ENSC 835: HIGH-PERFORMANCE NETWORKS

COMPARISON OF ROUTE OPTIMIZATION AND REVERSE ROUTING

Fall 2003

FINAL REPORT

Ada Pang
Edlic Yiu
Edwood Yiu
http://www.sfu.ca/~eyiu/
E-mail: {smpang, enyiu, eyiu}@sfu.ca

Abstract

For the past few years, wireless communications has had a profound impact on our society. Many analysts predict that connecting to the Internet with mobile equipments will soon be the dominant access method. However, the current IPv4 protocol does not provide adequate support of portable IP addresses. As a result, the Mobile IP Working Group of the Internet Engineering Task Force (IETF) introduced extensions to optimize datagram routing for IPv4.

In our project, we will complete the Route Optimization extension for Mobile IPv4 as implemented by Hao (Leo) Chen in Spring 2002. We will complete the remaining Route Optimization messages so that the proposed extension can be fully simulated. In addition, we will implement another type of Route Optimization, namely the Reverse Routing for Mobile IPv4 extension, so that the performance of the two proposals can be compared using NS-2.

Table of Contents

List of Figures

1 Introduction

The introduction of the Internet is often thought of as the emergence of the information superhighway. Vast amount of information are accessible via any Internet connection. Traditionally, the only means of connecting to the Internet is via wired connections such as analog modems and cable modems. However, technological advances have opened doors to wireless communications. Using Mobile IP [3], an extension developed by the Mobile IP Working Group of the Internet Engineering Task Force (IETF), the IPv4 protocol was expanded to manage and maintain IP traffic for mobile devices.

Although the Mobile IP protocol did provide transparent routing of IP datagrams for mobile devices, the proposed routing algorithm was not optimized. The Mobile IP protocol employs asymmetric routing, where packets sent to a mobile device are routed via its Home Agent and packets sent from a mobile device are routed through the Foreign Agent. This asymmetric routing, or more generally known as "Triangle Routing", forces packets destined for the mobile device to route along non-optimized paths.

To accommodate for the routing deficiency, the IETF introduces an extension to the Mobile IP protocol – Route Optimization [4]. Route Optimization solves the problem of "Triangle Routing" by maintaining binding caches in the Mobile Hosts, so that packets can be routed directly to a mobile device. Reverse Routing [6], an alternative solution to the "Triangle Routing" problem, allows the direct routing of packets to the mobile device and simplifies the complexity of Route Optimization.

This project focuses on the implementation and simulation of the Route Optimization extension for Mobile IPv4 as implemented by Hao (Leo) Chen in Spring 2002. We will complete the remaining Route Optimization messages so that the proposed extension can be fully simulated. In addition, we will implement the Reverse Routing for Mobile IPv4 so that the performance of the two proposals can be compared using NS-2.

2 Mobile IP

With the popularity of wireless communications and portable computing devices, the concept of being online anywhere anytime is no longer a fantasy. Wireless hot spots or access points have been integrated in many public areas, with many residential users switching to wireless networks within their homes. The popularity of wireless Internet is attributed by two factors. Technological enhancements such as laptops and PDAs have lower power consumptions, making them more suitable and affordable for wireless communications. Another factor is people's dependence on the Internet. Not only does the Internet provides vast sources of information, it also acts as a communication channel.

Unfortunately, wireless Internet is not as simple as replacing wires with wireless technology. The original TCP/IP architecture was designed under the assumption that the end hosts of the Internet were connected statically. IP addresses were used to identify the hosts and reflect their point of attachments. Obviously, this static model cannot be applied to wireless Internet. Thus, the Internet Engineering Task Force (IETF) introduced an extension called Mobile IP for supporting mobility in the Internet.

The Mobile IP protocol enables any end host to change its point of attachment to the Internet while being continually identified by its home IP address. This is accomplishment by assigning 2 IP addresses to each mobile end hosts (hereby referring as Mobile Hosts). One address, the home address, serves as the identifier for the Mobile Host. The other IP address, the Care-of-Address (COA), reflects the Mobile Host's current point of attachment. The above addressing mechanism offers a simple and scalable scheme for wireless Internet traffic. However, the drawback of this mechanism is a more complex protocol.

Although the Mobile IP protocol did offer a solution to support wireless Internet traffic, the protocol had routing anomalies. With Mobile IP, packets sent from one source to another may not be transversed via the shortest path to the destination. This anomaly, called Triangle Routing, severely affects performance in high traffic networks. Several enhancements have been proposed to address this problem. Two proposed protocols –

Route Optimization and Reverse Routing – will be examined in this project. More information concerning these two protocols will be provided in later sections.

2.1 Architecture Overview

To better understand the wireless Internet architecture, major components of the architecture must be examined first. Figure 2-1 illustrates the wireless Internet infrastructure.

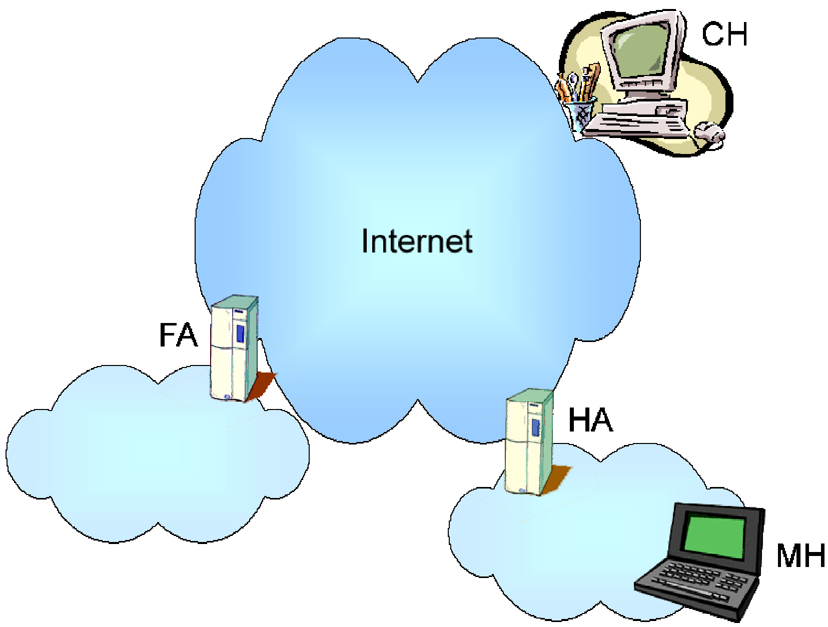

Figure 2-1 Wireless Internet Infrastructure

2.1.1 Mobile Host

The Mobile Host (MH) is a node that frequently changes its point of attachment to the Internet.

2.1.2 Home Agent / Foreign Agent

The Home Agent (HA), residing in the Mobile Host's home network, is responsible for forwarding packets destined to the Mobile Host. If the Mobile Host is away from its home network, the Home Agent is responsible for tunneling datagrams to the Mobile

Host. The Home Agent also maintains the current location of the Mobile Host and authenticates the Mobile Host during the registration process.

The Foreign Agent (FA), residing in the Mobile Host's visited network, provides routing services to the Mobile Host when it is away from its home network. The Foreign Agent is responsible for de-tunneling packets sent from the Mobile Host's Home Agent and delivering these packets to the Mobile Host.

2.1.3 Corresponding Host

The Correspondent Host (CH) communicates with the Mobile Host. The Correspondent Host can be a Mobile Host or a stationary host.

3 Overview

The following sections provide an overview of the Route Optimization and Reverse Routing protocol.

3.1 Route Optimization

As mentioned in Section 2, Triangle Routing, the anomaly of the Mobile IP protocol, introduces routing inefficiencies. In addition, the Mobile IP protocol does not account for handoff losses. When a Mobile Host moves from a Foreign Agent to another, packets in flights to the old Foreign Agent are not delivered to the Mobile Host. Thus, in September 2001, the IETF introduced the Route Optimization extension to the Mobile IP protocol. The two main objectives of this extension are:

- Route packets through optimized paths by adding a binding cache in the correspondent nodes
- Support for smooth handoffs between Foreign Agent

Details of the binding cache and smooth handoffs are described in Section 3.1.1 and Section 3.1.2 respectively. Although the Route Optimization extension introduces new features and functions, the underlying entities are the same as those from the Mobile IP protocol.

3.1.1 Binding Caches

To eliminate Triangle Routing, the Correspondent Host must know the current location of the Mobile Host. This information is maintained by incorporating a binding cache in the Correspondent Host. A binding cache contains the current location or the Care-of-Address of the Mobile Host. Prior to transmitting an IP packet, the Correspondent Host may retrieve the Care-of-Address for the Mobile Host and tunnel this datagram directly to the Care-of-Address.

In order to maintain an up-to-date binding cache at the Correspondent Host, the Correspondent Host must be promptly informed when the Mobile Host acquires a new Care-of-Address. Route Optimization accomplishes this by introducing new signaling messages. The formats and the utilization of these signaling messages will be discussed in Section 3.1.3.

3.1.2 Smooth Handoff

In the Mobile IP protocol, the Mobile Host's previous Foreign Agent is not informed when the Mobile Host acquires a new Care-of-Address. Any datagram that are transmitted to the Mobile Host's old Care-of-Address would not be received by the Mobile Host. If the previous Foreign Agent can maintain a binding cache entry for Mobile Hosts that have previously been visiting, the previous Foreign Agent can deliver the misdirected packets to the Mobile Host's current Care-of-Address. In essence, the previous Foreign Agent acts as a temporary forwarder for packets destined to the Mobile Host. This process is called Smooth Handoff.

Smooth handoff is achieved by including a Previous Foreign Agent Notification extension in the registration process to the new Foreign Agent. On recipient of this extension, the new Foreign Agent utilizes signaling messages from Route Optimization to create a binding cache in the previous Foreign Agent. Details of the signaling messages involved and the message handshaking process will be discussed in a later section.

3.1.3 Binding Cache Management Message Formats

Route Optimization introduces four signaling messages to manage binding cache entries. The transmission and the processing of these messages form the heart of the Route Optimization extension. The following sections provide an overview of each signaling message. Note that only fields that are of interests are described in each section.

3.1.3.1 Binding Update Message

The Binding Update message is used to convey the current location of the Mobile Host. On recipient of the Binding Update message, the host may create a binding cache for the Mobile Host. Figure 3-1 illustrates the format of the Binding Update message.

Type	A	I	M	G	Reserved	Lifetime
Mobile Node Home Address						
Care-of-Address						
Identification						

Figure 3-1 Binding Update Message Format

There are only four fields that are of interests in this message. The 'A' (acknowledge) bit is set by the node sending the Binding Update message to request for a Binding Acknowledge message in response. The Mobile Node Home Address field indicates the home address of the Mobile Host to which the Binding Update message refers. The Care-of-Address field contains the current Care-of-Address of the Mobile Host. The Lifetime field identifies the number of seconds remaining before this binding cache expires.

3.1.3.2 Binding Warning Message

The Binding Warning message is used to transmit a warning to the Home Agent that the Corresponding Host is using an out-of-date binding cache. On recipient of this warning, the Home Agent is triggered to transmit a Binding Update message to the Corresponding Host. Figure 3-2 illustrates the format of the Binding Warning Message.

Type	Reserved
Mobile Node Home Address	
Target Node Addresses …	

Figure 3-2 Binding Warning Message Format

As with the Binding Update Message, the Mobile Node Home Address identifies the home address of the Mobile Host that this message refers to. The Target Node Addresses identify the addresses that should receive the Binding Update message.

