NAIST-IS-DT0161009

Doctoral Dissertation

Studies on Measurement-Based Path Selection in Multi-Homed Wireless Networks

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December 17, 2003

Doctoral Dissertation
submitted to Graduate School of Information Science,
Nara Institute of Science and Technology
in partial fulfillment of the requirements for the degree of
Doctor of ENGINEERING

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Abstract

With the growing demand for mobility support, coverage areas for wireless connectivity are expanding and overlapping, and Internet access points exist everywhere. As personal computing devices are portable and have multiple network interfaces, they can connect to the Internet any time and everywhere: for example, a cable modem at home, a wide coverage wireless network on the commute, a wired Ethernet at the office, and a wireless local area network at the station. Personal computing devices have more than one Internet access. In other words, personal computing devices are in a multi-homed environment.

A multi-homed environment is supposed to enable personal computing devices to move across different wireless or wired networks without losing communication. In particular, mobile users expect seamless mobility for real-time communications such as video streaming and Voice over IP. However, the current migration techniques from one network to another network lead to loss of connection or degradation of communication quality. These problems result from insufficiently mobility support in an overlap area between different networks. In this overlap area, a mobile computing device connects with different networks. Nevertheless, a mobile computing device cannot switch to another network interface without closing the connection or degrading communication quality, because today's internet architecture and operating systems do not provide mobility support for a mobile computing device in a multi-homed network. Thus, mobility support for migration across different wireless or wired networks is needed.

The major objective of this dissertation is to maintain real-time communication quality during transfer by making good use of the multi-homed environment. This dissertation recognizes the importance of mobility support based on end-to-end in multi-homed networks, and answers the following question: When and how should a mobile computing device switch multiple network interfaces to prevent connection loss or degradation of communication quality in multi-homed wireless or wired networks? This dissertation presents two solutions: Path Selection Method (PSM) and Multi-Path Transmission Algorithm (MTA). PSM provides a method to select a better path for data transmission in multi-homed networks. A mobile computing device measures network condition for each path using control packets, and switches network interfaces according to four rules. Using the PSM, a mobile computing device can select a transmission path with better condition for real-time communication in multi-homed networks. Simulation results show that a mobile computing device gains better throughput and delay. On the other hand, MTA provides a method to improve communication quality in multi-homed networks. A mobile computing device has two modes: single-path transmission and multi-path transmission. When the transmission path becomes unstable, the mobile host switches to the multi-path transmission mode and sends the same packets along two paths. Then, when one of the transmission paths becomes stable, the mode returns to single-path transmission. Simulation results show that a mobile computing device acquires better goodput when it migrates from one network to another network.

Acknowledgements

First and foremost, I wish to express my gratitude to Professor Suguru Yamaguchi, my advisor and committee chairman, for his support, advice and encouragement. Without his kind cooperation, I could not have completed this dissertation.

I wish to thank Professor Hideki Sunahara for his helpful support on my committee. His invaluable comments helped me to finish my work.

I would like to thank Professor Yuji Oie of Kyushu Institute of Technology for his precious advice and sustained support for my work. When my work was stalemated, he gave me a hint to achieve a breakthrough.

Associate Professor Youki Kadobayashi is the final member of my committee. His novel and theoretical ideas encouraged me to reconsider my fixed ideas, and he led me to take a broader view of things. I would like to express my gratitude to him.

I am deeply indebted to Assistant Professor Katsuyoshi Iida, for his stimulating discussion and untiring support. His steady support always helps me, and has helped me to finish my work. I have learned a lot from him in my graduate school days. I would like to express my gratitude to him.

All members of SCTP and Renet group supported my work. I also would like to thank them. Dr. Hiroyuki Koga and Mr. Kosuke Hata, especially, provided useful comments and supports.

Professor Ian R. L. Smith taught me English writing, presentation and communication, and he always willingly helps me to revise my papers. His explanation was easy to understand, and I learned English delightfully. I would like to deeply appreciate what he has done for me.

I also would like to thank all members of IPLAB for their friendship, support and comments. Mr. Masataka Kanamori, Mr. Ryuji Somegawa, Mr. Teruaki Yokoyama and Mr. Masashi Eto have always supported and encouraged me in my work. Assistant

Professor Takeshi Okuda, Mrs. Tanida Natsue, and Ms. Keiko Nakano supported and gave advice to me in my school life. I will never forget my graduate school days.

Finally, I would never have been able to finish this work without the support and understanding of my parents and my sister. Many thanks go to my fiancee, Akane, for her support and patience. I also would like to thank her family.

The greatest appreciation goes to my parents, for their constant support and understanding.

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Chapter 1

Introduction

The Internet has spread widely and is becoming a critical infrastructure for our lives. Owing to the Internet, when people sit down in front of personal computers (PCs), they can, for example, search for information using web browsers, send e-mails to friends, chat with friends and watch movies. In particular, traffic for real-time communications such as Voice over IP (VoIP) and video streaming is increasing year by year [OOUY01]. We request real-time communications any time and everywhere: commuting to the office and school, going shopping, going on a journey.

