load indicates the density of the mesh built for each FA. The end-to-end delay is counted as the average time a data packet traverses from the source node to the geocast region. The ratio of the data packets which are received by the geocast nodes over the data packets which are transmitted by the geocast source nodes, the percentage of successful data packets, is called the goodput ratio. The goodput ratio represents the transmission accuracy. Using the above four simulation metrics, we comprehensively evaluate each FA from multiple facets.

There are three performance goals in our evaluation. The first is the comparison of the BOX FA with the CORRIDOR FA. The second is the comparison of the HYBYRID FA with three individual FAs, i.e., the CONE FA, the CORRIDOR FA and the FLOOD FA. The third is the comparison of two algorithms for the HYBRID FA, which are discussed in Section 3.2.2. In addition, for the evaluation of the HYBRID FA, we calculate the usage percentage of the three individual FAs within the HYBRID FA.

In our simulation results, we calculate an interval estimate for the unknown mean, such that the mean is in the interval with 95% confidence. We include these confidence intervals wherever they are appropriate. Since all of the intervals are quite small (some are smaller than the symbol used to represent the mean), we are convinced that the simulation results accurately represent the unknown mean.

5.2 The simulation results and analysis

The simulation results and analysis are presented in this section. We compare the CORRIDOR FA with the BOX FA in Section 5.2.1. We provide simulation results for the two algorithms of the HYBRID FA in Section 5.2.2. In addition, we compare the two algorithms of the HYBRID FA with three individual FAs in Section 5.2.2.

During our performance evaluation, we varied two key features in our simulation. First, the mesh-based geocast routing protocol was evaluated with six different FAs, i.e., the HYBRID-Passive, HYBRID-Active, CONE, CORRIDOR, BOX and FLOOD FAs. Second, we evaluate each FA with mean mobility speed of 1 m/s, 5 m/s, 10 m/s, 15 m/s, and 20 m/s. All results are shown as a function of the mean mobility speed in order to observe the effect of the protocol's performance on different topology changes.

5.2.1 The CORRIDOR FA vs. the BOX FA

In this section, we compare the BOX FA with our CORRIDOR FA via the four performance metrics defined in Section 5.1. Figure 5.1 illustrates the network-wide data load for the BOX and the CORRIDOR FAs as the mean mobility speed is increased. The CORRIDOR FA has a smaller average network-wide data load than the BOX FA for mobility speeds under 10 m/s. However, the CORRIDOR FA is approximately similar to the BOX FA in average network-wide data load for both 15 m/s and 20 m/s. Since the average network-wide data load for the CORRIDOR FA is equal or smaller than the average network-wide data load for the BOX FA at every speed, we conclude that the CORRIDOR FA has a smaller network-wide data load overall.

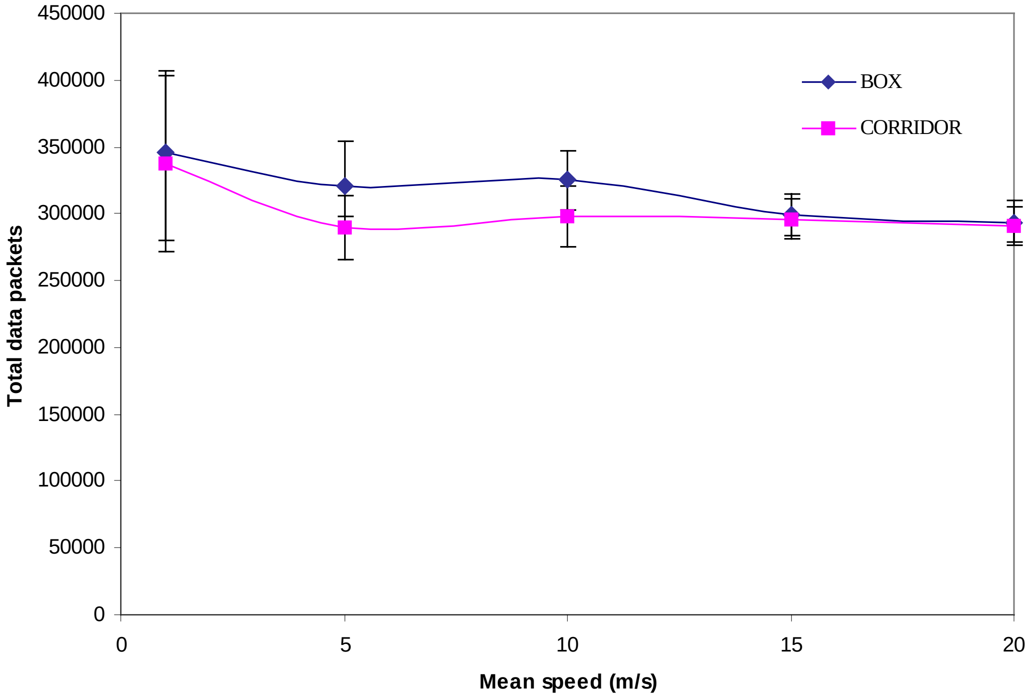

Figure 5.1: BOX vs. CORRIDOR: network-wide data load as a function of mobility speed.