3.1.3.3 Binding Request Message

The Binding Request message is used to request for the Mobile Host's current mobility binding from the Mobile Host's Home Agent. Upon recipient of this message, the Home Agent generates a Binding Update message to the requesting node. Figure 3-3 shows the format of the Binding Request message.

Type	Reserved
Mobile Node Home Address	
Identification	

Figure 3-3 Binding Request Message Format

The Mobile Node Home Address indicates the address to which the current mobility binding is desired.

3.1.3.4 Binding Acknowledge Message

The Binding Acknowledge message is used to acknowledge the recipient of a Binding Update message. This message is only triggered if the 'A'(Acknowledge) bit-field of the Binding Update message is set. Figure 3-4 shows the format of the Binding Acknowledge message.

Type	Reserved	Status
Mobile Node Home Address		
Identification		

Figure 3-4 Binding Acknowledge Message Format

The Mobile Node Home Address is copied from the Binding Update message that is being acknowledged.

3.1.4 Smooth Handoff Message Formats

The Mobile Host can initiate the smooth handoff process by including a Previous Foreign Agent Notification extension in the registration message to the new Foreign Agent. This extension instructs the new Foreign Agent to generate a Binding Update message and sends this message as a notification about the new location of the Mobile Host. On recipient of the Binding Update message, the old Foreign Agent should create a binding cache entry so that in-flight packets sent to the old Care-of-Address can be re-directed to the new Care-of-Address. Figure 3-5 illustrates the format of the Previous Foreign Agent Notification extension.

Type	Length	Cache Lifetime
Previous Foreign Agent Address		
New Care-of-Address		
SPI		
Authenticator		

Figure 3-5 Previous Foreign Agent Notification extension

The Previous Foreign Agent Address field identifies the IP address of the Mobile Host's previous Foreign Agent to which the new Foreign Agent should send a Binding Update message. The New Care-of Address field contains the updated Care-of-Address of the Mobile Host.

3.2 Reverse Routing

Although Route Optimization solves the problem of Triangle Routing, the protocol is more complicated than the basic Mobile IP protocol. Thus, P. Zhou and O. Yang introduced Reverse Routing in 1999 as an alternative to Route Optimization [6]. Compared with the four signaling messages defined in Route Optimization, the design of Reverse Routing only employs one signaling message to eliminate Triangle Routing. Nevertheless, the underlying entities are the same as those from the Mobile IP protocol.

3.2.1 Reverse Routing Message Formats

As previously mentioned, Reverse Routing only employs one signaling message. This single message is sufficient to enhance the Mobile IP protocol to support direct routing. The following section provides an overview of this single message - Reverse Routing Update Message. Note that only the fields that are of interests are described.

3.2.1.1 Reverse Routing Update Message

The Reverse Routing Update Message should only be initiated from the Mobile Host. This message is used to inform the Corresponding Host that every packet destined to the Mobile Host should be relayed to the specified care-of-address. Figure 3-6 illustrates the format of the Reverse Routing Update Message.

Type	Reserved	Lifetime
Target Node Address		
Mobile Node Home Address		
Care-of-Address		

Figure 3-6 Reverse Routing Update Message Format

As described in Section 4.2.2, the Reverse Routing Update Message can be embedded with the Registration Request Message that is sent from the Mobile Host to the Foreign Agent. The Target Node Address is provided to the Foreign Agent to determine the destination of the Reverse Routing Update Message after receiving a successful Registration Reply Message. The Care-of-Address field contains the IP address that the Foreign Agent loans to the Mobile Host when staying at that foreign network. The Mobile Node Home Address identifies the home address of the Mobile Host that this message refers. The Lifetime field identifies the number of seconds remaining before the Care-of-Address is invalid.

4 Signaling Process

This section illustrates the signaling process for Route Optimization and Reverse Routing. Note that marked signaling messages (messages with asterisks) in the figures are new signaling messages that are added in this project.

4.1 Route Optimization

Two scenarios are provided to illustrate the signaling process of Route Optimization. The first scenario shows the necessary signaling when the Mobile Host moves from the Home Agent to the Foreign Agent, while the second scenario shows the signaling when the Mobile Host moves from one Foreign Agent to another.

4.1.1 Home Agent → Foreign Agent

This section illustrates the signaling process when a Mobile Host moves away from its home network to a Foreign Agent network. It also demonstrates the triggered signaling when the binding cache is about to expired at the Corresponding Host.

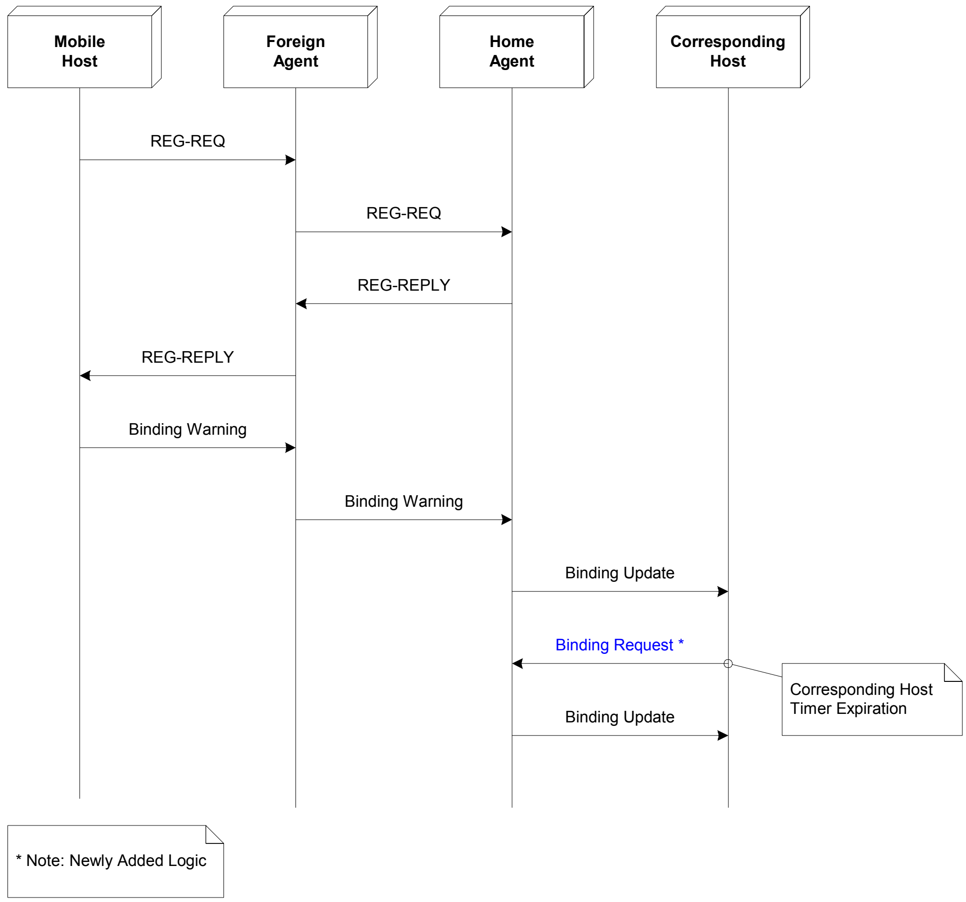

Figure 4-1 Home Agent → Foreign Agent Sequence Diagram

When a Mobile Host moves to a new network, it first sends a Registration Request (REG-REQ) to the Foreign Agent to register in the new network. The Foreign Agent then forwards this REG-REQ to the Home Agent for authentication of the Mobile Host. Once authentication is completed, a Registration Reply (REG-REPLY) is sent to the Mobile Host to indicate that the registration is successful. At this point, the Mobile Host is allowed to send and receive packets in the Foreign Agent network. Since the Mobile Host has successfully acquired a new Care-of-Address, a Binding Warning is sent to the Home Agent to trigger the generation of a Binding Update to the Corresponding Host.

The Corresponding Host has a timer that keeps track of the binding cache expiration time. Since the Correspondent Host wants to maintain this binding cache, the expiration timer is set such that sufficient time is allowed for renewing the binding cache. As shown in Figure 4-1, when the binding cache timer expires in the Correspondent Host, a Binding Request is triggered to the Home Agent. Upon receiving a new Binding Update message, the expiration timer at the Corresponding Host is renewed with the new lifetime according to the Binding Update message.

4.1.2 Foreign Agent → Foreign Agent

This section illustrates the signaling process when a Mobile Host moves from one Foreign Agent network to another. It also demonstrates the signaling that is involved for the Smooth Handoff process.

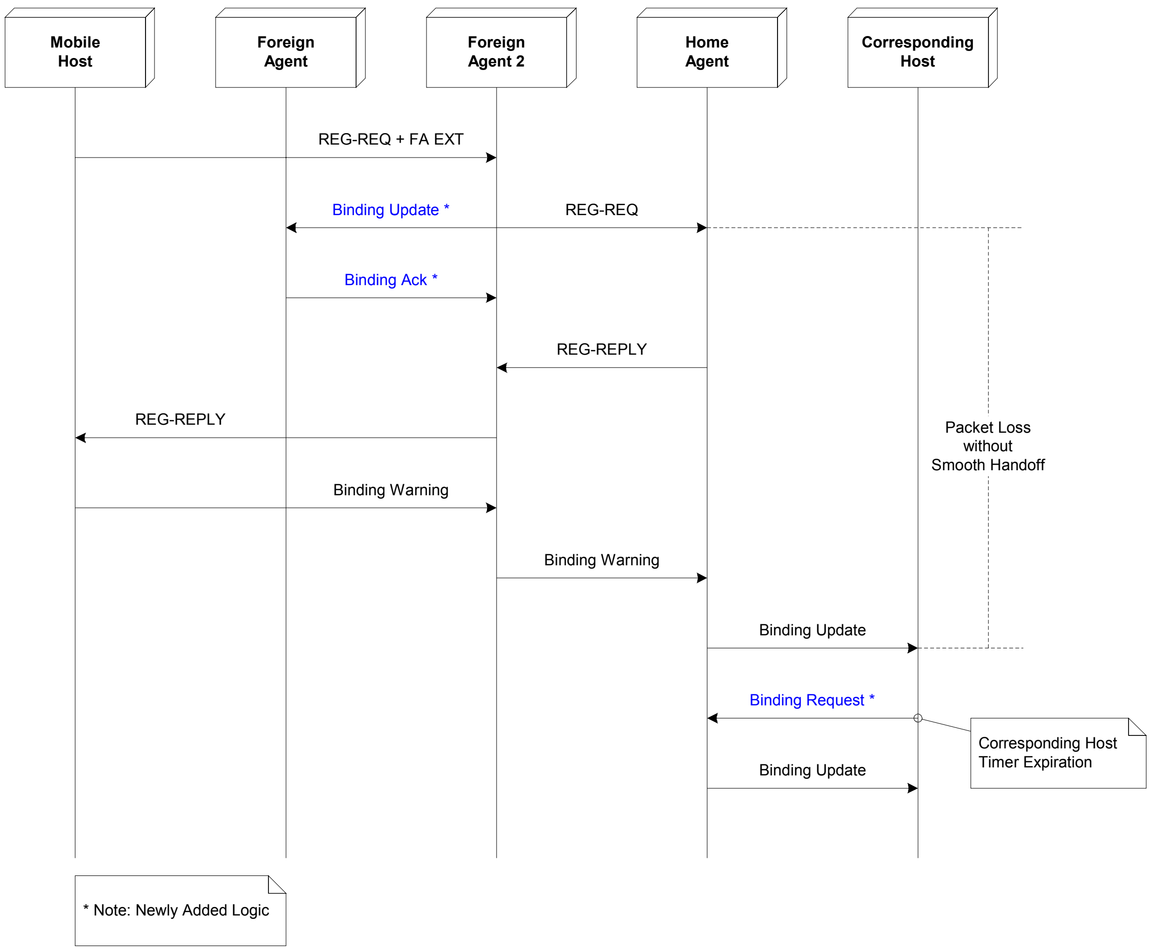

Figure 4-2 Foreign Agent → Foreign Agent Sequence Diagram

When a Mobile Host moves to a new foreign network, it first sends a Registration Request (REG-REQ) to the new Foreign Agent (Foreign Agent 2). Since the Mobile Host is moving from a foreign network to another foreign network, the Smooth Handoff process must be initiated. The Smooth Handoff process begins by the Mobile Host appending a Previous Foreign Agent extension in the Registration Request. Seeing the presence of a Previous Foreign Agent extension, the new Foreign Agent (Foreign Agent 2 in Figure 4-2) sends a Binding Update to the previous Foreign Agent (Foreign Agent 1) to create a binding cache for handling misdirected packets. The format of this Binding Update message is similar to that sent as a response to a Binding Warning, except that the 'A' (Acknowledge) bit is set in this Binding Update message. As illustrated in Figure 4-2, when Foreign Agent 1 receives the Binding Update to create a temporary binding cache, a Binding Acknowledge message is returned to indicate that a binding cache was successfully created.

