Implementation and Performance Evaluation of Route Optimization in Mobile IP

By

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A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Science

Ottawa-Carleton Institute for Computer Science

School of Computer Science
Carleton University
Ottawa, Ontario

Nov 1, 2001

The undersigned hereby recommend to
the Faculty of Graduate Studies and Research
acceptance of the thesis,

Implementation and Performance Evaluation of Route Optimization in Mobile IP

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In partial fulfillment of the requirements for
the degree of Master of Science of Information & System Science

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Carleton University
Nov 1, 2001

Abstract

With the convergence of two technological developments, wireless communication and compact computer devices, mobility support in networks is more desirable than ever. IETF provides two approaches to support the mobility in the current Internet infrastructure. They are mobile IP and Mobile IP with Route Optimization, both of which introduce new functional entities, the home agent, and the foreign agent, into the Internet. The triangle routing existing in Mobile IP is a big defect in terms of resource consumption and performance. Route Optimization overcomes the triangle routing in basic Mobile IP but introduces more security requirements. In order to investigate performance of Route Optimization, we explored different ways to implement Mobile IP with Route Optimization and chose user space approach by C++ under Linux platform, evaluated the performance and provided our enhancement to the Route Optimization draft. We obtained quantitative efficiency evaluation results. Our conclusion is that user space implementation is acceptable and a desirable way to implement Route Optimization. The efficiency gain of Route Optimization will depend on the relative location of the three entities: the mobile node, the home agent and the correspondent node as well as the quality of communication links between the three entities. In most case, the Route Optimization efficiency gain is great and can achieve 17 times in terms of throughput as compared to basic Mobile IP, at the mean time, only 3% losses in terms of throughput as compared to plain IP. To solve deployment difficulty in the plentiful correspondent nodes, we proposed a Binary Exponential Backoff Algorithm (BEBA) to relieve the home agent burden while a correspondent node does not equipped with Route Optimization functionality. Our work provides a valuable sample of the implementation of Route Optimization and gives out quantitative performance enhancement in Route Optimization. It is a useful work for verifying Route Optimization draft and future mobility deployment in the Internet.

Acknowledgments

I would like to express my sincere gratitude to my thesis supervisor, Dr. Thomas Kunz for his invaluable guidance, enthusiastic encourage and support in every stage of my thesis research. This thesis represents a great deal of time and effort not only on my part, but on the part of my supervisor. He introduces me the field of mobile networking and provides me many opportunities for growth: from reading papers, writing a survey, turning a ideas to implementation, to getting through the inevitable research setbacks, and finishing the thesis. He opens the door for me to enjoy a research work. What I learn from him will provide me with lifetime benefits. I consider myself luck to access his supervision.

I am grateful to John Knox for his technical support, encourage and consideration. Without his help, I would never have gotten the experimental setup and finished my coding and my experiments. I also thank Michael Ostrowski for his explanation of the previous work and suggestion to the new work.

Finally, I want to express my deepest feeling to my family. I am so grateful to my husband, Tao Chen, for his love and encourage. His creative mind, technology knowledge and skills in computer science provide me endless support during my study. I especially thank my sister, Maoning Wang, for the deep discussion along the way. Her creative idea, quick thinking, and smart personality inspire me through all these years. I owe my thanks to my little son. His brightness always fresh my mind. Finally, I would like to thank my mom and dad for their love, self-sacrifice, encouragement and support as well as being a great role model in my life. Without their encourage, I would not challenge myself and pursue new goals again and again. Without their support, my graduate study is impossible. During the five years, without their dedicated care, my son would not be so healthy and bright. I dedicate the thesis to my parents.

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Chapter 1

Introduction

With technological development and people's dependence on the Internet, a new branch in the network area, mobile networking, is becoming noticeable and develops quickly. In the chapter, some basic concepts and issues pertaining to mobile networking are introduced. From the discussion of the open issues, our motivation is drawn and our goal is set.

1.1 Network Mobility

Mobile computing enjoys more popularity with the convergence of two technological developments, portable computer or information access devices, and wireless communication as well as the people's dependency on the Internet day by day. Mobile computing is also called mobile networking, which means that a user does not notice the change of the host's point of attachment, that is, the movement is transparent to applications. The fact that mobile computing is more desirable than ever can be attributed to two technology enhancements. Hardware research results in affordable, portable, lower-power wireless computers such as laptops or personal digital assistants (PDAs). Wireless technology improvements address some constrains such as lower bandwidth, higher noise level and expensive access equipment in the wireless communication environment. Besides the technology development, the demand from people is also an important impetus to mobility support in the Internet. Users who get used to the services received from a stationary host expect to receive the same or even more fascinating services while they travel with their wireless information access device anywhere and anytime. For example, an automatic piloting system can utilize the wireless access and mobility support to plan a route and indicate traffic congestion dynamically during a trip. However, mobility support is a non-trivial task because location tracking and routing system reaction to the movement are two challenges in networking, especially in the Internet's TCP/IP suite. In order to provide an IP mobility solution, many research groups and industrial partners are involved, such as the Internet Engineering Task Force (IETF), the Third Generation Partnership Project (3GPP), and the Mobile Wireless Internet

Forum (MWIF). A general architecture for Third Generation Wireless Networking was introduced by these efforts.

1.2 Third Generation Mobile Networking

3G is the generic term used for the next generation of mobile communication systems. A 3G-IP network comprises all-IP wireless access networks and a wired IP backbone network. The IP backbone network is an end-to-end wired infrastructure that consists of regional wired IP networks and the IP Internet that connects all the regional wired IP networks together, as well as provides Internet services to all stationary hosts. A wireless access network consists of mobile stations, base stations and routers. Figure 1.1 depicts the skeleton of an example 3G-IP network. [1]

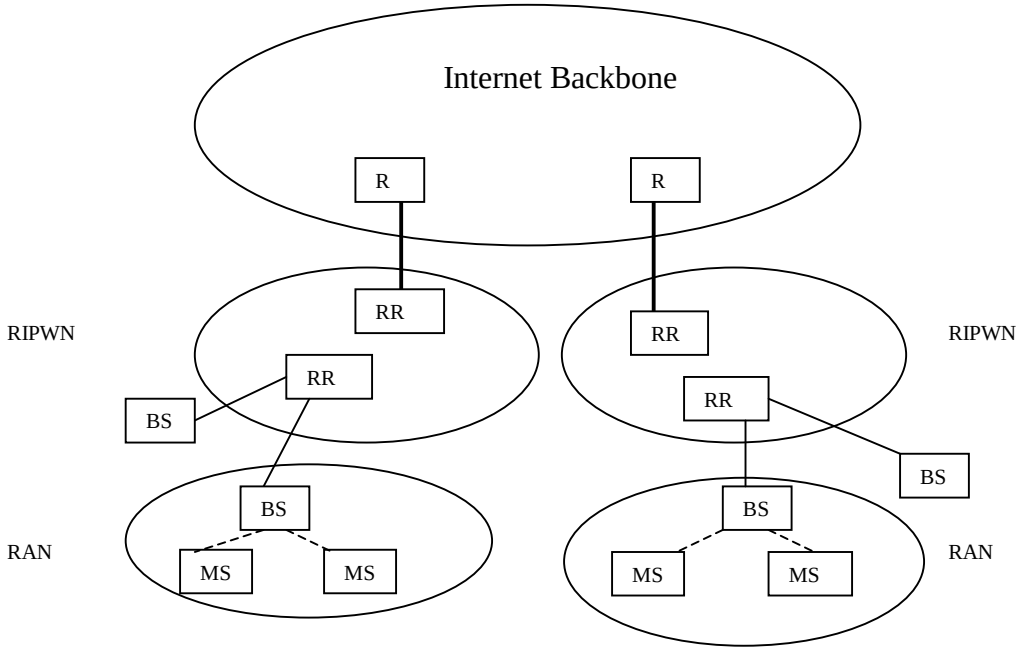

Figure 1.1 Example of 3G-IP Network Architecture

- Mobile Station (MS): the user mobile terminal that allows users to communicate.
- Base Station (BS): the radio access point to receive and send radio signals to MS.
- Radio Access Network (RAN): the wireless and back-haul infrastructure that provides MSs with wireless access to the wired infrastructure.
- Regional Router (RR): a router working in a regional wired IP network, which may use a wireless routing mechanism as the main routing scheme.
- Regional All-IP Wireless Network (RIPWN): the group of RR routers and wired infrastructure, which mainly supports wireless networking.
- Router (R): a router working in the global wired IP backbone, which employs the dominant IP routing protocols existing in the current Internet.
- Internet Backbone: global IP based wired backbone, which supports both the fixed and the mobile networking.

3G aims to provide mobile users ubiquitous access to the integrated data, voice and multimedia services of the Internet via their wireless terminals and appliances. The main benefit of the 3G technologies such as W-CDMA will substantially enhance capacity, quality and data rates. This enables the provision of advanced services transparently to the end user. The gap between the wireless world and the Internet world will be bridged. The development makes inter-operation apparently seamless regardless of the under lying access technologies. [4]

Mobility in the 3G can be divided into macro mobility and micro mobility according to the architecture. Mobility handled in a regional IP based wireless network is defined as micro mobility. Mobility handled in the global Internet backbone or between two IP based wireless networks is defined as macro mobility or global mobility [5]. Macro mobility support and micro mobility support have different characteristics. Fast and frequent hand off is the feature of Micro Mobility. In contrast, macro mobility needs to cooperate with current existing IP routing mechanisms and to integrate the fixed and mobile networking. For micro mobility support, the number of routers and the mobile nodes are restricted to a limit range. For fast handoff and optimal routing, several mobile routing protocols are proposed such as Cellular IP, HAWAII, IDMP, WIP [1]. In those protocols, various routing techniques for the mobile communication network are proposed. They provide different location tracking mechanisms and traffic delivery

mechanisms. All those micro mobility supporting protocols concentrate on the fact that all nodes are mobile. They consider the impact of mobility on the routing system design and the routing mechanism. However, as for the backbone wired Internet, it must support the routing system for the large number of stationary nodes as well as mobile nodes. Global Mobility has its own distinct characteristics. This thesis will focus on the global mobility and discuss several proposed protocols that aim to be compatible with the existing Internet infrastructure.

1.3 Routing Techniques in Mobile Network

To achieve mobility in a network, tracking location and adapting to changes in the location of a mobile node are two crucial aspects. The routing system is able to deal with the mobility in a network so that any movement is transparent to the application running on two communicating hosts. One approach is to let all routers be aware of the movement of any mobile hosts, cache the location information and propagate the movement in the whole network. The routing system uses host-specific routes to forward data packets. In this approach, the routing system will react to host movement and cache all hosts' location information. The routing system consumes network resources in direct proportion to the quantity and activity of mobile hosts. It is not a scalable and flexible solution for global mobile networking. The advantages of the approach are route optimality and smooth handoff. The routing protocol must respond to the movement faster than the topological changes. Generally, the routing system approach is suitable for the nonhierarchical architecture. In the architecture of third generation wireless networking, the solution is suitable for the wireless access network.

The other approach is to limit the location tracking and movement adaptation to particular entities and keep the routing system unaware of the movement. These particular entities record movements and redirect data packets. The routing system will forward data packets according to the hierarchical IP address architecture. Stationary networking and mobile networking can coexist in a unified network. Scalability and flexibility are the biggest advantages of the solution. It is suitable for the IP backbone network. However, sub-optimal routes, resource consumption, and difficulty in managing smooth handoff are the challenges in this solution.

1.4 Motivation

The routing protocols supporting micro mobility are optimized to provide fast and smooth handoff within restricted geographical area. They concentrate on pure wireless network and do not consider the great number of static hosts. In a global view, static hosts are a large population group, which depend on Internet infrastructure. However, TCP/IP architecture is designed under the assumption that the end hosts are connected to the Internet statically and that changes in the topology are caused by faults or the addition of new equipment. It is also assumed that these changes are infrequent. The IP address serves as dual purposes. One is the identifier of the host. The other reflects the host's point of attachment. A fundamental concept of the Internet architecture is that each end host has a unique network address, and network addresses form a hierarchy [2]. The routing mechanism is based on this hierarchical structure and uses the IP address as the directive to deliver an IP data packet. In the current TCP/IP suite, if a host moves from one network to another network, its IP address must change. However, many applications above TCP/IP use the IP address as the identifier. The IP address cannot be changed in this sense. The Mobile IP IETF working group proposes Mobile IP as a promising solution to solve the dilemma by applying two IP addresses to each mobile host. One IP address serves as the identifier, called home address. The other IP address serves as the directive of the point of attachment, which is used by the routing system to deliver data. However, the problems existing in Mobile IP such as routing anomalies, faulty congestion control, and lack of real transparency to the application are not desirable [3]. To solve the problem existing in basic Mobile IP, Route Optimization has been developed by the IETF. Either Mobile IP or Mobile IP with Route Optimization is a component of IP to provide mobility support at the IP layer. Any IP based network can support mobility by applying Mobile IP or Mobile IP with Route Optimization. The original IP routing scheme can work well without any disturbance. Any application above the TCP/IP suite can be applied in a seamless manner.

Mobile IP and its Route Optimization are two promising solutions to global mobility and occupy important positions in 3G networking. In basic Mobile IP or Mobile IP with Route Optimization, packets addressed to a mobile node are delivered to a temporary

address assigned to the mobile node at its actual point of attachment by using regular IP routing mechanism. The approach results in simple and scalable schemes that offer global mobility. Mobile IP and its Route Optimization keep the original Internet IP routing mechanism for static hosts by adding the home agent and foreign agent to provide mobility support. Especially Mobile IP with Route Optimization, which eliminates the triangle routing problem and reduces the network burden, can provide an efficient way to combine fixed networking and mobile networking in a unified network. However, how much efficiency gain is obtained in Route Optimization? Is it worth to overcome the deployment difficulty that exists in Route Optimization? Is there any improvement can be added into the Route Optimization protocol? The thesis addresses those and related questions.

1.5 Objective

The main goals of our project are as follows:

- Providing an implementation of Mobile IP with Route Optimization under Linux operating system by object oriented approach and investigating the problems existing in the implementation such as intercepting data packets in a home agent, updating binding cache, managing the binding cache and handling lack of mobility support in a correspondent node.
- Comparing Mobile IP with Route Optimization to basic Mobile IP, obtaining quantitative efficiency evaluation.
- Enhancing the Mobile IP with Route Optimization draft.
- Implementing the correspondent node's function in the user space in order to alleviate deployment difficulties.
- Providing a reference to the performance of other similar protocols with Route Optimization such as Mobile IPv6, in which the Route Optimization is intrinsic.

1.6 Road Map

The thesis is organized into six parts. Chapter 2 surveys various approaches to support mobility, especially in the Internet. Emphasis is placed on IP layer solutions such as

Mobile IP, Mobile IP with Route Optimization. Related implementation efforts are also mentioned. Chapter 3 introduces three choices to implement the Mobile IP or Mobile IP with Route Optimization as well as the relationship of Mobile IP with Route Optimization and the TCP/IP protocol stack from the implementation point of view. Chapter 4 describes the design and implementation details, which include packet interception, Binding Update message management and Binary Exponential Backoff Algorithm in a home agent, binding cache maintenance, binding cache management, and data flow control in a correspondent node. Chapter 5 gives a quantitative evaluation of the performance of Route Optimization as compared to basic Mobile IP and plain IP. It also demonstrates that the efficiency gain of Route Optimization differs with network situations and the location of associated entities. Chapter 6 draws our conclusions and discusses future work.

Chapter 2

Internet Host Mobility Review

In order to support mobility in the Internet, many efforts have been made and various proposals are provided. In this chapter, several representative approaches such as Mobile IPv4, Route Optimization in Mobile IPv4, Mobile IPv6, Cellular IP, DNS approach, and SIP approach are reviewed. At the end of this chapter, we also introduce related implementations of Mobile IPv4 with Route Optimization.

2.1 Overview

In today's Internet, an IP address has dual significance. One serves as an end host's identifier. The other acts as the routing directive. Mobile networking introduces a conflict between the two functions. When an end host moves, its IP address should change to reflect the new point of attachment to the network. However, the end host needs to keep the original IP address to identify itself in the network. In order to solve the contradiction, the two functions should be decoupled. One way is to find another identifier for the host, and an IP address just serves as the routing directive. Another way is that we use two IP addresses for each host. One IP address serves as end point identifier; another IP address serves as routing directive. Many researchers have done a lot of work to provide mobility in the Internet. Several approaches are proposed. IETF Mobile IPv4 [16,17] and Mobile IPv6 [11,12] consider two IP addresses for each mobile end host. SIP approach [1,8] and DNS approach [10] consider an email-like address or the domain name as the identifier. Cellular IP [5,6,7] replaces IP routing with hop-by-hop routing. Mobile IPv4 and Mobile IPv6 solve the mobility problem at the IP layer. Mobility is transparent to the TCP layer and application layer. Users of mobile end hosts are unaware of the mobility. DNS approach solves the mobility at the TCP layer. SIP solves the mobility at the application layer. Mobility is not transparent to the application any more. Users are aware of the mobility and anticipate the roaming process. Different proposals support mobility at different network layers. Actually, mobility has widely affected all Internet layers, from the physical layer to the application layer [13]. In this thesis, we will focus on the influence on the packet routing. Although the mobility management can be handled at

different layers, a mobility problem is a routing problem caused by a host's movement. Routing problems are solved at the IP layer. Therefore, the IETF Mobile IP solution has been widely accepted as the most promising candidate for global mobility support. In this chapter, we will introduce several approaches. However, emphasis is placed on the IETF Mobile IPv4 and Route Optimization in Mobile IPv4.

2.2 Abstract Function of Internet Mobility

In order to explain mobility further, [14,16] proposes a general network architecture. A few of definitions are introduced:

- **Mobile Node (MN)**

A wired or wireless end system that frequently changes its point of attachment to the network.

- **Home Network**

Within an administrative domain, a mobile node is assigned a unique identifier. The identifier can be a lifetime IP address, a DNS (Domain Name System) name or NAI (Network Access Identifier).

- **Foreign Network**

It is a sub network that a mobile node is visiting and its sub network address reflects a mobile node's current location.

- **Correspondent Node (CN)**

An end system that communicates with a mobile node. It can be a mobile node or a stationary node.

A network could operate as the home network to one mobile node, and at the same time as the foreign network to other mobile nodes.

Three basic entities are employed in the abstract expression of mobility: Address Translation Agent (ATA), Forwarding Agent (FA), and Location Directory (LD). Two functions, Mapping function and Address Translation function, co-operate with the three entities to achieve mobility.

- **Location Directory (LD)**

The LD contains the most up-to-date mapping between a mobile node and its associated FA. Mobile nodes will send its newest location data to the LD when it moves. It is ideally

located at the home network of the mobile node. It can also be cached by correspondent nodes.

- **Translation Agent (ATA)**

The ATA converts the mobile node's identifier to the address of the FA associated with the mobile node. The function that maps the identifier into a location address is an Address Translation function (f). The process of Address Translation involves querying the LD, obtaining the FA address, and using the FA address to send out the packets destined to the mobile node.

- **Forwarding Agent (FA)**

The FA provides an access point through which mobile nodes can attach to the network. It receives packets on behave of mobile node, and forwards the packets to mobile nodes. FA's address reflects the current location of a mobile node.

The function that reverses the location address into an identifier is a Forwarding function (g). Ideally, the Forwarding function is implemented in the FA and the FA is co-located with a mobile node.

A correspondent node that knows the identifier of a mobile node sends out a packet destined to the identifier. Somewhere, during the route, there is an ATA. It translates the identifier into the location address by querying the LD. After the packet leaves the ATA, its destination address should be the location address. When the packet gets to the foreign network, the FA resumes identifier as the destination address, and forwards the packet to the mobile node.

How to arrange the LD, where to implement the ATA, how to propagate the location information, and what kind of Address Translation mechanism used will depend on the specific mobility proposals. There is always a trade-off between different choices.

No matter what kind of solution it is, a mobility management scheme should take care of the following issues such as location detection, registration, configuration, dynamic binding, and location management and handoff on need basis [1].

- Location Detection is a process by which a MN is aware of its movement and its current point of attachment.
- Registration is a process by which a MN notifies its home network of its current location.

- Configuration is a process by which a MN updates its IP address to reflect its current location.
- Dynamic Address Binding allows a MN to maintain a constant identifier regardless of its point of attachment to the network.
- Location Management is responsible for updating the mapping between the identifier and location and supporting location/redirect services to authorized users and authorities.
- Handoff is a process that allows an established connection to continue when a MN moves from one cell to another without interruptions in the connection.

2.3 Cellular IP

Cellular IP [5,6,7] is an IP solution based on cellular mobile system. It inherits the advantages of the mobility management in cellular system such as passive connectivity and handoff control, but it is designed on the IP paradigm. It is optimized for frequent mobility and fast handoff in a restricted geographical area. It provides routing cache, page cache to route an IP packet in a cellular network and cooperate with mobile IP to route an IP packet in the global network.

A cellular IP network consists of a gateway, which connects the cellular network to the Internet, and some base stations (BS), which serve as a wireless access point and route IP packet from the gateway to mobile nodes or vice versa. An IP address in Cellular IP serves as the identifier of a mobile node. Instead of using IP address as the routing directive, the *Routing Cache* and the *Page Cache* are used in Cellular IP. The gateway is the information convergent point in a Cellular IP network. Any packet transmitted by a mobile node will be forward to the gateway. There are two directional data flows in Cellular IP. Downlink packets are routed from the gateway to mobile nodes. Uplink packets are routed from mobile nodes to the gateway. The intermediate base stations forward the downlink or the uplink packets. The mobility management is integrated with routing. In order to route the uplink packet, the gateway periodically broadcast a beacon packet. The beacon packet will be flooded in the cellular network. A base station records the interface that it receives the beacon packet and uses the interface to route a uplink packet toward the gateway. At the same time, in order to route downlink packets, when a

uplink packet which is transmitted by a mobile node is going through a base station, the base station will record the IP address of the source mobile node and the interface over which the packet entered the node. The mapping <IP address, Interface Num> about the location information of mobile nodes forms the *Routing Cache* in a base station. In this situation, regular data packets transmitted by mobile nodes are used to establish the location information. Packets traveling toward the gateway are monitored and the mapping between the sender's IP address and incoming port are created. In the future, packets addressed to the mobile node are routed along the reverse path, hop-by-hop by these *Routing caches* [5]. If there is no data packet transmitted by a mobile node, an empty IP packet can be transmitted to the gateway in order to maintain the location mapping. However, only a small percentage of mobile nodes are transmitting or receiving data packets while a large number of mobile nodes attach to a wireless network at a time. Inheriting passive connectivity in the telephone cellular system, *Page Caches* are established by sending *paging-update packets* periodically by idle mobile nodes. By monitoring passing *paging-update packets* and by mapping the sender's IP address to incoming port, nodes in the access network create a reverse path for *paging packet* destined to the mobile node. When IP packets arrive at the gateway, addressed to a mobile node for which no up-to-date routing information, exists a *paging packet* is routed along a reverse path taken by the *paging-update packet* from the idle mobile node to the gateway. Upon receiving the paging packet, the mobile node will send a *route-update packet* to gateway. Then, the mapping <IP address, Interface Num> will be inserted into *routing cache.* IP packets are transferred to the mobile node by using the *routing cache.* Smooth handoff is automatically ensured by the routing mechanism in Cellular IP. A mobile node always initiates a handoff by redirecting its data packets from the old to new base station when it approaches a new base station. When the first outgoing packet from the mobile node to the gateway travels along the uplink, the Routing Cache in a node records the mapping between the IP address of the mobile node and the node's incoming port. The next data packet destined to the mobile node will be transferred according to the reverse path to arrive the mobile node's new location.

The routing, paging and handoff mechanisms in Cellular IP can efficiently handle the mobility by a hop-by-hop basis in a local network. It is optimal for the frequent and fast handoff.

2.4 DNS Approach

In the DNS approach[10], the DNS name of a MN is used as the identifier of this MN instead of the home IP address. IP addresses fundamentally denote a point of attachment in the Internet topology and say nothing about the identifier of a MN. Each time a MN moves from a previous subnet to a new subnet, it obtains a new address to indicate its current location. This updated location information will be sent to Domain Name System (DNS). DNS will update its entry for this mobile node to form a mapping between the name of the MN and the new IP address. When a CN wants to initialize a communication, it sends an address resolution request to DNS. The DNS searches its database to get the MN's new IP address and sends it back to the CN. CN can send packets to the MN according to the new IP address. The indirection occurs only when the initial lookup is done via a control message (a DNS lookup). So, the DNS can be seen as LD in the abstract mobility architecture. In this proposal, the DNS is the third party. Three cases are considered in this approach:

- A MN initializes a conversation. No address lookup is needed. The CN will get the location address by receiving the first packet.
- A CN initializes a conversation. CN will get the MN's IP address by sending a control message (a DNS lookup) to DNS.
- A MN moves during an active TCP. This is the main consideration in this proposal. The architecture provides a new Migrate TCP option, included in SYN segments, that identifies a SYN packet as part of a previous established connection, rather than a request for a new connection. This Migrate option contains a token that identifies a previously established connection on the same <destination address, port> pair. The token is negotiated during initial connection establishment through the use of a Migrate-Permitted option. After a successful token negotiation, TCP connections may be uniquely identified by either their traditional <source address, source port, dest address, dest port> 4-tuple or a new <source address, source port, token> triple on each host. A

mobile node may restart a previously-established TCP connection from a new address by sending a special Migrate SYN packet that contains the token identifying the previous connection. The fixed host will than re-synchronize the connection with the mobile node at the new end point. A migrated connection maintains the same control block and state (with a different end point, of course), including the sequence number space, so any necessary retransmissions can be requested in the standard fasion. This also ensures that SACK and any similiar options continue to operate properly. Furthermore, any options negotiated on the initial SYN exchange remain in effect after connection migration, and need not be resent in Migrate SYN. Security is a problem in this architecture. An attacker who can guess both the sequence space and the connection token can hijack the connection completely. The key with an Elliptic Curve Diffie-Hellman key exchange is used to establish a secret connection key. Any SYN packet will be checked through the secret connection key.

2.5 SIP Approach

Session Initiation Protocol (SIP) [9] is an application-layer signaling protocol for establishing and tearing down Internet multimedia session. The user agents, proxy servers and redirect servers are three functional entities in SIP. A user is identified by an email-like address user@host, where “user” is a user name or phone number and “host” is a domain name or numerical address. SIP supports the ability of end users to originate and receive calls and access subscribed telecommunication services on any terminal in any location, which is called personal mobility [1,8]. In SIP, a mobile node is not required to have a fixed home IP address because an email-like address works as the identifier. By cooperating with the IETF protocol DHCP, an IP address is assigned to the mobile node when it moves to a new location. The user of a mobile node will send a registration with its new location to the redirect server each time it changes location. The redirect server stores the mapping between the user identifier and new IP address. When a caller initiates a call, the INVITE message containing a session description (the callee’s identifier) is sent to the redirect server. The redirect server consults the location mapping between the user identifier and the IP address to find out the callee’s current IP address and sends an answer with the IP address to the caller. The caller will send the INVITE message to the

new location after the redirection. The above is the procedure of setting up a call in SIP. IP automatically supports personal mobility. In order to support terminal mobility, which means that a user can change the IP address during an active connection, SIP is extended. If the mobile node moves during a session, it sends a new INVITE message to the communication peer to inform it of its new IP address and transport layer port in the SIP signal. The communication partner tunnels the following data flow to the new address and the mobile node detunnels the data flow to keep the session connectivity. Finally, the mobile node will register its new IP address in the redirect server of its home network. Then new calls will be redirected to the new location of the mobile node. By the SIP mobility support, the user of a mobile node is aware of the movement of the mobile node. The registration process is not transparent to the user of mobile devices. Security is ensured by the authentication mechanism existing in SIP protocol.

2.6 Mobile IPv4

Mobile IP is proposed by IETF to solve the mobility in the Internet. It is evolved from many efforts to solve the mobility in IP layer by modify routing mechanisms. Please refer to appendixes A for a survey of Mobile IP ancestors.