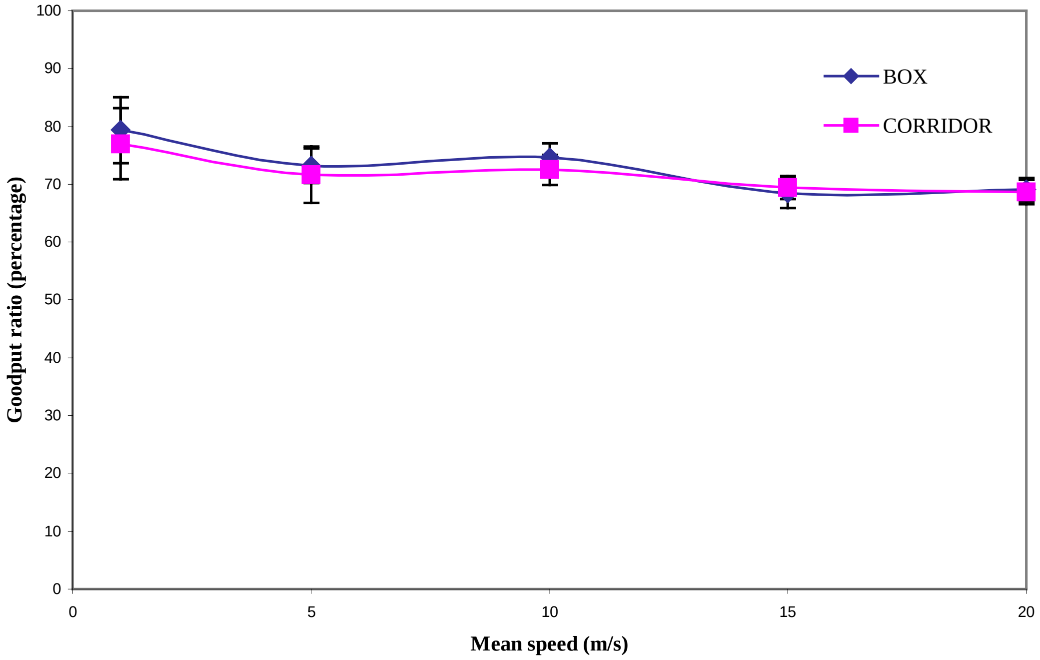

Figure 5.2: BOX vs. CORRIDOR: goodput ratio as a function of mobility speed.

Figure 5.2 compares the goodput ratio provided for the BOX FA with the goodput ratio provided for the CORRIDOR FA. Overall, the CORRIDOR FA and the BOX FA provide a similar level of transmission accuracy. Specifically, the average goodput ratios for the two FAs only differ by 2.5% or less. (Figure 5.2 illustrates that the symbols for the average goodput ratios overlap at every speed.) Furthermore, as Figure 5.2 illustrates, the confidence intervals of the BOX and CORRIDOR FAs overlap at every speed. Thus, it is impossible to determine which FA provides higher transmission accuracy. As the average speed is increased, the goodput ratio of both FAs slightly decrease. In other words, both FAs have difficulty maintaining accuracy at higher speeds.

The protocol overhead created by the BOX FA and the CORRIDOR FA are displayed in Figure 5.3. The CORRIDOR FA, compared to the BOX FA, decreases the average total control packets at speeds 5 m/s and 10 m/s. Although the confidence intervals overlap at all speeds, the average protocol overhead for the CORRIDOR FA is less than (or almost equal to) the average protocol overhead for the BOX FA for all speeds except at 1 m/s. The decrease by the CORRIDOR FA in the average protocol overhead is greater than 10% at 5 m/s and 8% at 10 m/s.

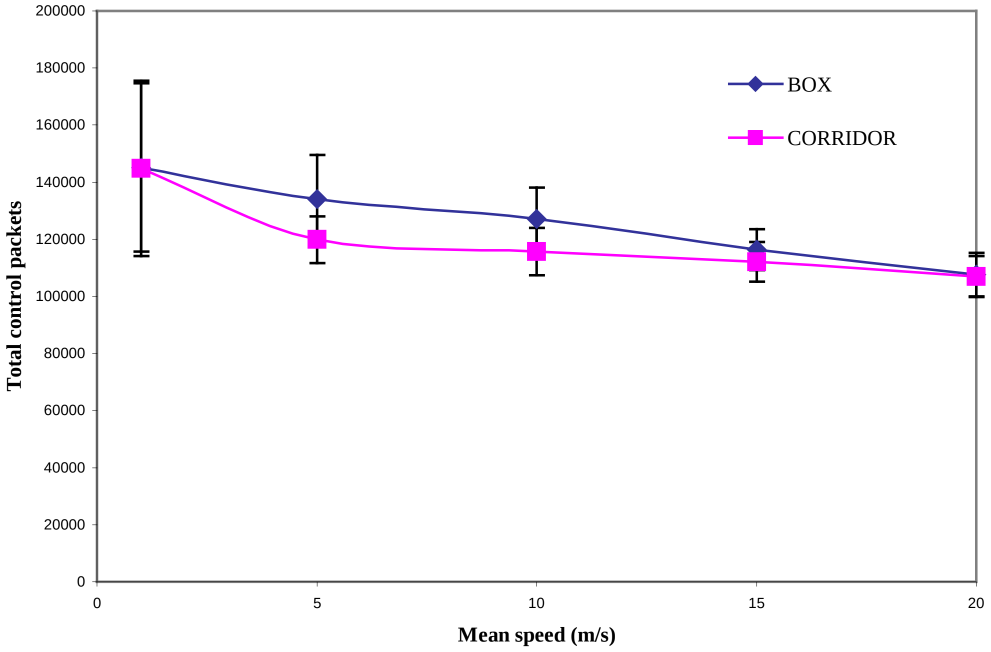

Figure 5.3: BOX vs. CORRIDOR: protocol overhead as a function of mobility speed.