The world of networking has been changing rapidly since the Internet was established. Today, we already have various wireless and wired networks: for example, Cellular networks, Wireless Local Area Networks (WLANs), Bluetooth, and Ethernet. The Internet is built upon these different wireless and wired networks. As a result, users can now connect to the Internet any time and anywhere, which was just a dream a few years ago.

1.1 Multi-Homed Environment

While various kinds of wireless or wired networks are available, several problems must be overcome to make full use of them. These wireless and wired networks have widely varying features in terms of coverage area, bandwidth, packet loss, and delay, and have an overlap area between different networks as illustrated in Figure 1.1. In Figure 1.1, two different kinds of wireless networks exist: wireless network A and wireless network B. In such networks, the most serious problem is connection loss due to changing the

IP address when a mobile host moves across different networks during communication. Originally, hosts were static and connected to only one network. For such a host, a single identification is sufficient to represent both the identity of a host as well as its location within the network. The IP address is sufficient identification. However, such a permanent identification is not appropriate in the mobile Internet, because a mobile host switches the network interface (that is, changes of its IP address) whenever it moves into another different network. Movement like this is called vertical handover. Moreover, there are other problems in moving across these different networks. In Movement A of Figure 1.1, a mobile host with wireless network A connects to wireless network B during roaming. At this time, the mobile host can use both of these two networks. That is the mobile host is multi-homed. However, since the mobile host does not have a way to switch network interfaces during communication, with the present technologies, it continues to use the wireless network it first connected to until the wireless network is unavailable. If communication quality of wireless network B is better than that of wireless network A, the mobile host cannot use wireless network B. Thus, the mobile host cannot make use of these networks. In Movement B of Figure 1.1, let us assume that a mobile host with wireless network A moves into a building with hotspot service (wireless network B). At this time, although communication quality of wireless network A becomes unstable, the mobile host connects to wireless network B and communication quality of wireless network B becomes stable. The mobile host is multi-homed while moving from wireless network A to wireless network B. However, if communication quality of wireless network A becomes unstable, the mobile host cannot prevent degradation of communication quality using wireless network B. Therefore, a mobile host cannot make full use of these networks.

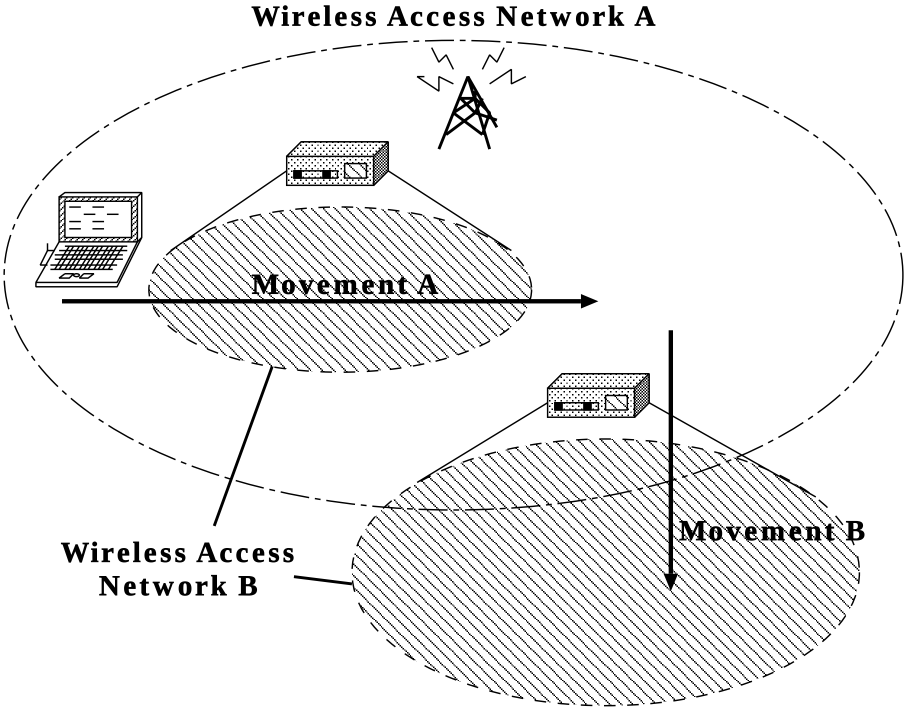

Figure 1.1: Movement across various kinds of networks

1.2 Categories of Mobility Management

To achieve hosts' mobility, mobile hosts need two technologies [CMSM03b]. One is location management technology, the other is handover technology. Location management includes update and paging, and enables the network to discover the current attachment point of a mobile user for call delivery. Handoff management maintains the user's connection as the mobile host continues to move and change its access point to the network. As shown Figure 1.2, there are two kinds of handover mechanisms: Horizontal handover and Vertical handover. Horizontal handover is handover between base stations with the same network interfaces. Vertical handover is handover between base stations that are using different network interfaces. Moreover, these two handovers are classified into three kinds of handover mechanisms: Smooth handover, Fast handover and Seamless handover [MIP]. Smooth handover is for low packet loss, fast handover is for low delay, and seamless handover is for low packet loss and delay. The focus of this dissertation is on seamless vertical handover for real-time communications in a multi-homed environment.