2.6.1 Terminology used in Mobile IPv4

- **Home Agent (HA):**

A host that maintains a list of registered mobile nodes in a binding cache in the mobile node's home network. It forwards packets destined to a mobile node to the MN's new location . [16,17]

- **Home Address:**

A permanent IP address that is assigned to a mobile node. It remains unchanged regardless of where the mobile node is attached to the Internet. It serves as the MN's identifier. [16,17]

- **Foreign Agent (FA):**

A host that provides an access point for a locally reachable mobile node that is away from its home network. It delivers information between the mobile node and the home agent. [16,17]

- **Care-of-address (COA):**

An address that reflects a MN's current point of attachment to a network. It can be the IP address associated with a FA or a temporary IP address configured by DHCP. [16,17]

2.6.2 Operation

- **Location Detection:**

A mobile node traces its location by listening to Agent Advertisement messages or by sending an Agent Solicitation message. An agent or a router anycasts the Agent Advertisement message periodically on a local sub network. A mobile node keeps listening to the message and compares the network prefix contained in the Advertisement message to its previous network prefix. If the network prefix is the same as its home network's prefix, the mobile node can determine that it is in the home network. If the network prefix is different from a previous one, the mobile node determines that it attaches to a new foreign network. If a mobile node does not receive the Agent Advertisement message for a certain time, it can send an Agent Solicitation to require an agent or a router to unicast an Agent Advertisement. [16,17]

- **Care-of-address Acquisition:**

After the location is decided, a mobile node will configure its care-of-address. The care-of-address can be assigned by DHCP or it is the foreign agent's IP address. [16,17]

- **Registration:**

As soon as a mobile node gets a new care-of-address, it will register its new IP address in its home agent by sending out the Registration Request message. The Registration Request can be sent to the HA directly or be forwarded by the FA. If the FA forwards the message, it will check whether it satisfies the registration request. If the FA rejects the request, it sends a reply to the MN to stop the forwarding. Otherwise, it will forward the request to the HA. When a HA receives the request, it sends a Registration Reply message back to notify the MN whether it accepts or refuses the request. The lifetime of this registration is included in the reply. It is the responsibility of a MN to re-send a Registration Request to its home agent when the lifetime expires. [16,17]

- **Home Agent Discovery:**

A MN can obtain the HA's address by one of the two ways: pre-assigned or dynamically discover. Dynamic discovery means that a MN can send a Registration Request to the

home network with a directed broadcast address. The Registration Request message can be received by any home agent in the home network. A home agent that is willing to serve the mobile node sends a Registration Reply to the MN. From the reply, the MN can find the HA's address and re-sends a Registration Request to the HA. [16,17]

- **Service:**

When the Registration Request is accepted by a HA, the HA will provide service to the MN. It caches the <Home address, Care-of-address> mapping until the lifetime expires. Any packets addressed to the MN are intercepted by the HA. HA encapsulates those packets by IP-in-IP, GRE, or minimal encapsulation. In the outer IP header, the care-of-address of the MN appears as the destination address. If the care-of-address is the FA's address, the FA decapsulates the packet and forwards it to the MN. If the care-of-address is a co-located address, the MN decapsulates the packet itself. [16,17]

- **Deregistration:**

When a MN returns to the home network, it drops the registered care-of-address by sending a Registration Request directly to its HA with the lifetime set to zero. The entry existing in the previous FA will be deleted automatically when the registration lifetime expires. [16,17]

2.6.3 Control Messages

Four types of control messages are used in IETF Mobile IP. [16,17]

- **Registration Request message**

A Registration Request message contains the up-to-date care-of-address of a MN and the required lifetime by a mobile node. It is sent out from a MN to a HA by a UDP packet. It may or may not be forwarded by a FA.

- **Registration Reply message**

A Registration Reply message contains the notification whether a Registration Request is accepted or refused. The lifetime approved by the HA is included in the message. It is sent out from a HA to a MN by a UDP packet. It may or may not be forward by a FA.

- **Agent Advertisement message**

Agent advertisement is anycasted by an agent to announce its service in a sub network. It is an extended ICMP route advertisement packet. The network prefix is included in the message. Therefore, it is used for a MN to decide if it attaches to a new foreign network.

- **Agent Solicitation message**

Agent solicitation is anycasted by a MN to request a service from a FA and to obtain a care-of-address. It cooperates with Agent Advertisement message to achieve location detection. It is an extended ICMP route solicitation packet.

2.6.4 Security

The mobile computing environment is potentially very different from the ordinary computing environment because of wireless links. Such links are particularly vulnerable to passive eavesdropping, active replay attacks, and other active attacks. Especially during the registration, the system is vulnerable to an attack. If there is no authentication, any attacker can send a registration request to the HA to pretend to be a MN, then redirect all the packets that are sent to the MN. Both a Registration Request and a Registration Reply must be authenticated. A algorithm known as keyed MD5. The quality of the random numbers used in authentication will determine the strength of the authentication. Some algorithms other than keyed MD5 may be supported and could be used. Besides this, a malicious agent can snoop a MN during registration, copy and replay the message. This kind of attack is called replay attack. To protect a mobile system from the replay attack, an identification field is added in the Registration Request and the Registration Reply. [16,17]

2.6.5 Problems with IETF Mobile IP Protocol

- **Triangle Routing**

All packets sent to a MN have to travel through the HA first and are then forwarded to the MN. In an extreme case, a MN happens to move to the same sub network as a correspondent node. A packet destined to the MN will travel all the way to the MN’s home network, which may be half a globe away, and then is tunneled and forwarded by the HA. Again, it travels halfway around the globe. If the packet is sent directly to the

MN, it might take only a fraction of a second. This "triangle routing" is inefficient and undesirable. This is the main reason that Route Optimization is proposed (Figure 2.1).

- **On-the-fly Packet Loss**

During the time interval that a MN leaves its previous foreign network and does not successfully register with its new care-of-address, any packet forwarded by its HA to its old care-of-address will be lost. The packet loss will degrade the upper layer's performance seriously.

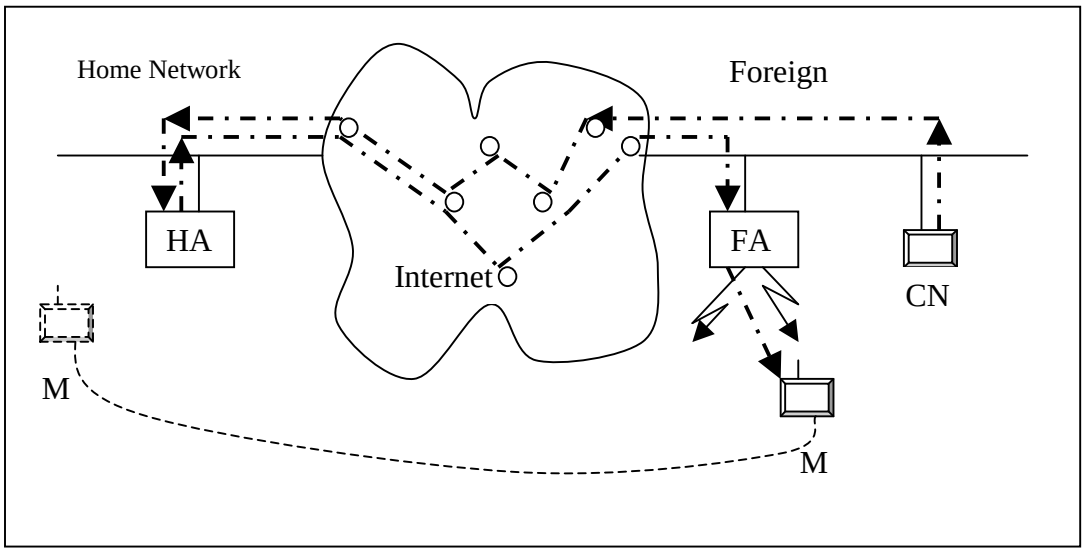

Figure 2.1: Triangle Routing

2.7 Route Optimization in Mobile IPv4

2.7.1 Why Route Optimization

Triangle routing is one of the main problems in IETF Mobile IP [3,18]. It increases the burden on the Internet especially in heavy traffic situation or when the number of mobile nodes roaming in the Internet increases. The second problem is that packets in flight are lost when a MN moves from one foreign network to another foreign network. Therefore, the IETF Mobile IP working group proposes the Mobile IP with Route Optimization protocol. This protocol has two main objectives:

- Routing packets through optimized paths by adding a Binding Cache in correspondent nodes, and
- Support for smooth handoff.

Route optimization is an attempt to solve problems by reducing or eliminating the routing anomalies and handoff loss introduced by the base Mobile IP specification.

In the Mobile IP with Route Optimization proposal, the same kind of entities are added to a network, HA and FA. FA is necessary in Route Optimization because of smooth handoff. Besides the main functions implemented in base Mobile IP, some new features and functions are added in this proposal. To eliminate the triangle routing, correspondent nodes must know the current location information of MN, in other words, the correspondent node will have to discover the MN's care-of-address, and maintain a Binding Cache for use in tunneling their own packets to the MN's care-of-address. Whenever the care-of-address changes later, the correspondent nodes must update their Binding Cache. Route optimization accomplishes this by sending a Binding Update to the correspondent node. The production and consumption of these Binding Updates form the heart of the operation of the route optimization protocol [3]. But the Binding Cache introduces a new problem. In order to ensure security, Binding Update messages should be authenticated. Two communication parties need a security association. In basic Mobile IP, binding information is stored in HA, and Binding Updates occur between HA and MN. Because HA and MN belong to the same network, they can easily share a security association. Now in this proposal, HA and correspondent nodes need to share a security association. HA and different correspondent nodes belong to different networks, this is one problem that needs to be solved in this proposal. When a Binding Cache is introduced into this proposal, how to keep these caches consistent is another point that needs to be considered. When a MN moves to a new care-of-address, any existing Binding Cache entries for the mobile node in different correspondent nodes' Binding Caches become out-of-date. An out-of-date binding cause a correspondent node to tunnel packets to an old care-of-address. In basic Mobile IP, these packets will be dropped. If there is an open TCP session, the packet loss degrades performance. If the previous FA can maintain a Binding Cache entry for a MN which had previously been visiting, that FA can deliver such misdirected packets to the MN's current care-of-address. The

previous FA act as a temporary forwarder for traffic destined to the mobile node, until all of the relevant correspondent nodes have updated their Binding Cache entries for the mobile node. The process is called smooth handoff. Smooth handoff introduces a new requirement for establishing trust between a MN and each of its foreign agents. All that the previous foreign agent has to know is that the Binding comes from the same mobile node that had been registered with it. This is accomplished by exchanging key information as part of the previous Registration Request and Registration Reply [18].

2.7.2 Binding Cache Maintenance Message

Four kinds of Binding Cache maintenance message are used in route optimization:

- Binding Update message.
- Binding Warning message.
- Binding Request message.
- Binding Acknowledgement message.

They cooperate together to achieve Route Optimization.

- Sending Binding Update during traffic monitoring

There are two ways that a correspondent node creates or update its Binding Cache entry. A correspondent node can request a binding entry actively or receive a binding entry passively. If a correspondent node does not have a cache entry for the MN, which it wants to communicate with, it can send a packet to the MN's home network. When HA intercepts the packet and forwards it to the MN, it also deduces that the correspondent node does not have a cache entry for this MN. HA will send a Binding Update message to the correspondent node. This Binding Update message does not need to be acknowledged. A correspondent node can adapt an active way to update its Binding Cache. When a correspondent node wants to keep a MN's location, it can send a Binding Request message to the MN's home agent to reconfirm the MN's binding information before expiration of the registration lifetime.

- Sending Binding Update during handoff process

If a MN moves during an active TCP session, packets sent from the correspondent node will arrive at the old FA. According to smooth handoff, the FA can deduce that the correspondent node has out-of-date Binding Cache entries. The FA will send a Binding

Warning message to the MN's HA to remind the HA that the correspondent node's Binding Cache need to be updated. HA will send a Binding Update message to the correspondent node. The Binding Update message is also used in smooth handoff, discussed below. Binding Acknowledgement message is only used in smooth handoff to answer Binding Update message.

2.7.3 Smooth Handoffs

In basic Mobile IP, when a MN moves to a new foreign network, the old FA does not know the absence. Packets sent to the MN will be dropped until the MN registers at its HA and the HA updates the Binding Cache. Resources occupied by the MN at the old foreign network will not be released until expiration of the MN registration lifetime. To solve these problems, smooth handoff is proposed in Route Optimization. When a MN registers with its HA through a FA, the FA will send a Binding Update message to the MN's previous FA .The previous FA will delete its Visitor List entry for the MN and add a Binding Cache entry for the MN. At the same time, the previous FA needs to reply with a Binding Acknowledgement message to the new FA. When on-the-fly packets arrive at the previous FA, the FA will forward the packets to the new FA by checking its Binding Cache and send a Binding Warning message to the MN's HA to notify the HA that the correspondent node has an out-of-date Binding Cache. Smooth handoff introduces a new requirement that a MN and its previous FA need to share a key in order to use in authentication. This is accomplished by exchanging key information as part of the previous Registration Request and Registration Reply.

2.7.4 Security

In route optimization, (1) a MN and a HA need to share a security association because of registration; (2) a CN and a HA need to share a security association because of Binding Update messages; (3) a HA and a FA need to share a security association because of Binding Warning messages; (4) a MN and a FA need to share a security association because of smooth handoff.

- For HA←→ CN, the HA chooses a key for a given node according to MD5, computing MD5(node-address || master-key ||node-address). The node-specific key is built by computing an MD5 hash over a string consisting of the master key with the node-address concatenated as a prefix and as a suffix.
- For HA←→ FA, the same scheme as HA←→CN is used, MD5(FA's address || master-key || FA's address).
- For MN←→FA, when a mobile node registers with a foreign agent, it typically does not share a security association with the foreign agent. However such a security association is necessary because the previous FA must make sure that it is getting authentic handoff information from the same previous MN. In order to establish some trustworthy secret between a MN and its FA when none exists beforehand, the following methods are employed during the registration process.
  1. If a FA and a HA have shared a security association, or a FA has a public key, the HA can act as a Key Distribution Center (KDC) for MN and its FA.
  2. If MN has a public key, the MN can include its public key in its Registration Request to the FA. The foreign agent chooses the new registration key and includes a copy of it in the Registration Request, encrpyted with the mobile node's public key. A foreign agent acts as KDC
  3. If MN and FA do not have any security association, including any public key, the Diffie-Hellman key exchange algorithm can be used. Diffie-Hellman is a public key encrypting system that allows two parties to establish a shared secret key.The mobile node and the foreign agent each independently form the (same) shared secret key [3,16].

2.8 Mobile IPv6

Mobile IPv6 is designed for the mobility support in IPv6 [11,12]. It is derived from mobility support for IPv4. However, some of the new mechanisms designed in IPv6 are adapted. It defines three functional entities: the mobile node, the home agent, and the correspondent node. Foreign agent does not exist any more. A mobile node detects its movement by listening /soliciting for ICMPv6 Router Advertisement/Router Solicitation. If the network prefix is different from the mobile node's previous one, the mobile node

will configure a new IP address in one of three ways: stateful, stateless (e.g. DHCPv6), and static way. The new IP address is defined as the care-of-address of the mobile node. In the meantime, the mobile node will keep its home IP address as identifier. After a mobile node obtains the care-of-address, it will register at a home agent in its home network by sending a Binding Update option in some packet's Destination Header. The mobile node also notifies correspondent nodes about its new location by sending a Binding Update option in some packet's Destination Header. If a correspondent node sends a packet to a mobile node without the binding cache entry, the packet will travel to the home network of the mobile node. The mobile node's home agent thereafter uses proxy Neighbor Discovery to intercept the data packet addressed to the mobile node's home address and tunnel the packet to mobile node's care-of-address. If a correspondent node has the binding cache entry for the mobile node, it uses the Routing Header to route the packet to the mobile node instead of tunneling the data packet. When the home agent or a correspondent requests the Binding Update message, it can send a Binding Request to a mobile node. The mobile node will reply to the request by sending a Binding Update message. In Mobile IPv6, a home agent address can be pre-assigned to a mobile node or dynamically discovered by a mobile node. A mobile node can send an ICMPv6 Home Agent Discovery Request to its home network. A home agent that can service this mobile node will send back an ICMPv6 Home Agent Discovery Reply to the mobile node. Route Optimization is built in as a fundamental part of Mobile IPv6. However, the deployment of Mobile IPv6 will depend on that of IPv6. Mobile IPv6 is an enhanced version of Mobile IPv4 with Route Optimization.

2.9 IP Layer Mobility vs. TCP Layer or Application Layer Mobility

The DNS proposal and SIP proposal can be summarized as the Naming approach. They do not require changes to the network layer. One of the arguments for the Naming approach is route optimality. The other argument is that significant performance enhancements can be achieved at the application level if end hosts are explicitly notified of mobility. However, according to our observation, there are several problems existing in the Naming approaches:

1. Two end hosts can not move simultaneously. At any specific time, only one end can move. The other end has to be static to receive the new IP address of the mobile end by getting the SYN packet sent by the mobile end. If two end hosts move at the same time, no end hosts can track the location of the other.
2. For security in the DNS approach, a secret connection key has to be calculated for every TCP connection between two conversation parties. However, key exchange computing will increase workload on the hosts. We know that the biggest problem existing in Mobile IP with Route Optimization is the security problem because conversation parties have to share a secret key. In the DNS proposal, the situation is even worse because every TCP connection needs a shared secret key. The security problem is more difficult to be solved in the end-to-end architecture.
3. Because the Naming approach uses the DNS name or an email-like name as an identifier, some applications using IP as an identifier can not work in the approaches.
4. Deployment is not easy. To implement the DNS proposal, all MN and CN have to be modified to add the TCP migrate function. And all DNS servers have to be modified to take care of the mapping between the DNS name and the location information—the current IP address. At least the deployment for the DNS architecture is not easier than Mobile IP with Route Optimization. For the SIP approach, the same difficulty exists.
5. The DNS approach only supports mobility for applications which are established above the TCP layer. If an application uses UDP or RTP as the transport layer protocol, mobility is not supported. If mobility for every kind of applications needs to be supported, UPD and RTP need to be modified too. The SIP approach only supports application using UDP as the transport layer protocol. For applications using TCP, the SIP approach does not support the mobility during a connection.

Considering the above reasons, we think Mobile IP with Route Optimization is the best solution for network mobility.

2.10 Related Work

Because of its simplicity and compatibility, Mobile IP has been approved by IETF as RFC2002. Several research groups in universities or industry companies are

implementing it based on different architecture designs and different operating system choices. IETF encourages different implementations in order to find out potential problems and enhance the protocol. However, the triangle problem and long access time because of the single central binding cache, are the obvious problems in the basic Mobile IP. To overcome the existing problem in the basic Mobile IP, IETF proposes Route Optimization in Mobile IP [18]. In the Route Optimization draft, a correspondent node will cache parts of the binding mapping and tunnel the data directly from a correspondent node to a mobile node. It eliminates the triangle problem and saves network resources. Because a correspondent node caches the binding message, the single database access burden will be mitigated. As far as we know, two research groups are implementing the IETF Mobile IP with Route Optimization draft. Because Route Optimization is still a draft, some definitions are not complete and needs to be verified. The implementation will help to justify existing definitions, to find out potential problems, and to provide possible improvements. It will provide a way to compare the performance of the Route Optimization and other approaches, including Mobile IP without Route Optimization. For a protocol, whether it is easy to be implemented is also one of the important factors, which needs to be considered.

As far as we know, many research groups in different organizations such as National University of Singapore, Carnegie Mellon University, Stanford University, Sun Microsystems, etc are implementing either Mobile IPv4 or Mobile IPv6. Only two of them are working on Route Optimization. They are National University of Singapore and Carnegie Mellon University.

2.10.1 Route Optimization in NUS

Mobile IP 3.0beta is an implementation done by the National University of Singapore. It is based on the Linux operating system and all the functions reside in Linux kernel space. More information can be found at

http://mip.ee.nus.edu.sg/mip.html

2.10.2 Route Optimization in CMU

Mip-2.0.0-alpha is an implementation conducted by Carnegie Mellon University. It is based on Unix operating system and all the functions exist in Unix kernel space. More information can be found at http://www.monarch.cs.cmu.edu/software.html

Chapter 3

Mobile IP over Linux

3.1 Mobile IP Converge into Existing TCP/IP Stack

3.1.1 TCP/IP Architecture

The Internet consists of 5 layers: physical layer, data link layer, internet layer, transport layer and application layer. The transport layer provides a flow of data between two Internet nodes. There are two different transport protocols: UDP (User Datagram Protocol) and TCP (Transport Control Protocol), are end-to-end protocols. The Internet layer handles the movement of packets around the network. Routing system and routing mechanism resides in this layer. It includes IP (Internet Protocol), ICMP (Internet Control Message Protocol), and IGMP (Internet Group Management Protocol). The Internet consist of many interconnected routers. IP is responsible for constructing a route table, consulting the route table and deciding a proper next hop for any packet going through a router. A route table consists of a set of entries, each of which regulates a next hop for a specific destination address or a collection of destination addresses. Different routing algorithms will generate different route table entries. A route table entry will decide the relative packet's next hop. The route table is the key structure in the IP layer. Another important data structure is the ARP cache, which contains a mapping between the IP address and the data link layer address. When a packet gets to the router of the destination subnetwork, the router will consult its ARP cache to get the correspondent data link address for the packet and forward the packet to the destination node.

3.1.2 IP Layer Traffic Flow

Three types of data flow in TCP/IP: outgoing data, incoming data and forwarding data. When a network frame arrives at a host, a network device driver collects the frames, assembles the network packet and sends it to IP layer. The IP layer will determine if the IP packets is destined to itself or other hosts. If a packet is for the host, the IP header is removed and the packet is sent to TCP or UDP. If a packet is for another host, the route table is consulted and the packet is send out via the data link layer. When a TCP or UDP

layer passes an outgoing packet to the IP layer, the IP layer will construct the IP header and consult the route table, then send the packet to the data link layer. The data link layer consults the ARP cache to form the network frame and the frame is sent out by a device driver.

3.1.3 Related Control Message Types: UDP, ICMP

Eight types of control messages are defined and used in the Mobile IP with Route Optimization. All of them are carried by currently existing TCP/IP protocols. The two protocols used are UDP and ICMP. Agent Advertisement and Agent Solicitation control messages are sent by ICMP. Registration Request, Registration Reply, Binding Update, Binding Warning, Binding Acknowledge, and Binding Request are exchanged by UDP .

3.1.4 Related Data Structures: Route Table, ARP Cache

- Route Table and ARP Cache in a Home Agent

The home agent needs to intercept any packet destined to a registered mobile node. It should represent the mobile node to reply to any ARP request to modify all the ARP caches in the local nodes, which reside in the same local network as the mobile node.

- Route Table and ARP Cache in a Mobile Node

The route table of a mobile node will be modified when the mobile node attaches to a new foreign network because the mobile node will send all its outgoing packets to the foreign network's router instead of its home network router. A new default network entry is added into the route table of a mobile node. The old default network entry is deleted. The ARP cache in a mobile node will save the association between the foreign router's IP address and the foreign router's MAC address.

- Route Table and ARP Cache in a Foreign Agent

A foreign agent also needs to modify its route table and ARP cache in order to detunnel and forward a packet to the mobile node. Otherwise, according to the normal routing mechanism, any packets destined to a foreign IP address will be sent to an outgoing router instead of the mobile node. A new host route entry is added to the route table of a foreign agent for a mobile node which currently registers in the foreign agent. ARP will cache the association between the mobile node's IP address and the mobile node's MAC

address. How many mobile nodes are registering in the foreign agent, home many new host entries will be added into ARP.

3.1.5 Related Traffic Control: Tunneling, Traffic Monitor

A home agent or a correspondent node will tunnel the packets destined to a registered mobile node. A home agent needs to monitor all the traffic forwarded. Either tunneling a packet or monitoring all forwarding traffic is a behavior below the TCP or UDP layer. The implementation has to cooperate internally with the IP protocols. How to implement them will be discussed in Chapter 4.

3.2 Linux

Linux is a multi-user, multitasking operating system. It supports various processors and is used as operating system for routers, gateways, mail servers, news servers, ftp servers, etc. Linux has such advantages as flexibility, reliability, robust, security, scalability [21]. It is a clone of Unix and is completely 32 bit POSIX-compatible. Other contemporary operating systems such as Apple MAC OS/X and Windows NT are moving to the POSIX standard. Any code implemented over Linux is easy to port to Unix.

Linux kernel source code is open to public. Users can freely download it, modify its kernel and patch it. If any needed feature is not supported in the Linux kernel, the open kernel source code provides the facility for users to enhance it.

Similar to Unix, Linux provides plentiful socket interfaces for generic communication programming. The socket types it supplies include TCP socket, UDP socket, ICMP raw socket, IP raw socket and Ethernet raw socket. With those socket interfaces, an application can flexibly control the kernel's behaviors from the user space. By creating a TCP socket, an application can enjoy the reliable connection-oriented service. By opening an UDP socket, an application can receive the connectionless and non-reliable service. ICMP raw socket and IP raw socket can facilitate the direct access to the raw packet forms such as setting IP-in-IP encapsulation, modifying the standard ICMP formats, or controlling the data link layer header in a frame. A packet bound to a raw socket can bypass the kernel process and is send to the application directly. The application can control the processing of the packet. Raw sockets can also be used to

achieve some non-standard I/O controls. For example, we can use a raw socket to monitor the link status of a network interface device.

Because of the advantages of Linux, this work decided to use Linux as platform to research Mobile IP. Linux supports all IPv4 features except mobility. There are many different approaches to implement Mobile IP over Linux according to different design decisions. However, they can be cataloged into three models according to which space the Mobile IP code exists in. We define them as kernel space model, user space model, and user and kernel space model. Because of protection and security consideration in the design of an operating system, all contemporary operating system use processors which support supervisor mode and user mode. Memory is partitioned into two parts: kernel space and user space. An application process which runs in the user space can not access the kernel space. A user space process communicates with a kernel space process by specific mechanism instead of normal IPC [20]. If a new feature is added into the system, it can be added into the kernel, or in the user space or parts in the kernel and parts in the user space. In the next section, the advantages and disadvantages of the three models will be discussed. Then we will justify our decision to implement Mobile IP following the user space model.

3.3 Three Implementation Models

3.3.1 Kernel Space Model

The whole TCP/IP stack is implemented in the Linux kernel. From a logical point of view, the Mobile IP layer resides between the TCP and IP stack. It should be implemented in the kernel. As we discussed in Chapter 2, in the control parts, Mobile IP agents use ICMP packets to send out advertisements. Mobile nodes use ICMP packets to send out solicitations. ICMP is in the kernel. If Mobile IP resides in the kernel, it is easier to invoke related ICMP functions instead of system calls from the user space. Especially for data control parts, Mobile IP home agents have to tunnel traffic for mobile nodes and also have to monitor the packets destined to mobile nodes. The traffic control part is embedded in the Linux kernel. Mobile IP code implemented in the kernel can make use of the traffic control by invoking the related functions. The new functions can share memory with embedded functions. All system calls are avoided. The benefit of this

model is performance. Any system call from the user space involves three steps. First, a software interrupt is implemented to transfer control to kernel code. After the switch to kernel mode, the processor must save all of its registers and dispatch execution to the associated kernel function. When the associated function finishes, the interrupt return is executed and all of registers are restored. The overhead of a system call is obvious and makes it undesirable for some functions to be performed in user space. However, nothing comes for free. Implementing complex services in the kernel can lead to system crashes if those services are not extremely robust. For the sake of maintaining, debugging, and porting code, what has always been performed in user space should not be converted to run in kernel space, unless that is absolutely necessary to meet performance or size requirements. Besides this, Linux is a moving target. From 1999 to 2001, its kernel version has changed 109 times from version 2.2.0-pre3 to version 2.4.4. Even the stable version has changed 28 times from Version 2.2.0 to Version 2.2.19. If the Mobile IP code is implemented in Kernel space, it has to keep the same pace as the movement of Linux kernel itself. Another weakness is that any implementation in the kernel will highly depend on the kernel structure and source code. It is not easily portable. Microkernel is a relatively new trend in the operating system design area. A Microkernel provides a high degree of flexibility, portability and modularity as key benefits. The philosophy underlying the microkernel is that only absolutely essential core operating system functions should be in the kernel. Less essential services and application are built on the microkernel and execute in the user mode [19]. From this analysis, we can observe the advantages and disadvantages of kernel space model for Mobile IP implementation. The structure of this approach is illustrated in Figure 3.1

In this approach, all Mobile IP code exists in the kernel space. Mobile IP code is inserted into the TCP/IP stack. Mobile IP code will directly anticipate the process of monitoring and controlling the IPv4 packets. It also needs to interact with the data link layers to control traffic tunneling. If there are large amounts of control and traffic message, this implementation can work efficiently because no control and traffic messages are being transferred between the user space and the kernel space. However, this approach requires Linux kernel to be changed. More work has to be done in order to adapt to different Linux releases. Besides this, the code is not portable between different operating system.