In Figure 5.4, the end-to-end delays of the BOX and CORRIDOR FAs are illustrated. We note that the end-to-end delay is less than 0.004 seconds for both FAs. As shown, there is no significant difference between these two FAs in terms of delay. The average number of hops for the BOX and the CORRIDOR FAs were similar in our simulation results. Specifically, the average number of hops was within the range of 3.6 to 3.9 (the average is 3.82) for the BOX FA and within the range of 3.6 to 3.9 (the average is 3.68) for the CORRIDOR FA. In other words, on average the BOX FA includes slightly longer paths in the mesh than the CORRIDOR FA.

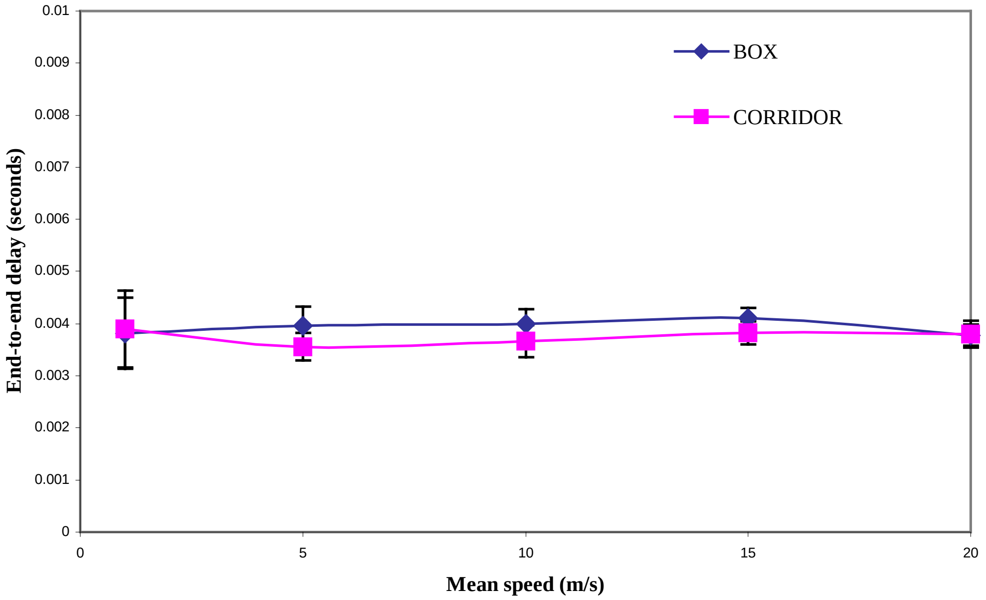

Figure 5.4: BOX vs. CORRIDOR: end-to-end delay as a function of mobility speed.

The CORRIDOR FA creates a polygon zone in the direction of the geocast region, while the BOX FA creates a wider rectangular zone. Thus, in general, the forwarding zone for the CORRIDOR FA is smaller than the forwarding zone for the BOX FA, which slightly decreases protocol overhead and network-wide data load. In addition, the CORRIDOR FA does not decrease the transmission accuracy compared to transmission accuracy of the BOX FA. There are two factors that influence the size of the CORRIDOR FA's forwarding zone: the location of the source node and the size of the geocast region compared to the simulation area. If the source node is far from the geocast region and the geocast region is quite small compared to the simulation area, the forwarding zone formed by the CORRIDOR FA is extremely narrow. Thus, the mesh built within the forwarding zone is either extremely sparse or non-existent. In the BOX FA, the location of the source node to the geocast region is the only factor affecting the size of the forwarding zone. Therefore, there are some cases where the transmission accuracy of the BOX FA is better than the CORRIDOR FA. However, in these cases, the BOX FA functions similar to the FLOOD FA (i.e., a large forwarding zone exists). Thus, for the HYBRID FA, the CORRIDOR FA is preferred over the BOX FA.

5.2.2 The HYBRID FA vs. individual FAs

In this section, we compare the HYBRID FA to the CONE, CORRIDOR, and FLOOD FAs. Figure 5.5 shows the network-wide data load as a function of mobility speed for the two algorithms of the HYBRID FA (passive and active) and the three individual FAs.