If the Mobile Host failed to receive a Binding Acknowledge message, the Mobile Host must re-initiate the Smooth Handoff process. Binding Updates will be retransmitted to the previous Foreign Agent until a Binding Acknowledge message is received at the Mobile Host.

Figure 4-2 also illustrates the period in which packet loss will occur if Smooth Handoff is not supported. This period is especially evident if the Corresponding Host is very far from the Home Agent.

4.2 Reverse Routing

The Reverse Routing Update Message is sent when the Mobile Host, residing at the foreign network, detects a new stream of packets tunneled from the Home Agent or when the Mobile Host arrives at a new foreign network. These two scenarios are discussed in the following sections.

4.2.1 Mobile Host Obtains a New Stream of Tunneled Packets

In Figure 4-3, the Mobile Host starts at the foreign network by registering with the Foreign Agent and Home Agent. After the Mobile Host is accepted into the foreign network, the Mobile Host detects a new stream of tunneled packets from the Home Agent. As a result, the Mobile Host sends the Reverse Routing Update Message with the latest Care-of-Address directly to the Correspondent Host via the Foreign Agent. After the Correspondent Host receives this Reverse Routing Update Message, the

Correspondent Host will route packets directly to the Mobile Host using the new Care-of-Address; triangle routing is thus eliminated.

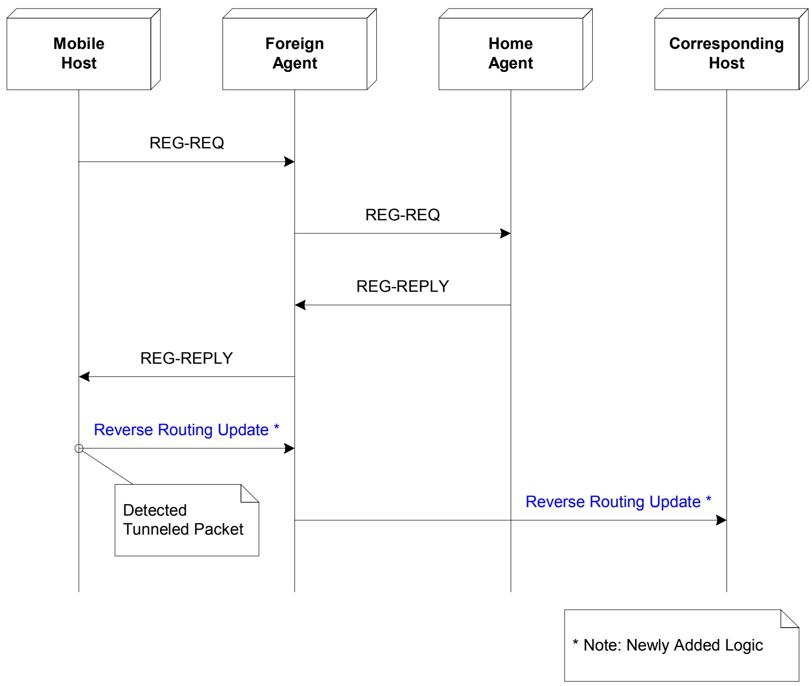

Figure 4-3 Reverse Routing Sequence Diagram for Detecting Tunneled Packets

4.2.2 Foreign Agent → Foreign Agent

In Figure 4-4, the Mobile Host is moving from one foreign network to another foreign network. When the Mobile Host arrives the new foreign network (Foreign Agent 2), the Mobile Host will send the Reverse Routing Update Message containing the latest Care-of-Address along with the Registration Request Message. The Foreign Agent 2 will then relay the Registration Request Message to the Home Agent. If the Home Agent returns a successful Registration Reply Message, the Foreign Agent 2 will relay the Registration Reply Message to the Mobile Host and will forward the Reverse Routing Update Message to the Correspondent Host. Consequently, the Correspondent Host will route packets destined to the Mobile Host with the new Care-of-Address.

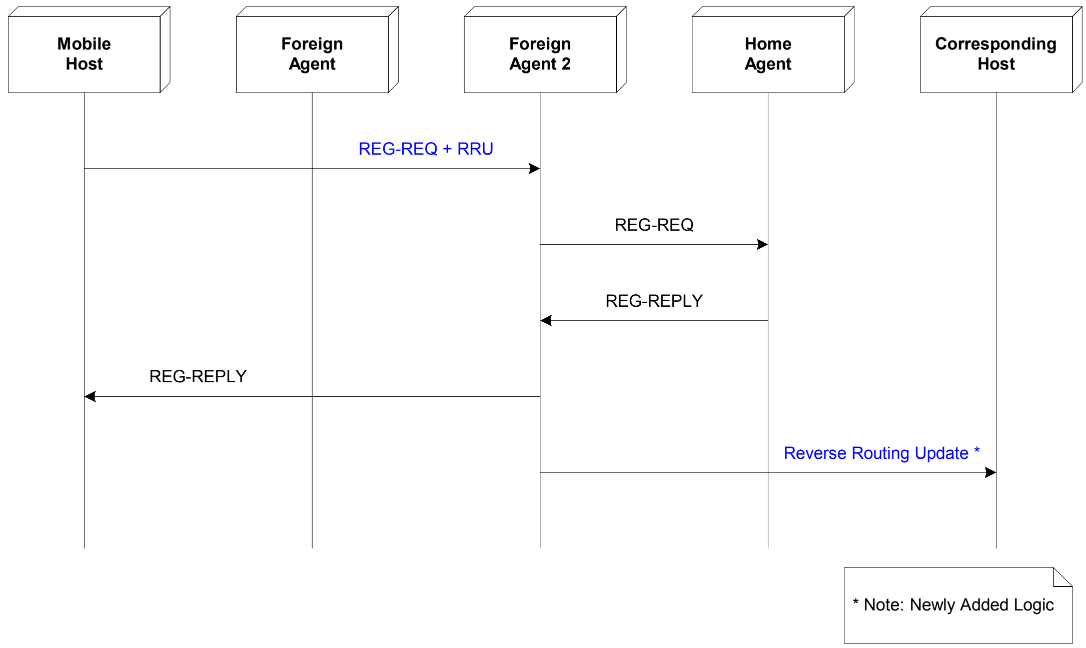

Figure 4-4 Reverse Routing Sequence Diagram for Moving to Foreign Agent 2

5 Design

5.1 Route Optimization

To facilitate the design of Route Optimization, detailed flow charts have been created to illustrate the high-level processing requirements of each message in the protocol. The following sections provide design overviews of the following messages: Binding Update, Binding Warning, Binding Request, Binding Acknowledge, and Previous Foreign Agent Extension.

5.1.1 Binding Update Message

The following figure illustrates the process for generating Binding Update message.

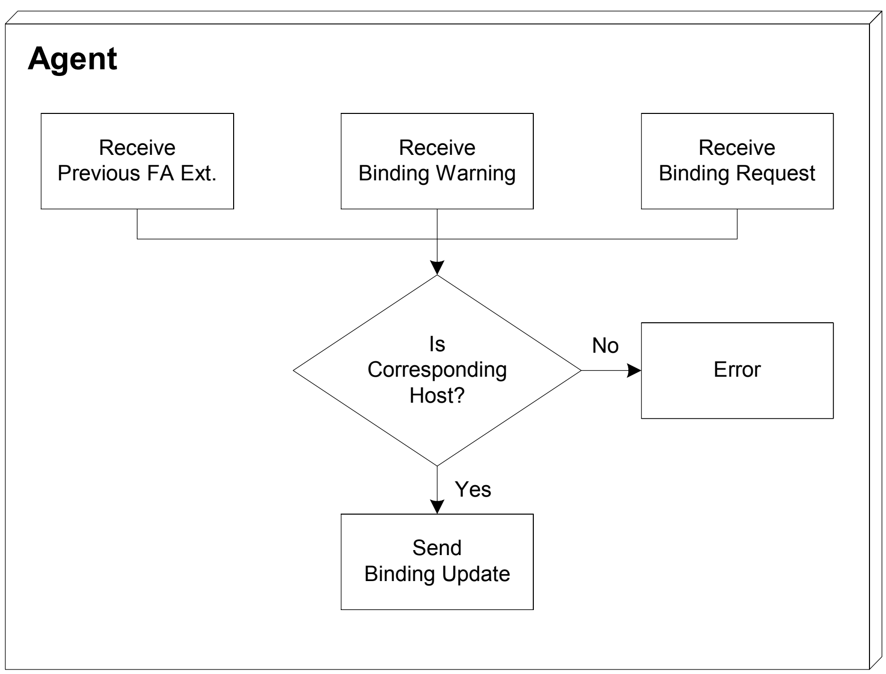

Figure 5-1 Flowchart of Sending Binding Update Message

The Binding Update message can be generated by the Home Agent or the Foreign Agent. The Home Agent generates the Binding Update message in response to a Binding Request or Binding Warning message. The Foreign Agent generates a Binding Update message to the previous Foreign Agent when a Previous Foreign Agent extension is received.

The following figure illustrates the process for receiving Binding Update message.