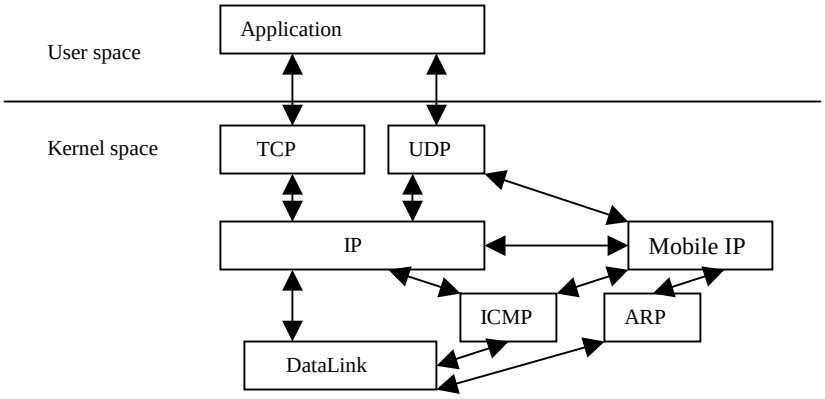

Figure 3.1 Kernel Space Model

3.3.2 User Space Model

The new trend in operating system--Microkernel, and the disadvantages of the kernel space model, motivate us to consider a user space model. Even if the Mobile IP logically exists between the TCP and IP layers, implementation in the user space would not violate the relationship. Portability is an attractive feature of a user space implementation. Changes needed to port the implementation to a new operating system are fewer and tend to be limited to the API (Application Program Interface). As for Linux itself, nothing needs to change when the Linux kernel migrates from one version to another version because it will keep the API backward compatible. Extensibility and maintainability is another attractive feature of the user space implementation. Mobile IP and its Route Optimization are still RFCs or in draft stage. Many factors are open to discussion and change. Adding a new feature or modifying some old definitions is to be expected. IETF encourages different implementations to verify the definitions in the RFC or draft. In order to keep the system open to modification, object-oriented implementations are considered. An object-oriented architecture helps limiting potential interactions of different parts of the software, ensuring that changes to the implementation of a class can be made with little impact on the rest of the system. If the architecture of the implementation is object-oriented, implementing it in user space by C++ is the best choice. Beside these, rebuilding a kernel is a tedious and error-prone process.

Downloading a patch file declared working, patching it, and recompiling the kernel and finding it does not work is a frustrating experience. Mobile IP with Route Optimization requires that all correspondent nodes are equipped with supporting code. Recompiling the kernel of all the existing nodes in the Internet that may potentially communicate with mobile nodes is a nontrivial task. An implementation based on the user space model can be installed easily and spread widely. One potential disadvantage of a user space implementation is performance. Because of the data exchange between kernel space and user space, there are penalties in speed and memory usage. However, if the performance requirements still can be met, why should we bother to suffer the kernel trouble. The structure of this approach is illustrated in Figure 3.2.

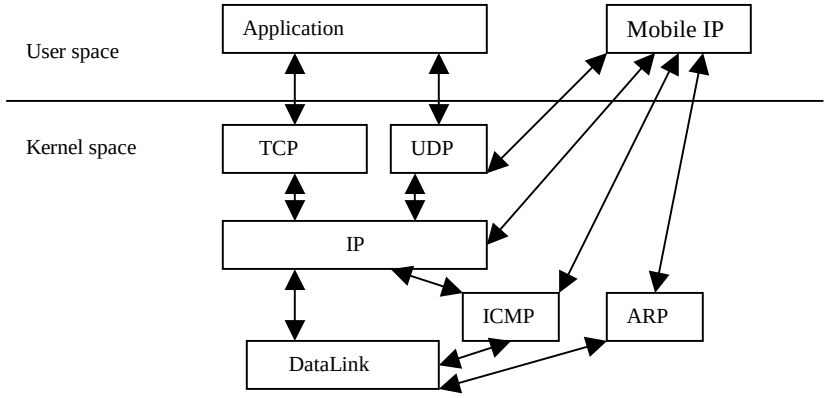

Figure 3.2 User Space Model

In this approach, the Mobile IP module listens to or sends registration request or reply messages by UDP socket, listens to or sends advertisements or solicitations by ICMP raw socket. The Mobile IP module also monitors or tunnels traffic via the ioctl() system call. The approach can be ported to different Linux releases or Unix platforms because most of the Linux/Unix socket interface is standard. Only requiring minor modification to the Linux kernel, Linux can support all the system calls and socket features required by the Mobile IP code. Because of the above advantages, we decide to choose it as our implementation model.

3.3.3 User and Kernel Space Model

Can we eliminate or reduce the performance penalty and at the same time improve flexibility, and portability? Can we put the part which affects performance mostly in the kernel space and put the others which would not affect performance so seriously in the user space? The structure of this approach is illustrated in Figure 3.3.

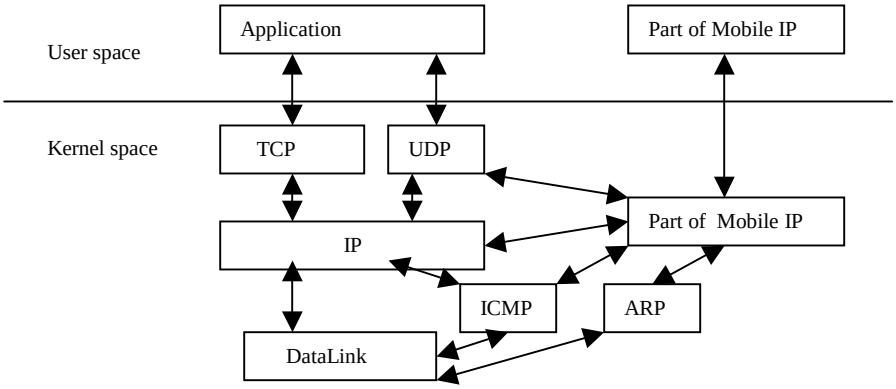

Figure 3.3 Kernel Space Model

In this approach, part of the Mobile IP code exists in kernel space and part of the Mobile IP code exists in the user space. How to divide the functions and put which parts in the kernel or in user space is still an open question. Certainly, the other reason to implement the Mobile IP code by this model is that some system calls needed by Mobile IP code are not provided by the operating system. In this case, improvements to the Linux kernel have to be done. If the improvement is not too much, we prefer to catalog this kind of implementation as the user space model instead of the mixed model because it is not exactly a mixed model in the sense of implementation consideration.

3.4 Linux Platform and Basic Mobile IP

As defined by RFC2002, there are three entities in the Mobile IP system, the home agent, the foreign agent, and the mobile node. The home agent acts as the location dictionary. It creates and maintains the binding cache. The whole function of the protocol can be divided into a control part and a traffic part. The control part concentrates on how to

acquire, update and maintain an entry in the binding cache. The traffic part is in charge of intercepting packets and forwarding them to mobile nodes.

Basic Mobile IP uses UDP to send and receive registration requests and replies. It can be implemented by using UDP socket in the user space. Basic Mobile IP uses ICMP to send and receive advertisements and solicitations. Linux also provides raw socket to send and receive ICMP packets from user space. For the control part in the basic Mobile IP, everything can be accomplished in the user space. For the traffic part in the basic Mobile IP, the packets destined to mobile nodes needs to be tunneled and forward. The package iproute2+tc also provides a way to set the tunnel, modify the route table, and control ARP from the user space. Therefore, the Linux platform completely supports the idea to implement the basic Mobile IP in user space.

3.5 Linux Platform and Route Optimization

The main difference between the Mobile IP with Route Optimization and the Mobile IP without Route Optimization is that only one binding cache exists in the home agent for the Mobile IP without Route Optimization, however, for the Mobile IP with Route Optimization, besides the major binding cache, many subsets of the major binding cache exist distributed in the network. How to keep consistency between the major binding cache and all its subsets is a key problem in Route Optimization.

Mobile IP with Route Optimization requests more services from Linux. For the control part, the Binding Update, Binding Request, Binding Acknowledge, and Binding Warning messages make use of UDP packets. Linux provides UDP sockets to send and receive UDP packets from user space. The difficult part is the traffic monitor. There is no easy way to provide an efficient packet filter who satisfies our requirements. Section 3.5.1 will introduce the Route Optimization requirements to the traffic monitor. Then, Section 3.5.2 investigates the existing ways to intercept packets from the Linux kernel and compares them with our requirements. Section 3.5.3 describes our approach.

3.5.1 Route Optimization Requirements

In the Mobile IP without Route Optimization, there is no need to monitor traffic forwarded by a home agent to mobile nodes. However, the idea behind the Mobile IP with Route Optimization is that a correspondent node caches the mobile node's location information. With Route Optimization, a home agent has to monitor the traffic to check whether a correspondent node has a mobile node's current location information. If not, the home agent needs to get the <source address, destination address> pair of this packet. Then it organizes the Binding Update message, and sends this message to the correspondent node. The home agent does not have to modify the original packet. After the correspondent node receives the update message, it will modify its binding cache. Next time, any packet destined to the mobile node will be tunneled by the correspondent node and sent directly to the mobile node. Triangle routing is avoided.

3.5.2 Capturing Packets from the Linux Kernel

After searching through the related Linux documentation, web pages and sending message to some news groups, we conclude that there are three existing approaches for a user space application to monitor the kernel space IP or ICMP packets. They are divert sockets, netlink sockets, and raw sockets.

- *Divert socket:* only works with 2.4 kernel version

The divert socket intercepts packets traveling up or down the IP stack of a host and filters out certain packets based on firewall specifications and bring them to user space. Applications then have the freedom of simply reinjecting them back as if nothing happened, modifying them first and then reinjecting them, or not reinjecting them at all. They are a special type of RAW sockets called divert (IPPROTO_DIVERT) that allow users to receive and send on them just like regular sockets. Anything that a firewall can filter out can be sent into a divert socket. The sample usage is:

```
/* open a divert socket */
fd=socket(AF_INET, SOCK_RAW, IPPROTO_DIVERT);
```

To use the divert sockets, Linux kernel has to be patched.

The divert socket will bring the whole packet to the user space and then sends it back to the intercepting point. What the Route Optimization requires is only to get the

<source address, destination address > pair. If every packet is diverted to the user space and send back to the kernel space, the operation will significantly increase the workload on the host system because the frequent switch between the kernel mode and user mode will consume system resources. Beside this, diverting the whole packet may increase the error probability of this packet. Another disadvantage is that divert sockets only work for 2.4 kernel version.

- *Netlink sockets*

Netlink sockets can intercept packets just like divert sockets by using a firewall filter. They have a special type (AF_NETLINK) and on the surface seem to do the same thing as divert sockets. However, netlink sockets have no easy way of injecting the packets that are outbound (going on the wire) because no special precautions are taken not to reintercept the same packet over and over again as it is injected. In general, the netlink mechanism is intended to allow communication between kernel and user space. The scope of netlink sockets is wider than divert socket. For instance, there are netlink routing sockets that allow you to communicate with the routing subsystem. However, as a packet interception mechanism, they are not as robust as divert sockets.

The netlink socket has the same problem as divert socket when it is intended to be used for the Route Optimization purpose. Besides this, there is no easy way to inject the packet back. This increases the difficulties to use it in Mobile IP with Route Optimization.

- *Raw sockets*

RAW sockets can be a good way to listen in on traffic. Especially under Linux, RAW sockets can listen in on TCP and UDP traffic. A RAW socket does not stop a packet from propagating through the IP stack. It simply gives the application a copy of the packet and there is no way to inject it inbound. Also, it can only filter packets out by the protocol number, which is specified when you open a RAW socket. A raw socket can return the destination IP address of a packet. However, there is no way that a raw socket returns the source IP address of a packet. Obviously, RAW sockets do not satisfy the requirements of Mobile IP with Route Optimization because what the home agent needs is exactly the <source address, destination address> pair. If the source address is missing in the RAW socket, the home agent cannot obtain the correspondent node’s address and there is no destination to send a Binding Update message to.

In conclusion, there is no efficient way among the existing approaches to achieve the Route Optimization goal.

3.5.3 Our Approach: IP Firewall Packet Filter

The IP firewall is a very good packet filter in the Linux kernel. It checks every packet against the rules set by setsockopt() or ipchains command. All sockets related to traffic control finally invoke the ip_fw.c. We also make use of ip_fw.c to capture packets in this implementation. How does IP firewall work? There are three Chains existing in the IP firewall. They are input chains, forward chains and output chains. The input chain is traversed by all packets that come into the host - packets that are addressed to it and packets that will be forwarded by it. The output chain is traversed by all packets originating in the host and by all forwarded packets. The forward chain is traversed only by the forwarded packets. A chain is a checklist of rules. A rule specifies a criteron and a target. The criteron indicates what kind of packet should be filtered out. The target indicates what to do with the filtered packet, ACCEPT, DENY,REJECT, REDIRECT or RETURN etc. ACCEPT means to let the packet through. DENY and REJECT means to drop the packet. REDIRECT means packets will be redirected to a local socket, even if they were sent to a remote host.

A set of rules is maintained for each chain. These rules will be examined one by one when a packet arrives. If any rule is matched, this packet will be filtered and dealt with according to the target, for example ACCEPT, REDIRECT or RETURN. RETURN is a special feature here. It means when a packet matches this rule, the following rules in this chain will be ignored. Otherwise, all the following rules will be checked one by one. Other targets indicate the fate of a matched packet. RETURN has a completely different meaning from the other targets. It decides if the following rules are needed to be checked. That is a useful feature for our implementation. It will help us to implement the Binary Exponential Backoff Algorithm, which is introduced in Section 3.6. A rule can be set in two ways: using setsockopt API in a program or using the ipchains command. After setting a rule, any packets matching the rule will be noticed.

The next step in Route Optimization is to extract the source IP address and destination IP address in the packet and put them in a buffer. None of the four targets in the existing

code can provide this kind of service for us. Therefore, we modify ip_fw.c to implement a Route Optimization target. The implementation detail will be discussed in Chapter 4. After we modify ip_fw.c, the <source address, destination address> pair is put in a kernel buffer. The next step is how to send this data to a user space application? Then the home agent can send the Binding Update message to a correspondent node.

3.5.4 Data Exchange between Application and Kernel

All operating systems separate the status of a computer into two modes: the supervisor mode and user mode. The operating system uses a different address space from the user application. A process in the application space can not directly access the data in the kernel space and vice versa. There is no standard inter-process communication mechanism between the kernel and application process. A system call is a way to communicate between the user process and kernel process. A system call can pass some parameters to the kernel as well as get some data from the kernel space. However, the existing system calls do not support our specific usage. To achieve the goal, we need to either create a new system call or extend an existing system call. Creating a new system call needs more knowledge about the system. Extending an existing system call is an easier way if our requirement is not too complex. What this implementation needs is only to get the specific buffer defined by ip_fw.c from the kernel. It is a simple request and can be achieved by adding two new entries in the system call table. The extension to the existing system call ioctl() is discussed in detail in Chapter 4.

3.6 Improvements to Mobile IP Protocol

There are several features which are not defined by the Route Optimization in Mobile IP draft clearly. However, they are important to our implementation. We discuss the detail in this section.

3.6.1 Binary Exponential Backoff Algorithm

By setting the packet filter’s rule and modifying ip_fw.c to capture the Route Optimization target, any packets forwarded by the home agent and destined to mobile nodes will be intercepted. An update message will be sent to the correspondent node.

However, in the existing Internet system, many correspondent nodes do not support Route Optimization yet. In this case, any Binding Update message will be ignored by the correspondent node and packets originating from the correspondent node will continually arrive at the home agent. This traffic will flood the home agent. This thesis proposes a backoff algorithm to support such nodes. It is a contribution to reduce the sending rate of Binding Update messages in the IETF Route Optimization draft. There is only an obscure definition about the sending rate of the Binding Update message in the home agent. In the Route Optimization in Mobile IP draft, it reads that " A home agent is required to provide some mechanism to limit the rate at which it sends Binding Update messages to the same node about any given mobility binding. This rate limiting is especially important because it is expected that, within the short term, most Internet nodes will not support maintenance of a binding cache. In this case, continual transmissions of Binding Update messages will only waste processing resources at the home agent and correspondent node, and along the Internet path between these nodes."

We propose the Binary Exponential Backoff Algorithm.

When a home agent intercepts a correspondent node's packet destined to a mobile node away from home for the first time, it will send out a Binding Update message immediately. In the next period, if the home agent continually receives packets destined to the same mobile node from the same correspondent node, the home agent will delay sending the Binding Update message until the end of this first waiting period and double the next waiting period. Suppose that the first waiting period is T, the second waiting period will be 2T. In the third period, which is twice the previous waiting time, if the home agent still receives packets that have the same source addresses and destination addresses as previous packets, the Binding Update message will be delayed by twice the previous waiting time again. After n periods, the home agent will stop sending Binding Update messages and stop monitoring any forwarding packets coming from the correspondent node. The mechanism to limit the sending rate of Binding Update message is proposed by the thesis. We call it Binary Exponential Backoff Algorithm.

The time calculation expression is:

$$T_n = 2^n * T$$

T_n — The waiting time in the n_{th} period, T — the first waiting time

According to the Route Optimization assumption, only the first packet destined to a mobile node will be forward by the home agent. After that, the correspondent node will receive the Binding Update message from the home agent and modify its binding cache. The second packet destined to the mobile node will be directly tunneled and sent out by the correspondent node. If the home agent receives the second packet, the Binding Update message may be lost on the way to correspondent node or still in transit. The home agent delays a fixed amount of time and resends the Binding Update message. However, in the following periods, if the home agent keeps receiving packets from the same correspondent node again and again, it can guess two possibilities. One is that the correspondent node does not support binding cache updates. The other possibility is traffic congestion on the way between the home agent and the correspondent node. If it is traffic congestion, the home agent should delay sending the update message. If it is because of the lack of Route Optimization support, the home agent should stop sending the update message. Our proposal is to reduce the sending rate by a binary exponent until a fixed number of time periods is reached. If the Binding Update message is ignored because of traffic congestion, the Binary Exponential Backoff algorithm will relieve the burden of network resource along the way. If the message is ignored because of a lack of Route Optimization support, the algorithm will finally give up the effort to modify the correspondent node's binding cache. The BEBA algorithm will be of benefit during this migration period.

3.6.2 Binding Cache Management Strategy

For a binding cache in the correspondent node, it is not only impossible but also unnecessary to keep the binding entries for all mobile nodes. Any cache has a limited memory space. When a cache is full, how to replace the old entry by a new entry, or delete some old entries and create space for the new entry has not been defined clearly. We considered three strategies to manage the Binding cache.

- FIFO
- LRU
- LFU

FIFO means First In First Out. Replace or delete the entry that has stayed in the cache for the longest time.
NRU represents Not Recently Used. Replace or delete the entry that has not been used for the longest time.
LFU indicates Least Frequently Used. Replace or delete the entry whose used frequency is the fewest.
The advantages and disadvantages of the three strategies are similar to the page replacement algorithms. FIFO is easy to implement and saves the system's resource. However, the performance is not the best. NRU deduces the future behavior of a host by previous actions. If a mobile node's entry is not used for a long time, it means the communication between the correspondent node and the mobile has terminated. There is no need to keep this binding entry for recent usage. LFU is based on the deduction that the communication always happens repeatedly. If a mobile node's entry is used frequently in the past, it will be visited in the future. Is the performance of the NRU and LFU better than FIFO? This will depend on the correspondent node's application model. The statistic result is not known yet. Therefore, the easy way is the best way. The binding entry in a correspondent node is replaced by FIFO.

Chapter 4

Route Optimization Implementation

In Chapter 3, we investigated several implementation strategies. In this chapter, more implementation details such as timer management, packets intercepting, Binding Update message management, the correspondent implementation and the home agent implementation will be discussed.

4.1 Implementation and Environment

Our Route Optimization is built above a basic Mobile IP implementation, which was written by Michal Ostrowski at the University of Waterloo. To keep consistence with the basic Mobile IP, our Route Optimization implementation also bases on Linux 2.2.16. Our Route Optimization implementation follows the IETF Route Optimization in Mobile IP draft (draft-ietf-mobileip-optim-10.txt) [18]. In the implementation, Route Optimization makes use of the movementdetection and the registration in basic Mobile IP. In order to add the Route Optimization functionality into basic Mobile IP, we add the packet intercept function into the home agent to monitor the packets destined to a mobile node that belongs to the network. In order to inform the correspondent node that does not have a binding cache for the mobile node, the home agent needs to send the Binding Update message to the correspondent node. We call this function “update management”. In order to handle the lack of Route Optimization in a correspondent node, we propose the BEBA algorithm and implemented BEBA in the home agent.

Because no correspondent node’s function is needed in basic Mobile IP, the correspondent node’s functions are implemented from scratch. The functions in a correspondent node include receiving the Binding Update message, managing the binding cache, and controlling data traffic. All the features described above are fulfilled in the implementation. In this chapter, we discuss several specific difficult aspects in the implementation first and then introduce our detailed design and implementation of the home agent and correspondent node from three aspects: software architecture, data structure, and control flow.

4.2 Binding Control Message Structure

Compared to basic Mobile IP, in Route Optimization, there are four new types of control messages: Binding Update, Binding Request, Binding Warning and Binding Acknowledgement. A Binding Update message is used by a home agent to notify a correspondent node of the current location of a mobile node. A Binding Update message is also used by a new foreign agent to notify a previous foreign agent of the movement of a mobile node. It must be authenticated. Therefore, between a home agent and a correspondent node, or between a new foreign agent and an old foreign agent, there must be a shared secret. The shared secret is obtained from the configuration file in the current implementation. A Binding Acknowledgement message is used by a previous foreign agent to confirm its reception of a Binding Update message. A Binding Request message is used by a correspondent node to require a Binding Update message from a home agent whenever necessary. A Binding Warning message is sent by a previous foreign agent to the home agent when the previous foreign agent receives a packet to a previously registered mobile node, the home agent will send a Binding Update message to the correspondent node.

In this implementation, the Binding Update message has the following structure:

```
#define UPD_WRN         16
#define UPD_REQ         17
#define UPD_MSG         18
#define UPD_ACK         19

//Binding Update Message
struct mip_bind_update{
        u8 type;
        u8 flags;
        u16 lifetime;
        u32 h_addr;
        u32 co_addr;
        ident_t ident;
        mip_ext_t ext[0];

        void set_ident(ident_t req_id){
           ident[0]=time(NULL);
           ident[1]=req_id[1];
        }
```

```
}
```

A Binding Request message has the following structure:

```
struct mip_bind_request{
        u8 type;
        u8 resv1;
        u16 resv2;
        u32 h_addr;
        ident_t ident;

        void set_ident(){
           ident[0]=time(NULL);
           ident[1]=random();
        }
}
```

A Binding Acknowledge message has the following structure:

```
struct mip_bind_ack{
        u8 type;
        u8 resv1;
        u8 resv2;
        u8 status;
        u32 h_addr;
        ident_t ident;
        mip_ext_t ext[0];

        void set_ident(ident_t req_id){
           ident[0]=time(NULL);
           ident[1]=req_id[1];
        }
}
```

A Binding Warning message has the following structure:

```
struct mip_bind_warning{
        u8 type;
        u8 resv1;
        u16 resv2;
        u32 h_addr;
        u32 cpd_addr;
}
```

The Mobile IP identification data structure used by Binding Update message, Binding Request message and Binding Acknowledgement message has the following structure:

```
union ident_t{
        u32 id32[2];
        u64 id64;

        u64& operator=(u64 id){
           return id64=id;
        }
        u32* operator=(u32 id[2]){
           id32[0]=id[0];
           id32[1]=id[1];
           return id32;
        }
        u32& operator[](int index){
           assert(index==0 || index==1);
           return id32[index];
        }
        operator u64(){
           return id64;
        };
}
```

The Mobile IP extension data structure used by Binding Update message and Binding Acknowledgement message has the following structure:

```
#define UPDATE_AUTH_EXT        35
struct mip_ext_t{
        u8 type;
        u8 length;
        mip_ext_t* next() const{ return (mip_ext_t*)((char*)(this)+2+length);};
        int len()const { return length+ sizeof(mip_ext_t);};
}
struct mip_auth_ext_t:public mip_ext_t{
        u32 spi;
        u8 authenticator[0];
}
```

4.3 Mobile IP Packet Filter

The Mobile IP packet filter in a home agent is used to monitor the packets destined to mobile nodes who belong to this home agent. It is an important part existing only in Route Optimization. The packet filter consists of three parts: ipchains, which sets packet filter rules, improvement to *ip_fw.c*, which obtains the <source, destination> IP address pair in kernel space, and extension to *ioctl()*, which transfers the IP address pair to user space.

4.3.1 ipchains

As discussed in section 3.5.4, a chain is a checklist of rules. Each rule specifies a set of conditions the packet must meet, and what to do if a packet meets them. If the rule does not match the packet, then the next rule in the chain is consulted. The home agent has to set a rule for each mobile node that is away from the home network and registers itself in the home agent. The usage is shown as following:

ipchains –A input –d a MN's IP address

For every mobile node, there will be a rule. A rule indicates the IP packet filter to pay attention to any packets destined to a mobile node.

4.3.2 IP Packet Filter

Mobile IP packet filter has specific features. The home agent needs to monitor all packets destined to mobile nodes away from the home network and get the <source, destination> IP address pair of these packets. As we discussed before, in the existing methods, there is no way to obtain a packet's <source, destination> IP address pair only, not touching on this packet. However, we notice that all the packet interception or filter mechanisms finally call *ip_fw.c*, which is the real packet filter in Linux kernel space. The Linux kernel needs to be improved to satisfy Mobile IP traffic management requirements. The function *ip_fw_check* in kernel source file *ip_fw.c* is enhanced as following:

```
1.  char fw_msg[10][128];
2.  int fw_msg_count = 0;
3.  static int
4.  ip_fw_check(struct iphdr *ip,const char *rif,__u16 *redirport,struct ip_chain *chain,
        struct sk_buff *skb, unsigned int slot, int testing)
5.  {… …
6.      count = 0;
7.       do {
8.      for (; f; f = f->next) {
9.              count++;
10.             if (ip_rule_match(f,rif,ip,  tcpsyn,src_port,dst_port,offset!=0)) {
11.                 if (!testing && !ip_fw_domatch(f, ip, rif, chain->label, skb, slot,
src_port,       dst_port,count, tcpsyn))
12.             {
13.                     ret = FW_BLOCK;
```

```
14.                     goto out;
15.              }
16.              /*write to fw_msg if it is not going to  RETURN target*/
17.              if(f->simplebranch != FW_SKIP+1)
18.              {
19.                     ++fw_msg_count;
20.                     if(fw_msg_count>9)
21.                      fw_msg_count = 0;
22.                      switch(ip->protocol)
23.                      {
24.                           case IPPROTO_TCP:
25.                              printk("TCP package \n");
26.                              sprintf(fw_msg[fw_msg_count],"TCP src: %u %u dst: %u
                                     %u",
                                    ip->saddr, src_port, ip->daddr, dst_port);
27.                              break;
28.                           case IPPROTO_UDP:
29.                              printk("UDP package \n");
30.                              sprintf(fw_msg[fw_msg_count],"UDP src: %u %u dst: %u
                                 %u",
                                    ip->saddr, src_port, ip->daddr, des_port)
31.                              break;
32.                          case IPPROTO_ICMP:
33.                              printk("ICMP package \n");
34.                              sprintf(fw_msg[fw_msg_count],"ICMP src: %u %u dst:
                                     %u %u",
                                    ip->saddr, src_port, ip->daddr, dst_port);

35.                              break;
36.                     }
37.              }
38.              break;
39.       }
40. }
```

The main function of *ip_fw.c* is to consult a set of rules to determine whether to pass each IP packet that is destined to the host or forwarded by the host.. Undesirable or potentially unsafe packets can be blocked based on such things as the source and destination IP addresses, protocol type, source or destination port, TCP flags, etc. In the *ip_fw.c*, the function *ip_fw_check( )* is responsible for checking if a packet matches a rule. If a packet matches a rule, the *ip_fw.c* will check whether there is a target in this rule and call different functions to take different actions according to the different targets. The original *ip_fw_check()* does not have the code in line 17 --- line 35. We add the code into

ip_fw.c to meet the Route Optimization requirement. When *ip_fw_check* finds that a rule is matched, line 17 checks if this rule's target is return. If so, do not check the following rules. This works for the BEBA algorithm. If a correspondent node does not support Route Optimization, set an ipchains whose target is RETURN for this correspondent node. Then, line 18---line 35 will be ignored. If not, get the protocol type of this packet. According to different protocols, put the protocol type, source address, destination address into *fw_msg* buffer. This buffer is declared by this implementation and is managed by a FIFO strategy. After the improvement, *ip_fw.c* will filter the packets according to the rules set by ipchains and put the packets' source address, destination address and protocol type in a kernel buffer. The next step is how to read a kernel buffer (*fw_msg* buffer) from user space.