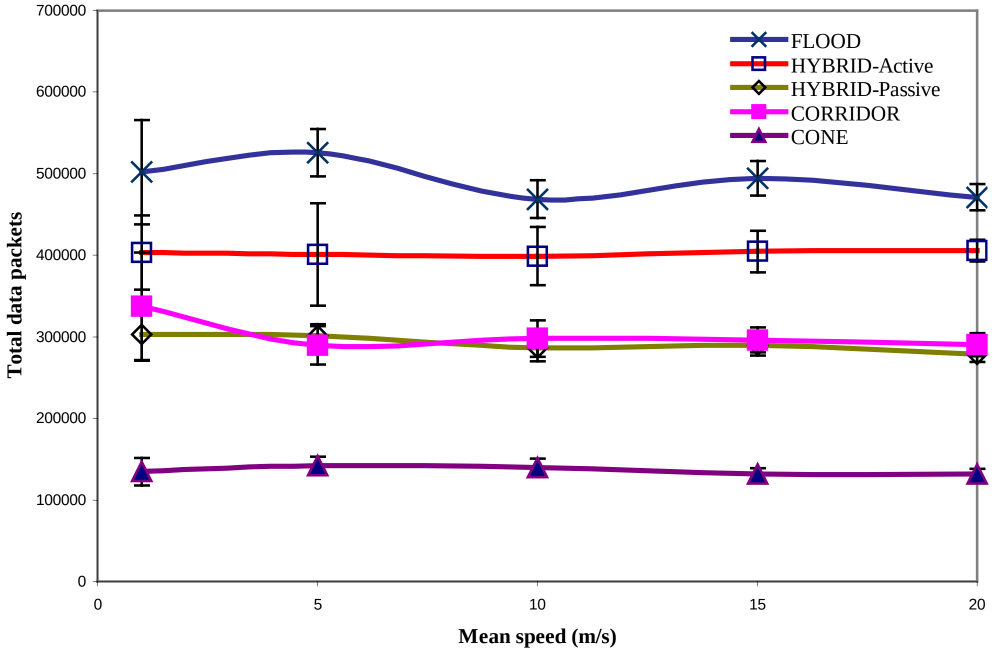

Figure 5.5: Network-wide data load as a function of mobility speed.

As discussed in Section 5.1, the network-wide data load indicates the density of the mesh built by the routing protocol. Figure 5.5 illustrates that the FLOOD FA, compared to the other FAs, builds the most dense mesh, the HYBRID-Active FA builds the second most dense mesh, the HYBRID-Passive FA and the CORRIDOR FA build a similar density mesh, and the CONE FA builds the least dense mesh. As speed increases, the density of the mesh built by the FLOOD FA and the CORRIDOR FA slightly decreases; the density of the mesh built by the other approaches does not change significantly as speed increases. The density of the mesh in a given FA has a direct relationship to the size of the forwarding zone. In other words, as the size of the forwarding zone is increased, the density of the mesh is increased.

Protocol overhead is the cost to build and maintain the mesh. The total number of JD and JT packets transmitted at each hop is counted in the total control packets metric. Figure 5.6 shows the protocol overhead as a function of mobility speed for the different FAs. As illustrated, the ranking of the FAs in terms of protocol overhead (Figure 5.6) is identical to the ranking of the FAs in terms of network-wide data load (Figure 5.5). In other words, creating and maintaining a mesh is done by sending JD and JT packets; thus, a more dense mesh means more control packets are transmitted.

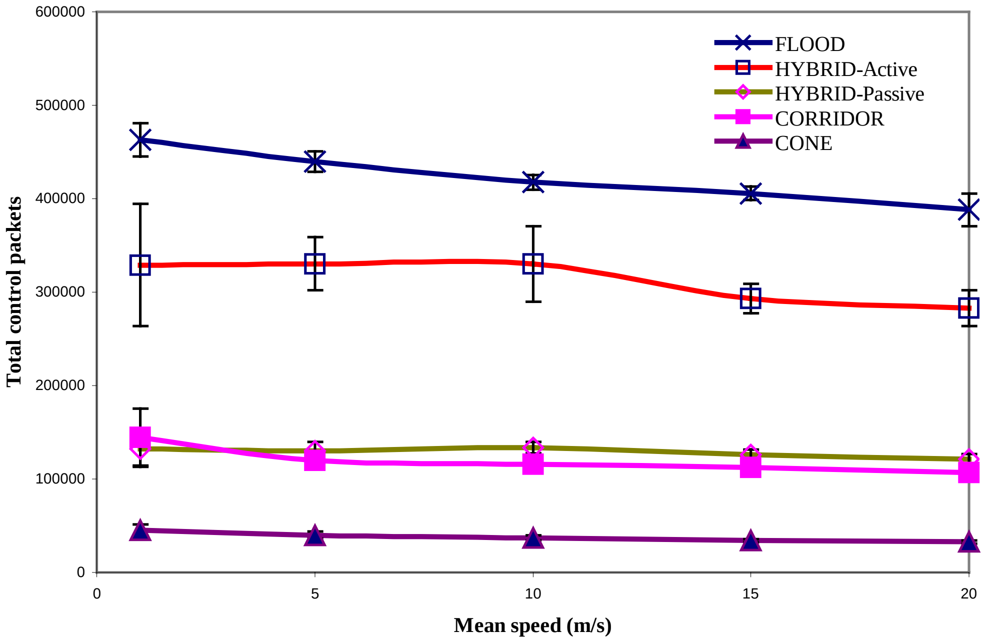

Figure 5.6: Protocol overhead as a function of mobility speed.

Although the total number of JD packets transmitted by the geocast source nodes is the same for the FLOOD, CORRIDOR, CONE and HYBRID-Passive approaches, the total number of JD packets transmitted by the non-source nodes is significantly different in each approach. In other words, the FAs with a larger forwarding zone transmit more JD packets. In addition, the more JD packets that reach the geocast region means more JT packets are returned. The total number of JD packets sent from the source node in the HYBRID-Passive, FLOOD, CORRIDOR and CONE FAs is approximately 1000 during the 1000 seconds of simulation time; in the HYBRID-Active FA, the total number of JD packets sent from the source node varied from 1200 to 2400. As shown in Figure 5.6, the

HYBRID-Passive FA created a similar level of protocol overhead as the CORRIDOR FA. The total number of control packets created by the HYBRID-Active FA is higher than that of the HYBRID-Passive, CORRIDOR and CONE FAs; however, it is much lower than that of the FLOOD FA.