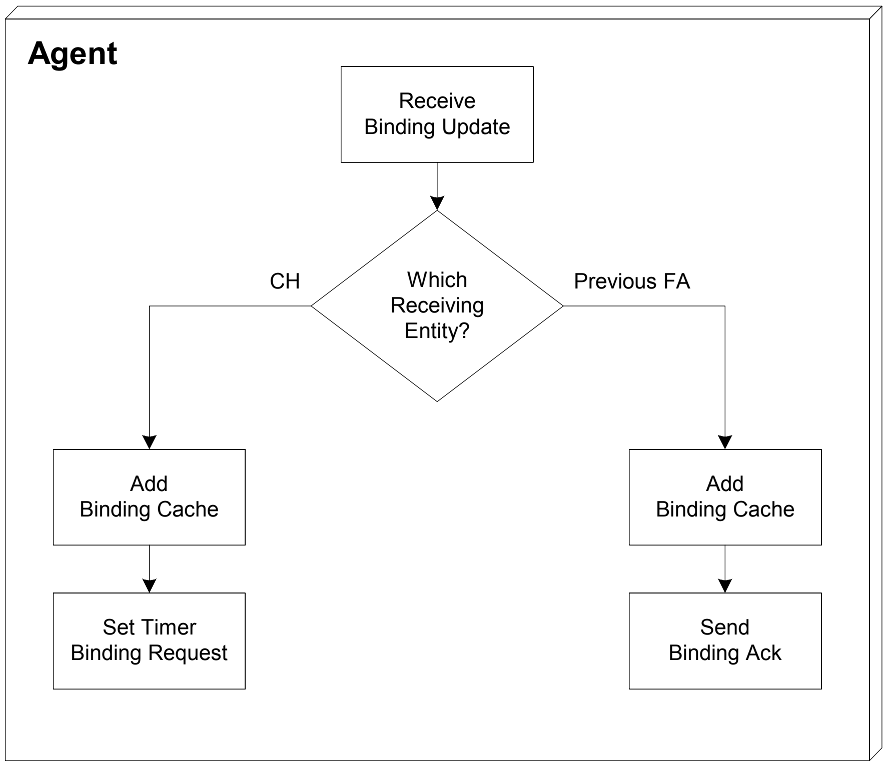

Figure 5-2 Flowchart of Receiving Binding Update Message

As illustrated in Figure 5-2, different actions are performed depending on the entity that receives the Binding Update message. If the Correspondent Host receives the Binding Update, the Correspondent Host must store the new Care-of-Address in its binding cache. Furthermore, the Correspondent Host must update its local timer so that a Binding Request is triggered prior to the expiration of a binding cache entry.

If the Previous Foreign Agent receives the Binding Update, then this Binding Update is part of the Smooth Handoff process. Using the new Care-of-Address extracted from the message, the previous Foreign Agent should establish a binding cache to re-direct datagrams to the new Care-of-Address.

5.1.2 Binding Warning Message

The following figure illustrates the process for generating Binding Warning message.

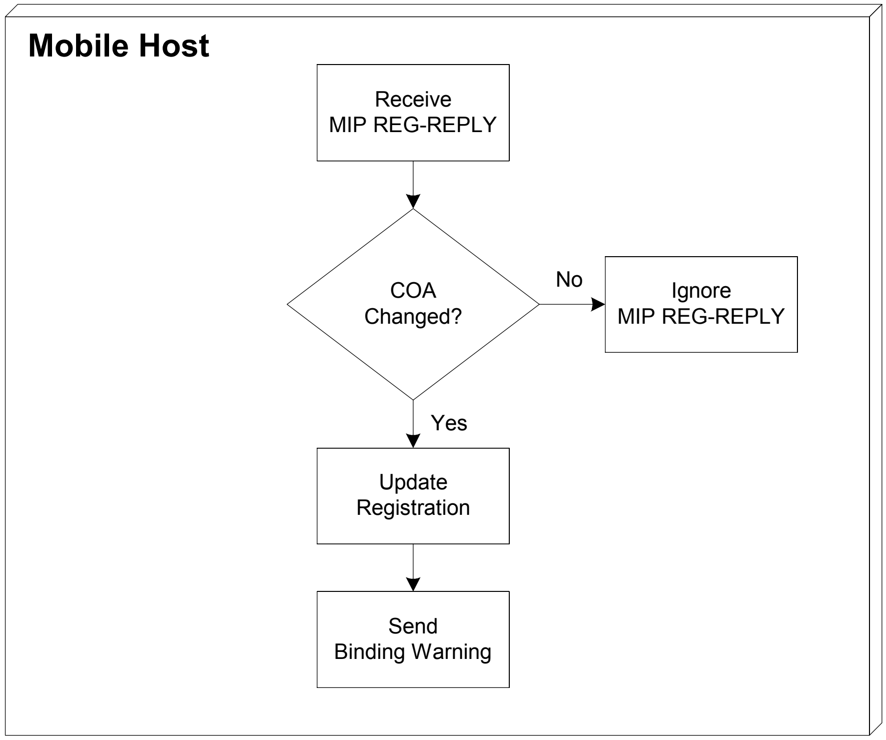

Figure 5-3 Flowchart of Sending Binding Warning Message

On recipient of a new Care-of-Address, the Mobile Host updates its registration and generates a Binding Warning to the Home Agent. In response, the Home Agent sends a Binding Update to the appropriate node to modify the binding cache for the Mobile Host.

If a new Care-of-Address is not received, a Binding Update is not required since the Mobile Host did not move to another subnet.

The following figure illustrates the process for receiving Binding Warning message.

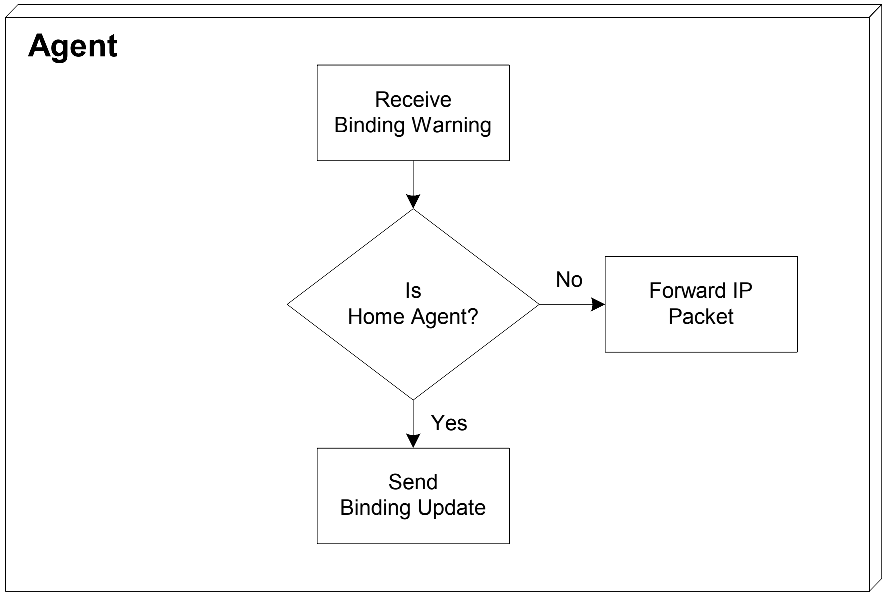

Figure 5-4 Flowchart of Receiving Binding Warning Message

When an agent (Home Agent / Foreign Agent) receives a Binding Warning message from a Mobile Host, it first checks whether it is the Home Agent of the Mobile Host. If it is the Home Agent, a Binding Update is sent to the appropriate recipient. If, however, it is the Foreign Agent, the Binding Update message is forwarded via normal routing procedures to the appropriate Home Agent.

5.1.3 Binding Request Message

The following figure illustrates the process for generating Binding Request message.

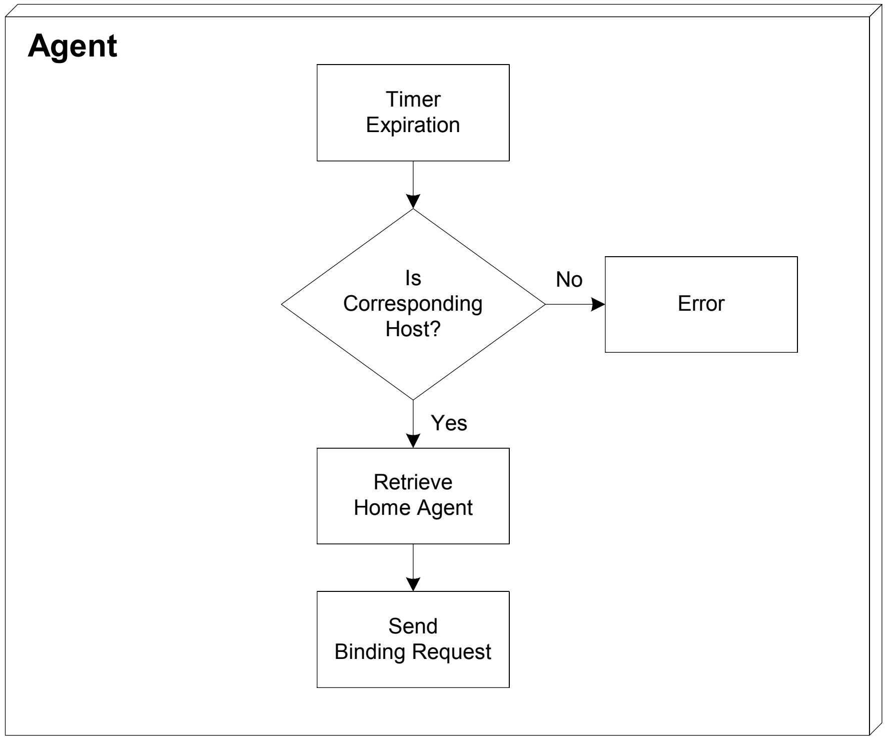

Figure 5-5 Flowchart of Sending Binding Request Message

When the binding cache timer expires at the Corresponding Host, the Correspondent Host generates a Binding Request to the Home Agent.

The following figure illustrates the process for receiving Binding Request message.

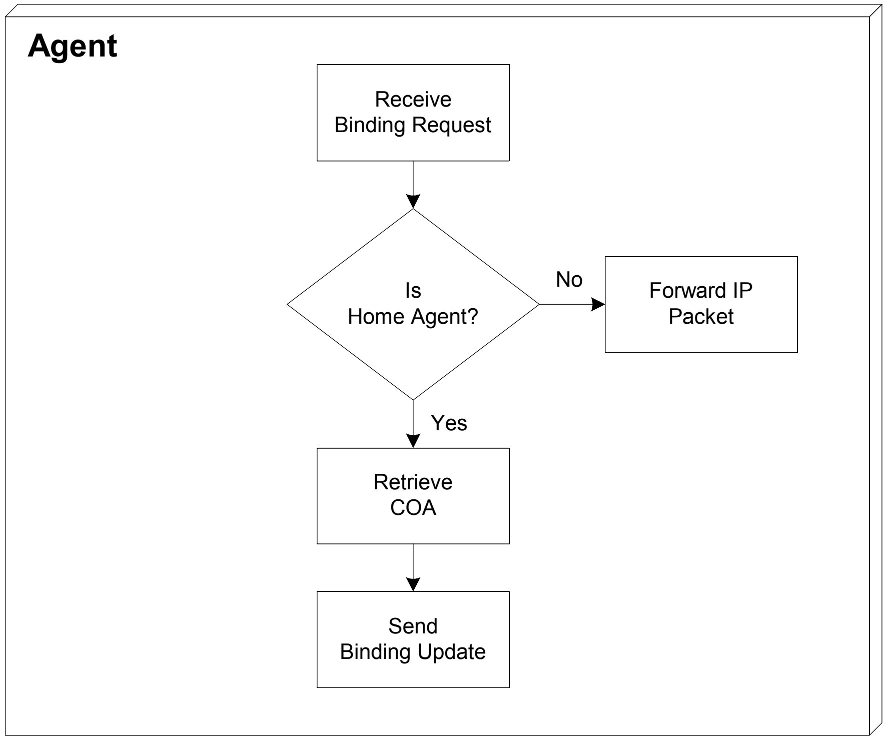

Figure 5-6 Flowchart of Receiving Binding Request Message

A Binding Request message is only processed by the Home Agent. When the Home Agent receives the Binding Request, it retrieves the Care-of-Address of the corresponding Mobile Host and generates a Binding Update. All other agents that receive the Binding Request must ignore this message and forward the packet to the appropriate Home Agent.