4.4 Communication Between User Space and Kernel Space

As discussed in Section 3.5.2 , to communicate between kernel process and user space, there are two ways: creating a new system call or extending an existing system call. Since our implementation only needs to get data from kernel space, an existing system call *ioctl ()* is extended to transfer the <source, destination> data in the kernel buffer to a user space process.

The function *inet_ioctl* in the kernel source file *af_inet.c* is extended as following:

```
1.  static int inet_ioctl(struct socket *sock, unsigned int cmd, unsigned long arg)
2.  {
3.   ……
4.      switch(cmd)
5.      {
6.      ……
7.            case SIOCFWMSG: /*send fw msg to the user space*/
8.              sprintf((char*) arg, "");
9.              for(c_msg_c = 0; c_msg_c<10; c_msg_c++)
10.             {
11.                   if(strlen(fw_msg[c_msg_c])>0)
12.                   {
13.                       sprintf((char*) arg, fw_msg[c_msg_c]);
14.                           return (0);
15.                       }
16.             }
17.           case SIOCFWCLR: /*clear fw msg*/
```

```
18.                 sprintf(fw_msg[c_msg_c], "");
19.                 return (0);
20.                 ……
21.       }
22.       …….
23. }
```

The SIOCFWMSG, SIOCFWCLR are user extended commands in this implementation. SIOCFWMSG is used to get the content of kernel buffer *fw_msg[ ]*. SIOCFWCLR is used to clear the kernel buffer after every time the kernel buffer is read by SIOCGWMSG. When a user space process needs to obtain the kernel buffer *fw_msg[]*, it will open a raw socket and invoke system call *ioctl()* as following:

```
sd=socket(AF_INET, SOCK_RAW, IPPROTO_ICMP);
ioctl(sd, SIOCFWMSG, (void*) msg);
```

msg is a pointer to data transmitted from kernel. After the extension to the *ioctl( )* system call, the implementation can obtain data related to IP packet filter from the Linux kernel.

4.5 Set Tunnel

For every outgoing packet, the correspondent node has to check whether it is sent to a mobile node of which the correspondent node has a binding cache entry. If there is an entry for the destination mobile node, the packet needs to be tunneled by adding an outer IP header and sent directly to the mobile node's current location. This is the traffic management part in this implementation.

In order to set a tunnel in the Linux kernel from a user space application, iproute2+tc packets should be included in the implementation. Iproute2+tc is the Linux traffic control engine, which allows access to a variety of new networking features in the Linux 2.2.* kernel, including setting up a tunnel and adding an entry into the route table from a user space process. The following is a sample code to use the iproute2+tc to set a tunnel in Linux:

```
1. #include <sys/socket.h> //for AF_INET
2. #include < linux/if_tunnel.h> //define struct ip_tunnel_parm
3. #include < net/if.h> //define struct ifreq
```

```
4. tunnel_t::tunnel_t()
5. {
6.    …… ……
7.       sock= socket(AF_INET, SOCK_DGRAM, 0);
8.   }

9.  void tunnel_t::do_add_ioctl(int cmd, const char *basedev, struct ip_tunnel_parm *p)
10 .{
11.     struct ifreq ifr;
12.     strcpy(ifr.ifr_name, basedev);
13.     ifr.ifr_ifru.ifru_data = (char*)p;
14.     ioctl(sock, cmd, &ifr);
15. }


16. void tunnel_t::do_add_tunnel(ip32 local,ip32 remote,char* tunl_name)
17. {
18.  struct ip_tunnel_parm p;
19.  bzero(&p,sizeof(ip_tunnel_parm));
20.      p.iph.version = 4;
21.      p.iph.ihl = 5;
22.      #define IP_DF     0x4000        /* Flag: "Do not Fragment"     */
23.      p.iph.frag_off = htons(IP_DF);
24.      p.iph.protocol = IPPROTO_IPIP;
25.      p.iph.daddr=remote;
26.      p.iph.saddr=local;
27.      strncpy(p.name,tunl_name,IFNAMSIZ);
28.      do_add_ioctl(SIOCADDTUNNEL,"tunl0",&p);
29.      cout<<"Add tunnel: "<<p.name<<" "<<endl;
30.  }
```

The implementation wraps the tunnel work in the *tunnel_t* class. In the constructor of *tunnel_t*, *tunnel_t* creates an AF_INET socket for later use. Function *do_add_ioctl( )* uses the *ioctl ( )* system call to send tunnel commands and related parameters to the Linux kernel. Function *do_add_tunnel ( )* accepts two IP addresses along with the tunnel device name and assembles the struct ip_tunnel_parm, then calls *do_add_ioctl()* to accomplish setting up the tunnel. Ip32 local is the local end IP address (the correspondent node's IP address). Ip32 remote is the remote end IP address (the mobile node's care_of_address). This tunnel will exist as a network device. Then, a new entry needs to be added into the correspondent's route table. This new entry specifies a route to a host via a specified network device. In the correspondent node, the new entry specifies a route to a mobile

node via a tunnel device, which is created by *do_add_tunnel()*. How to add a new entry into the route table will not be discussed here. It can also be implemented by using the iproute2+tc package. In this implementation, it is encapsulated in the *route_t* class.

4.6 Timer Management

Timer management is a very important consideration in this implementation. All states in the Mobile IP protocol are soft states. They have a predefined lifetime and need an associated timer to maintain their existence. Beside these, some activities have to be done periodically. All entries in the binding cache also have an associated lifetime. If the time is expired, this entry has to be deleted from the binding cache or a Binding Request has to be sent out. Every mobile node entry in the binding cache needs a timer to keep track of its lifetime.

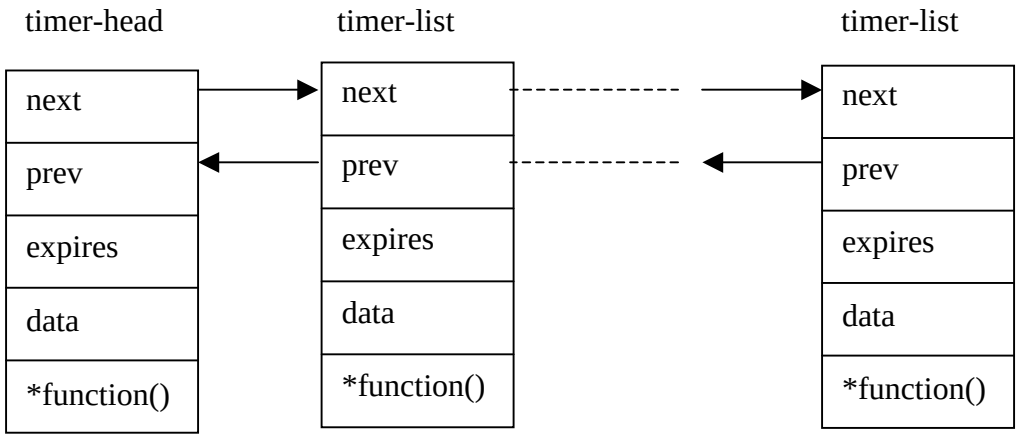

Figure 4.1 Timer Structure

How to keep track of so many timers? The implementation uses a linked list of timer event data structures that are held in ascending expiry time order. Every expired timer is removed from the list and its callback routine is called. This mechanism has the advantage of being able to pass an argument (a callback function pointer) to the timer routine. When an object or a route wants to use the timer, it only needs to call *add_event()* to put its lifetime into the timer list. When the lifetime is expired, the

associated callback function predefined in the object or function will be called. An object or function also can cancel its predefined expire timer by calling *rm_event()*. Our timer management mechanism is very similar to the Linux kernel timer structure. It is an effective way to manage such a heavily timer dependent system. The timer management list is illustrated in Figure 4.1.

4.7 Some Graphic Expression

In order to describe the design and implementation details of the home agent and the correspondent node, we introduce some graphic representations used in the following sections.

4.7.1 Class Relationship

"There are two relationships between two classes: client-server associations and peer-to-peer associations. In the client-server association, the client is the object with the reference; the server is the object with data or operation invoked by the client. Clients must know about the servers to be able to invoke services from them. Servers should not know about their clients. In the peer-to-peer association, there is recursion of operations between the two classes. In client-server association, a server object has an association to a client object in order to register itself with client. Once registered, the client object can invoke methods on the server object." [22]

In our thesis, we use a rectangle to indicate a class, a bidirectional arrow to express the peer-to-peer association and a unidirectional arrow to express the client-server

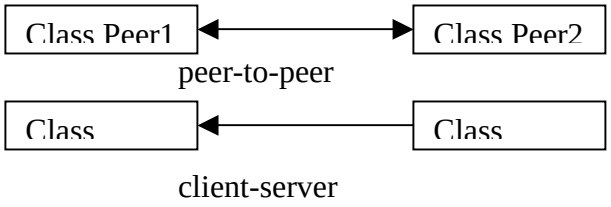

Figure 4.2 Class Relationship

association. In the unidirectional direction arrow situation, the class which is pointed to by the arrow is the client, the class which is at the state of the arrow is the server. Figure 4.2 shows the graphic expressions.

4.7.2 Activity Diagrams

Activity diagrams represent the behavior of an operation as a set of action. In this thesis, activity diagrams describe the activities inside a class. Figure 4.3 displays the graphic representations of activities.

A filled circle indicates the start activity.

A filled circle with another outside circle indicates the end activity

A rectangle with circular corner indicates the general activity

A rectangle with one convex pentagon side indicates a sending activity

A rectangle with one concave pentagon side indicates a receiving activity

A diamond indicates a logical decision activity, it is labeled by multiple output transition with different guard conditions.

Activities are linked by automatic transitions that are indicated by an arrow.

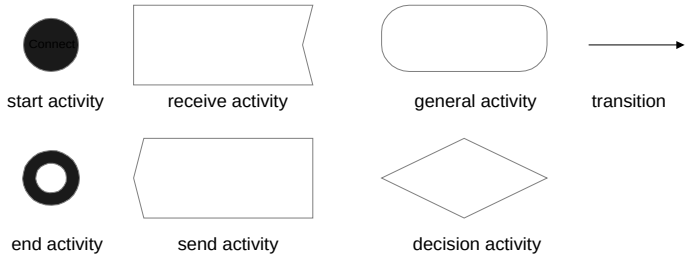

Figure 4.3 Activity Diagram Graphic Expression

4.8 Basic Mobile IP Architecture

The basic Mobile IP implementation is our starting point. Our Route Optimization makes use of agent advertisement, agent solicitation, and registration components in basic Mobile IP. The basic Mobile IP architecture and design style influences the Route Optimization implementation. As part of the Route Optimization components, we will summarize the design and implementation of basic Mobile IP. From the high level

consideration, there are two major approaches to implement the three entities. One is based on functions and procedures. The other is based on Object-Oriented principles. Because of the well known advantage of OO, the basic mobile IP implementation choose the second approach. To consider about the software efficiency, the home agent and the foreign agent are implemented as one entity: agent. Any agent can act as a home agent and a foreign agent at the same time. For the mobile nodes who belong to this home network, the agent acts as the home agent. For the mobile nodes who belong to foreign networks, the agent will act as the foreign agent. Dynamic binding in C++ facilitates this design idea. Here, we introduce some useful classes created in the basic Mobile IP implementation.

In the home agent:

- Class *ag_reg_t* , responsible for registration.
- Class *ag_advert_t* , responsible for agent's advertisement or mobile node's solicitation .
- Class *mobile_t*, a super class to be inherited by *local_mobile_t* and *remote_mobile_t* in order to combine the home agent and the foreign agent as the agent.
- Class *local_mobile_t*, responsible for home agent related functions.
- Class *remote_mobile_t*, responsible for foreign agent related functions.
- Class *netmng_t*, responsible for getting host's system configuration information.

In the mobile node:

- Class *cl_agent_t*, a super class to be inherited by *cl_home_t* and *cl_foreign_t*
- Class *cl_home_t*, responsible for registration
- Class *cl_foreign_t*, responsible for solicitation or advertisement .
- Class *cl_mng_t*, responsible for getting host's system configuration information

There is a binding cache in each home agent, which stores the location information for all registered mobile nodes.

4.9 Correspondent Node

Mobile IP without Route Optimization does not need any support from a correspondent node. That is one of the reasons why Mobile IP without Route Optimization is popular. In a short term, deploying the Route Optimization support in every Internet host is almost impossible. Especially for implementation existing in kernel, patching additional source code and recompiling the kernel is a very tedious and error-prone process. Keeping this reason in mind, for easy installation and usability, we choose to implement Route Optimization functionality in the user space rather than embedded it in the kernel. It will help the deployment of Route Optimization in the whole Internet. A user space implementation especially facilitates the deployment of Route Optimization in correspondent nodes. Certainly, in the future, with Mobile IP gaining popularity, we can expect a large number of computers to be equipped with Route Optimization software. No matter whether it is implemented in user space or kernel space, our software will contribute to this migration period. Performance is a problem that may exist in the user space implementation. However, the balance between simplicity and performance is one of the considerations in this research. Good design and implementation will improve the performance. In Chapter 5, we will get an insight of the performance of our user space implementation. The implementation fulfills features of a correspondent node according to the IETF Route Optimization draft. The functionality includes binding cache management and traffic control. Binding cache management includes exchanging control messages with home agents, authenticating control messages and maintaining binding cache. Traffic control includes selecting traffic that the correspondent node has a binding entry for, encapsulating those packets and sending them out directly. The software is implemented in C++, following an object-oriented architecture. This section describes implementation details of the correspondent node from several aspects: software architecture, data structure, control flow.

4.9.1 Architecture

In Mobile IP with Route Optimization, a correspondent node fulfills the following functions:

- Receiving Binding Update message from a home agent.

- Updating its binding cache and deleting the expired binding entry.
- Detecting traffic and tunneling packets that it has a binding entry for their destinations.

The functions can be separated as five components: Binding Update message listener, binding cache management, timer management, traffic controller, and security management. Because our implementation is based on object-oriented principles, we encapsulate the five components into seven classes: *cpd_update_t*, *select_cb_t*, *cpd_mobile_t*, *tunnel_t*, *route_t*, *timer_t*, and *sec_mng_t*. The binding cache is a central data structure in the correspondent node, which is implemented by a STL (C++ Standard Template Library) associative container: Map.

select_cb_t class: responsible for listening to socket messages.

cpd_update_t class: responsible for managing the binding cache.

cpd_mobile_t class: responsible for managing the related mobile node and recording the associated information.

tunnel_t class and *route_t* class: responsible for tunneling packets destined to mobile nodes.

timer_t class: responsible for tracing all the timers in the system.

sec_mng_t class: responsible for authenticating a Binding Update message or a Binding Acknowledgement message.

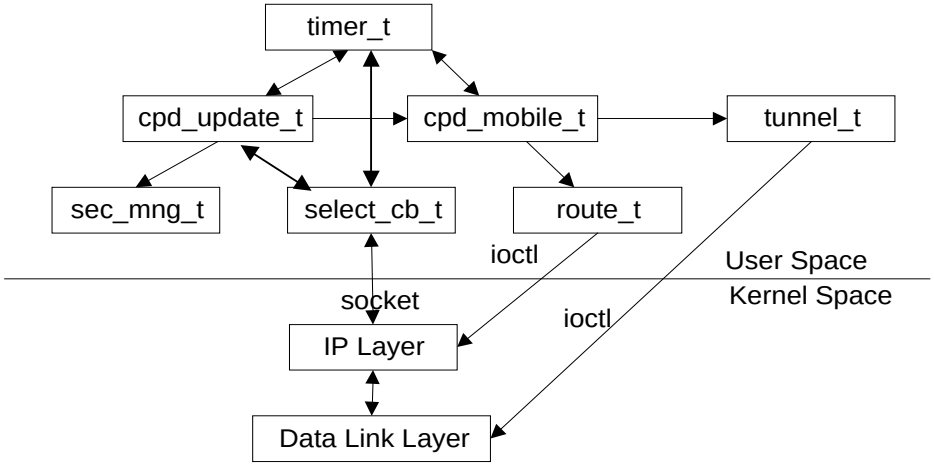

Figure 4.4 Class Relationship in a Correspondent Node

The relationships between these classes are illustrated in Figure 4.4:
Class *cpd_mobile_t* and class *timer_t* are a peer-to-peer association instead of a client-server association because of the consideration of software reusability and extensibility. Once a *cpd_mobile_t* object registers itself with the *timer_t* object, the *timer_t* object can invoke methods on the *cpd_mobile_t* object. There is callback relationship between *cpd_mobile_t* and *timer_t*. A *timer_t* object can accept different classes' registration requirements, then can trace different timers for different classes and objects as we mentioned in Section 4.6. All time stamped objects can register themselves with the *timer_t* object. When a timer is expired, the *timer_t* object will invoke the callback function associated with the time stamped object. Every mobile node will associate with a *cpd_mobile_t* object and has a lifetime. In the same way, *cpd_update_t* and *select_cb_t* are a peer-to-peer association. Once a *cpd_update_t* object registers itself with the *select_cb_t* object, the *select_cb_t* object can invoke methods on the *cpd_update_t* object. *Select_cb_t* can listen on different sockets. If *select_cb_t* listens to a socket message for *cpd_update_t*, it will call the *read_sock()* function in cpd_update_t. This feature enables software extensibility and reusability.
Associated with these classes, there are the following objects in the correspondent node:
A *cpd_update_t* object: *updater*
A *select_cb_t* object: *select_obj*
A timer_t object: *timer_obj*
A *sec_mng_t* object: *sec_obj*
0 --- N *cpd_mobile_t* objects, 0 ---N *tunnel_t* objects, 0 --- N *route_t* objects.
N means the objects' number, which is associated with the number of mobile nodes. *tunnel_t* objects, and *route_t* objects have the same lifetime, decided by the correspondent *cpd_mobile_t* objects' lifetime.

4.9.2 Data Structure

The binding cache is implemented as a STL Map. Objects stored in a map consist of a pair < key, value >. A value is associated with a key. Iterating through all the keys is very efficient in STL maps. Our < key, value > pair in the binding cache map is <MN's ip address, cpd_mobile_t object representing this MN>, that is, every entry in the binding

cache is a pair of <ip address, cpd_mobile_t object>. It is easy and efficient to find a mobile node's entry and maintain it by using a STL iterator. *cpd_mobile_t* class integrates the data and functions related to a mobile node in one object, which include a mobile node's home address, care of address and home agent address. The tunnel device and the route table entry that are associated with this mobile node are also included in the *cpd_mobile_t* object. *cpd_update_t* is responsible for updating the binding cache and deciding how to discard an old entry and add a new entry in it. A *timer_t* object is responsible for keeping track of every entry's lifetime. When a mobile node's binding is expired, the associated tunnel and route entry will be deleted.

4.9.3 Control Flow

When the Mobile IP with Route Optimization starts, the system reads the associated key between correspondent node and all home agents from the configuration file, then

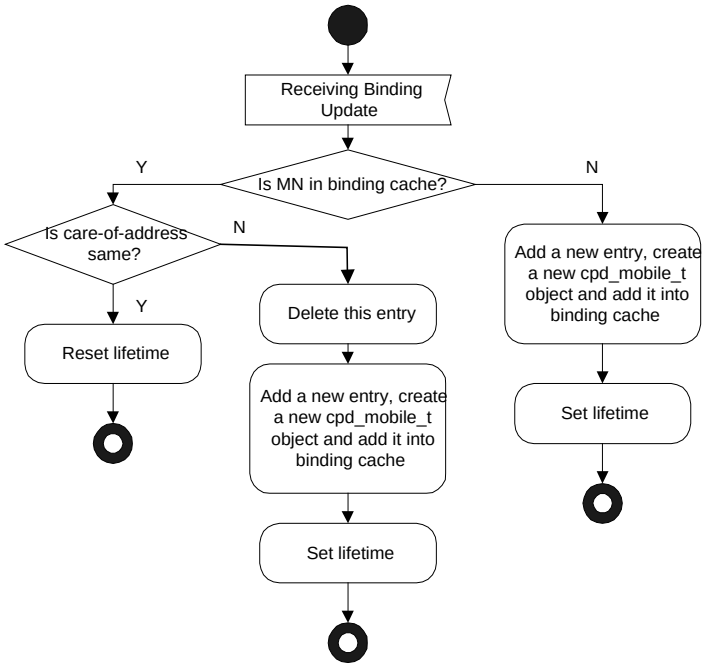

Figure 4.5 Class cpd_update_t: Process Binding Update Message

generates all the objects described in Section 4.9.1. The *select_obj* listens to all Binding Update messages from different home agents. If there is a Binding Update message received through the UDP socket, the *select_object* will invoke the *cpd_update_t:: read_sock(*). The *Updater* object parses the received message and updates the binding cache. If this is a new mobile node for the correspondent node, the *updater* object will add a new entry into the binding cache. If the binding cache is full, the updater will discard an old entry based on a FIFO strategy and insert the new entry. If the mobile node already exists in the binding cache, the *updater* object will determine whether the care of address remains the same as previous. If it is, just reset the mobile node's lifetime. If not, then delete the old entry and create a new entry for this mobile node. The procedure is shown on Figure 4.5. (Process Binding Update Message). The other procedures are also illustrated by Figure 4.6 – Figure 4.9.

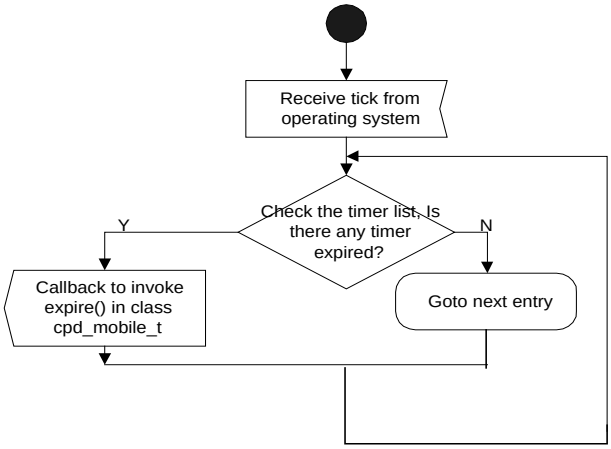

Figure 4.7 Class timer_t: Timer Management

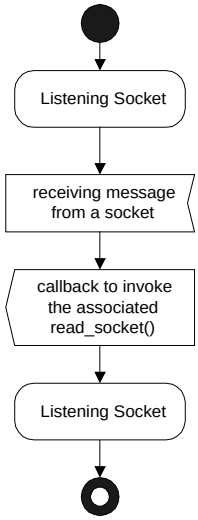

Figure 4.6 Class select_t: Receiving Binding Update Message

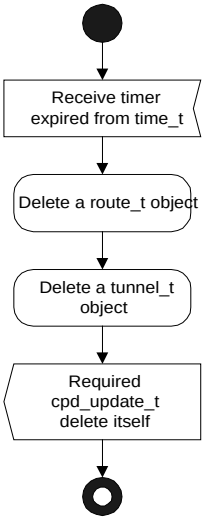

Figure 4.8 Class cpd_mobile_t: a mobile node expires

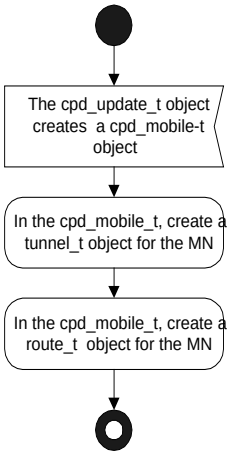

Figure 4.9 Class cpd_mobile_t: a mobile node is created

4.10 Home Agent

This section describes the implementation details of the home agent for Route Optimization.

4.10.1 Architecture

The Route Optimization adds two functional components into basic Mobile IP:

- traffic monitoring.
- Binding Update message management.

In order to monitor traffic by the packet filter in Linux kernel, *ip_fw.c* and *af_inet.c* source code is extended. We also modify class *ag_reg_t* in basic Mobile IP to enable traffic monitoring and create a new class *ag_update_t* to manage update message sending. As soon as a mobile node registers with its home agent, the *ag_reg_t* class notifies the Linux kernel to monitor all traffic destined to the mobile node by setting ipchains for this mobile node. By improving the Linux kernel and extending the *ioctl()* system call, *ag_update_t* object can obtain the address of a correspondent node, which sends packets to a mobile node through the mobile node's home agent. *ag_update_t* class is responsible for implementing the BEBA algorithm, managing the correspondent node cache, and receiving data from the traffic monitor. *cpd_node_t* class is responsible for data and functions related to a correspondent node. The three classes *ag_update_t*, *cpd_node_t*, and *ag_reg_t* collaborate with classes *timer_t* , *sec_mng_t*, and *mobile_t* to achieve the Route Optimization in a home agent. The relationships between these classes are illustrated by the class diagram in Figure 4.10:

Class *cpd_node_t* and class *timer_t* are in a peer-to-peer association instead of a client-server association because of the consideration of software reusability and extensibility. Once a *cpd_node_t* object registers itself with the *timer_t* object, the *timer_t* object can invoke *expire()* methods on the *cpd_node_t* object. There is a callback relationship between class *cpd_node_t* and class *timer_t*. This feature enables software extensible and reusable.

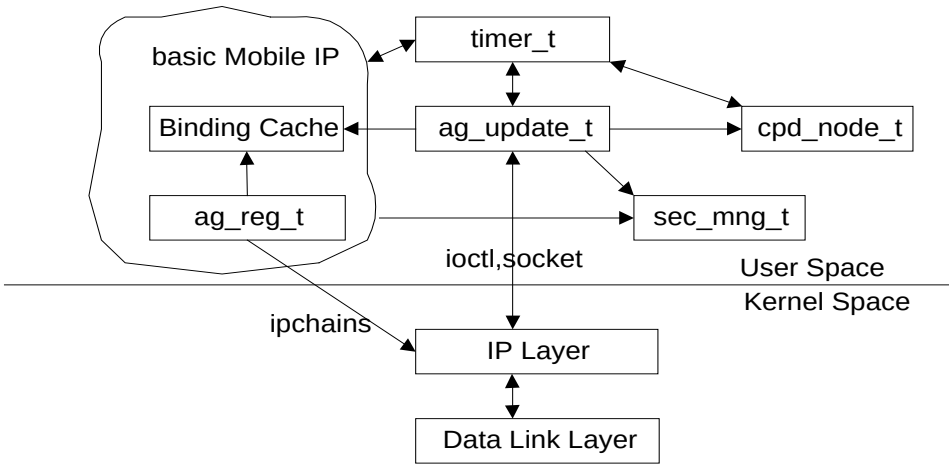

Figure 4.10 Class Relationship in a Home Agent

Associated with these classes, there are the following objects in the home agent:

A *cpd_update_t* object: *updater*

A *timer_t* object: *timer_obj*

A *sec_mng_t* object: *sec_obj*

0 --- N *cpd_node_t* objects. The number N indicates the number of correspondent nodes that are currently communicating with mobile nodes who belong to this home agent.

4.10.2 Data Structure

There are two caches in the home agent now. One is the binding cache and the other is the correspondent node cache. The binding cache stores the mobile nodes' binding information, which is the same cache as in the basic Mobile IP. The correspondent node cache is a new cache appearing in the Route Optimization implementation, which is implemented as a link list. The correspondent node cache is created for the implementation of the BEBA algorithm. *ag_update_t* collaborates with the correspondent node cache and the binding cache to send Binding Update messages to a correspondent node.