The end-to-end delay measures the time to transmit a data packet at the source to the time the data packet is received at the destination. Figure 5.7 illustrates the end-to-end delay as a function of mobility speed for the different FAs. The average number of hops for the CONE FA ranged from 2.5 to 3.0; the average number of hops for the CORRIDOR, FLOOD, HYBRID-Passive and HYBRID-Active FAs ranged from 3.5 to 4.5. Figure 5.7 shows that the end-to-end delay for the CONE FA, which is within the narrow range from 0.0023 to 0.0025 seconds, is lower than that of the other approaches. The confidence intervals for the end-to-end delay of the other FAs overlap with each other and range from 0.003 seconds to 0.005 seconds. Since the average number of hops for the CONE FA is less than the average number of hops for the other FAs, it is not surprising that the average end-to-end delay for the CONE FA is the smallest.

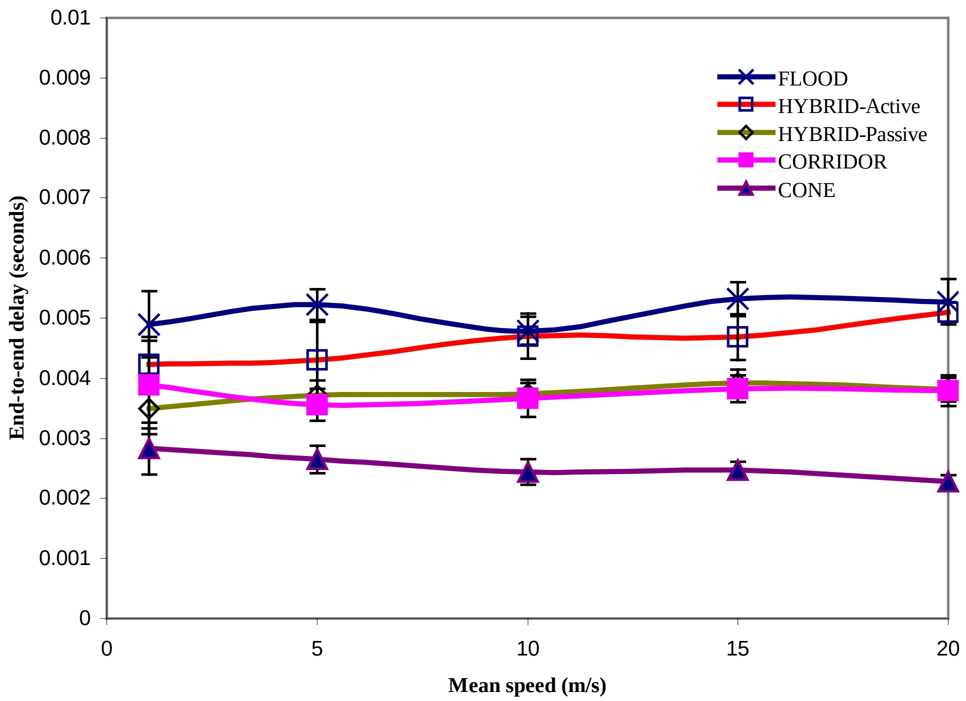

Figure 5.7: End-to-end delay as a function of mobility speed.

The goodput ratio measures the accuracy of the data transmissions. Figure 5.8 illustrates the goodput ratio as a function of mobility speed. As shown, the HYBRID-Active FA provides the best goodput ratio overall. Furthermore, the ratio is high (e.g., 98% at low speeds and near 90% at high speeds). The HYBRID-Passive FA provides good accuracy in data transmissions at low speeds. For example, the goodput ratio, when the average speed is 1 m/s, is as high as that of the HYBRID-Active FA. Although the goodput ratio of the HYBRID-Passive FA decreases substantially when the average speed is increased, the HYBRID-Passive FA provides a higher goodput ratio than both the CORRIDOR and CONE FAs. The CONE FA offers the lowest goodput ratio at all speeds and the CORRIDOR provides the second lowest goodput ratio at all speeds. The goodput ratios of the HYBRID-Active FA at all speeds and the HYBRID-Passive FA at low speeds are higher than the goodput ratio of the FLOOD FA. Figure 5.5 and 5.6 illustrates that the network-wide data load and protocol overhead of the FLOOD FA is much higher than the HYBRID FAs. The higher packet load on the network adversely affects the transmission accuracy due to congestion and contention problems.