5.1.4 Binding Acknowledge Message

The following figure illustrates the process for generating Binding Acknowledge message.

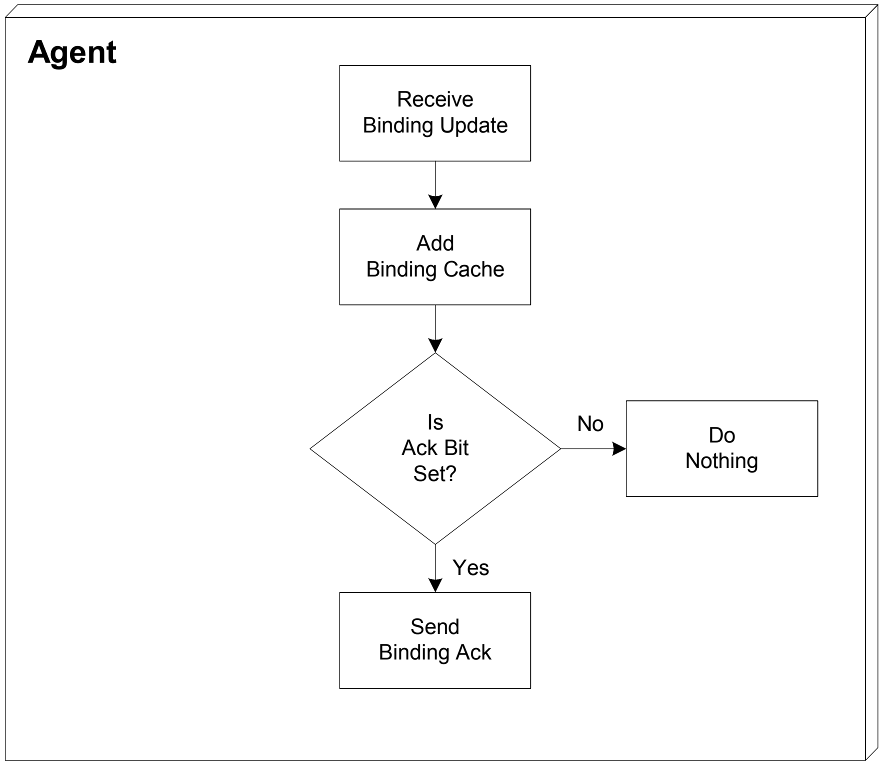

Figure 5-7 Flowchart of Sending Binding Acknowledge Message

A Binding Acknowledge message is generated only if the 'A' (acknowledge) bit of the Binding Update message is set.

The following figure illustrates the process for receiving Binding Acknowledge message.

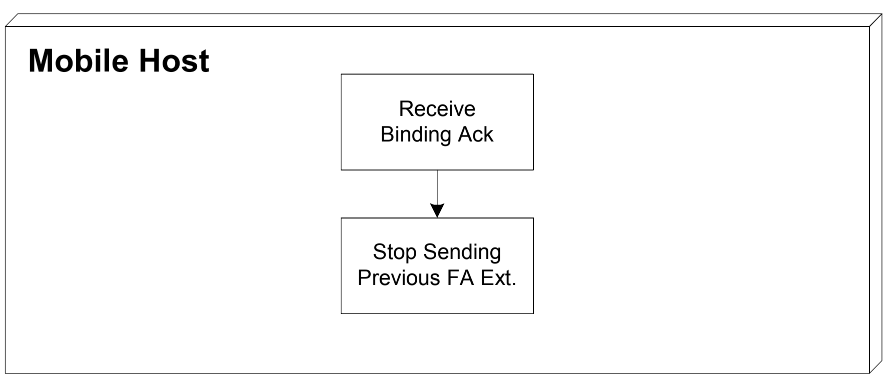

Figure 5-8 Flowchart of Receiving Binding Acknowledge Message

As discussed in Section 4.1.2, the Mobile Host will retransmit the Previous Foreign Agent extension until a Binding Acknowledge is received. This retransmission ensures that the previous Foreign Agent has properly established the binding cache.

5.1.5 Smooth Handoff

The following figure shows the process on the sending side of Smooth Handoff.

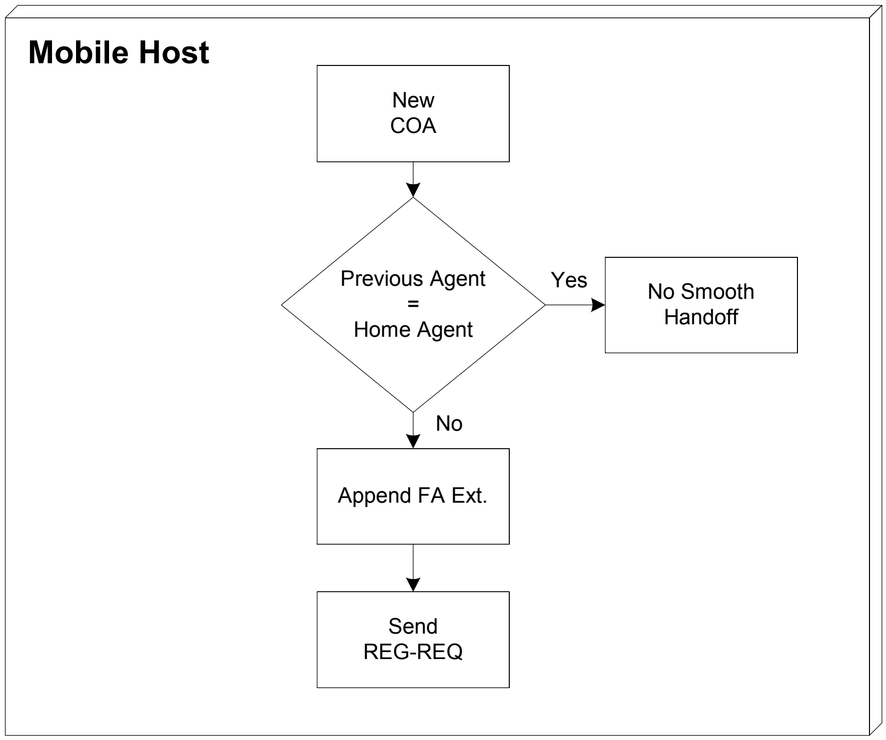

Figure 5-9 Sending Side of Smooth Handoff

Upon receiving a new Care-of-Address, the Mobile Host checks whether its previously visited network is the home network. If the previous network is the home network, then Smooth Handoff is not required since the Home Agent knows the new Care-of-Address for the Mobile Host. If, however, the previous network is a foreign network, then Smooth Handoff is triggered. Smooth handoff is initiated when the Mobile Host appends a previous Foreign Agent extension to the Registration Request. This extension contains the IP address of the previous Foreign Agent.

The following figure shows the process on the receiving side of Smooth Handoff.

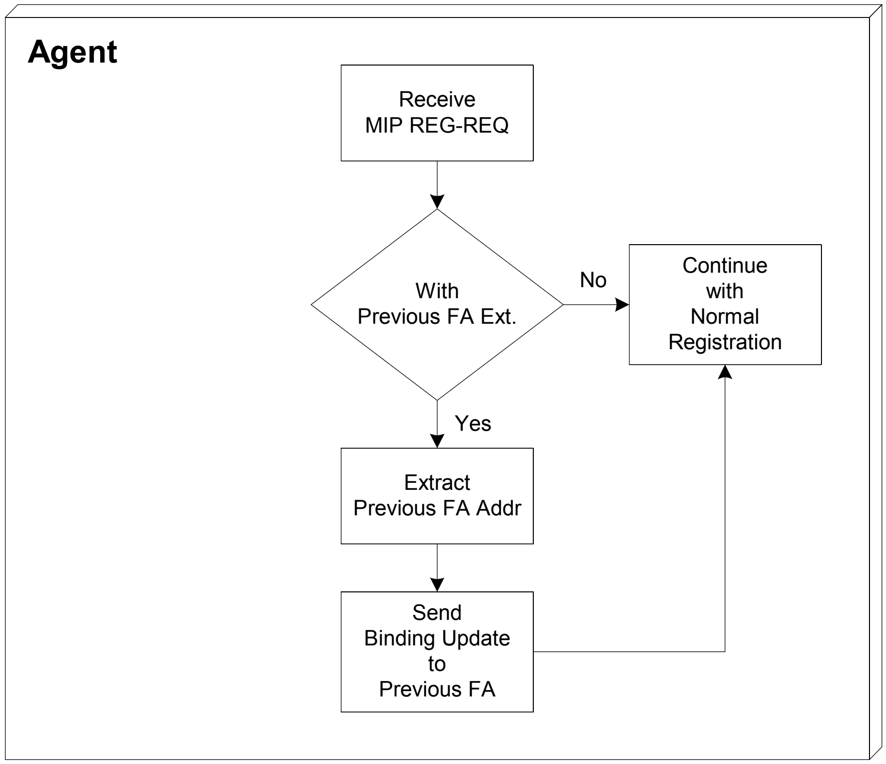

Figure 5-10 Receiving Side of Smooth Handoff

When the Foreign Agent receives the Registration Request, it first checks whether a Previous Foreign Agent extension is present. If no extension is specified, normal registration process as described in Section 4.1.2 are carried out. If a Previous Foreign Agent extension is present, the Foreign Agent must extract and validate the previous Foreign Agent address from the extension. Once the address is properly verified, a Binding Update is sent to the previous Foreign Agent to create a binding cache for the Mobile Host. The Foreign Agent then proceeds with normal registration process.

5.2 Reverse Routing

To document our design of Reverse Routing, detailed flow charts have been created to illustrate the high-level processing requirements of the Reverse Routing Update Message in the protocol.

5.2.1 Reverse Routing Update Message

The following figure illustrates the process for generating Reverse Routing Update Message.