4.10.3 BEBA (Binary Exponenial Backoff Algorithm) Implementation

As discussed in Section 3.6.1, the sending rate of Binding Update messages is reduced by a binary exponent until a fixed number of periods is reached. For each correspondent node, there must be a timer to record how long this period will last and a counter to trace how many periods have expired. In our implementation, a user can set the first wait period and the max number of waiting periods. An entry in the correspondent binding cache is a *cpd_node_t* object. The *cpd_node_t* has the following structure:

```
Class cpd_node_t
{
 private:
      ip32 cpdAddr;     //correspondent node IP address
      ip32 mobAddr;    //mobile node IP address
      u32 periodLifetime;       //current period
      int counter;                  //current period number
      int maxPeriod;    //max period number
      event_t cpdExpire;        //expire event, be added to timer_t object
      cpd_node_t * next;        //pointer to next cpd_node_t object
      void expire();      //timer_t callback expire() function
      void increase();   //increase periodLifetime to support BEBA algorithm
      void setimer();    //set a new expire time in timer_t object
 public:
      cpd_node_t(ip32 cpd, ip32 mobile, u32 lifetime, int max); //constructor
      static void expiring(event_t*); //global wrapper to support timer_t callback.
      ~cpd_node_t ( ); //destructor
}
```

When the *timer_t* object traces the expiration of the current period, the *expire()* function will be invoked. In *expire()*, if there is new traffic coming from the correspondent node and forwarded by the home agent, then periodLifetime=2*periodLifetime, and the new periodLifetime will be set in the *timer_t* object. If there is no traffic forwarded by the home agent during this period, this correspondent node entry will be deleted from the correspondent node cache. After the maximum period is reached, if there is still traffic coming from the correspondent node, the home agent can deduce that this correspondent node does not support Mobile IP with Route Optimization, the correspondent node entry

will be deleted from the cache eventually and any packet filter rule related to this correspondent will be bypassed and the traffic will be forwarded.

4.10.4 Control Flow

The Route Optimization component in the home agent will collaborate with the basic Mobile IP code to implement the Route Optimization function. The Route Optimization code will consult with the binding cache in the home agent to obtain a mobile node's binding information. Therefore, besides the initialization of the basic Mobile IP, when the Route Optimization component starts, the system reads the associated key between the home agent and all correspondent nodes from the configuration file, then generates all the objects described in Section 4.10.1. The *select_obj* will listen on all sockets. If there is a mobile node registering with its home agent, the modified *ag_reg_t* object will set an ipchains for this mobile node as follows:

If the mobile node's home address is 134.117.57.204, then set the ipchains as:

ipchains –A input –d 134.117.57.204

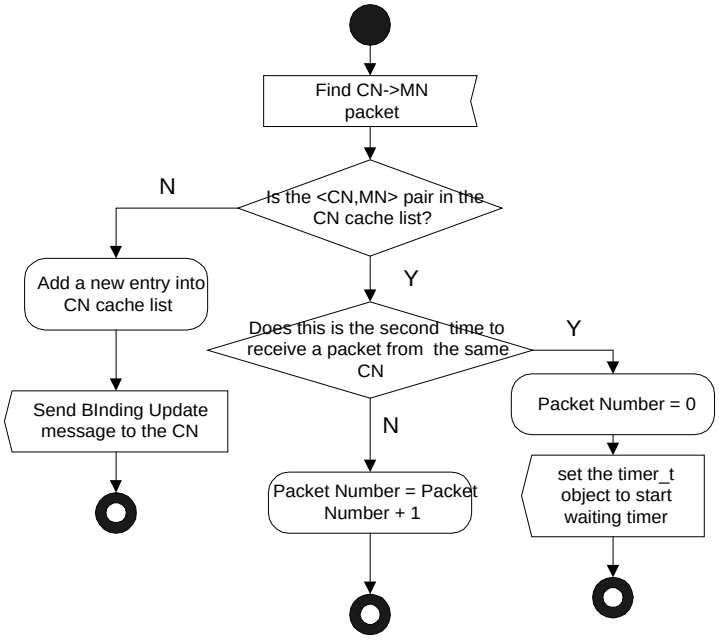

Figure 4.11 Class ag_update_t: Receive CN→MN Message

This sets a rule in the Linux kernel to indicate that any packet destined to the mobile node 134.117.57.204 will be noticed and the source address and destination address of this packet will be extracted and sent to a buffer. Another object, the *ag_update_t* object will invoke the extended system call *ioctl()* to get the <src,dest> pair. Then *ag_update_t*

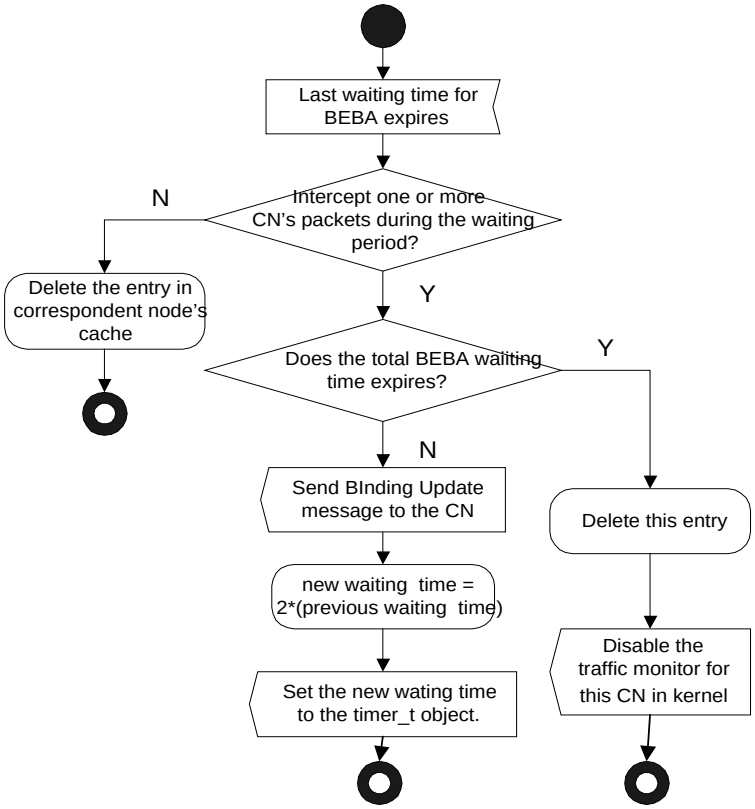

Figure 4.12 Class ag_update_t: Send Binding Update Message

object implements the BEBA algorithm to decide if it is necessary to send a Binding Update message to the correspondent node. If a Binding Update message is to be sent out, the *ag_update_t* object will inquire the binding cache to get the care of address and lifetime of the mobile node, then assemble the Binding Update message and send it to the correspondent node. A home agent also listens on all Binding Requests from correspondent nodes and replies to them with a Binding Update message. These procedures are illustrated by Figure 4.11 to Figure 4.16.

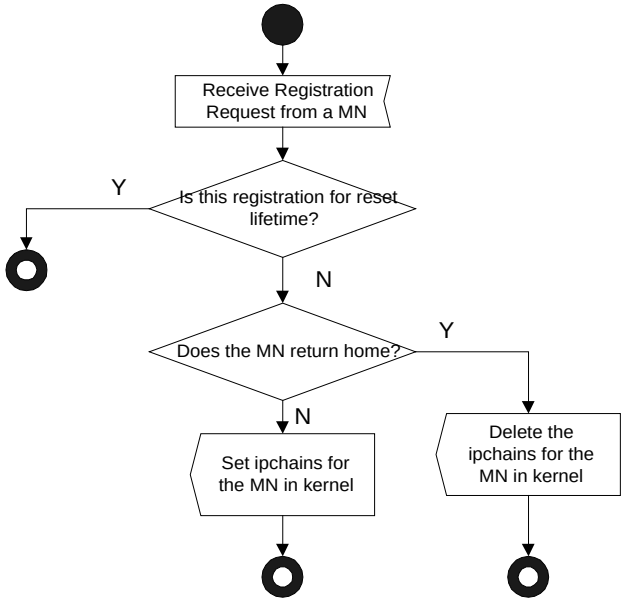

Figure 4.13 Class ag_reg_t: Set Traffic Monitor for a MN

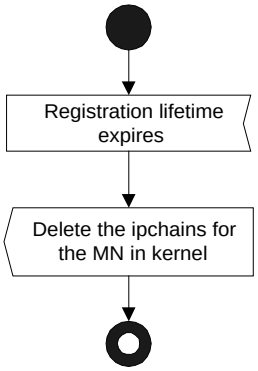

Figure 4.14 Class ag_reg_t: Registration Lifetime Expires

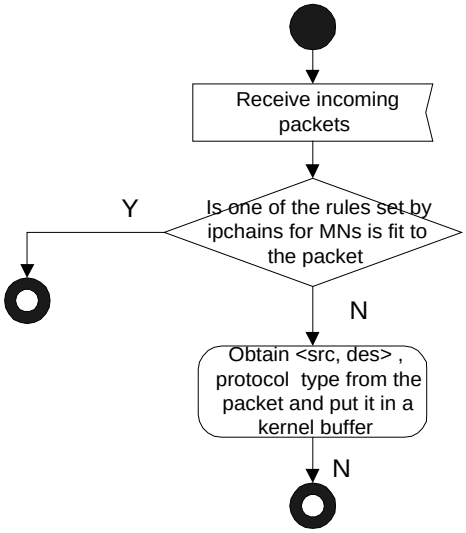

Figure 4.15 ip_fw.c: Enhancement to Support HA's Traffic Monitor

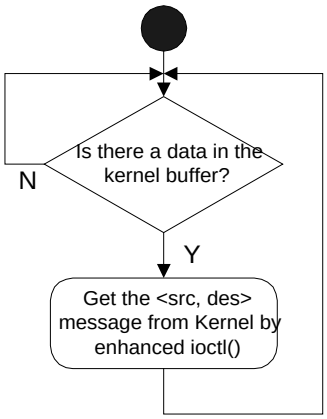

Figure 4.16 ag_update_t: Obtain Traffic Monitor Message from Kernel

Chapter 5

Experiment and Evaluation

The previous chapters introduce the Mobile IP with Route Optimization approach and its implementation to support the mobility in an IP-based backbone network. Although the architecture possesses the features to support the mobility and eliminates the triangle routing existing in basic Mobile IP, the performance improvement will depend on the relative positions of communication peers and the bandwidth of links. In this chapter, two aspects are tested. One is to demonstrate that this implementation accomplished the functions defined in the draft of Mobile IP with Route Optimization. The other is to evaluate the performance. The performance will be evaluated in different cases. Through this chapter's investigation, the benefits obtained from Route Optimization will be demonstrated.

5.1 Testbed

The experimental system configuration (Figure 5.1) consists of three subnets: 134.117.57.0, 134.117.66.0, and 134.117.67.0. Subnet 134.117.57.0 is the mobile node's home network with a 10 Mbps LAN (compliant with IEEE 802.3 specification). Subnet 134.117.66.0 acts as the mobile node's foreign network with a 10 Mbps LAN and a 2 Mbps WaveLAN (2.4 GHz WaveLAN compliant with IEEE 802.11 specification for wireless LANs). There are two correspondent nodes. One exists in the 134.117.66.0 subnet. The other resides in the 134.117.67.0 subnet. A mobile node will move from the 134.117.57.0 subnet to the 134.117.66.0 subnet. The mobile node is a Dell Inspiron 3500 laptop. The domain name of the mobile node is WMC-057204. Its home IP address is 134.117.57.204. The domain name of the home agent is Kunz3-57. Its IP address is 134.117.57.101. The domain name of the foreign agent is WMC-066021. Its IP address is 134.117.66.21. The domain name of the correspondent node is WMC-067140. Its IP address is 134.117.67.104. The link between the mobile node and foreign network is the wireless WaveLAN. The other three entities (the home agent, the foreign agent and the correspondent node) are stationary hosts connected to10 Mbps LANs. The communication bottleneck in this experimental system is the wireless WaveLAN.

Therefore, the bandwidth is restricted to 2 Mbps by the wireless segment. Routers kunz2, kunz3, and kunz3-57, connect the three subnets together. Two routers are equipped with the network emulator NISTnet. NISTnet operates at the IP layer. It allows us to emulate a variety of network conditions such as bandwidth limitation, delay, and the drop or duplication rate. In our experiments, we use it to emulate the various network conditions among different entities and investigate the Route Optimization performance under the different network situations.

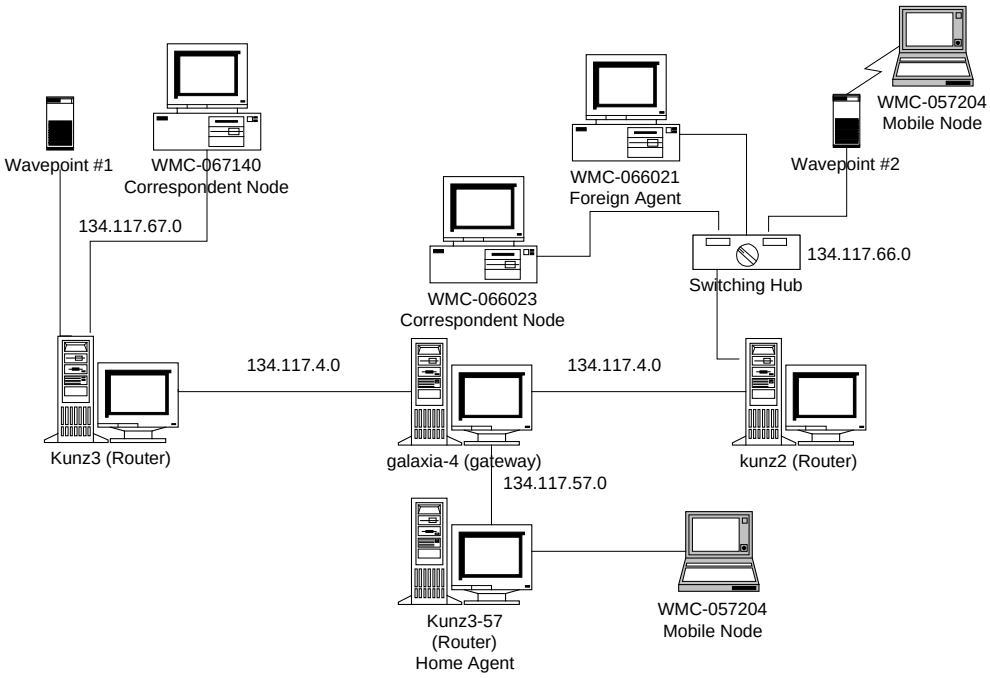

Figure 5.1 Mobile IP with Route Optimization Experiment System Setup

We choose Mobile IP without Route Optimization as the base case because Route Optimization aims to avoid triangle routing existing in basic Mobile IP. Both basic Mobile IP and Mobile IP with Route Optimization support global mobility based on the existing infrastructure. They co-exist with the regular routing protocols for stationary hosts. Both protocols are implemented on the same platform, Linux, and use the Object Oriented C++ language. We implemented Route Optimization based on the agent advertisement process and the registration process existing in basic Mobile IP. Based on these common points, we can determine the improvement with Route Optimization and

demonstrate that Mobile IP with Route Optimization is a better choice than basic Mobile IP in terms of performance. We also use plain IP as a comparison purpose to quantify the performance degradation because of the overhead incurred by data tunneling and Binding Update message processing.

5.2 Functionality

As we discussed in the previous chapters, one of the main differences between Mobile IP with Route Optimization and basic Mobile IP is that correspondent nodes will cache the location information for mobile nodes. One of the main components added by Route Optimization is to monitor the IP packets destined to mobile nodes and to send a Binding Update message to the correspondent node by the home agent. After receiving the Binding Update message, the correspondent node will cache the mobile node's current location information and set the associated tunnel. The routes taken by packets after the correspondent nodes have the binding cache are shorter than that taken by packets before route optimality. In order to demonstrate that our implementation achieves the goals, we use the *traceroute* utility to trace the route before Route Optimization and that after Route Optimization.

5.2.1 Traceroute

The *traceroute* utility traces the route of an IP packet by launching a UDP probe packet with small ttl (time to live). The simplest usage is:

traceroute destination IP address

From the output of traceroute, we can observe the intermediate routers that the UDP packet travels through.

5.2.2 Binding Update Experiment

According to the draft of Route Optimization in Mobile IP, when a correspondent node sends a packet to a mobile node for the first time, it does not know the current location of the mobile node. The first packet will travel to the home agent of the mobile node, and then it is delivered by the home agent to the foreign agent. After that, it is forwarded to the mobile node by the foreign agent. This first packet will follow a route that every

packet in basic Mobile IP takes. However, when the first packet travels through the home agent, the Route Optimization component in the home agent should capture it and send a Binding Update message to the correspondent node. Following packets sent by the correspondent node will travel directly to the mobile node instead of going through the home agent triangle. In order to demonstrate these effects, we design three experiments:

1. Experiment one: traceroute on basic Mobile IP
   a) Running basic Mobile IP on the testbed.
   b) Issuing command "*traceroute 134.117.57.204*" on WMC-067140 (the correspondent node).

   The *traceroute* utility shows the route of the packet as follows:

   kunz3 (router) → galaxia-4 (gateway) → kunz3-57 (router and the home agent) → galaxia-4 (gateway) → kunz2 (router) → wmc-066021 (the foreign agent) →134.117.57.204 (the mobile node).
2. Experiment two: traceroute the very first packet on Mobile IP with Route Optimization
   a) Running Mobile IP with Route Optimization on the testbed
   b) Issuing command "*traceroute 134.117.57.204*" on WMC-067140 (the correspondent node).

   The *traceroute* utility shows the route of the packet as follows :

   kunz3 (router) → galaxia-4 (gateway) → kunz3-57 (router and the home agent) → galaxia-4 (gateway) → kunz2 (router) → wmc-066021 (the foreign agent) →134.117.57.204 (the mobile node).
3. Experiment three: traceroute the second packet on Mobile IP with Route Optimization
   a) Running Mobile IP with Route Optimization on the testbed
   b) Issuing command "*ping –c 1 134.117.57.204*" on WMC-067140 (the correspondent node).
   c) Issuing command "*traceroute 134.117.57.204*" on WMC-067140 (the correspondent node).

   The *traceroute* utility shows the route of the packet as follows :

   kunz3 (router) → galaxia-4 (gateway) → kunz2 (router) →wmc-066021 (the foreign agent) → 134.117.57.204 (the mobile node).

From the above three experiments, the observation shows that the first packet in Mobile IP with Route Optimization follows the same route taken by all the packets in basic Mobile IP. However, the second packet sent by *traceroute* travels a shorter route to the mobile node after the first packet is sent to the mobile node in the third experiment. Between the first packet and the second packet, our Route Optimization component works correctly.

5.3 Performance

5.3.1 Evaluation Criteria

Usually, there are two criteria to measure the performance of a network and its protocols: throughput and latency. The throughput is the amount of data transferred by a network in a time unit. Generally, it is expressed as Mbps, a million bits per seconds. Latency is the time taken by a packet from a host to another host. It consists of propagation delay and processing delay. Ideally, we hope to place our implementation in the actual network and vary the location and distance of the three entities to evaluate the performance. However, there are some difficulties to deploy our entities in different locations of the Internet. We exploited the emulation environment in our Lab. Because the actually physical distance is short and NISTnet is unable to emulate the latency effectively, we do not evaluate latency. We use the throughput as the performance criteria in our evaluation.

5.3.2 Benchmark

TCP is a representative transport layer protocol used in many applications. Mobile IP with Route Optimization supports the mobility at the IP layer and is transparent to the transport layer. Either TCP or UDP can be used as the transport layer protocol in our experiments. We use TCP as the upper layer protocol because it is more sensitive to packet loss and delay than UDP. The throughput of an application exploiting TCP is more representative than that of UDP. Besides, TCP is used widely because it provides reliability and guarantees delivery. TCP performance is widely used for the evaluation of the underlying IP layer [23]. Based on the choice of TCP, we select FTP as the benchmark because it provides the throughput measurement. Another reason we select FTP as the benchmark is that FTP is used in several similar experiments to evaluate mobility performance [23]. As for the transferred file size, we also took hints from these

experiments. A medium file size is chosen in order to reduce the TCP's start overhead. We use FTP to download a 20 Mb file from the correspondent node to the mobile node. The performance is measured as TCP throughput inside FTP.

5.3.3 Scenarios Design

To demonstrate and quantify the enhancement in Route Optimization, we consider a base scenario of triangle routing. Longer routes mean increased variance on the way, such as more constraints on available bandwidth, increased drop rates, longer physical distances, more processing time and the need to pass through more intermediate routers. In a nutshell, longer routes typically mean lower bandwidth, higher drop rate, longer latency and more unpredictable factors. At the same time, for the network itself, longer routes result in bandwidth waste and other resource waste such as router's processing time and intermediate buffer consumption. The triangle routing overhead may be significant in some cases, for example when a mobile node moves to a position which is very near to a correspondent node, and is far away from the home network. An extreme situation is that the mobile node moves to the same network as the correspondent node and the home agent is far away. We explore this case in our experiment. To simulate the influence of longer routes, we design two clusters of experiments. The two clusters separate the effects of a longer distance into two factors. One cluster focuses on the bandwidth degradation resulting from the increased distance. The other cluster concentrates on the increase of the drop rate while the distance is longer. We will investigate how the changes of available bandwidths between the three paths (from the correspondent node to the home agent, from the correspondent node to the foreign agent, and from the home agent to the foreign agent) will impact the performance of Mobile IP with Route Optimization. We also simulate the relationship of the locations of the three entities by their drop rates and evaluate the performance under the associated network situation. The performance of running a TCP application above the IP layer with Route Optimization as the mobility supporter is compared with that of Mobile IP without Route Optimization. To quantify the overhead incurred by Route Optimization, we also use FTP to download the same file without any mobility support. In the same network situation, the two different underlying mobility protocols will generate different results. The benefits of Route Optimization will be demonstrated in these different scenarios.

5.3.4 Experimental Data Process

Our testbed is not a dedicated network. It is part of the sub network belonging to the Department of System and Computer Engineering. The throughput will fluctuate with various factors such as a unpredictable data flow sent by other network users or different test time periods. In order to obtain more reliable data, we take several measures. First, we did all the experiments at the same time periods –from 10 pm to 6am. In this time period, relatively few interference appears. Second, every single test was repeated 20 times to calculate the average and the confidence interval by the follow formulas:

Suppose we have N=20 values v(i) measured,

average A = (sum of v(i))/N

standard deviation S^2= (sum of (v(i) - average)^2)/N

95% confidence interval for 20 samples = A +/- 2.09*sqrt(S^2/N)

Here, we introduce the confidence interval to evaluate our test results because of the fact that (average value of A) > (average value of B) does not means series A(i)>series B(i). It could well be that some of the B(i) are bigger than some of the A(i), and the fact that A and B are different is just a random occurrance. However, if the 95% confidence interval for A is [a_low, a_high] and the 95% confidence interval for B is [b_low, b_high], then: if A > B and b_high < a_low (i.e., the confidence intervals do not overlap), there is strong statistical evidence that A indeed is bigger than B (or in more technical terms: A > B is statistically significant at a 95% confidence level). There are actually more refined test in case the confidence intervals overlap, such as a t-test. Should the confidence intervals overlap AND the means are in the overlap region, then there is no statistical support for A really being bigger than B.

5.3.5 Typical Case

The scenario that the mobile node moves into the same subnet as the correspondent node is the typical case we will investigate. To explore the performance under the impact of the network link between the foreign network and the home network, two groups of experiments are done in terms of the decrement of bandwidth and the increment of the drop rate between the foreign agent and the home agent. Table 5.1 and Table 5.2 show the throughput for the various bandwidths and drop rates. Conf. Int. is the abbreviation of confidence interval.

Table 5.1 MN and CN in the Same Sunnet, Varying HA↔FA Bandwidth

HA ↔ FA Max Bandwidth		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
2 Mbps	Average	1.561	1.341	1.543
	Conf. Int.	[1.548, 1.574]	[1.165, 1.517]	[1.518, 1.568]
1.5 Mbps	Average	1.552	1.264	1.538
	Conf. Int.	[1.551, 1.553]	[1.119, 1.409]	[1.517,1.559]
1 Mbps	Average	1.556	0.944	1.527
	Conf. Int.	[1.555, 1.557]	[0.907, 0.981]	[1.506, 1.547]
0.5 Mbps	Average	1.553	0.469	1.529
	Conf. Int.	[1.552, 1.554]	[0.438, 0.5]	[1.517, 1.541]
0.1 Mbps	Average	1.557	0.087	1.532
	Conf. Int.	[1.556, 1.558]	[0.075, 0.099]	[1.507, 1.55]

Table 5.2 MN and CN in the Same Subnet, Varying HA↔FA Drop Rate

HA↔FA Drop Rate		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
0%	Average	1.558	1.39	1.531
	Conf. Int.	[1.557, 1.559]	[1.398, 1.391]	[1.53, 1.532]
0.5%	Average	1.561	1.214	1.517
	Conf. Int.	[1.56, 1.562]	[1.213, 1.215]	[1.516, 1.518]
1.5%	Average	1.556	1.184	1.53
	Conf. Int.	[1.555, 1.557]	[1.183, 1.185]	[1.529, 1.531]
2.5%	Average	1.558	1.139	1.537
	Conf. Int.	[1.557, 1.559]	[1.138, 1.14]	[1.536, 1.538]
5.0%	Average	1.56	1.035	1.534
	Conf. Int.	[1.559, 1.561]	[1.034, 1.036]	[1.533, 1.535]

We choose 2 Mbps as the maximum bandwidth because of the constraints of WaveLAN. The minimum bandwidth of 0.1 Mbps is a restriction that comes from the emulator. NISTnet utilizes buffers to achieve the simulation of low bandwidth. If the simulating

bandwidth is too low, the buffer will overflow and cannot generate normal simulation result. The general maximum drop rate is 5% in the Internet [25]. Therefore, we keep it as the maximum drop rate in our experiments.

We can make several observations from the tables. First, as bandwidth becomes narrower from 2 Mbps to 0.1 Mbps, the throughput of Route Optimization or plain IP keeps unchanged. In contrast, the throughput of basic Mobile IP degrades dramatically along with the available bandwidth between the foreign agent and the home agent. Especially, when the bandwidth decreases to 0.1 Mbps, Route Optimization has nearly 17 times the throughput as compared to basic Mobile IP. However, this is only a 1.6% loss compared to plain IP. Considering the impact of the drop rate, the throughput of basic Mobile IP drops from 1.39 Mbps to 1.035 Mbps when it increases from 0% to 5%. When the drop rate reaches 5%, there is about 48% efficiency gains in Route Optimization as compared to basic Mobile IP, and only 1.7% loss in Route Optimization compared to plain IP. It is clear that in the extreme case the advantage of Route Optimization is obvious.

Second, the test results confirm to our expectations. For plain IP, the FTP throughput varies from 1.558 Mbps to 1.561 Mbps while the maximum bandwidth of the wireless segment is 2 Mbps. Every 1480 byte payload has 20 bytes TCP header, 20 bytes IP header and 42 bytes Ethernet header [26]. TCP payload data rates are thus:

$$1480 / (20+20+42+1480) = 94.75\%$$

Ideally, over 2M WaveLAN, TCP throughput can reach 2 Mbps * 94.75% = 1.89Mbps. However, FTP may add extra processing overhead and the varying error rate of the wireless links may decrease the throughput further. More detail analysis done in M.I.T laboratory shows an even lower maximum throughput of 1.7 Mbps on a 2M wireless links [27]. Therefore, in our experimental environment, the 1.56 Mbps TCP throughput is a reasonable value.

Third, with any bandwidth and at any drop rate, Route Optimization has only 1.4% to 1.7% efficiency loss compared to plain IP. The loss is caused by the tunneling overhead. Every 1480 bytes data involves 20 bytes IP-in-IP header. The logical efficiency loss is about $20 / 1480 \approx 1.4\%$. It is very close to our test results.

Fourth, there are some overlaps between the confidence interval of throughput of plain IP and that of Mobile IP with Route Optimization when the HA↔FA bandwidth are 2 Mbps and 1.5 Mbps. Statistically, we can not say the throughput of plain IP is greater than that of Mobile IP with Route Optimization. Theoretically, there is tunnel overhead in Mobile IP with Route Optimization. We can observe from the overlap that sometimes the tunnel overhead is insignificant when the fluctuation in the network is big. However, on most case, there is no overlap between those confidence intervals.