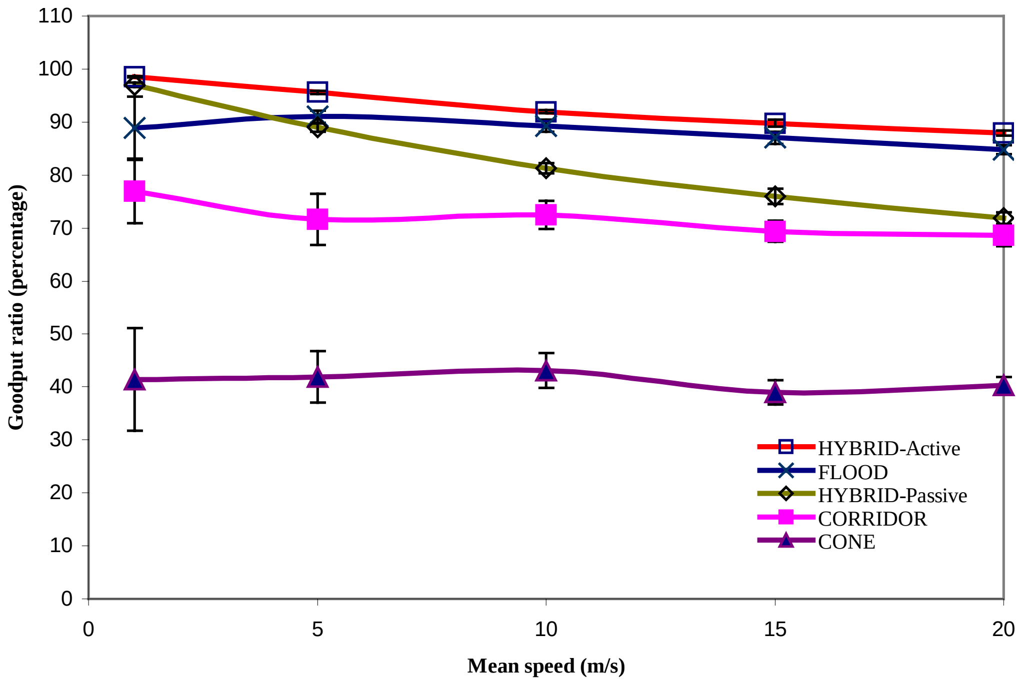

Figure 5.8: Goodput ratio as a function of mobility speed.

Figure 2.8 illustrates the goodput ratios for the FLOOD, BOX, and CONE FAs as presented in (Boleng, et al, 2001). The goodput ratios for the FLOOD, CORRIDOR (which corresponds to the BOX FA), and CONE FAs in Figure 5.8 are significantly different than the corresponding goodput ratios in Figure 2.8. For example, the goodput ratio of the CONE FA is 80% at 5 m/s in Figure 2.8 and only 40% at 5 m/s in Figure 5.8. As discussed, our simulations were implemented in ns-2, which provides a complete simulation of the MAC protocol; the simulations from (Boleng, et al, 2001) were not done in ns-2 and an ideal MAC environment often existed (e.g., no contention on the wireless links). Due to the large packet load in the simulations, ignoring contention on the wireless links allows a significantly higher level of transmission accuracy.

There is a common characteristic in Figures 5.1 - 5.8; that is, the confidence intervals can be large when the average mobility speed is low (e.g., 1 m/s). At higher speeds (e.g., 15 m/s – 20 m/s) the confidence intervals are so small that they are sometimes covered by the symbol representing the average mean. This phenomenon has to do with the random waypoint model used in the simulations. When the average speed is low, it takes a long time for an MN to arrive at its chosen destination. In order words, a change in direction at low speeds is less frequent than at high speeds. Thus, the MNs are less likely to distribute in the average MN distribution for the random waypoint model at low speeds. Hence, a larger variability in results is obtained at low speeds, which creates larger confidence intervals.

Since the performance of the HYBRID FA depends on how often each individual FA is used, we present the percentage of JD packets and data packets that are transmitted by each forwarding approach. Specifically, Figure 5.9 and Figure 5.10 show the percentage of each individual FA used by the two HYBRID FAs to transmit JD packets. Figure 5.9 presents the results for the HYBRID-Passive FA and Figure 5.10 presents the results for the HYBRID-Active FA.

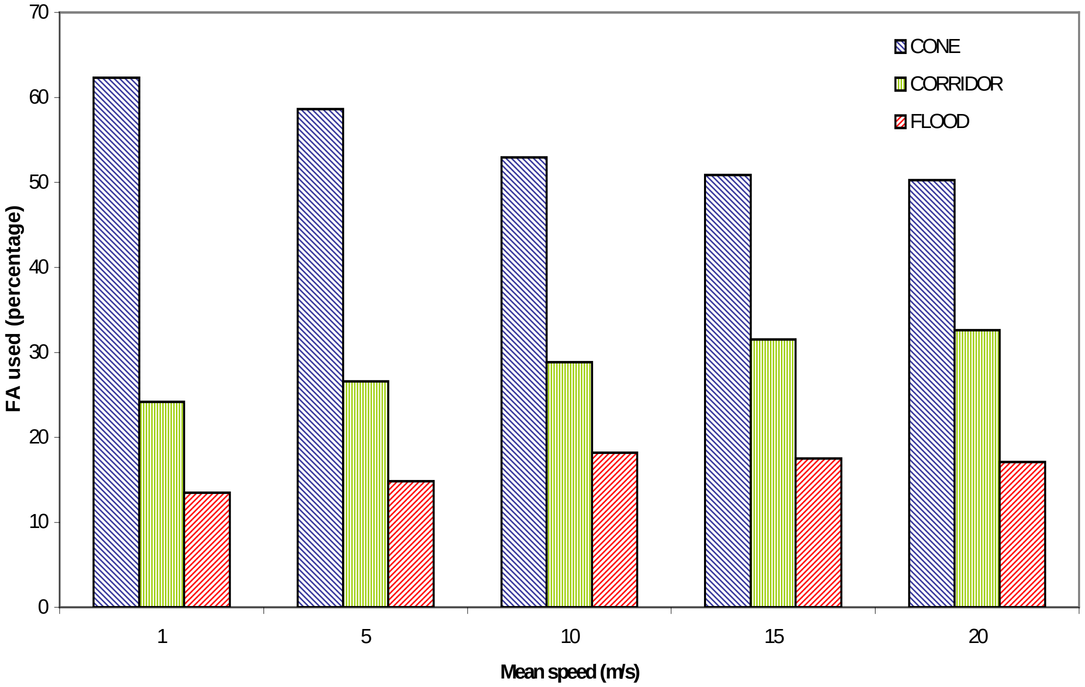

Figure 5.9: FA percentage to send JD packets in the HYBRID-Passive FA.