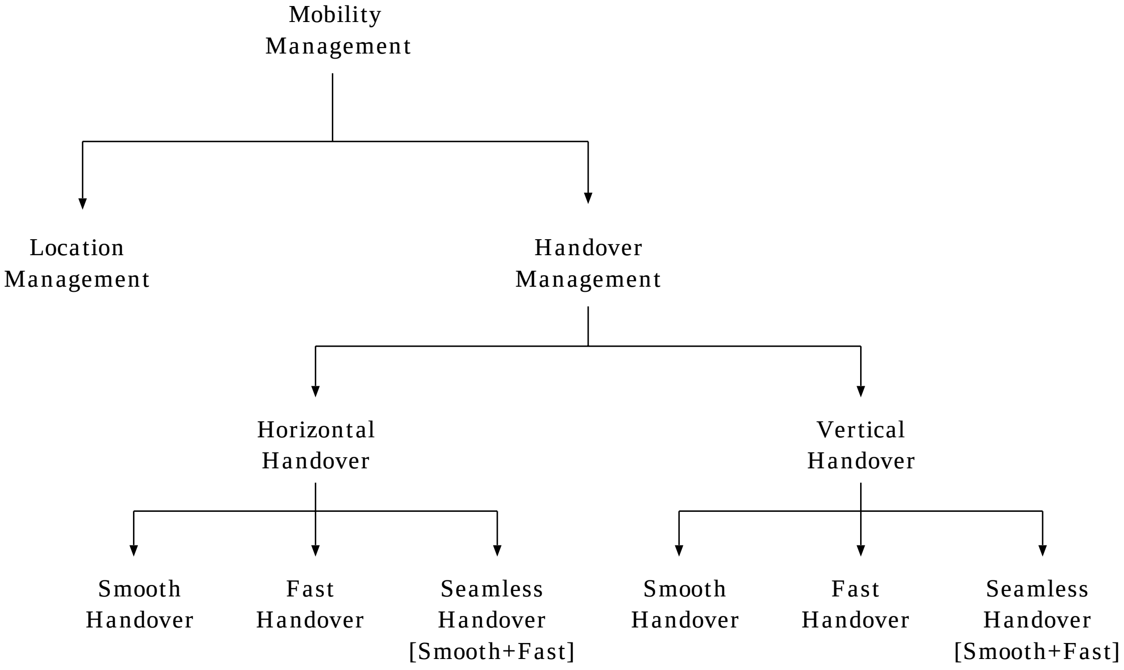

Figure 1.2: Categories of Mobility Management

1.3 The Challenges

The mobile Internet is not adapted for enabling a mobile host to move across different wireless and wired networks. That is, today's Internet architecture and operating systems lack support for a mobile host having multi-homed networks. This dissertation recognizes the importance of mobility support in multi-homed networks, and answers the following question: When and how should a mobile host switch multiple network interfaces to prevent connection loss or degradation of the communication quality in multi-homed wireless and wired networks. The primary contributions of this dissertation are as follows:

- When a mobile host connects to multiple networks, it can select a network with good condition.

  To select a network with good condition, the mobile host measures delay and bottleneck bandwidth, and selects a network according to selection rules.

- When a mobile host moves from one network to another network, a mobile host can move without closing the connection or degradation of communication quality.

  A mobile host sends probe packets to investigate packet loss of each path. If it detects that the network condition of the data sending path becomes unstable, it switches to multi-path transmission mode to avoid quality degradation, and sends the same packets to multiple paths simultaneously. After that, if one of the transmission paths becomes stable, the mobile host switches back to single-path transmission mode to reduce unnecessary consumption of network resources. As a result, goodput during handover is improved.

1.4 Dissertation Overview

This dissertation is organized as follows. Chapter 2 surveys related work in fields of vertical handover, explains features in network mobility and end-to-end mobility, and then introduces existing solutions for vertical handover.

Chapter 3 describes a method to select a network with good condition, and evaluates this method through simulations. The main goal is that when a mobile host roams an overlap area among two different wireless networks, it maintains quality of real-time communication by selecting a network with good condition.

Chapter 4 describes an algorithm to improve goodput during movement from one network to another, and evaluates this method through simulations. When a mobile host detects that the network condition of the data-transmitting path becomes unstable, and it sends the same packets to multiple paths simultaneously. After that, if one of the transmission paths becomes stable, the mobile host switches back to single-path transmission to reduce unnecessary consumption of network resources. Finally, Chapter 5 suggests future directions of research and concludes this dissertation.