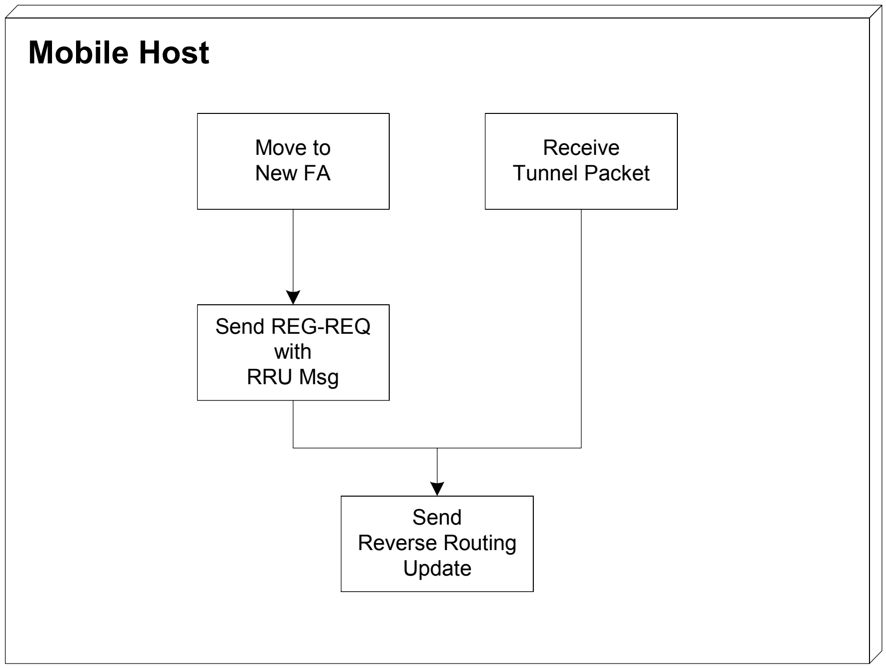

Figure 5-11 Flowchart of Sending Reverse Routing Update Message

Two scenarios can trigger the Mobile Host to send this message. In the first scenario, when the Mobile Host staying at the foreign network receives a stream of tunneled packets from the Home Agent, the Mobile Host will send the Reverse Routing Update Message directly to the Correspondent Host. In the second scenario, when the Mobile Host moves to a new foreign network, the Mobile Host will send the Reverse Routing Update Message along with the Registration Request Message to the Foreign Agent. After the Foreign Agent receives the Registration Reply Message with a success status as a result of relaying the Registration Request Message to the Home Agent, the Foreign Agent will forward the Reverse Routing Update Message to the Correspondent Host.

The following figure illustrates the process for receiving Reverse Routing Update Message.

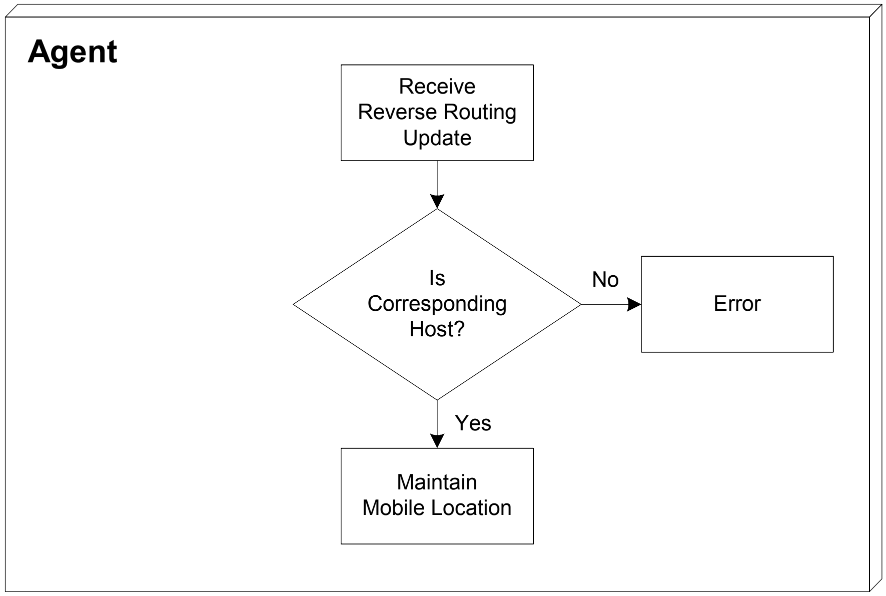

Figure 5-12 Flowchart of Receiving Reverse Routing Update Message

Upon receiving the Reverse Routing Update Message, the Correspondent Host will update the destination address of the Mobile Host with the new Care-of-Address. When the Correspondent Host wants to send packets to the Mobile Host, the latest Care-of-Address will be used in order for the packets to be routed to the Mobile Host resided at the foreign network.

6 NS-2 Implementation

Section 5 provided an overview of the design requirements of this project. In this section, implementation details of these requirements are discussed.

6.1 Route Optimization

Upon complete understanding of the Mobile IP code as well as Leo's enhancements for Route Optimization in NS-2, we modified both the C++ and the Tcl source code to support the full Route Optimization protocol. The following is a summary of the source code modification.

- MIP.H
    - Expanded MIP message type to include Binding Request, Binding Acknowledge, and Previous Foreign Agent extension
    - Added function prototypes for the generation of the Binding Request and Binding Acknowledge message
    - Added a new function prototype to generate previous Foreign Agent extension
    - Updated the MIP header to incorporate new fields for the Binding Request and Binding Acknowledge message
    - Added a new logging interface to effectively print debug messages
- MIP-REG.CC
    - Modified the recv function in MIPBSAgent to handle Binding Request, Binding Acknowledge, and Previous Foreign Agent Extension message according to the behavior described in Section 5.1.
    - Added the send_br function in MIPBSAgent to generate a binding request
    - Added the send_ba function in MIPBSAgent to generate a binding acknowledge
    - Modified the timeout function in MIPBSAgent to trigger a Binding Request when the binding cache is about to expire
    - Modified the recv function in MIPMHAgent to trigger the generation of the Foreign Agent extension when a new Care-of-Address is obtained

  - Modified the recv function of MIPMHAgent to handle Binding Acknowledge according to the behavior described in Section 5.1
  - Modified the reg function in MIPMHAgent to append a Previous Foreign Agent extension

- NS-MIP.TCL

  - Added the setCOA function to maintain the Care-of-Address of a Mobile Host

6.2 Reverse Routing

Our design of Reverse Routing contains the changes in both the C++ and the Tcl source code. The following is a summary of the source code modification.

- MIP.H

  - Expanded MIP message type to include Reverse Routing Update extension
  - Added function prototypes for the generation of the Reverse Routing Update message
  - Revised the MIP header to incorporate new fields for the Reverse Routing Update message

- MIP.CC

  - Modified the recv() function in MIPDecapsulator to save the Corresponding Host to the Mobile Host for later use.
  - Modified the recv() function in MIPDecapsulator to send the Reverse Routing Update Message after receiving tunneled packets.

- MIP-REG.CC

  - Modified the recv() function in MIPBSAgent to handle Reverse Routing Update Message according to the behavior described in Section 5.2.1.
  - Modified the recv() function in MIPBSAgent to forward Reverse Routing Update Message after receiving Registration Reply Message with a success status as specified in Section 5.2.1.

  - Added the send_rru() function in MIPBSAgent to generate a Reverse Routing Update Message.

  - Modified the recv() function in MIPMHAgent to save the address of the Correspondent Host so that the Mobile Host can send Reverse Routing Update Message later on.

- NS-MIP.TCL

  - Added the setCHAtMH() function in Classifier/Addr/MIPDecapsulator to save the address of the Correspondent Host to the Mobile Host.

  - Added the send-rru() function in Classifier/Addr/MIPDecapsulator to send Reverse Routing Update Message.

- NS-MOBILENODE.TCL

  - Add the node variable to Node/MobileNode so that the TCL code can be called in MIPDecapsulator

7 Simulations

Several scenarios have been simulated to verify our implementation for Route Optimization and Reverse Routing. The simulation results of each scenario are discussed in the following sub-sections.

7.1 Route Optimization

7.1.1 Route Optimization vs. Mobile IP

To demonstrate the performance of the completed Route Optimization protocol, multiple Foreign Agents are used in the simulation. The following NAM screen shot illustrates the topology of the simulation.

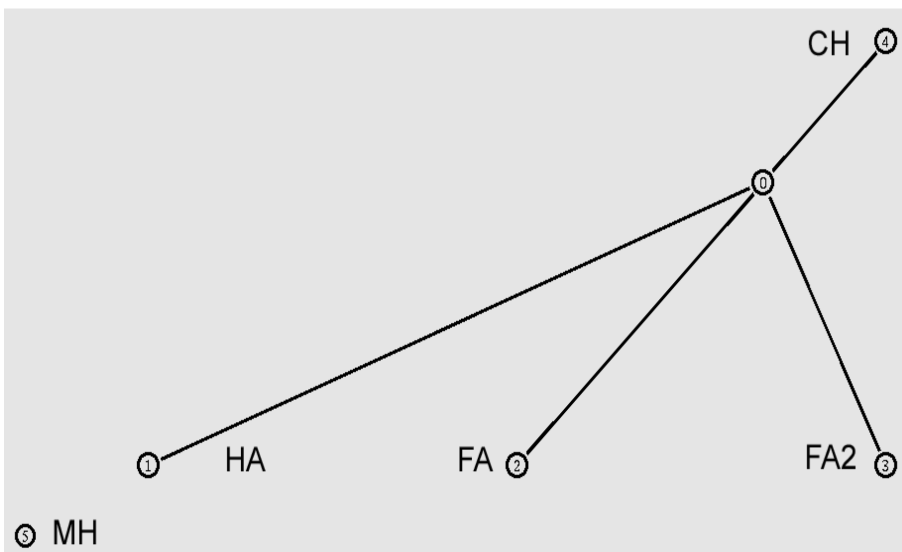

Figure 7-1 Route Optimization Simulation Topology

The following parameters are used in the simulation:

- Radio Coverage: 75m
- Position of HA: (200,200), FA: (350,300), FA2: (500,300), CH: (800,800)
- Movement of MH: (150,275) → (560,275)
- Traffic Type: CBR
- Link delay between CH → HA: 25 ms, CH → FA: 20 ms, CH → FA2: 20 ms