At each speed, the percentage of the CONE, CORRIDOR and FLOOD FAs for sending JD packets are arranged like a stair in both Figure 5.9 and Figure 5.10. In other words, the CONE FA is used the most often, the CORRIDOR FA is used the second most often and the FLOOD FA is used the least often. This result corresponds to the implementation of the two HYBRID FAs. That is, the protocol attempts to build a mesh in the smallest forwarding zone first; if the protocol fails, then the forwarding zone is increased. When the average speed is increased from 1 m/s to 5 m/s, the percentage of using the CONE FA is decreased and the percentage of using the CORRIDOR FA is increased. In other words, as speed increases, the protocol is less likely to build a mesh successfully in the small forwarding zone provided by the CONE FA.

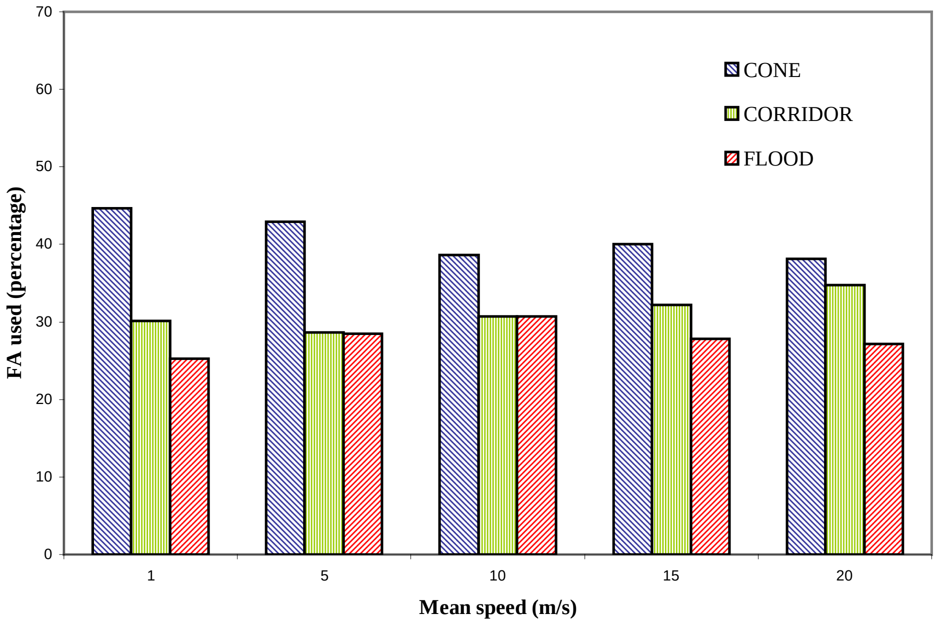

Figure 5.10: FA percentage to send JD packets in the HYBRID-Active FA.

In comparing the HYBRID-Passive and the HYBRID-Active FAs, the percentage of using the CONE FA in the HYBRID-Passive FA is much higher than that in the HYBRID-Active FA. For example at 1 m/s, the percentage of using the CONE FA is within the range of 62% in the HYBRID-Passive FA while it is only slightly higher than 45% in the HYBRID-Active FA. Correspondingly, there is a lower percentage for both the CORRIDOR and the FLOOD FAs in the HYBRID-Passive FA compared to the HYBRID-Active FA. For example, at 1 m/s, the percentage of using the CORRIDOR FA in the HYBRID-Passive FA is 25%, while the percentage of using CORRIDOR FA in the HYBRID-Active FA is 30%. In addition, in the HYBRID-Passive FA, the FLOOD FA is only used 14% at 1 m/s; however, in the HYBRID-Active FA, the FLOOD FA is used 25%. This phenomenon illustrates that the HYBRID-Active FA switches to a larger forwarding zone more quickly than the HYBRID-Passive FA. Furthermore, this phenomenon explains the higher goodput ratio (Figure 5.8) and corresponding higher protocol overhead (Figure 5.6) and higher network-wide data load (Figure 5.5) provided by the HYBRID-Active FA compared to the HYBRID-Passive FA.

Figure 5.11 and Figure 5.12 show the percentage of each FA used to send data packets from the geocast source node in the two HYBRID FAs. Figure 5.11 presents the results for the HYBRID-Passive FA and Figure 5.12 presents the results for the HYBRID-Active FA.

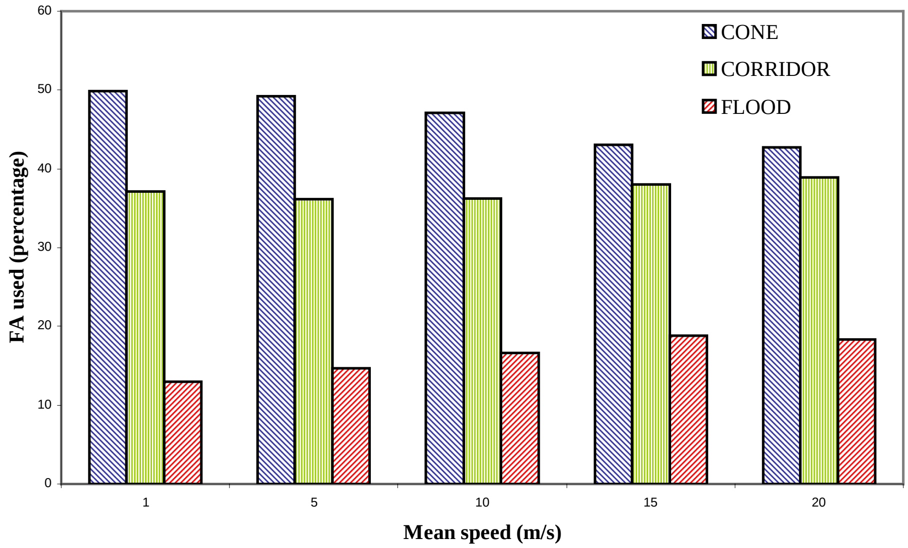

Figure 5.11: FA percentage to send data packets in the HYBRID-Passive approach FA.