Chapter 2

Related Work

Mobility has been studied for many years. This chapter provides an introduction to mobility protocols from the point of view of vertical handover. These protocols are categorized into network mobility and end-to-end mobility, and solutions at various layers are introduced.

2.1 Classification of Mobility Protocols

Mobile communication technologies in the mobile Internet are being investigated by a number of researchers. This section classifies previous approaches into Network Assisting Mobility Support (NAMS) and End-to-end Assisting Mobility Support (EAMS). In NAMS, each mobile host communicates with a special network device to maintain mobility. In EAMS, on the other hand, each mobile host maintains the location state of the corresponding host without special network devices.

2.1.1 Network Assisting Mobility Support

Examples of NAMS are Mobile IP [CP02a, JPA03], Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) [RPT+99], Cellular IP [Val99], Session Initiation Protocol (SIP) [MBC99], and Location Independent Networking for IPv6 (LIN6) [IKU+01]. Below, We consider Mobile IP as a representative of NAMS.

Mobile IP was invented to resolve the address portability of the Internet. We provide an overview of the Mobile IP protocol which was introduced by Charles Perkins in the Internet Engineering Task Force (IETF) [IET]. Although many articles and books have been written on the subject of Mobile IP, it was yet to gain a stable foothold in the Internet. At present, Mobile IPv4 and Mobile IPv6 are being developed. In Mobile IPv4, RFC2002 [CP96] was updated to RFC3220 [CP02b], which was in turn replaced by RFC3344 [CP02a]. On the other hand, Mobile IPv6 remains a plan in draft. We will simply describe overviews of Mobile IPv4, and then Mobile IPv6. Figure 2.1 illustrates how to support mobile hosts' movement. A mobile host has an unchangeable IP address in its home network. This IP address is called the Home Address (HAddr). When a mobile host moves to a foreign network, the mobile host gets a Care-of Address (CoA), which is a temporary address, from a Foreign Agent (FA) in the visited network. After that, the mobile host informs the Home Agent (HA) in its home network of this CoA. The HA manages this CoA and the HAddr of the mobile host. When a host wants to communicate with the mobile host, it sends data to the HAddr of the mobile host, whose HA then forwards the data to the CoA of the mobile host. These functions enable the corresponding host to communicate with the mobile host in a foreign network. Figure 2.2 illustrates how to communicate with a mobile host. Therefore, mobile hosts need special network devices to enable them to move during communication.

Mobile IPv6 allows mobile hosts to remain reachable while moving around in the IPv6 Internet. One of the most distinguishing features of Mobile IPv6 compared with Mobile IPv4 is the deletion of FAs. Handover in Mobile IPv6 is classified into mobile-controlled handover and network-controlled handover. In mobile-controlled handover, the process is initiated by the mobile host roaming to a new network. On the other hand, in network-controlled handover, the process is initiated by the network to permit roaming of the mobile host to a new network. In either case, a relationship between the previous and new networks is needed to enable mobile hosts to move from one network to another.

The advantage of Mobile IP is its fully-transparent mobility support, which is general and sufficient for many mobile applications. However, Mobile IP also has some disadvantages. The main problem in vertical handover is multi-homing [MWEN03]: Mobile IP needs to handle several HAddrs and CoAs when mobile hosts are multi-homed. For that reason, service providers must prepare HAs or FAs to manage mobile hosts' mobility. Moreover, Mobile IP has a routing process known as triangular routing, where all packets sent to the mobile host must first be sent to the mobile's home network and then forwarded to the mobile's current location. These problems also apply to NAMS.