Our log file created by the above simulation is shown below. The highlight log messages illustrate that the Binding Request and Binding Acknowledgement message are successfully sent and received.

```
num_nodes is set 5
HA id : 1
FA id : 2
FA2 id : 3
CH id : 4
MH id : 5

Rate = 448000
Starting Simulation...
[0.009803] - new ADS recved for 4194304.  Replacing old addr -1, expire_time =
             1.009803
             appending FA Notification extension for old CA = 0.  Sending Reg to
             4194304
[0.639490] - MIPT_REG_REPLY received for MH
[1.001848] - identical ADS received (4194304) - renewal, expire_time = 2.001848
             appending FA Notification extension for old CA = 0.  Sending Reg to
             4194304
[1.006269] - MIPT_REG_REPLY received for MH
    :
    :
              TO for addr 4194304...saving oldcoa_
              coalost: reg...
[36.559414] - new ADS recved for 8388608.  Replacing old addr -1, expire_time =
              37.559414
              appending FA Notification extension for old CA = 4194304.  Sending Reg
              to 8388608
[41.066694] - REG-REQ received...I am not the HA: 8388608, ack bit = 9, seqNum = 41
[41.066694] - not generating BU to previous FA
[41.121925] - MIPT_REG_REQUEST! SA:8388608, DA:4194304, HAddr:4194305, COA:8388608
              encap-route added!
[41.148001] - Send out BU ! Saddr:4194304, Sport:0, Daddr:2048, Dport:0,
              Time:41.148001
[41.148001] - Send out BU ! HA:4194304, Haddr:4194305, COA:8388608, TS:41.148001
[41.179444] - MIPT_REG_REPLY received for MH
[41.179444] - Send out BW ! HA:4194304, Haddr:4194305, COA:8388608 TS:41.179444
[41.200154] - CH [2048] Received BU ! SA[4194304] DA[2048]
              CH Received BU ! Haddr[4194305] Ha[4194304] COA[8388608]
[41.200154] - CH set BU info ! SA [4194304] Expire Time[44.200154]
[41.242742] - Received BW ! Saddr[8388608] Sport[0] Daddr[4194304] Dport[0]
              Received BW ! Haddr[4194305] Ha[4194304] COA[8388608]
    :
    :
[45.088123] - CH confirms BR expiration ! Expire Time[44.294896]
[45.088123] - CH sends BR! DA:4194304, HAddr:4194305
[45.088123] - HA received BR: SA[2048] DA[4194304] HAddr [4194305]
[45.088123] - HA sends BU: SA [4194304] DA [2048] HAddr [4194305] COA [8388608]
[45.088123] - Send out BU ! Saddr:4194304, Sport:0, Daddr:2048, Dport:0,
              Time:45.088123
[45.088123] - Send out BU ! HA:4194304, Haddr:4194305, COA:8388608, TS:45.088123
    :
    :
[77.088123] - CH confirms BR expiration ! Expire Time[76.140276]
[77.088123] - CH sends BR! DA:4194304, HAddr:4194305
[77.088123] - HA received BR: SA[2048] DA[4194304] HAddr [4194305]
[77.088123] - HA sends BU: SA [4194304] DA [2048] HAddr [4194305] COA [8388608]
[77.088123] - Send out BU ! Saddr:4194304, Sport:0, Daddr:2048, Dport:0,
              Time:77.088123
[77.088123] - Send out BU ! HA:4194304, Haddr:4194305, COA:8388608, TS:77.088123
[77.140276] - CH [2048] Received BU ! SA[4194304] DA[2048]
              CH Received BU ! Haddr[4194305] Ha[4194304] COA[8388608]
```

```
[77.140276] - CH set BU info ! SA [4194304] Expire Time[80.140276]
              appending FA Notification extension for old CA = 8388608.  Sending Reg
              to 12582912
[77.526833] - REG-REQ received...I am not the HA: 12582912, ack bit = 9, seqNum = 79
[77.526833] - previous FA Notification extension present...generating BU
[77.526833] - Send out BU ! Saddr:12582912, Sport:0, Daddr:8388608, Dport:0,
              Time:77.526833
[77.526833] - Send out BU ! HA:4194304, Haddr:4194305, COA:12582912, TS:77.526833

[77.533974] - FA Received BU ! SA[12582912] DA[8388608]
              FA Received BU ! Haddr[4194305] Ha[4194304] COA[12582912]
[77.533974] - 8388608 updating COA for MH 4194305
[77.533974] - sending BA! Daddr:12582912, Dport:0, Haddr:4194305, ackStatus:0
[77.543171] - Binding Ack received
[77.579108] - MIPT_REG_REQUEST! SA:12582912, DA:4194304, HAddr:4194305, COA:12582912
    :
    :

[89.131588] - identical ADS received (12582912) - renewal, expire_time = 90.131588
[89.140276] - CH [2048] Received BU ! SA[4194304] DA[2048]
              CH Received BU ! Haddr[4194305] Ha[4194304] COA[12582912]
[89.140276] - CH set BU info ! SA [4194304] Expire Time[92.140276]
[89.181419] - REG-REQ received...I am not the HA: 12582912, ack bit = 0, seqNum = 92
[89.233630] - MIPT_REG_REQUEST! SA:12582912, DA:4194304, HAddr:4194305, COA:12582912
[89.369923] - MIPT_REG_REPLY received for MH
NS EXITING...
```

Figure 7-2 Log Messages for Route Optimization

Figure 7-3 compares the performance of the basic Mobile IP protocol with the completed Route Optimization protocol.

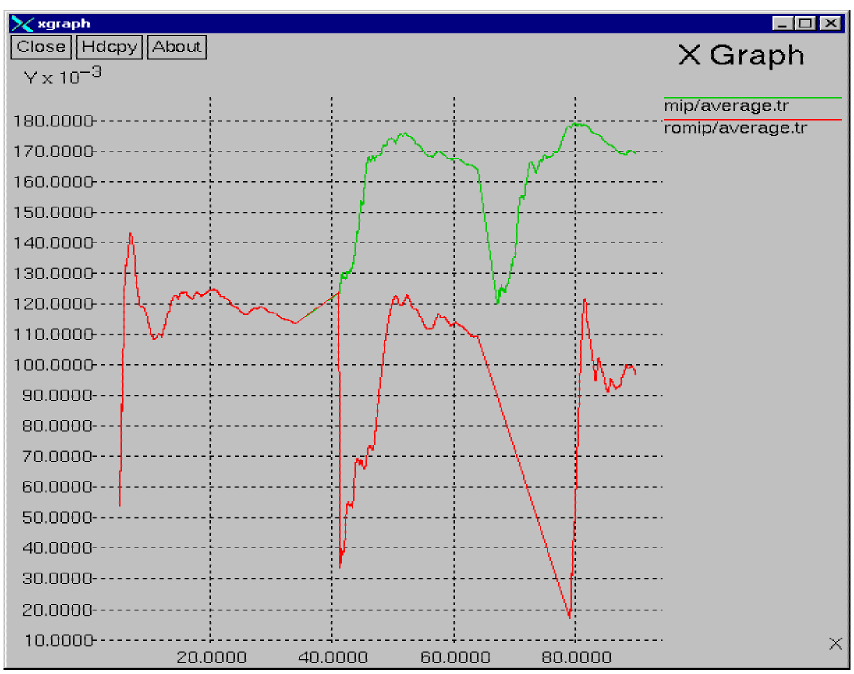

Figure 7-3 Performance between Mobile IP and completed Route Optimization

The red graph represents the average end-to-end delay with Route Optimization while the green graph represents the average end-to-end delay without Route Optimization. The average end-to-end delay curve for Route Optimization is significantly lower than that without Route Optimization. This justifies that the completed Route Optimization provides better performance than basic Mobile IP.

7.1.2 Smooth Handoff Performance

To demonstrate the performance of Smooth Handoff, the same topology from Section 7.1.1 is used. Instead of comparing the completed Route Optimization with the basic Mobile IP protocol, we compare the completed Route Optimization with Leo's implementation (that is, the half-completed Route Optimization protocol with no Smooth Handoff support). We also changed the traffic type from TCP to UDP so that packet lost is more evident. Also, instead of comparing the end-to-end delay, we examined the packet lost performance. Figure 7-4 compares the performance with and without Smooth Handoff support. On the y-axis is the packet lost in bytes while the x-axis represents the time in seconds. The packet lost is calculated based on the accumulated packet lost for a 1 second window. The black graph is Leo's implementation while the red graph has Smooth Handoff support.

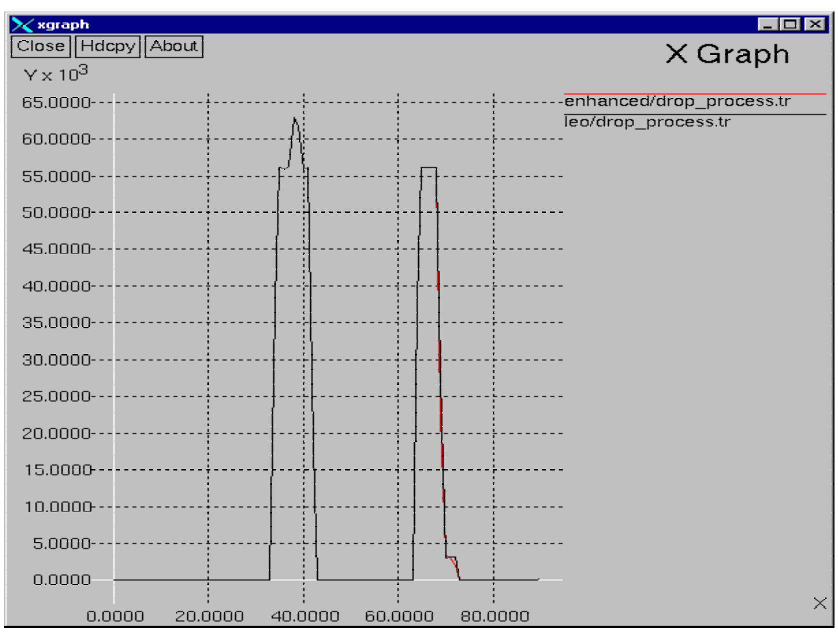

Figure 7-4 Packet Lost with and without Smooth Handoff

Figure 7-4 shows that packet lost is observed between 36 to 42 seconds. This is the time when the Mobile Host moves from the Home Agent to the Foreign Agent. Since Smooth Handoff does not operate in this scenario, the two graphs (with and without Smooth Handoff) are the same in this time period.

The Mobile Host moves from one foreign network to another foreign network between 66 to 72 seconds. This agrees with the second peak of Figure 7-4. Smooth Handoff is used in this scenario because the previous visited network for the Mobile Host is a foreign network. The two graphs in Figure 7-4 starts to differ at around 70 seconds. This is the time when Smooth Handoff is initiated. A magnified view of Figure 7-4 at around 70 seconds is provided in the following figure.

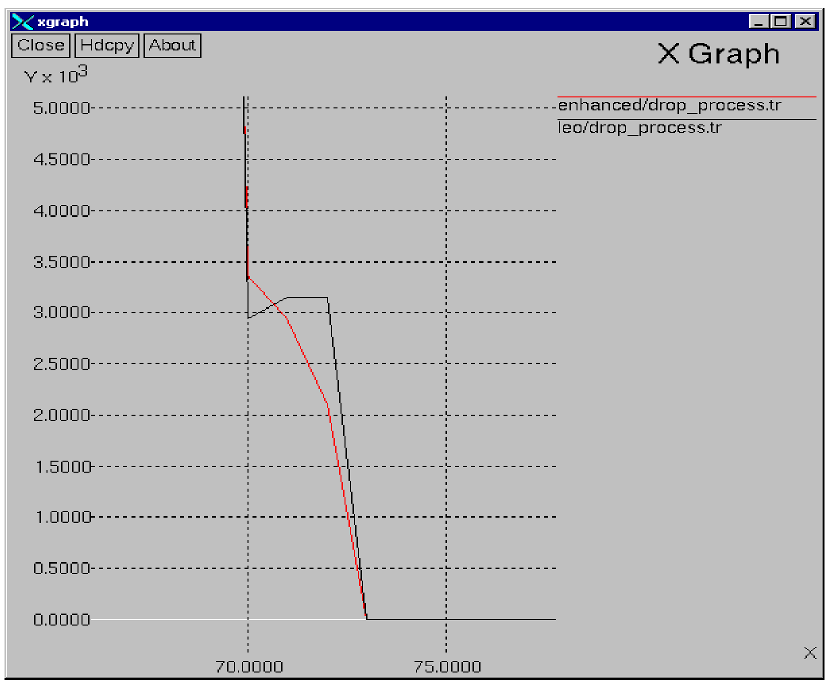

Figure 7-5 Packet Lost with and without Smooth Handoff (zoom)

Figure 7-5 clearly shows that at 70 seconds, the performance with Smooth Handoff is better than that without Smooth Handoff. At 70 seconds, the graph with Smooth Handoff yields a packet lost of 2950 bytes while the graph without Smooth Handoff yields a packet lost of 3350 bytes. Thus, the above figures have demonstrated that Smooth Handoff does reduce packet lost.

7.2 Reverse Routing

In order to validate our implementation of Reverse Routing and to compare the performance of Route Optimization and Reverse Routing, we decided to simulate the Mobile Host moving from the Home Agent to the Foreign Agent. The following NAM screen shot illustrates the topology of the simulation.