5.3.6 Bandwidth and Performance

Three links CN↔MN, CN↔HA, and HA↔MN are involved in the experiments of performance versus bandwidth. The individual experiments differ in terms of the specific degrading link bandwidth among the three links. Other factors such as drop rate and delay are minimized. The performance of Route Optimization under the variation of bandwidth are investigated in each scenario. Basic Mobile IP and plain IP are also employed for comparison purpose.

5.3.6.1 CN ↔HA and HA↔MN Link Bandwidth Degrading Simultaneously

As Figure 5.3 shows, the maximum bandwidth between the correspondent node and the mobile node is constant 2 Mbps. The available bandwidth between the correspondent node and the home agent, and between the home agent and the mobile node degrade from 2 M to 0.1 M at the same time. Table 5.3 shows the throughput of Route Optimization, basic Mobile IP and plain IP under varying bandwidths between CN ↔HA and HA↔MN. Conf. Int. is the abbreviation of confidence interval.

There are some similarity between this scenario and the scenario in Section 5.3.5. In the experiment in Section 5.3.5, the bandwidth between the home agent and the foreign agent degrade at the same time. It has the same logical impact as the bandwidth between the correspondent node and the home agent, and between the home agent and the mobile node degrading simultaneously. However, in Section 5.3.5, the correspondent node is WMC-066023 (Figure 5.1) and the mobile node resides physically at the same sub network 134.117.66.0 with the correspondent node. In this scenario, the correspondent node is WMC-067140 (Figure 5.1), which resides at sub network 134.117.67.0. The

mobile node moves to sub network 134.117.66.0. Physically the mobile node and the correspondent node are not in the same network. We separate the two experiments because of the following reason. When the mobile node and the correspondent node are physically in the same network, the mobile node will use the same links between foreign network and home network to communicate. In our testbed, the segments of LAN between Kunz3 and galaxia-4, between galaxia-4 and kunz3-57, are doubly used. Link usage is double, while actual throughput remains the same. If link usage was more than half the link capacity, this effect may even reduce the actual data throughput [23].

The data in Table 5.3 demonstrates three observations:

First, when the links between CN ↔HA and HA↔MN degrade at the same time while the bandwidth between CN ↔MN is constant, the efficiency of Route Optimization and plain IP keeps unaffected. Second, the efficiency of Mobile IP with Route Optimization as compared to basic Mobile IP is shown to be more and more significant (from 5.6% to 17 times) when the bandwidths between CN ↔HA and HA↔MN become narrower and narrower (from 2 Mbps to 0.1 Mbps). Third, even when the maximum bandwidths between CN ↔HA, HA↔MN, and CN ↔MN are the same 2 Mbps, the throughput of Route Optimization has 5.6% gain compared to basic Mobile IP because of the longer physical distance involved by the route of basic Mobile IP and one more forwarding in the mobile node's home network. In our experiment environment, the actual distances involved are pretty short, only about 200 m between CN ↔HA and HA↔MN. We can deduce that if the distance increases, the efficiency gains will increase more. The quantitative relationship between the efficiency gain and the physical distance have to be explored by future internetworking experiments.

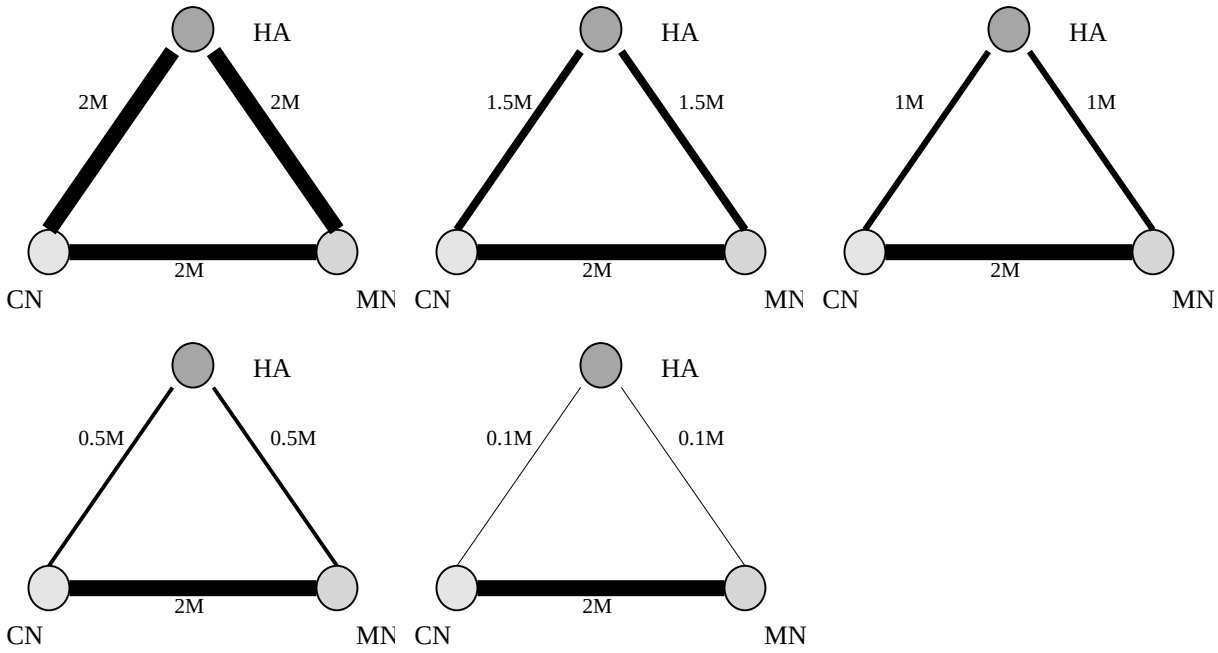

Figure 5.3 CN ↔ HA and HA↔ MN Bandwidth Degrading

Table 5.3 CN ↔HA and HA↔MN Link Bandwidth Degrading Simultaneously

CN ↔ HA, HA↔ MN Max Bandwidth		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
2 Mbps	Average	1.547	1.442	1.524
	Conf. Int.	[1.546, 1.548]	[1.418, 1.466]	[1.515, 1.533]
1.5 Mbps	Average	1.543	1.341	1.518
	Conf. Int.	[1.542, 1.544]	[1.32, 1.362]	[1.507, 1.529]
1 Mbps	Average	1.537	0.907	1.516
	Conf. Int.	[1.536, 1.538]	[0.863, 0.937]	[1.507, 1.525]
0.5 Mbps	Average	1.54	0.47	1.506
	Conf. Int.	[1.539, 1.541]	[0.462, 0.478]	[1.492, 1.52]
0.1 Mbps	Average	1.542	0.084	1.512
	Conf. Int.	[1.541, 1.543]	[0.077, 0.091]	[1.498, 1.526]

5.3.6.2 CN↔HA Link Degrading

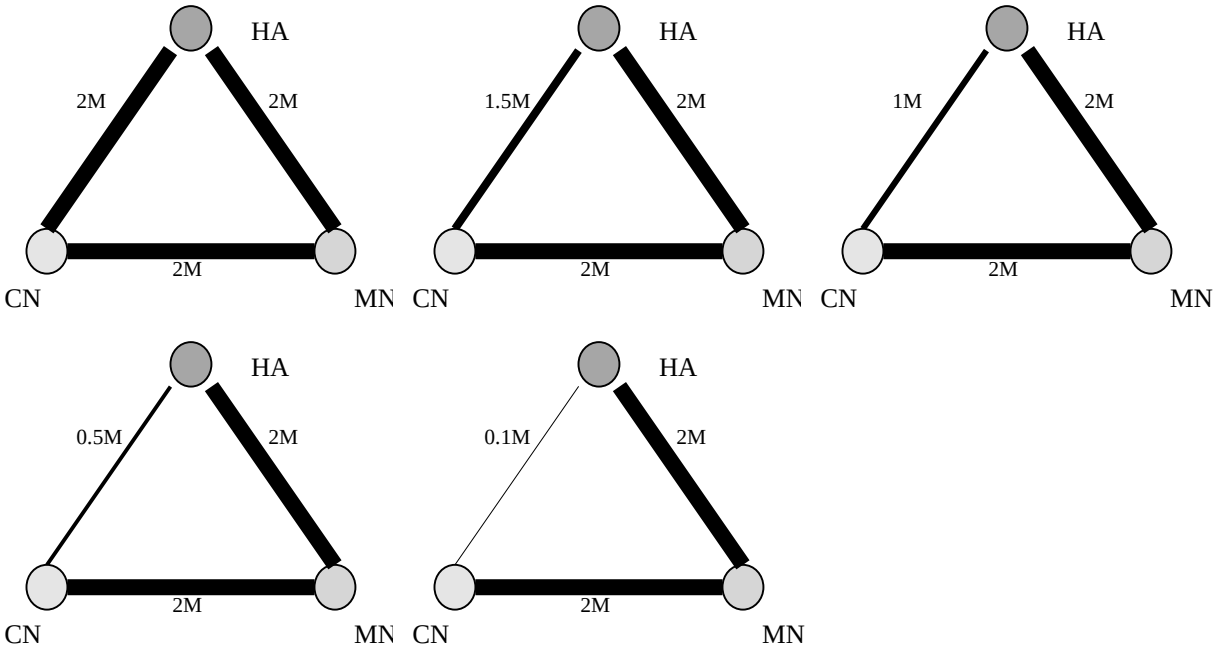

Figure 5.4 CN ↔ HA Bandwidth Degrading

Table 5.4 Only CN↔HA Link Bandwidth Degrading

CN ↔ HA Max Bandwidth		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
2 Mbps	Average	1.547	1.442	1.524
	Conf. Int.	[1.546, 1.548]	[1.418, 1.466]	[1.515, 1.533]
1.5 Mbps	Average	1.543	1.342	1.512
	Conf. Int.	1.542, 1.544]	[1.321, 1.363]	[1.501, 1.523]
1 Mbps	Average	1.533	0.907	1.514
	Conf. Int.	[1.532, 1.534]	[0.877,0.937]	[1.503, 1.525]
0.5 Mbps	Average	1.53	0.47	1.511
	Conf. Int.	[1.529,1.531]	[0.461,0.479]	[1.503, 1.519]
0.1 Mbps	Average	1.536	0.091	1.518
	Conf. Int.	[1.535, 1.537]	[0.088,0.094]	[1.514, 1.522]

Section 5.3.6.1 shows the efficiency gains of Route Optimization while the links between CN↔HA and HA↔MN degrade simultaneously. However, in actual situations, it is more likely that only one of the links degrades instead of two links. Here, we explore the performance of Route Optimization if only the maximum bandwidth between CN↔HA drops while the bandwidths between HA↔MN and CN↔MN keep constant at 2 Mbps. Figure 5.4 expresses the scenario graphically. Table 5.4 records the experimental data. From the data, we make the same conclusions about the Route Optimization performance as Section 5.3.6.1 no matter whether the links between CN↔ HA and HA↔ MN degrade simultaneously or only the link between CN↔ HA degrades.

5.3.6.3 HA↔MN Link Bandwidth Degrading

Next, the link degradation between HA↔MN is considered because the registration in Route Optimization will be influenced by the degradation. Figure 5.5 shows the scenario and Table 5.5 records the throughputs under various bandwidths between HA↔MN while the links between CN↔HA and CN↔MN keep constant at 2 Mbps. We can make the same observation about Route Optimization efficiency as Section 5.3.6.1. Route Optimization keeps the same efficiency gains compared to basic Mobile IP. However, including our earlier experiments, we can make an extra observation. The degradation of the link used by the registration process in Route Optimization does not seem to affect the performance of Route Optimization because the registration message is sent every 30 seconds and is a very small UDP packet. The small UDP packet is not as sensitive to the degradation of the communication link.

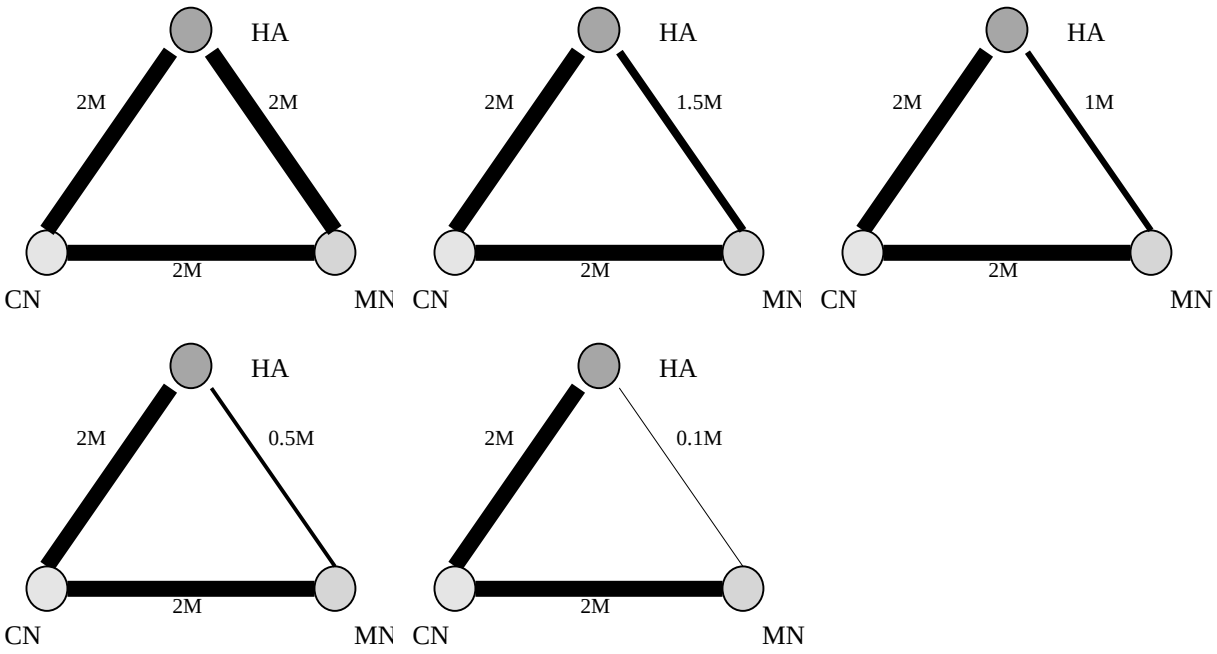

Figure 5.5 HA↔ MN Bandwidth Degrading

Table 5.5 Only HA↔MN Link Bandwidth Degrading

HA↔ MN Max Bandwidth		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
2 Mbps	Average	1.547	1.442	1.526
	Conf. Int.	[1.546, 1.548]	[1.418, 1. 466]	[1.515, 1.537]
1.5 Mbps	Average	1.539	1.37	1.516
	Conf. Int.	[1.538, 1.54]	[1.2, 1.387]	[1.504, 1.528]
1 Mbps	Average	1.547	0.95	1.519
	Conf. Int.	[1.546, 1.548]	[0.93, 1.03]	[1.511, 1.527]
0.5 Mbps	Average	1.527	0.474	1.515
	Conf. Int.	[1.526,1.528]	[0.454, 0.494]	[1.506, 1.524]
0.1 Mbps	Average	1.529	0.081	1.518
	Conf. Int.	[1.528, 1.53]	[0.074,0.088]	[1.511,1.525]

5.3.6.4 CN↔MN Link Bandwidth Degrading

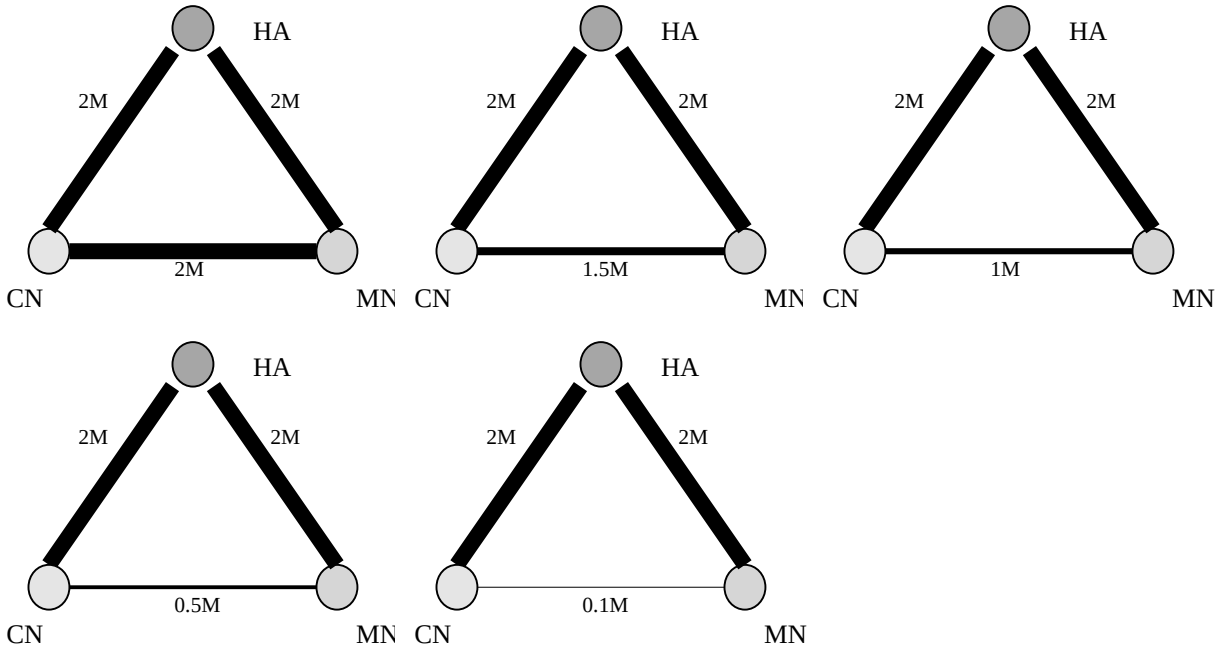

Figure 6.6 CN ↔ MN Bandwidth Degrading

Table 5.6 CN↔MN Link Bandwidth Degrading

CN ↔ MN Max Bandwidth		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
2 Mbps	Average	1.547	1.442	1.524
	Conf. Int.	[1.546, 1.548]	[1.418, 1.466]	[1.515, 1.533]
1.5 Mbps	Average	1.42	1.447	1.394
	Conf. Int.	[1.419, 1.421]	[1.431, 1.463]	[1.388, 1.4]
1 Mbps	Average	0.967	1.448	0.949
	Conf. Int.	[0.966, 0.968]	[1.431, 1.465]	[0.947, 0.951]
0.5 Mbps	Average	0.481	1.443	0.472
	Conf. Int.	[0.48, 0.482]	[1.425, 1.461]	[0.465, 0.479]
0.1 Mbps	Average	0.096	1.444	0.094
	Conf. Int.	[0.095, 0.097]	[1.422, 1.466]	[0.093, 0.095]

In the last set of experiments in this group, we investigate the Route Optimization performance when the link between CN↔MN degrades from 2 Mbps to 0.1 Mbps while the links between CN↔HA and HA↔MN keep the constant 2 Mbps bandwidth. Figure 5.6 shows the scenario. Table 5.6 records the experimental data. From Table 5.6, several observations are made. This is the only case that the efficiency of basic Mobile IP is higher than that of Route Optimization because it takes a different route from a normal IP packet. Although the route taken by basic Mobile IP packets is longer than normal IP packets, however, in this special case, the state of the other route is better than that of a normal route. Especially when the bandwidth between CN↔MN drops to 0.1 Mbps, there is about 15 times efficiency loss in Route Optimization. However, plain IP almost has the same efficiency loss as Route Optimization because the routes taken by Route Optimization packets are decided by normal IP routing protocols. It is not the problem of Route Optimization but the intrinsic characteristic of IP routing mechanism. If the performance of plain IP routing mechanism is improved in this situation, the performance of Route Optimization will be enhanced as well.

5.3.7 Location and Performance

The distance of the communication link has a direct relationship with error rates[24]. Based on the locations between the three entities: CN, HA and MN, with the same available bandwidth among CN↔HA, HA↔MN, CN↔MN, three groups of scenarios are designed. The individual groups differ in terms of locations of the three entities. The groups reflect several typical location patterns existing among the three entities. We use 5% as the maximum drop rate. 5% drop rate corresponds to the maximum distance among the three entities because the maximum drop rate can be limited to 5% by end-to-end congestion control [25]. When one of the entities moves between the other two entities, the related link's drop rate will change according to the proportion of the distance. The performance improvement in Route Optimization is mainly based on the decrement of drop rate because of the shorter distance. We use NISTnet to emulate the drop rate and compare the throughputs of Mobile IP with Route Optimization to that of basic Mobile IP and plain IP.

5.3.7.1 HA in the Middle

The HA resides between CN ↔ MN. We investigate five positions of HA. Suppose the distance between CN ↔ MN is 1. HA positions itself at 0, ¼, ½, ¾, and 1 in terms of the distance to CN (Figure 5.7). Because we use drop rate to represent the distance, Table 5.7 list the drop rates between different entities according to the HA's different positions. The FTP throughputs between CN ↔ MN are explored under the different positions of the HA. The performance of Route Optimization is shown in Table 5.7. Basic Mobile IP and plain IP are employed for comparison purpose.

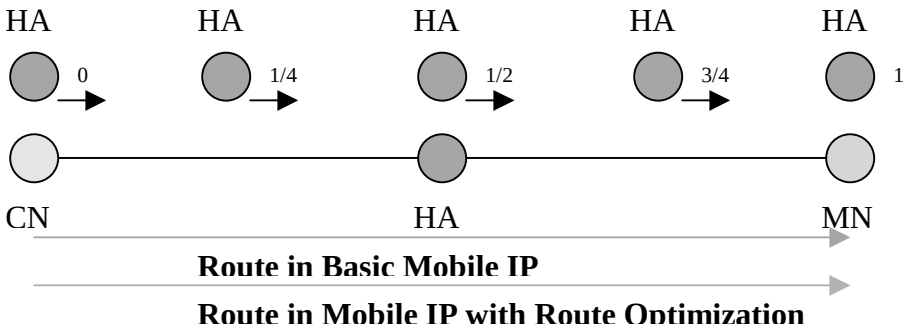

Figure 5.7 HA locates between CN and MN

Table 5.7 HA's Position and the Associated Drop Rate

HA's Position between CN↔MN	CN↔HA Drop Rate	HA↔MN Drop Rate	CN↔MN Drop Rate
0	0	5%	5%
1/4	1.25%	3.75%	5%
1/2	2.5%	2.5%	5%
3/4	3.75%	1.25%	5%
1	5%	0	5%

Table 5.8 HA Between the CN and MN

HA's Position between CN↔MN		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
0	Average	1.412	1.313	1.332
	Conf. Int.	[1.411, 1.413]	[1.312, 1.314]	[1.331, 1.333]
1/4	Average	1.406	1.312	1.331
	Conf. Int.	[1.405, 1.407]	[1.311, 1.313]	[1.33, 1.332]
1/2	Average	1.408	1.31	1.33
	Conf. Int.	[1.407, 1.409]	[1.281, 1.339]	[1.303,1.357]
3/4	Average	1.411	1.299	1.332
	Conf. Int.	[1.41, 1.412]	[1.298, 1.3]	[1.331, 1.333]
1	Average	1.41	1.311	1.329
	Conf. Int.	[1.409, 1.411]	[1.281, 1.341]	[1.3, 1.358]

We can make the following observation from Table 5.8. When CN ↔ MN has a constant distance and the three entities have the same bandwidth, no matter where HA is between CN ↔ MN, the throughput of Route Optimization is not affected. The efficiency loss of Route Optimization vs plain IP is about 4%. The efficiency gains of Route Optimization via basic Mobile IP is about 1.6%. Obviously, the performance of Route Optimization does not show a big improvement in this case. However, at least, it does not decline.

5.3.7.2 CN in the Middle

MN has a constant distance to HA. Suppose the distance as logical value 1. CN exists in five positions between MN↔HA. CN resides at 0, ¼, ½, ¾, 1 in terms of the distance to HA. In the five cases, the performance of Route Optimization is explored as compared to basic Mobile IP and plain IP. Figure 5.8 shows the cases graphically. Table 5.10 demonstrates the experimental results.

We can make an observation about the efficiency gain of Route Optimization. As CN becomes closer and closer to MN while the distance between HA↔MN keeps constant, the efficiency gain of Route Optimization increases from 4.8% → 35.1% as compared to basic Mobile IP. Figure 5.8 displays the tendency. The experiment only considers the

increment of the drop rate as the distance increases. If a longer delay and other link degradation's factors are calculated based on longer distances, the efficiency gain of Route Optimization will be greater than shown here.

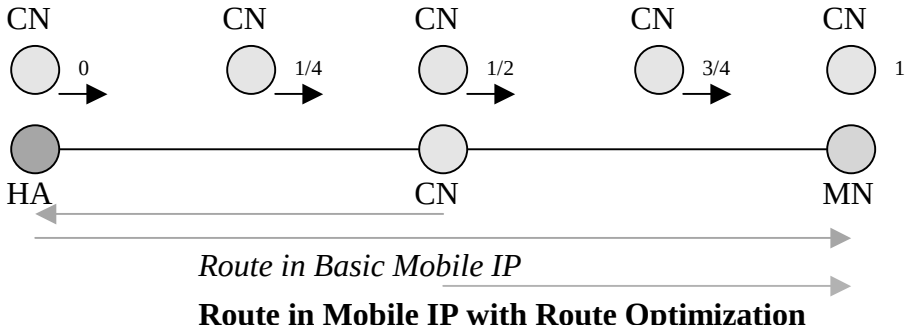

Figure 5.8 CN locates between HA and MN

Table 5.9 CN's Position and the Associated Drop Rate

CN's Position between HA↔MN	CN↔HA Drop Rate	HA↔MN Drop Rate	CN↔MN Drop Rate
0	0	2.5%	2.5%
1/4	0.625%	2.5%	1.875%
1/2	1.25%	2.5%	1.25%
3/4	1.875%	2.5%	0.625%
1	2.5%	2.5%	0%

Table 5.10 CN Between HA and MN

CN's position between HA↔MN		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
0	Average	1.376	1.269	1.33
	Conf. Int.	[1.375, 1.377]	[1.251, 1.287]	[1.306, 1.354]
1/4	Average	1.383	1.213	1.365
	Conf. Int.	[1.382, 1.384]	[1.18, 1.242]	[1.345, 1.385]
1/2	Average	1.419	1.192	1.41
	Conf. Int.	[1.418, 1.42]	[1.167, 1.217]	[1.394, 1.426]
3/4	Average	1.456	1.128	1.419
	Conf. Int.	[1.455, 1.457]	[1.092, 1.164]	[1.381, 1.457]
1	Average	1.509	1.087	1.468
	Conf. Int.	[1.508, 1.51]	[1.021, 1.153]	[1.456, 1.48]

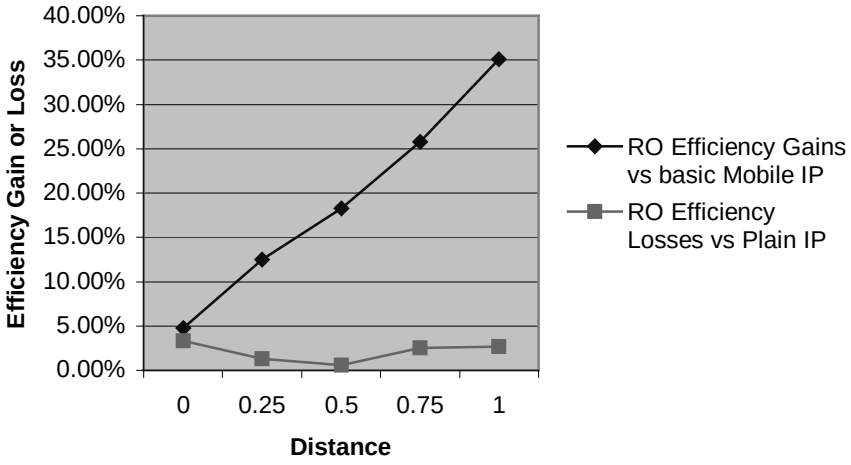

Figure 5.9 Route Optimization Efficiency (CN in the Middle)

5.3.7.3 MN in the Middle

HA↔CN has a constant distance. MN moves between HA↔CN. We select five representative positions to investigate the performance tendency while the MN moves

from HA to CN. The distance between HA and CN is expressed as logical value 1. The distances from MN to HA are displayed on Figure 5.10 as logical values: 0, ¼,½, ¾, 1.