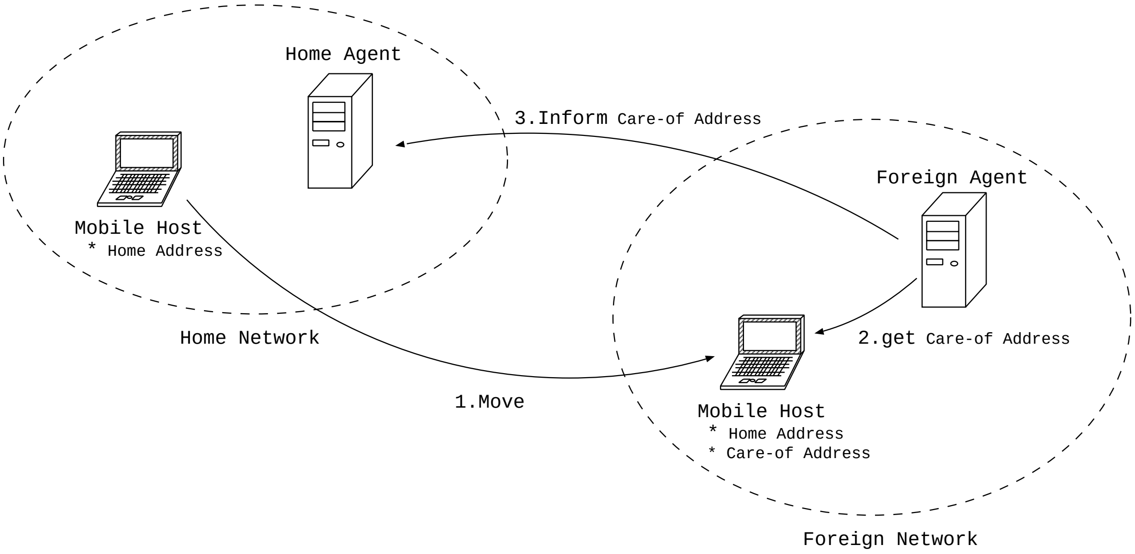

Figure 2.1: Movement from home network to foreign network

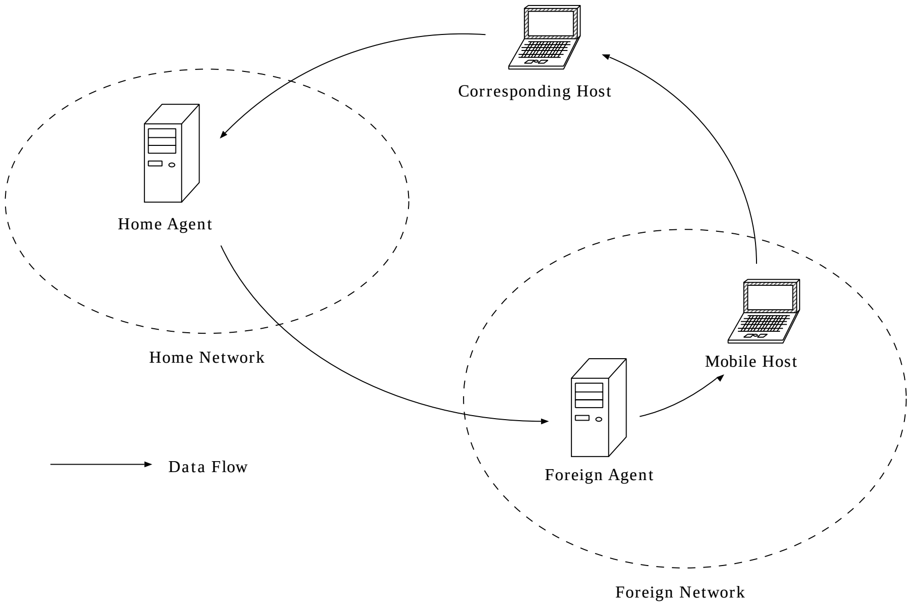

Figure 2.2: Communication with a mobile host

2.1.2 End-to-end Assisting Mobility Support

EAMS needs special end-to-end protocols for maintaining host mobility. Examples of EAMS are TCP migration [SB00], Multimedia Multiplexing Transport Protcol (MMTP) [MK01], Transparent Extensible Session-Layer Architecture (TESLA) [SSB03], and Stream Control Transmission Protocol (SCTP) [SXM$^+$00, SX01]. In these protocols, a mobile host maintains a corresponding host's mobility without special network entities.

As mentioned Section 2.1.1, current NAMS approaches such as Mobile IP solve problems for mobility management. While general, these approaches have some unappealing characteristics; limited performance and additional complexity for the network architecture are the two most serious shortcomings. Adding complexity to the network runs counter to some of the basic design principles of the Internet, in particular the end-to-end principle [SRC84]: anything that can be done in the end system should be done there. And, in fact, supporting mobility is an end system issue. Thus, the question arises whether it would be possible and beneficial to attempt to support mobility in IP networks at layers higher than the network layer. As the transport layer is considerably affected by mobility - e.g., it has to be able to quickly adapt its flow and congestion control parameters to new network situations during and after handover - it is a natural candidate for mobility support. Attempting to support mobility in the transport layer might enable it to improve its parameter adaptation; it could also make the entire networking architecture simpler by working without additional entities within the network.

Moreover, a mobile host must be able to switch seamlessly between different network interfaces to take advantage of whatever connectivity is available. For example, users may need to switch from an Ethernet connection to a radio modem as they leave their office, taking their computers with them. If they arrive at a site where there is a higher speed connection, they may want to switch once again to take advantage of that, even if the wireless service is still available. From this illustration, it is clear that mobile hosts need to support hosts' mobility with an end-to-end system.

2.2 Solutions at various layers

In this section, we provide a review and comparison of some existing solutions for mobility management. The architectures we review here are vertical handover-based solutions at various layers of communication protocols.