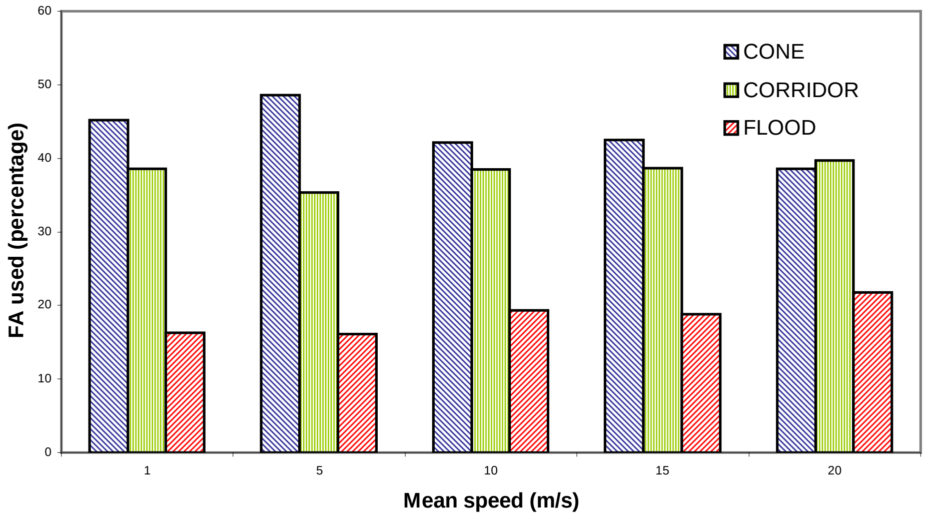

Figure 5.12: FA percentage to send data packets in the HYBRID-Active FA.

Similar to Figures 5.9 and 5.10, the percentages of the CONE, CORRIDOR, and FLOOD FAs for sending data packets are arranged like a stair in both Figure 5.11 and Figure 5.12. This result illustrates that the protocol is often successful in its attempt to build a mesh in the smallest forwarding zone possible.

When we compare Figure 5.9 with Figure 5.11 and Figure 5.10 with Figure 5.12, we discover that the protocol is not 100% successful in its attempt to build a mesh in the smallest forwarding zone possible. For example, at 1 m/s, the HYBRID-Passive FA attempts to use the CONE FA 65% (see Figure 5.9); however, the HYBRID-Passive FA is only able to transmit data packets with the mesh built by the CONE FA 50% (see Figure 5.11). Since the HYBRID-Active FA is more active in adjusting to the current network environment than the HYBRID-Passive FA, Figures 5.10 and 5.12 correspond closer than Figures 5.9 and 5.11.

Lastly, also similar to Figure 5.9 and Figure 5.10, the percentage of using the CONE FA to send data packets in the HYBRID-Passive FA is higher than the percentage of using the CONE FA to send data packets in the HYBRID-Active FA. The percentages of using the CORRIDOR and FLOOD FAs in the HYBRID-Active FA is higher than the percentages of using the CORRIDOR and FLOOD FAs in the HYBRID-Passive FA. As previously discussed, the result illustrates that the HYBRID-Active FA switches to a larger forwarding zone more quickly than the HYBRID-Passive FA.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

We have improved the mesh-based geocast routing protocol from (Boleng, et al, 2001) in this thesis. Specifically, we have developed the HYBRID FA, which combines the CONE, CORRIDOR and FLOOD FAs together. The geocast agent dynamically sets the FA in real time according to the current network environment. In typical computing fashion, there is a trade-off between the amount of overhead that a protocol expends and the performance that the protocol provides in most of our results. We define two algorithms for the HYBRID FA: HYBRID-Passive FA and HYBRID-Active FA.

From our evaluation results, we conclude that the two algorithms for the HYBRID FA both improve the transmission accuracy significantly without increasing the control overhead significantly. For example, the HYBRID-Passive FA has the same level of control overhead as the CORRIDOR FA; however, the transmission accuracy provided by the HYBRID-Passive FA is much higher than that of the CORRIDOR FA. Furthermore, the HYBRID-Active FA has half the control overhead created by the FLOOD FA; however, the HYBRID-Active FA provides a higher level of transmission accuracy than the FLOOD FA. Therefore, the two algorithms for the HYBRID FA improve the FAs developed by (Boleng, et al, 2001).

In the future, we plan to have the geocast agent chose the FA based on other network environment features (e.g., the location of the source node to the geocast region). In addition, we could also add more features to the geocast agent, such as allowing the geocast agent to mark the more efficient paths in the mesh as higher priority. When a path in the mesh fails, the geocast agents local to the failure could attempt to fix the failure locally. Lastly, at low speeds, the HYBRID-Passive FA has lower protocol overhead and lower network-wide data load than the HYBRID-Active FA, without sacrificing transmission accuracy. Thus, a combination of the HYBRID-Passive FA (for low speeds) and HYBRID-Active FA (for high speeds) is an avenue of future work.

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