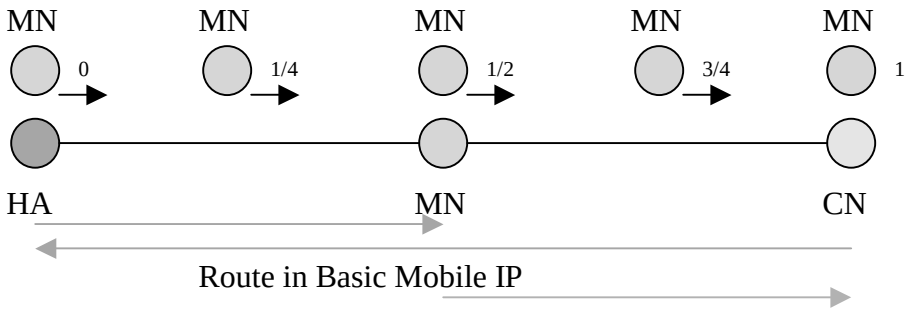

Figure 5.10 MN locates between HA and CN

Table 5.11 MN's Position and the Associated Drop Rate

MN's Position between HA↔CN	HA↔CN Drop Rate	HA↔MN Drop Rate	MN↔CN Drop Rate
0	2.5%	0%	2.5%
1/4	2.5%	0.625%	1.875%
1/2	2.5%	1.25%	1.25%
3/4	2.5%	1.875%	0.625%
1	2.5%	2.5%	0%

Table 5.12 MN Between HA and CN

MN's position between HA↔CN		Plain IP Throughput (Mbps)	Basic M-IP Throughput (Mbps)	Route Optimization Throughput (Mbps)
0	Average	1.353	1.271	1.315
	Conf. Int.	[1.352, 1.354]	[1.241, 1.301]	[1.286, 1.344]
¼	Average	1.414	1.219	1.383
	Conf. Int.	[1.413, 1.415]	[1.182, 1.256]	[1.369, 1.397]
½	Average	1.426	1.197	1.41
	Conf. Int.	[1.425, 1.427]	[1.176, 1.218]	[1.398, 1.422]
¾	Average	1.469	1.135	1.469
	Conf. Int.	[1.468,1.47]	[1.11, 1.16]	1.468, 1.47]
1	Average	1.509	1.087	1.499
	Conf. Int.	[1.508, 1.51]	[1.077, 1.098]	[1.487, 1.511]

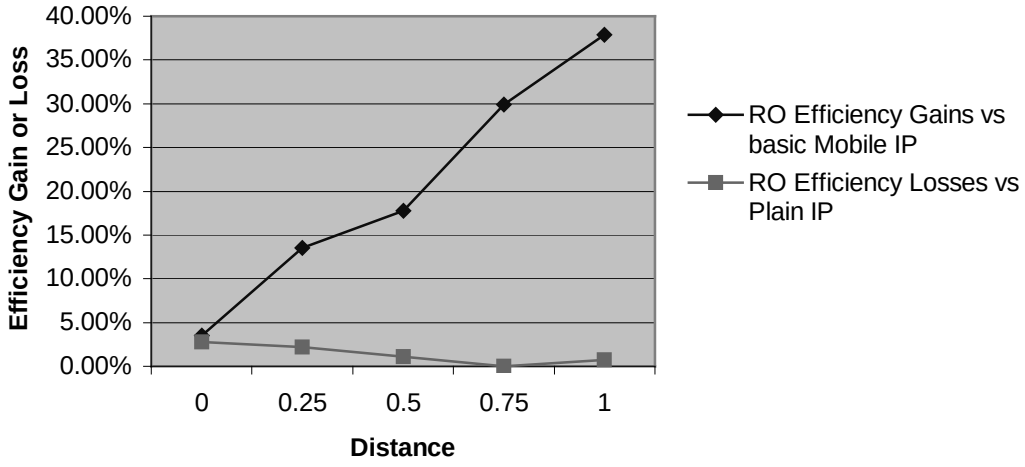

Figure 5.10 Route Optimization Efficiency (MN moves from HA to MN)

Table 5.12 records the TCP throughputs of CN→MN when MN moves among the five positions while Route Optimization is being used as the mobility protocol, or basic

Mobile IP being used as the mobility protocol. We also use another static host in the same location as MN to transfer a file from CN by using plain IP for comparison purposes. Two observations can be made from the table. When MN moves toward CN, the throughput of Route Optimization increases from 1.315 to 1.499 while the throughput of basic Mobile IP decreases from 1.271 to 1.087. The efficiency gain of Route Optimization rises from 3.5% to 37.9% as compared to basic Mobile IP. The efficiency losses compared to plain IP is not bigger than 2.8%. Figure 5.10 shows the tendency as the MN moves.

5.4 Result Analysis

The above experiments demonstrate that the performance improvement of Mobile IP with Route Optimization depends on the link's states and the entities' distances as well as the MN's moving patterns. The minimum efficiency gain is 3.3% and the maximum efficiency gains can reach 17 times. When the link between CN↔ HA, or between HA↔ MN degrades, Route Optimization enjoys the maximum benefits. While MN moves away from HA, the closer the MN is to CN, the greater benefits Route Optimization obtains. When it comes to the efficiency losses of Route Optimization as compared to plain IP, no matter what scenarios it is, it is always below 3%. In most cases, it conforms to the theoretical calculation value 1.4% by adding the tunneling overhead to plain IP packets. Comparing our test results to related work done at the National University of Singapore [23], their experiments demonstrates that the triangle routing causes 80% more time to transfer a file, or the throughput degrades from 1 to $1/(1+0.8) \approx 0.56$. The efficiency loss of basic Mobile IP because of triangle routing is $(1-0.56)/1 \approx 44\%$. Form this we can deduce that Route Optimization efficiency gain should be about 44%. Their test is based on 10 Mbps Ethernet and one scenario. The performance of Route Optimization can only be deduced. Our experiment chooses more realistic access methods for the MN, WaveLan, and tests on 10 different scenarios to investigate Route Optimization performance more intensively. Our experiment shows that the 44% gain is only one of the specific cases among different scenarios and various gains. Researchers at the National University of Singapore implement the basic Mobile IP code in the Linux kernel space. Their TCP throughput has a 44% loss compared to plain IP. In our wireless access

environment, when the wireless bandwidth becomes the bottleneck of the whole transferring process, the TCP throughput based on Route Optimization has only a 3% loss as compared to plain IP even though our implementation exists in the Linux user space.

Chapter 6

Conclusion and Future Work

In order to allow portable device users to access network services anywhere and anytime regardless of their movement, mobility support in a network is more desirable than ever. Many approaches are investigated, some of which provide micro mobility by focusing on adaptive routing technologies while others provide macro mobility. As for macro mobility, solutions mainly concentrate on how to provide mobility based on the existing routing mechanism in the Internet TCP/IP infrastructure. Among them, Mobile IP is a promising approach. To overcome the routing anomaly existing in Mobile IP, Route Optimization in Mobile IP is presented. The implementation of Mobile IP or Mobile IP with Route Optimization varies in terms of different operating system support as well as different design considerations and architectures.

In the thesis, we presented our experience with the implementation of Route Optimization based on the basic Mobile IP implementation. Based on our implementation, the performance of Route Optimization is evaluated via various network conditions. For comparison purposes, basic Mobile IP and plain IP are also employed. In this chapter, we will summarize our work, draw some conclusions and provide suggestions for future work.

6.1 Contributions

We classified the contribution performed in this thesis into four categories. The first part is our exploration to implement Route Optimization on a Linux platform in C++. The functionality and our approach performed in the home agent and the correspondent node are presented. The second part is a performance evaluation to Route Optimization. The third part presents the role for Mobility in IPv6. The fourth part is two enhancements suggested by us to the draft of Mobile IP with Route Optimization.

6.1.1 Implementation of Route Optimization

6.1.1.1 Home Agent Traffic Monitoring

In order to inform a correspondent node of the current location of its mobile peer, the home agent must monitor any traffic destined to the mobile nodes that belong to the home network. Because Linux lacks on API (Application Program Interface) to achieve this goal, a unique approach is employed in this thesis. We utilized the IP firewall model as our traffic monitor. The ipchains is used to set the requirements into the Linux kernel. The file ip_fw.c in the Linux kernel is enhanced to capture the address of the correspondent node that is communicating with a mobile node. The Linux system call ioctl() is extended to provide an approach to transfer data from the kernel space to the user space.

6.1.1.2 Home Agent Binding Update Management

The Binding Update Management module organizes and sends Binding Update messages to a correspondent node if the home agent notices that the correspondent node is routing its traffic through the home network. The function is implemented in the user space using UDP socket calls.

6.1.1.3 Correspondent Node Binding Updating

The Binding Updating module in a correspondent node is responsible for listening to the Binding Update message from the mobile node's home agent, processing the message and calling related modules.

6.1.1.4 Correspondent Node Binding Cache Management

The Binding Cache Management module in a correspondent node is responsible for maintaining the binding cache, including adding a new entry, deleting an expired entry, and acquiring, modifying, or replacing an existing entry in the binding cache.

6.1.1.5 Correspondent Node Traffic Control

The Traffic Control module filters out the traffic destined to mobile nodes whose location information is cached in the correspondent node and tunnels the traffic.

6.1.2 Evaluating Route Optimization Performance

Our work provides quantitative evaluation of the performance of Route Optimization, compared to basic Mobile IP and plain IP. The evaluation allows us have an insight look at the efficiency gains via basic Mobile IP under various network conditions and provides convincing support for Route Optimization in Mobile IP.

6.1.3 Supporting Mobility in IPv6

The development of Route Optimization techniques for IPv4 has played an important role in the development of mobility support for IP Version 6 [27, 12]. Route Optimization is intrinsic in IPv6. There are several similar aspects between Route Optimization in IPv4 and Mobility in IPv6, such as route optimality, or Binding Updates in the correspondent node. Because the popular deployment of IPv6 still needs some time, the deployment of Route Optimization in IPv4 will provide a reference to performance evaluation of IPv6 in advance and determine common problems in both protocols.

6.1.4 Enhancing Route Optimization Protocol

6.1.4.1 Binary Exponential Backoff Algorithm (BEBA)

In the absence of Route Optimization support in a correspondent node, sending out the Binding Update message repetitively by a home agent will degrade the home agent's performance and waste network bandwidth and the home agent's resources. Especially during the transient period, a great number of correspondent nodes still lack the Route Optimization support. The waste of resources and the degradation of performance will be prominent. In the existing Route Optimization draft, there is no specific consideration of these problems. The thesis suggests the Binary Exponential Backoff Algorithm to increase the interval between two successive Binding Update messages to the same correspondent node exponentially. If a correspondent node does not support the binding cache, the home agent will stop sending the Binding Update message to the correspondent node when the interval time achieves a predefined value. The Binary Exponential Backoff Algorithm will keep sending the Binding Update message to a

correspondent node if previous messages are lost because of congestion or intermediate router overflow. It is an effective solution to the absence of the Route Optimization support in correspondent nodes during the transient period.

6.1.4.2 Binding Cache Management Strategies

Binding Cache Management Strategy is an implementation technique. When a binding cache is full, there are several strategies to replace an existing entry by a new adding entry. Similar to the operating system memory management, the thesis considered three mechanisms: FIFO, LRU, and LFU. In the implementation, we chose FIFO because of its simplicity.

6.2 Conclusion

The implementation of Route Optimization varies with different underlying operating systems. We chose Linux as platform because of consideration to keep consistency with the implementation platform of basic Mobile IP as well as its various advantages such as open source code, Unix API, and popularity. We implemented the correspondent node's functionality in the user space to relieve the deployment difficulty. Because of the lack of support to monitor the traffic in the user space, the kernel module ip_fw.c is enhanced. Our practice provides an implementation sample of Route Optimization in Mobile IP. The wide spread of Route Optimization support in correspondent nodes is a non-trivial task. Considering about the deployment difficulties, evaluation of the efficient gains in Route Optimization can present effective evidence to the choice between Mobile IP with Route Optimization and basic Mobile IP. Based on our implementation, the performance of Route Optimization is analyzed quantitatively under diverse network conditions. Our conclusion is that the efficiency gain in Route Optimization is influenced by network conditions but it is considerable in most situations. The performance tradeoff existing in the user space implementation is insignificant under a wireless access environment because the bottleneck of the system is wireless bandwidth instead of processor speed in the home agent, the foreign agent, the mobile node and correspondent node. Comparing the Mobile IP's kernel space implementation which were done in National University of Singapore[19], our experimental result shows that there is no penalty of our user space

implementation. In our wireless access environment, when the wireless bandwidth becomes the bottleneck of the whole transferring process, the TCP throughput based on Route Optimization has only a 3% loss as compared to plain IP even though our implementation exists in the Linux user space. It is the direct consequence of a well-conceived architecture design and artful implementation in this thesis.

6.3 Future Work

Another important aspect of Route Optimization is smooth handoff. Packets on the fly will be received by the previous foreign agent and forwarded to the new foreign agent when a mobile node is moving from one network to another network. Smooth handoff will reduce the packet loss during the movement. However, more work such as creating the visiting list in a foreign agent and handling the Binding Update message from the new foreign agent to the previous foreign agent, is necessary. The performance of smooth handoff needs to be evaluated to decide whether smooth handoff is worthy being added to Route Optimization.

Security Association in Route Optimization is more complex than that in basic Mobile IP because of increasing messages that affect the packet routing to a mobile node [3]. Especially many correspondent nodes need to share secret keys with home agents. A general solution to the problem may depend on the appearance of an Internet public key infrastructure. In this implementation, the authentication algorithm is MD5 and all shared secret keys are assigned in advance.

In the thesis, three binding cache management strategies are discussed. The performance of the strategies needs be evaluated in the future.

In order to receive data from the kernel space, the ioctl() system call is extended and the Binding Update module in a home agent keeps polling the kernel cache via a raw socket. If the kernel module can send out a signal to the Binding Update module when the data is prepared instead of the periodic polling, the efficiency of the Binding Update module will increase.

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Appendix A

IP Based Mobility Proposals

Mobile IP evolves from several previous proposals. All these proposals focus on how to modify the IP layer and add new features or new entities to support mobility in the Internet. In this appendix, we will introduce four ancestors of Mobile IP. All these proposals are IP based mobility proposals.

A.1 Sony Mobile IP Proposal

When a mobile node connects to a foreign network, it will obtain a temporary address, serving as location address, from a local address server. Then, it will notify the home network gateway of the new location and identifier association. And every packet send out from the mobile node will carry this mapping information by using IP options to put two source addresses, one is the identifier address, another is the location address, in the source address field. Routers (also called Sony gateways) that forward the packet will cache this mapping information. This is the propagating cache method, which distributes the LD information throughout the network besides sending the LD information to the home network. A correspondent node sends out a packet with identifier address as destination address. The packet should be routed to the home network of the mobile node. On its way to the home network, if any transit router (a Sony gateway) has a LD cache about the mobile node, the packet will be intercepted and is forwarded to the mobile node's current location. Otherwise, the packet will arrive at the home gateway, and then it is forwarded to the mobile node [A.4,A.5,A.6].

From the point of the abstract Mobile IP architecture view, the LD cache is distributed among routers. ATA collocates in routers with LD caches. In fact, ATA is distributed among networks. ATA at the home network is used if there is no ATA along the way to the home network. FA is collocated with the mobile node in this proposal.

The main advantages of the Sony Mobile IP proposal are:

(1) If the communication is activated by a mobile node first, packets will always go through an optimal route because correspondent hosts get the location information

and the gateway of a correspondent network also updates its LD cache by using the location information contained in the packet. The gateway of the correspondent network will act as ATA. Then the return packet will travel an optimal route.

(2) The system is robust. This is the advantage of any distributed system. In the Sony proposal, LD caches and ATA are distributed throughout the Internet.

(3) Large amounts of correspondent nodes do not need to be modified.

The main disadvantages of the Sony Mobile IP proposal are:

(1) Maintaining the consistency of LD caches make the system complex. When a mobile node migrates, purging all obsolete cache entries network-wide will be extremely difficult. If using time-outs, the time-out length is difficult to determine.

(2) All routers who function as Sony gateways need to be modified. If the MN number is big, the LD cache in every router will be extremely large. It is not practical. Therefore, the scalability of the Sony IP is poor.

(3) Every MN needs a temporary address to reflect its current location. It makes the originally scarce address space more scarce.

A.2 Columbia Mobile IP Proposal

The Columbia proposal has two versions; one is intended for local networks. The other, so called popup Columbia Mobile IP, is a modified version for wide-area networks [A.2, A.7]. A new mobile facility is introduced in the Columbia proposal. It is called an MSR (Mobile Subnet Router). These MSRs construct a virtual mobile subnet. When a MN registers in a MSR, the MSR is responsible for spreading the MN’s location information and forms a LD directory for this MN. In this schema, all MNs that register in the same MSR will share a common location address, the MSR IP address. When a packet, sent to an MN, arrives at the nearest MSR, the MSR will check its LD to find out if it has the location and identifier mapping of the destination identifier address. If the MSR does not have the mapping, it will broadcast its query to all MSRs. The MSR who has this mapping information will answer the query. The packet will be sent to the MSR who claims to have the MN registered. MSRs can cache the LD information for future use. These caches are purged periodically. In the Columbia schema, MSRs act as both ATA

and FA. For packets addressed to mobile nodes in its coverage area, an MSR acts as a FA. For packets addressed to other mobile nodes, it acts as an ATA [A.1]. The LD cache is distributed. There is no fixed home network. A current network is a home network. The main difference between Columbia Mobile IP and Popup Columbia Mobile IP is that there is a fixed home network for each mobile node in the popup Columbia proposal. The Columbia proposal works only for small networks because all MSRs have to communicate with each other frequently. In a wide-area network, the number of MSRs will be large, the frequent communication between all these MSRs will be extremely expensive, and managing all these LD cache is not easy [A.2, A.7].

The Popup Columbia Proposal is a wide-area version. The home network concept is introduced. A MN has a home network. The MSR in the home network takes charge of the LD of all mobile nodes belonging to the home network. When a MN arrives at a new location, it acquires a temporary address and registers with the MSR in its home network. The MSR acts as an ATA. The MN acts as a FA for itself. Every packet sent to the MN will arrive at the MSR in the home network. The MSR acts as ATA to look up the LD and encapsulates and tunnels the packet to the MN.

The main advantages of the Columbia Proposal are:

(1) Existing hosts and routers do not need to be modified.
(2) All mobile nodes registering in a MSR share a common location address. Scarce address space is saved.
(3) Packets arrive at a destination by optimal route.
(4) It is suitable to small wireless networks.

The main disadvantage of the Columbia proposal is:

A new mobile facility (MSR) has to be added to the network. MSRs need to communicate with each other frequently, if the number of MSRs is large and the MSRs are separated in a large geographically area, the communication is expensive. So, scalability is not good. It is not a good schema for wide-area networks.

The main disadvantage of the Popup Columbia proposal is:

When a mobile node is away from its home network, packets sent to it always travel by a sub-optimal route. It increases the network traffic.

A.3 LSR Mobile IP Proposal

The LSR Mobile IP proposal is based on the use of an existing IP option: LSR. It uses a Mobile Router (MR) relative to Mobile nodes in their home network. There are also one or more mobile access stations (MAS) in each foreign network. When a MN walks into a wireless cell, it attaches to a wireless access station. Then, the address of the MAS represents the location address of this mobile node. The MN will inform its home network MR of the current MAS address. The home network MR updates its route table. When a correspondent host sends a packet to the home network, the MR will insert an LSR option in the packet, specifying the current location address (MAS address) as a transit address. The packet will arrive at the MN via the MAS. In the reply packet, the MN will define MAS as first transit router via LSR option. When the reply packet arrives, the correspondent host reverses the LSR and sends all outgoing packets with LSR option, using the MAS address (MN Location address) as transit address. Subsequent packets originating from the stationary host will be automatically routed along an optimal path [A.8, A.9, A.3] .

In this proposal, there is a main LD, stored in MR, after that, every packet carries a LD entry that will be used immediately. Therefore, a correspondent host has an on-demand LD entry for currently communicating MNs. LD is distributed on-demand. At first, MR acts as ATA. After the first reply packet from MN arrives at the correspondent node, the correspondent host will act as ATA for itself. MASs serve as FA.

The main advantages of the LSR proposal are:

(1) Packets are almost routed along optimal path, except that the first packet in a session will go through MR.

(2) LD is distributed on-demand. There is no LD cache consistency problem. Scalability is good.

The main disadvantages of the LSR proposal are:

(1) Packets with LSR have low priority in routers. When traffic is heavy, this kind of packet will be dropped.

(2) Most hosts do not support LSR reversal because of security problems.

(3) New mobile facilities (MR, MAS) have to be added to the system.

A.4 IBM Mobile IP Proposal

In the IBM Mobile IP proposal, new network facilities MR and MSR also need to be added just as in the LSR proposal. The main difference is that encapsulation is used instead of LSR. Therefore, a correspondent node can not use LSR reversal. Every packet has to go through MR in the home network to get to MN [A.1, A.10]. This is the original version of the IETF Mobile IP proposal. We have discussed it in the Chapter 2.

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Appendix B

Multicast Support for Mobile Hosts

In this appendix, we will discuss some approaches to support multicast service for mobile hosts.

B.1 Abstract Function and Architecture in Multicast Support

Multicast is a mechanism for efficient one-to-many communication in which the source transmits a single packet, and the network performs the task of delivering the packet to multiple destinations. For fixed host networks, multicast is achieved by constructing a delivering tree. Multicast applications such as weather reports, travel information and stock market reports may become widely used by mobile users. Multicast addresses are defined independent of location and use an address class separate from the normal unicast addresses. According to this characteristic, mobility should not be a problem for multicast. However, all existing multicast routing proposals (DVMRP, MOSPF, CBT, and PIM)[B.3] implicitly assume stationary hosts when configuring the multicast delivery trees. How to achieve multicast service for mobile nodes becomes a challenging problem. For a MN that wishes to receive a group multicast datagram, it should join the group. We think the delivery trees with MNs as receivers are actually dynamic delivery trees. The branches and leaves will change along with the node's mobility. MNs have to choose a place to describe their membership. Where a MN describes its membership decides the structure and charactistics of the dynamic tree. Because the network must deal with dynamic group membership, can we make use of it to deal with the dynamic location of mobile host? We can declare the MN's group membership at the home network, declare the membership at the current attached network or declare the membership at several combined networks. Different methods will make the dynamic tree grow in different ways. We call the declaration network the dynamic tree's growth point. Different declaring methods will choose different growth points. This is an abstract architecture of the multicast support for mobile hosts. All multicast proposals for mobile hosts can be describe by this abstract architecture. We will introduce them in detail in this appendix.

B.2 Four Proposals for Multicast Support

B.2.1 IETF Mobile IP Foreign Agent Based Multicast (Remote-Subscription Multicast)

In the IETF Mobile IP Foreign Agent Based Multicast proposal, when a MN moves, it will subscribe its membership at the foreign network. The multicast router in the foreign network propagates this information for the MN [B.1,B.2]. According to the same processing for dynamic group membership, the delivery tree will extend to the foreign network, and the MN will receive multicast packets. According to our abstract architecture, the network that the MN currently resides in is chosen as the growth point. (Figure b.1).

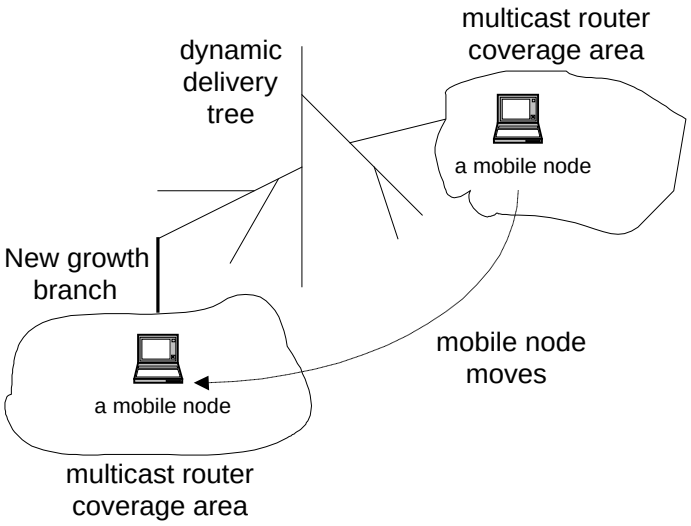

Figure b.1: Dynamic Delivery Tree in Remote

The advantage of choosing the current network as growth point is the simplicity and route optimality. Especially when this membership has been subscribed by other local nodes, the delivery tree will not change. No additional operation is needed. No encapsulation is required. With this proposal, the MN is required to resubscribe to the multicast group on each foreign network and must use a co-located care of address. However, the biggest problem is that every foreign network visited by MNs must have a multicast router. Between the hand-off period, the MN can not receive multicast packets. The lost packets

will affect the quality of service. If there are many MNs, then the dynamic tree will be reconfigured frequently. This will seriously increase the multicast router's burden. If the MN is highly mobile, packets will be lost owing to the set-up time associated with multicast subscription. Therefore, if the host is likely to be stationary for an extend period of time, the option is preferred. As [B.3] said: "Remote subscription does provide the most efficient delivery of multicast packets, but this service may come at a high price for the networks involved and the multicast routers that must manage the multicast tree. For hosts that want guaranteed two-way communication with the multicast group and are unable to acquire a co-located address, or hosts that are highly mobile, a different method is needed that will not overload the multicast routers."

B.2.2 IETF Mobile IP Home Agent Based Multicast (Bi-Directional Tunnelling Multicast)

In the IETF Mobile IP Home Agent Based Multicast proposal, when a MN is roaming in a foreign network, multicast packets will be encapsulated by the home agent and delivered to the MN by the same tunneling mechanism as other unicast packets. The MN

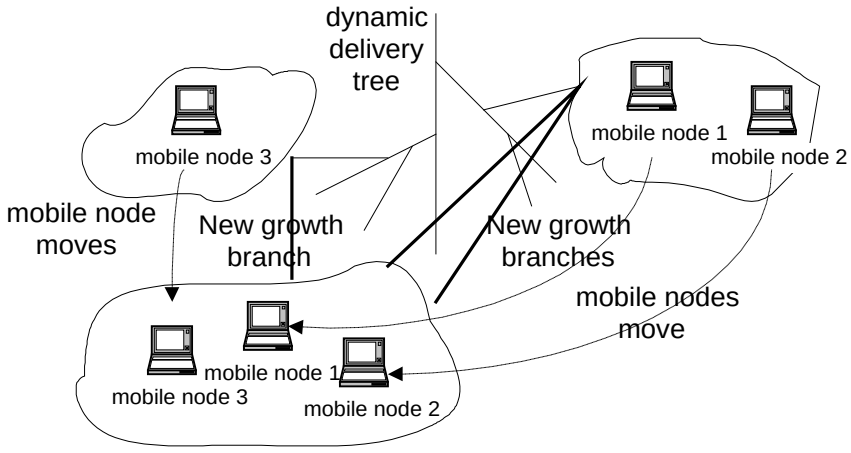

Figure b.2 The Dynamic Delivery Tree in Bi-Directional Tunnelling Proposal

only subscribes its multicast group membership to the multicast router in its home network. Its multicast group membership is transparent to any foreign network. The FA will forward the multicast packets in a similar way to unicast packets[B.1,B.2]. In this

proposal, the home network works as growth point of the dynamic delivery tree. The dynamic delivery tree will extend a branch for a MN from the home network to the foreign network.

If the MN is far away from its home network and in the same network with the source of the multicast tree, the extended branch will be extremely long because the multicast packet will travel to the home network and then travel back to the source network. If the number of MNs is large, many branches are extended from the home network (Figure b.2). This will increase the network traffic significantly. Encapsulating and forwarding is designed to solve the problem of topologically incorrect destination addresses in packets by requiring traffic for the mobile host to be routed to the home network through a home agent to foreign agent tunnel. A multicast address is location free. This method ignores the multicast address location free advantages. Duplicate packets will increase network traffic. Consider the follow scenario: the MN roams into a foreign network, which is a member of the multicast group. But the MN's membership is transparent to the foreign network, the MN still receives the multicast packets from its home network via a unicast tunnel. If two or more MNs belong to the same home agent and subscribe to the same multicast group, the home agent will duplicate two or more unicast packets from the same multicast packet, and send them separately to the same foreign agent (Figure b.3) [B.6]. Packet duplication and triangle routing are the main disadvantages of this proposal. In this proposal the dynamic tree extends to a non-optimal tree.