2.2.1 Data link layer solutions

Stemm and Katz developed a vertical handover mechanism for different wireless networks [SK98]. Their work focuses on the performance of a mobile host roaming among different wireless networks, and its primary objective is to minimize the vertical handover latency for a mobile host while keeping bandwidth and power overheads as low as possible. This allows the mobile host to communicate with a corresponding host on the network until communication using the current network interface is interrupted by disconnection. In this approach, the mobile host makes a decision to perform a handover from one network interface to another whenever a disconnection or weakening of signal strength is detected. This work relied heavily on the mobile host making handover decisions based on packet loss thresholds, and therefore the handover time is quite long. This approach does not provide Quality of Service (QoS) support for application during vertical handover; it supports vertical handover due to disconnections, but does not support network changes due to QoS degradation.

2.2.2 Network layer solutions

There are numerous proposed methods that are based on the Mobile IP. The most widely known of these proposals is Mobile IP, which is also the oldest one. These methods mainly need the use of proxies and Internet Protocol (IP) tunnelling to support connection for mobile hosts.

Mobility protocols at the network layer are generally categorized into three mobilities: micro-mobility, macro-mobility and global mobility [CMSM03a]. Micro-mobility covers the management of user movements at a local level, inside a particular wireless network. Many solutions have been proposed to manage this type of mobility within IP networks; they are often called IP Micro-mobility protocols. Macro-mobility concerns the management of user movements at a large scale, between different wide wireless access networks connected to the Internet. Macro-mobility is often assumed to be managed through Mobile IP. The goal of mobility management is to ensure continuous and seamless connectivity during micro-mobility and macro-mobility, which occur over short timescales. Examples are Cellular IP [Val99, CGK$^+$02, CGK$^+$00], TeleMIP [DMAD00], Hierarchical MIP [GJP02, SCEMB03], HAWAII [RPT$^+$99] and DMA [MDMD01]. Global mobility, on the other hand, is assumed to be managed using vertical handover. The MosquitoNet [BZCS96] extends Mobile IP to support vertical handover. MosquitoNet allows a mobile host to maintain connectivity during roaming, when a mobile host moves from its home network to a foreign network. In Mobile IP, a Mobility Binding Table is used to keep track of information about the mobile host's HAddr and CoA. The Mobility Binding Table allows the home agent to route packets from the home network to the mobile host. However, this routing assumes that both the foreign network and home network of the mobile host are operating on the same type of network interface. MosquiteNet can enable a mobile host to maintain a connection, even when the foreign network has a different network interface.

MosquitoNet has a Mobility Policy Table at the IP layer of the network stack. This table contains binding information about the mobile host's communication stream and the address of the network interface that will be used to transport the stream. Using this information, a proxy server in the home network redirects the communication stream to a new network interface of the mobile host. A variety of network interfaces are supported by MosquitoNet, including Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). MosquitoNet is a solution to support vertical handover for a mobile host, but it would remain unsuitable for applications that require support for QoS. Moreover, as indicated in Section 2.1.1, these proposal methods at the network layer needs special devices to manage hosts' mobility between networks.

2.2.3 Transport layer solutions

A number of solutions at the transport layer have been proposed to support vertical handover. The list is as follows: MSOCKS [MB98], TCP migration [SB00], Multimedia Multiplexing Transport Protcol (MMTP) [MK01], and Stream Control Transmission Protocol (SCTP) [SXM$^+$00, SX01].

MSOCKS solves the problem of location management by having the proxy servers handle address mapping between a mobile host and an application server. To preserve the connection semantics of a TCP/IP communication session, this architecture introduces a protocol called TCP Splice. This allows the proxy to establish separate communication streams with the server and mobile hosts, and then splice the streams together to provide the illusion that the mobile host and server are both communicating using a single communication session. This solution only supports the TCP protocol; it does not provide mobility support for UDP. While MSOCKS allows operability with different network interfaces, it does not provide options for routing optimizations such as triangular routing. However, MSOCKS lacks support for QoS. This is because there is no way for the mobile host to know when to switch to a more suitable network interface whenever one becomes available, since MSOCKS is not concerned about the type of network interface being used to facilitate a TCP communication stream.

TCP migration was designed by Snoeren and Balakrishnan [SB00]. They designed a new end-to-end TCP option to support the secure migration of an established TCP connection across an IP address change. Using this option, a TCP peer can suspend an open connection and reactivate it from another IP address, transparent to an application that expects uninterrupted reliable communication with the peer. TCP migration does not support QoS as well as MSOCKS.

MMTP was designed for multimedia traffic by Luiz and Robin. It is a rate-based protocol designed for transferring multimedia data in a mobile environment, and makes simultaneous use of every communication channel available to send data at the required rate. The use of multiple channels to transport user data provides five benefits:

1. a fatter pipe
2. a fast feedback path
3. the retransmission of selected lost messages, without delaying the playout of the data stream
4. less sensitivity to minor bandwidth fluctuations on any one individual channel
5. smooth vertical handover for active data streams

Transmission in MMTP is constructed from two mechanisms. The first is a set of rate control protocols associated with each outgoing channel, and the second is a scheduling algorithm that places incoming packets on the appropriate channel.