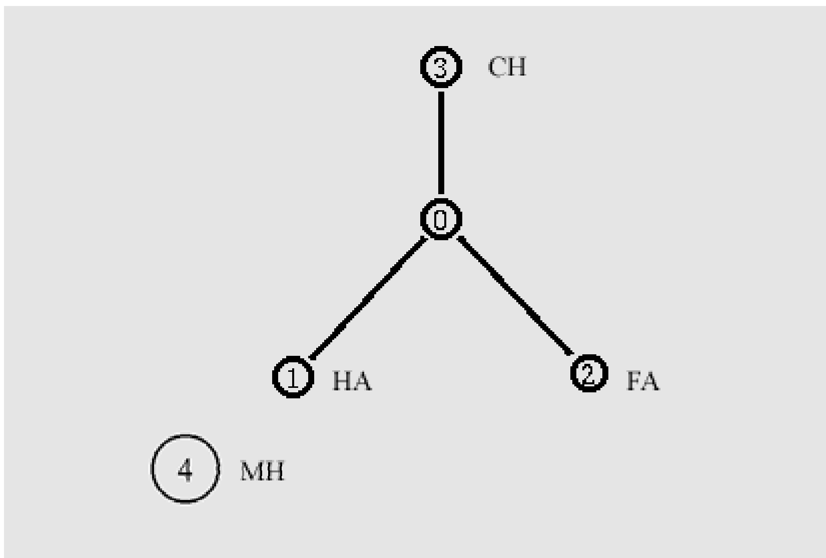

Figure 7-6 Reverse Routing Simulation Topology

The following parameters are used in the simulation:

- Radio Coverage: 75m
- Position of HA: (200,300), FA: (330, 300), CH: (800, 800)
- Movement of MH: (150, 275) → (410, 275)
- Traffic Type: CBR
- Link delay: CH → HA : 25ms, CH → FA : 10ms

Our log file created by the above simulation is shown below. The highlight log messages illustrate that the Mobile Host successfully sent the Reverse Routing Update Message and the Correspondent Host successfully received the Reverse Routing Update Message.

```
num_nodes is set 4
HA id : 1
FA id : 2
CH id : 3
MH id : 4
Starting Simulation...
encap-route added!
Tunnelled datagram is detected by FA!
Sending RRU by the FA now!
TCL: Trying to send RRU at Decapsulator!
TCL: Decapsulator input parameters (daddr = 2048, haddr = 4194305,
coa = 8388608)!
RRU is required by the TCL Decapsulator!
FA sent out RRU! SAddr:8388608, SPort:0, DAddr:2048, DPort:0,
Time:26.816369
FA sent out RRU! HA:4194304, HAddr:4194305, COA:8388608, TS:26.816369
Successfully send the RRU
CH received RRU! SAddr[8388608] SPort[0] DAddr[2048] DPort[0]
TS[26.816369]
CH received RRU! HAddr[4194305] HA[4194304] COA[8388608]
Registration at CH after RRU received!
encap-route added!
NS EXITING...
```

Figure 7-7 Log Messages for Reverse Routing

The End-to-End Delay graphs of Route Optimization and Reverse Routing are compared in Figure 7-8. The red line displays the End-to-End Delay for Route Optimization, while the blue line shows the End-to-End Delay for Reverse Routing. Note that the first part of the red line is exactly behind the blue line. This result coincides with our implementation, because the same signaling messages from the base Mobile IP protocol are employed for both Route Optimization and Reverse Routing when staying at the home network. The difference between the End-to-End Delay of Route Optimization and Reverse Routing starts to emerge when the Mobile Host starts to move to the Foreign Agent. During the Mobile Host's transition to a new Foreign Agent, both graphs drop tremendously, because the end-to-end delay of lost packets cannot be calculated by NS. When the Mobile Host arrives to another Foreign Agent, the End-to-End Delay jumps back up and stabilizes. As you can see, the End-to-End Delay still exhibits similar characteristics even after the transition. With this result, we can conclude that the performance of Reverse Routing is very similar to that of the Route Optimization. However, Reverse Routing only employs one signaling message, while Route Optimization uses four signaling messages. Therefore, Reverse Routing can eliminate complexity of the Route Optimization and can retain the simplicity of the base Mobile IP protocol.

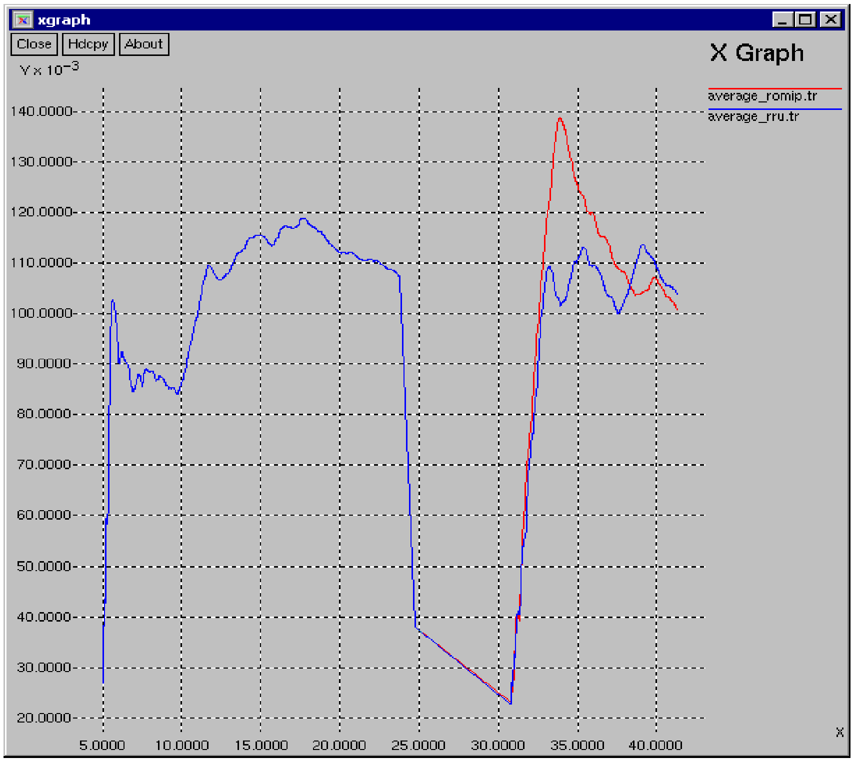

Figure 7-8 End-to-End Delay for ROMIP and RRMIP

8 Our Accomplishment

This section describes the accomplishment of the project.

8.1 Resolved Hardware Problems

In order to implement both Route Optimization and Reverse Routing protocols in NS-2, we allocated a dedicated computer for our project. Due to system constraints and memory deficiencies of this computer, we ran into various hardware issues such as RAM incompatibility and segmentation faults. After some trouble-shooting and hardware replacements, we've successfully installed NS-2 on a stable Linux system for our development.

8.2 Verified Previous Project

Since our project is based on a previous project by Leo Chen, one of the initial actions for our project is to verify his work. Unfortunately, there were discrepancies between his Tcl script which simulates the network topology and the Perl script which performs post-process data analysis. Due to these discrepancies, no data could be extracted from the trace file.

To resolve the problem, we had to be competent with Tcl, NS-2, and Perl. After understanding Leo's work and analyzing his scripts, we found that Leo had overlooked the trace format in NS-2. The new wireless trace feature must be enabled to properly perform post-process data analysis on the trace file.

8.3 Completed Binding Cache Management Messages

In the previous project, only 2 of the 4 binding cache management messages were implemented. We have successfully implemented the 2 remaining management messages (Binding Request and Binding Acknowledge), thereby completing the route optimization protocol for maintaining binding caches.

8.4 Added Smooth Handoff Support

The Smooth Handoff feature was successfully implemented in our project. Comparing the performance with and without this feature, we have shown that Smooth Handoff does reduce packet losses when the Mobile Host moves between foreign networks.

The design for Smooth Handoff was carefully thought out to reduce unnecessary signaling. Smooth Handoff should not be triggered if the previous Foreign Agent is the Home Agent.

8.5 Designed Reverse Routing Message Format

The architects of the Reverse Routing protocol did not specify the format of the Reverse Routing Update message. Thus, we have designed the Reverse Routing Update message so that it contains the necessary information to inform the Correspondent Host on the current location of the Mobile Host. In addition, the Reverse Routing Update message was designed such that it is compatible with other Mobile IP message formats and it accounts for future extensions to the message.

8.6 Added Reverse Routing Support

The Reverse Routing protocol was carefully designed and successfully implemented in our project. The two scenarios presented in Section x have demonstrated that triangle routing can be eliminated with only 1 signaling message (as opposed to 4 signaling messages for Route Optimization).

8.7 Comparison of Route Optimization and Reverse Routing

As described in Section 7, we have presented quantitative efficiency evaluations between Route Optimization and Reverse Routing. Various scenarios have been simulated to demonstrate the performance of the two protocols. In addition, comparisons have been made to discuss the advantages and drawbacks of each protocol.

8.8 Upgrade to NS-2.26

This project was initially developed using NS 2.1b8 because this was the version that Leo used for his development. We have successfully upgraded this project to use the latest stable NS release – NS 2.26. The upgrade went very smoothly. The numerous problems that we encountered during the installation of NS 2.1b8 have all been resolved in the latest NS release.

9 Conclusion and Future Work

The goal of this project is to simulate both the Route Optimization and Reverse Routing protocol in NS-2. This project provides an overview and a comparison between the two protocols. In addition, the design and the implementation of the two protocols are presented. Major accomplishments for this project includes:

- Completed Route Optimization Protocol (Added Binding Request, Binding Acknowledge, and Smooth Handoff)
- Added Reverse Routing
- Upgraded to NS 2.26

This project was successfully implemented. Different simulation scenarios were examined, and the simulation results validated the implementation of this project. Possible future development of this project is to compare Route Optimization and Reverse Routing with other optimization protocols. In addition, comparison of mobility support between IPv4 and IPv6 can also be explored.

10 Reference

[1] H. Chen and Lj. Trajkovic, “Route optimization in mobile IP,” Proc. Workshop on Wireless Local Networks (WLN) 2002, Tampa, FL, Nov. 2002, pp. 847-848.

[2] C. Perkins, "IP Mobility Support," RFC 2002, October 1996: http://www.ietf.org/rfc/rfc2002.txt (accessed in October 2003).

[3] C. Perkins, "IP Mobility Support For IPv4," RFC 3220, January 2002: http://www.ietf.org/rfc/rfc3220.txt (accessed in October 2003).

[4] C. Perkins and D. Johnson, "Route Optimization in Mobile IP," Internet Draft, February 2000: http://people.nokia.net/~charliep/txt/optim/optim.txt (accessed in October 2003).

[5] P. Calhoun and C. Perkins, "Mobile IP Challenge/Response Extensions," RFC 3012, November 2000: http://www.ietf.org/rfc/rfc3012.txt (accessed in October 2003).

[6] P. Zhou and O. Yang, "Reverse Routing: An Alternative to MIP and ROMIP Protocols," Proceedings of 1999 IEEE Canadian Conference on Electrical and Computer Engineering, Volume 1, pp. 150-155.

[7] R. Jain, T. Raleigh, et al. “Enhancing Survivability of Mobile Internet Access Using Mobile IP with Location Registers”, INFOCOM’99. Proceedings of Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Volume: 1 pp. 3 – 11.

[8] The NS Manual, Edited by Kevin Fall & Kanna Varadhan, Oct 2003: http://www.isi.edu/nsnam/ns/doc/index.html (accessed in November 2003).

Appendix – NS-2 Coding

A Compact Disc is submitted as part of this report.