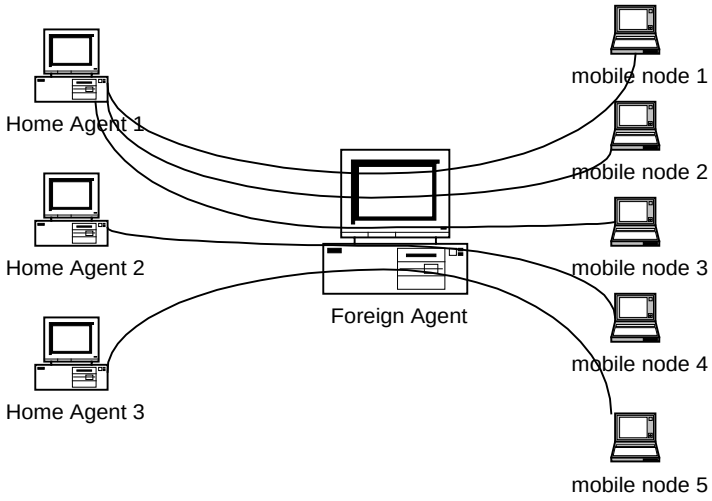

Figure b.3 Bi-Directional Tunnelling Proposal Multicast

B.2.3 MOM Proposal (Mobile Multicast Protocol)

Because of the duplication and triangle routing problem with the Bi-Directional Tunnelling proposal, the MOM proposal came up with some new ideas to solve these problems. The first idea is that a home agent only forwards a single copy of multicast packets to a foreign network even if two or more MNs belonging to this home agent roam in the foreign network. The foreign network uses link layer multicast to distribute the packets to separate MNs. In this way, the packet duplication will decrease. However, the tunnel convergence problem still exists. Consider the following scenario: multiple tunnels from different home agents can terminate at one foreign agent. When multiple home agents have mobile hosts visiting the same foreign network, one copy of every multicast packet is forwarded to the same foreign agent by each home agent. The foreign agent suffers from the convergence of tunnels set up by each home agent (Figure b.4) [B.5]. The second new concept in MOM is DMSP (Designated Multicast Service Provider), designed to solve the tunnel convergence problem. DMSP is one home agent selected by a foreign agent and it takes charge of forwarding only one copy of a multicast datagram to a foreign network, rather than every home agent which have MNs in this foreign agent sending a packet to the foreign network [B.5] (Figure b.5). Mapping the multicast abstract architecture to this proposal, the dynamic tree's growth point is still the home

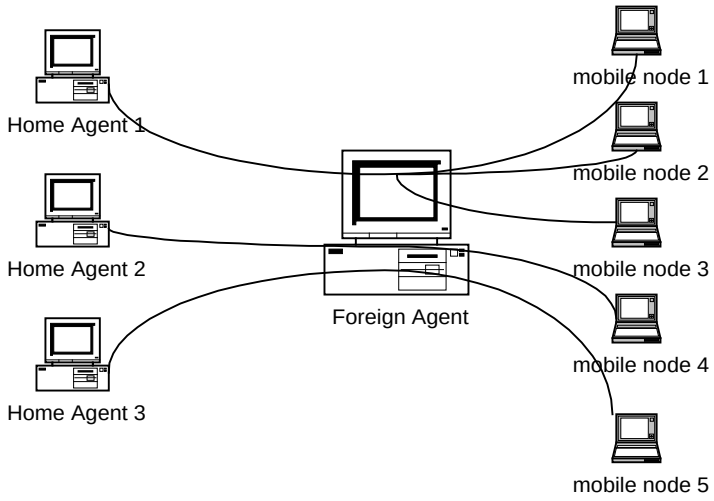

Figure b.4 Tunnel Convergence Problem

agent, as in the Bi-Directional Tunnelling proposal. However, the branches grow in a different way(Figure b.6). Only one home agent acts as a growth point instead of all

home agents being growth points if multiple tunnels from different home agents can terminate at one foreign agent. The dynamic tree is more optimal than that in the Bi-Directional Tunnelling proposal. It has less branches stretching out. However, during the implementation, how to manage the DMSP is a problem. If a MN whose home agent

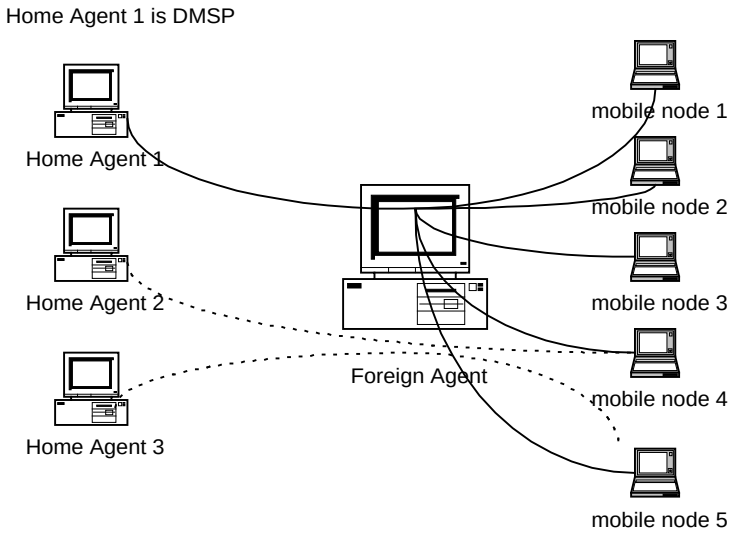

Figure b.5 MOM Proposal Multicast

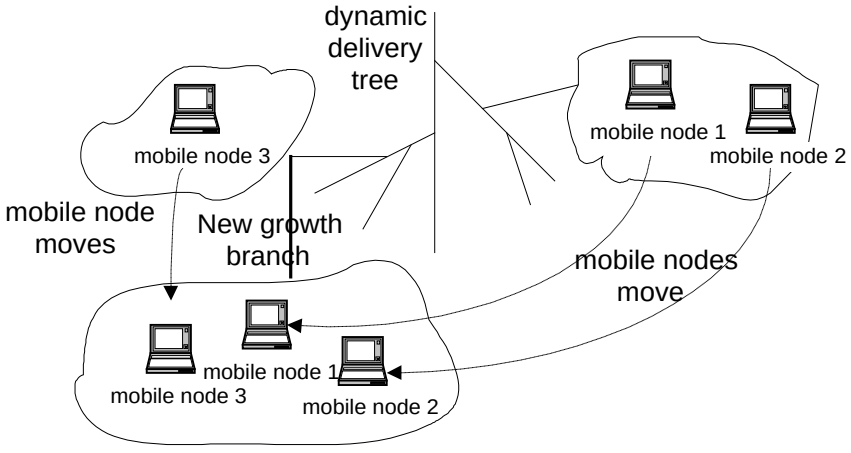

Figure b.6 Dynamic delivery tree in MOM

works as DMSP moves out of the foreign network, the foreign agent must select another DMSP. The dynamic delivery tree will be modified according to the selection. How to smooth hand-off the DMSP is the difficulty of MOM. The dynamic delivery tree is not optimal yet because of the encapsulation and triangle unicast routing from home agent to foreign agent. Especially, if the foreign network is near to the source or a branch of the delivery tree, a home agent still needs to forward a multicast packet from far away.

B.2.4 MMA (Multicast by Multicast Agent) Proposal

Because the dynamic delivery tree is not optimal in the MOM proposal and the Bi-Directional Tunneling proposal, researchers in Korea suggested MMA[B.4]. The MMA approach uses a Multicast Agent (MA) that provides multicast services to mobile hosts. A mobile host receives multicast traffic from the tunneling of a certain MA or directly from the multicast router at the current network. Each MA has to support a certain group service that has one Multicast Forwarder (MF) per group. A MF is one of the MAs that is in charge of forwarding multicast data to other MAs. For each network, both the MF of the MA and the MF of the mobile host, which resides in the same network, have an equal MF value. Initially, if a MN wants to join a group in any foreign network, subscriptions are done through the MA on the foreign network, which must be a multicast router. This MA becomes a MF itself, and in this network mobile hosts receive multicast service directly from the multicast router. Then, when the mobile host moves to another network, the mobile host notifies the MA in the new network of its Group ID and its MF during registration. The MF information of the MN is used by the MA in the new network as the previous MF of the visiting MN. If the MA in the new network does not have a group member, then it configures its own MF value with the previous MF of the MN. Otherwise, if the new network has group members and an MF, at this time the MA executes the MF selection algorithm and selects one of these two MFs: the current MF of the MA or the MF of the visiting MN. Then both the MA and the MN replace their MF value with the newly selected MF. There are two MF selection algorithms: the closest-MF selection algorithm and the oldest-MF selection algorithm. According to the closest-MF selection algorithm, the MF that is closer to the current MA is selected as a new MF.

In case of using the oldest-MF selection algorithm, a MF is never changed before a current network joins the multicast tree [B.7].

From the point of the dynamic delivery tree, a MA selects the growth point as an MF among adjacent networks that belong to the multicast delivery tree for the group. Because the mobility of MNs has locality characteristics, the new growth point of the dynamic tree is one of the more adjacent multicast tree nodes from the current network. Therefore the dynamic tree extends in a more optimal way, compared to MOM (Figure b.7).

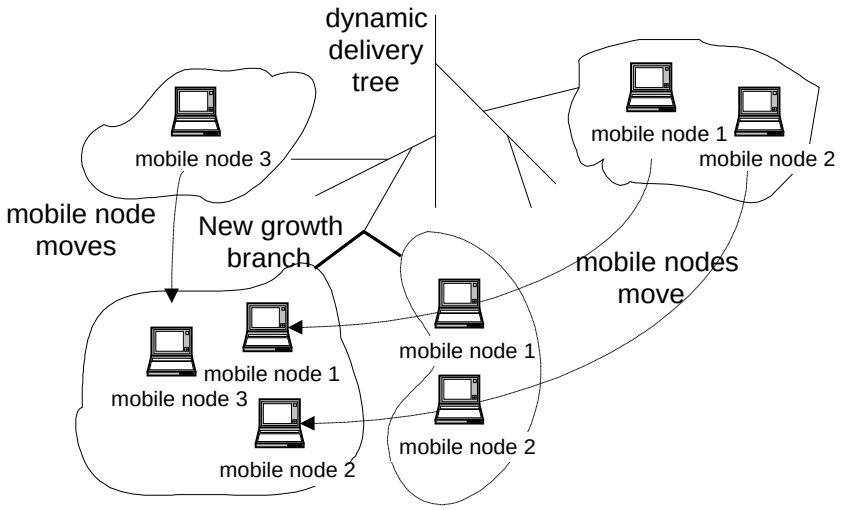

Figure b.7 Dynamic delivery tree in MMA proposal

B.2.5 Multicast Summary

Comparing the four proposals, the dynamic delivery tree in the Remote-Subscription proposal is the most optimal one. But frequent movement requires to frequently re-compute the dynamic delivery tree. This puts a high load on the multicast routers. The MMA proposal has the second best tree, and not every movement will cause to re-compute the delivery tree. From this point of view, it is a good multicast support for MNs. However, every foreign network has to deploy MAs. This new entity has to be added to every foreign network. Do we really need to pay too much for the multicast service? In the long run, this proposal will be a good choice.

B.3 Route Optimization in Multicast Support for Mobile IP

The Bi-Directional Tunnelling and MOM rely on home agents as the dynamic delivery tree's growth points. They can only co-operate with base Mobile IP. In the Mobile IP with Route Optimization, multicast packets still need to travel to HA first and are then forwarded to MNs. For multicast packets, the triangle routing still exists in Mobile IP with Route Optimization. The Remote-Subscription and MMA do not rely on home agents as the dynamic delivery tree's growth points. Mobile IP with Route Optimization considers unicast packets only. In Remote-Subscription, the routing of multicast packets is also optimal. In MMA, the routing of multicast packets is nearly optimal. Therefore, to achieve Route Optimization for both unicast packets and multicast packets, we can combine Remote-Subscription and Mobile IP with Route Optimization together by using Mobile IP with Route Optimization to support unicast and using Remote-Subscription to support multicast. We can combine MMA and Mobile IP with Route Optimization together by using Mobile IP with Route Optimization to support unicast and using MMA to support multicast. However, as we know, re-computing the dynamic delivery tree puts a heavy workload on multicast router, we prefer to use MMA as multicast Route Optimization and to use Mobile IP with Route Optimization as unicast Route Optimization.

B.4 Security in Multicast Support for Mobile IP

For Bi-Directional Tunnelling Multicast, MNs and HAs share security keys. For Remote-Subscription and MOM, MNs need to share a group membership security key with these FAs. For MMA, MNs have to share a group membership security key with the new entity MAs and MFs. For the multicast support, the security problem is that all group members in a specific group share a common membership key. Wherever the MN roams, it can use the membership key to identify itself as belonging to a specific multicast group. If there is an access point to this specific multicast group, the MN can get multicast service by identifying itself. However, the security level in multicast is lower than that in unicast because most current multicast applications, such as weather broadcast etc, do not require high security. Actually, mobility does not increase the security risk for multicast support compared with current networks without MNs. No matter whether a node moves or not, it

needs a membership key to join a specific multicast group. For multicast support, the security problem in a static network and the security problem in a mobile network are the same. Therefore, all these multicast proposals for Mobile IP do not discuss security and the group membership key issues.

Appendix B Reference

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Appendix C

Basic Mobile IP Code Guide

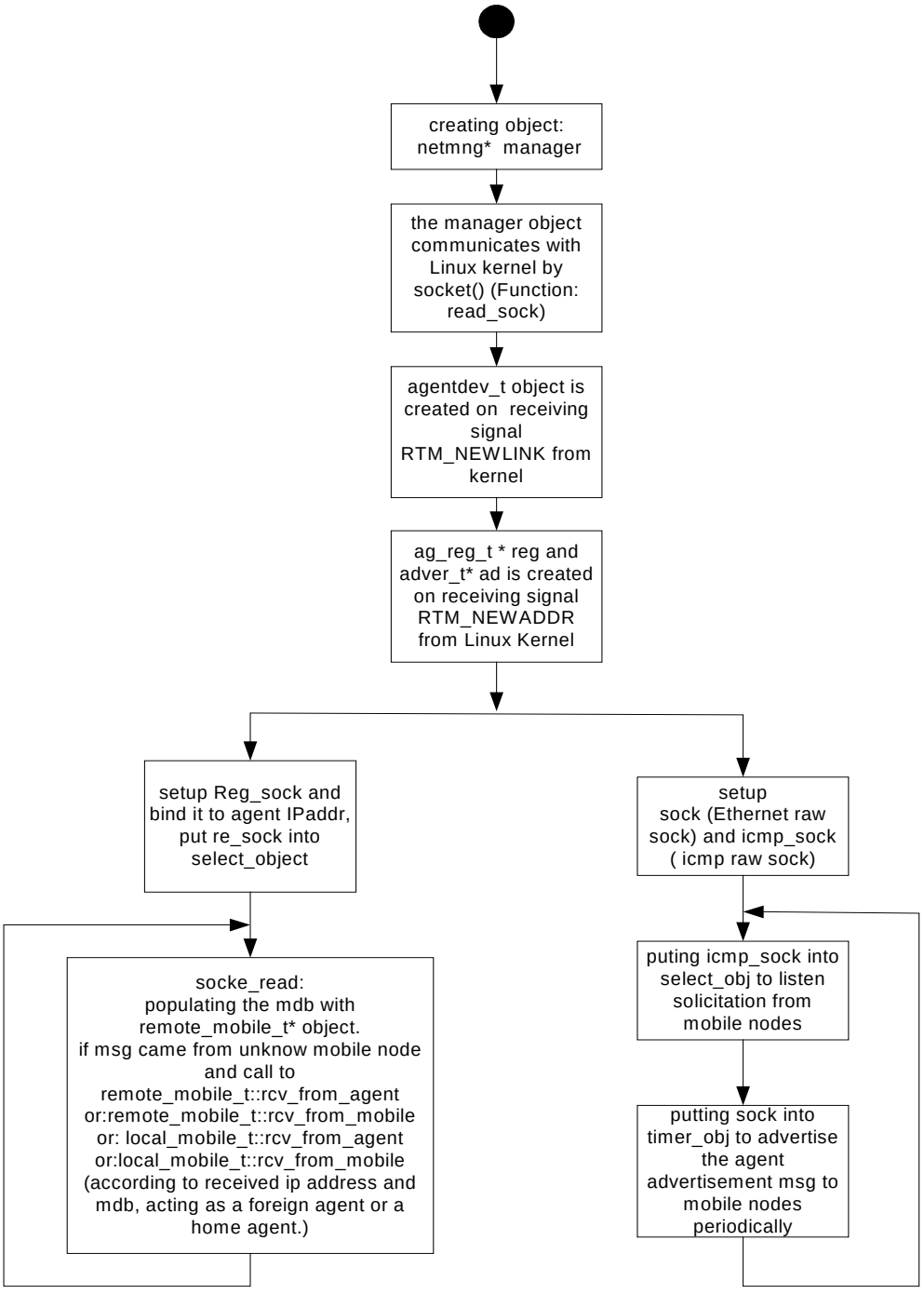


Figure C.1 Mobile IP Agent Control Flow in Basic Mobile IP Implementation

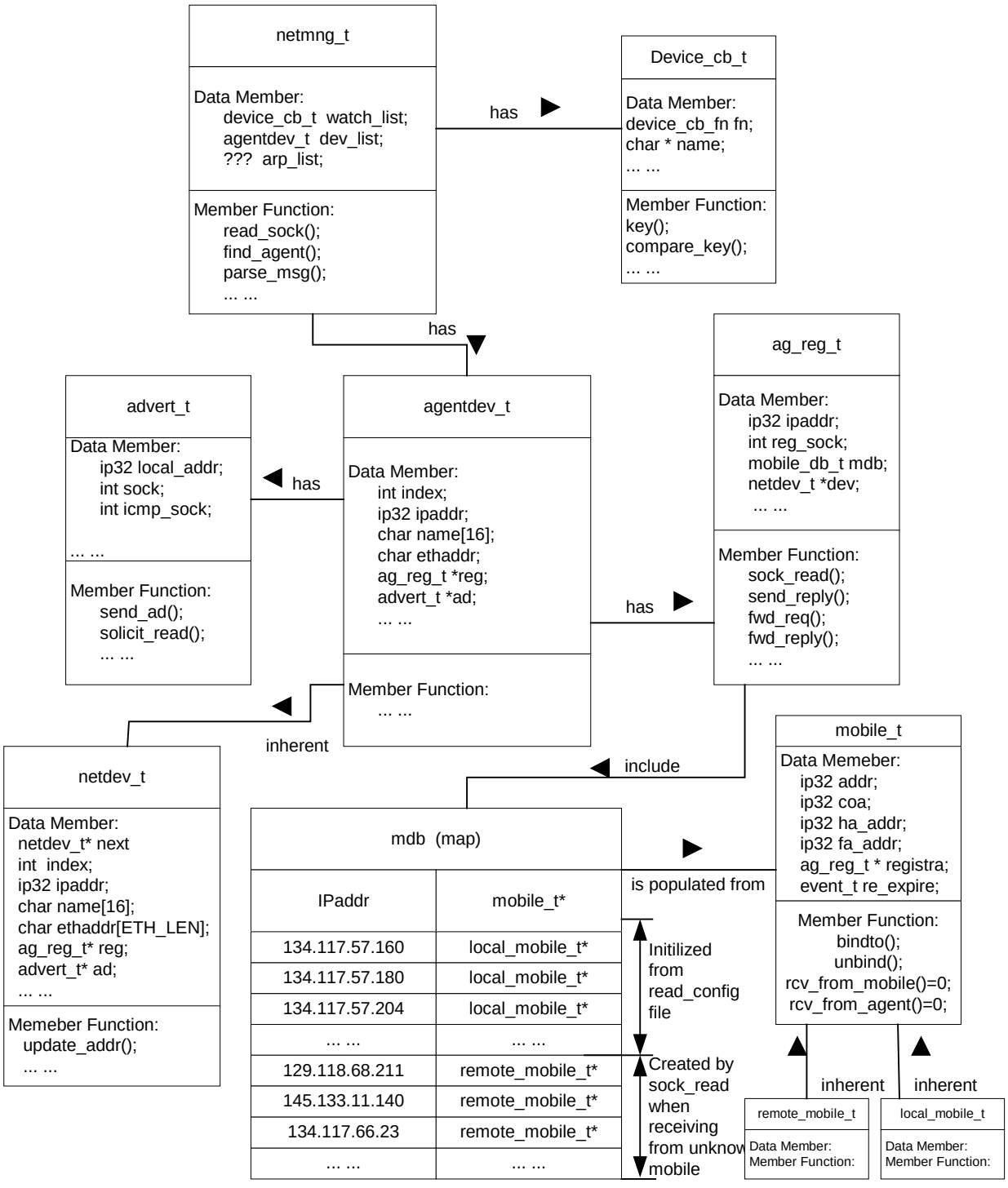
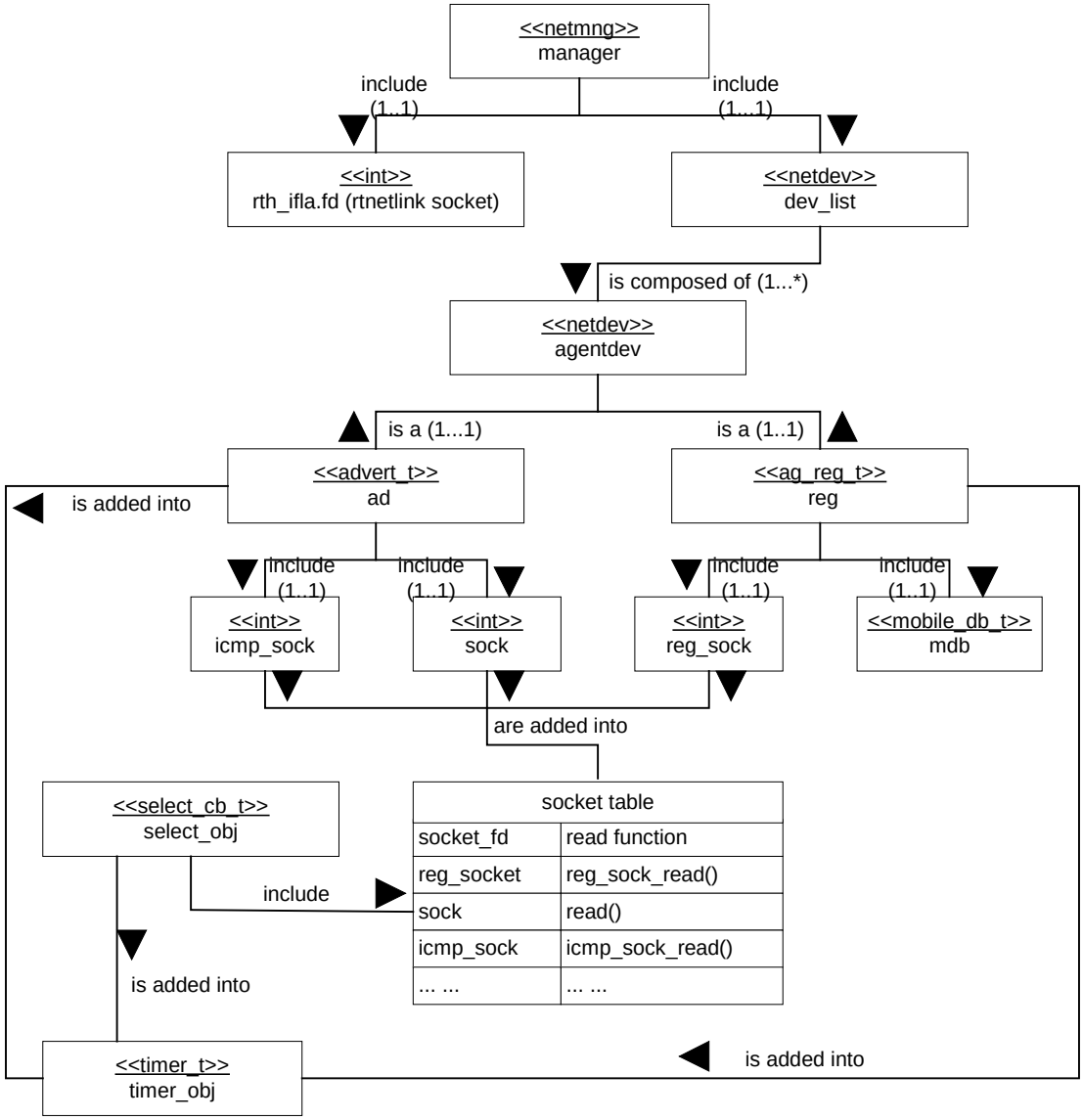


Figure C.2 Class Relationship of Mobile Agent in Basic Mobile IP Implementation



Notice:
1. <<name>> represents a class type
2. name under the class type represents an object of the class type.

Figure C.3 Object Relationship of Mobile Agent in Basic Mobile IP Implementation

Appendix D

Mobile IP with Route Optimization HOWTO

This appendix describes how to install and run the Mobile IP with Route Optimization.

Step 1: Unzip the mipro2.tar.gz

```
$unzip mipro2.tar.gz
$tar –xvf  mipro2.tar
```

Step 2: Configure the system

By default the configuration file used is ".mip", which exists in /mipro2/agent, /mipro2/mobile and /mipro2/correspondent directory.

The configuration file accepts the following statements:

```
mobile {mobile ip addr}{agent ip addr}
agent {agent ip addr}
ignore {network interface}
key {addr1}{addr2}{spi}{key}
```

Here is a sample configuration file

```
agent 134.117.66.21 eth0
mobile 134.117.57.204 134.117.57.101
ignore eth1
key 134.117.57.204 134.117.57.101   5 abcdef05abcdef05abcdef05abcdef05
key 134.117.67.140 134.117.57.101   4 abcdef04abcdef04abcdef04abcdef04
key 134.117.66.21 134.117.57.101   3 abcdef03abcdef03abcdef03abcdef03
key 134.117.57.204 134.117.66.21   2 abcdef02abcdef02abcdef02abcdef02
key 134.117.57.204 134.117.67.140   1 abcdef01abcdef01abcdef01abcdef01
key 134.117.66.21 134.117.67.140   6 abcdef06abcdef06abcdef06abcdef06
```

Step 3: Compile the code under mipro2 directory

1. Compile and link the source files except that under the subdirectory ./agent and ./correspondent
   ```
   $make
   ```
2. Compile and link the source files under the subdirectory ./agent and ./correspondent
   ```
   $cd ./agent
   $make
   $cd ../correspondent
   $make
   ```

Step 4: Modify Linux kernel source files

1. Copy modified sockios.h file to Linux kernel source file directory
   ```
   $cp /mipro2/kernel/sockios.h /usr/src/linux/include/linux/
   ```
2. Copy modified af_inet.c and ip_fw.c to Linux kernel source file directory
   ```
   $cp /mipro2/kernel/af_inet.c /usr/src/linux/net/ipv4/
   ```

$cp /mipro2/kernel/ip_fw.c /usr/src/linux/net/ipv4/

3. Recompile the Linux kernel
   1) $make mrproper
   2) $make config
      To run the software, the following options must be enabled:
      Code Materty level Options
         Prompt for development and/or incomplete code/drives
      Networking Options
         Kernel/User Netlink Socket
         Routing Messages
         IP: tunneling
         IP: ARP daemon support
   3) $make dep
   4) $make bzImage
   5) $make modules
   6) $make install
   7) $make modules_install
   8) Modify lilo.conf
      $cd /usr/src/linux/arch/i386/
      $ls –l
      You can see a new file. It is the new kernel image. Suppose its name is vmlinux
      $cp /usr/src/linux/arch/i386/vmlinux /boot/vmlinux
   9) $vi /etc/lilo.conf
      In the lilo.conf, create a new entry for boot choice
   10) Save the new lilo.conf for reboot by using “wq” to exit vi.
   11) $lilo -v
   12) $reboot

Step 5: Run Mobile IP with Route Optimization

1. In the Home Agent, go to the /mipro2/agent directory.
   $./mipa
2. In the Foreign Agent, go to the /mipro2/agent directory.
   $./mipa
3. In the Mobile Node, go to the /mipro2/mobile directory.
   $./mipc
4. In the Correspondent Node, go to the /mipro2/correspondent directory.
   $./mipcpd