SCTP is a next-generation transport layer protocol. SCTP encompasses many basic functions of TCP, and adds a number of interesting protocol mechanisms. One core feature of SCTP is multi-homing, which enables a single SCTP endpoint to support multiple IP addresses within a single association which consists of some connection. This feature can handle multiple different network interfaces. Thus, a mobile host can switch network interfaces without connection closure. However, the purpose of multi-homing is to increase association reliability in wired networks. Therefore, the IP addresses of mobile hosts are fixed and known in advance. SCTP can rely on all communicating peers to learn about all the IP addresses before the association is completely established, and these IP addresses must not be changed during the session in the classical SCTP. To enable a mobile host to roam in mobile networks, Dynamic Address Reconfiguration (DAR) [SRX$^+$03] has been proposed. A mobile host changes an address list in a running association using DAR. SCTP with DAR enables a mobile host to add, delete and change a primary IP address dynamically in an active association, using Address Configuration chunks. Several mobility management methods using DAR have been proposed [KJKL03, XKWM02, MYLR03, KLR$^+$03, Rie03]. SCTP with DAR mobility management has the following advantages:

1. No third party other than the mobile host participates in the handover.
2. It can support concurrent usage of any type of access routers.
3. Additional network components or modification of intermediate routers are not required.

2.2.4 Above the transport layer solutions

Mobility management methods at the application layer have been proposed [DVC$^+$01, WS99]. Session Initiation Protocol (SIP) [HSSR99] is rapidly gaining wide spread acceptance as the signalling protocol of choice for Internet multimedia and telephony services, which can be used for the wireless Internet as well. SIP relies on the use of SIP's registration mechanism for providing terminal and personal mobility. Every mobile host has a URI, which could be an e-mail address. When a mobile host moves to a new network, it registers its new position with the SIP register server, so that the SIP register server knows the mobile host's current position. This kind of registration can provide user-level mobility. SIP-based mobility offers attractive benefits when used in mobile multimedia applications. However, there are some inherent problems with this approach which make the adoption of this scheme difficult. For example, it cannot handle mid-call subnet changes, since it is an application layer solution. This is where it requires the support of a lower level mobility protocol, such as Mobile IP. One other important issue is that of inter-operability with Mobile IP. Home Agent and Foreign Agent registrations in Mobile IP serve the same purpose with the SIP register server, so that their joint deployment becomes problematic.

2.3 Summary

In this chapter, we introduced many mobility management methods from two points of view: NAMS and EAMS, and layers. Currently, mobile computing projects have emerged at major universities, and have addressed issues in mobile computing [Sat01]. Examples at universities include Project Aura at Carnegie Mellon [Aur], Oxygen at MIT [Oxy], Endeavour at UC Berkeley [End], and Renet at NAIST [Ren]. Through this chapter, we believe that vertical handover should be proposed at the transport layer. Proposed methods above or below a transport layer would remain unsuitable for applications that require support for QoS. Moreover, these proposed methods need special devices to manage hosts' mobility in networks. On the other hand, the proposed methods at the transport layer do not need special network devices to manage hosts' mobility in networks, because the transport layer is the lowest layer to support end-to-end services. In this dissertation, we employ SCTP with DAR to propose vertical handover for real-time communication, so that SCTP with DAR can handle multiple network interfaces without connection closure.

Chapter 3

Path Selection Method using Active Measurement

The mobile Internet is built upon a number of different wireless access networks with widely varying features in terms of coverage area, bandwidth, packet loss, and delay. To move across these different networks smoothly, issues associated with the changing features need to be addressed. In this chapter, a path selection method for the coverage overlap area is proposed in which the mobile host actively measures the round trip time (RTT) and bottleneck bandwidth for each path and a path is selected based on four rules.

3.1 Introduction

With the growing demand for mobility support, the coverage areas for wireless connectivity are expanding and beginning to overlap. These coverage areas correspond to a range of different types of wireless access networks, such as cellular networks and wireless local area networks (WLANs), with quite different features in terms of coverage area, bandwidth, delay, and packet loss rate.

A number of handover technologies have been proposed to allow mobile users to traverse these different networks. These technologies are based on either a network-assisted approach or an end-to-end approach. Mobile IP [JPA03, CP02a] is the major proposal for network-assisted handover. Network-assisted handover is achieved through the use of handover management facilities embedded in the networks to support handover for mobile hosts. However, there are a number of problems associated with this handover mechanism, the most important being that the facilities become a single point of failure because mobile hosts need to communicate with the facilities to manage mobility. The end-to-end handover mechanism has been proposed as part of the TCP migration option [SB00], the Multimedia Multiplexing Transport Protocol (MMTP) [MK01], and the Transparent, Extensible Session-Layer Architecture (TESLA) [SSB03]. End-to-end handover does not require handover management facilities because each of the hosts manages the locations of the other hosts directly.

However, a mobile host cannot make efficient use of multi-homed networks using these two handover technologies alone. For example, in a multi-homed network, a connection may be closed due to a change of IP address when a mobile host switches from one network interface to another. Furthermore, a mobile host cannot automatically select the better path for data transmission at present even if within the coverage overlap area, that is, there is no mechanism to trigger handover if the current network is within range, even if the performance of the overlapping network is superior. Therefore, the development of a technology to allow selection of the path offering the highest performance among the overlapping networks will provide a significant enhancement of wireless connectivity performance, particularly for real-time communication.

In this chapter, a path selection method (PSM) based on active measurement of path performance is proposed to allow path switching in coverage overlap areas. The research platform employed for development of this PSM is the stream control transmission protocol (SCTP) [SXM$^+$00]. The simulation presented in this report demonstrates that PSM provides an appreciable increase in throughput performance for mobile hosts.

3.2 Path Selection Method

In this chapter, a path is defined as a route constructed by a combination of source and destination addresses. One SCTP transport connection may contain multiple paths. Among these paths, the primary path is defined as the path that has been actively chosen for data transmission. The other paths are called backup paths.

3.2.1 SCTP modifications

One major advantage of the SCTP is the multihoming function, which can handle multiple network interfaces and switch between these network interfaces without closing the connection. However, the current implementation of the SCTP cannot provide real-time communication, although real-time support is part of the final implementation. Therefore, it is necessary to modify the SCTP to support real-time communication for this study. The modifications are to (i) disable the congestion control mechanism and the acknowledgment mechanism for data packets, and (ii) periodically send HEARTBEAT packets to all paths. The congestion control and acknowledgment mechanisms are provided in the current SCTP implementation as an optimization for non-real-time communication. As these mechanisms obstruct real-time communication, they are disabled for the present simulation. The second modification is related to path reachability tests. The two kinds of reachability tests used in the current SCTP are an acknowledgment mechanism for data packets and a HEARTBEAT mechanism involving two special control packets, HEARTBEAT (HB) and HEARTBEAT acknowledgment (HB-ACK) packets. In the HEARTBEAT mechanism, the host periodically sends an HB packet to backup paths, and the corresponding host sends back an HB-ACK packet as soon as it receives the HB packet. On the primary path, the acknowledgment mechanism is used instead of the HEARTBEAT mechanism. As the acknowledgment mechanism for data packets was omitted by the first modification, the HEARTBEAT mechanism is used instead to test reachability for the primary path. Note that the sending interval for HB packets (H) is adjusted to allow sensitive tests of reachability for each path. The interval H is calculated by

$$H = HB.Interval \times (1 + \delta), \tag{3.1}$$

where $HB.Interval$ is a constant, and δ is a random value uniformly distributed between -0.5 and 0.5 to represent the fluctuation of loads of computers or networks.

3.2.2 PSM Algorithm

To select the path offering the highest available performance in a coverage overlap area at a given time, in this case focusing on real-time communication, two measurement factors are introduced: Round Trip Time (RTT), bottleneck bandwidth (BBW).

RTT reflects the degree of congestion and the packet loss rate on a path. In the proposed method, the mobile host measures the RTT using HB and HB-ACK packets. However, as RTT fluctuates sensitively, the concept of a smoothed RTT ($SRTT$) is introduced [Off81]. $SRTT$ is the exponential weighted moving average of RTT and is given by

$$SRTT = \alpha SRTT + (1 - \alpha) \times RTT \quad (0 \leq \alpha \leq 1), \tag{3.2}$$

where a is a smoothing factor with default value of 0.9. When HB or HB-ACK packets are lost, the current value of the retransmission timeout (RTO), which is larger than RTT, is used instead of RTT to indicate the poor condition of the path.

The BBW measurement allows the mobile host to decide which paths are currently providing the bandwidth necessary for real-time communication. In the past, many researchers have studied bottleneck bandwidth measurements [LB01a, Kes91, Bol93, CC96, Pax97, Jac97, LB99, LB01b]. We make use of the packet pair method, which is the basic idea in these methods, as the simplest measurement method for estimating the bottleneck bandwidth. In this method, the mobile host sends two HB packets consecutively, and BBW is calculated from the difference between the arrival times of the two packets (diff-time), as given by

$$BBW = \frac{\text{HB packet size}}{\textit{diff-time}}. \tag{3.3}$$

For this simulation, the HB packet size is fixed at 60 bytes.

Some protocol parameters are also introduced to compare the condition of each path. B_A is the bandwidth required by an application. As an example, in the case of Voice over IP (VoIP), B_A ranges from 24 to 64 kb/s. A coefficient of the required bandwidth (γ) is defined to adjust the operating point for switching paths. The required bandwidth (B_R) is then given by B_A multiplied by γ as follows.

$$B_R = \gamma B_A \quad (1 \leq \gamma). \tag{3.4}$$

The $SRTT$ values of the primary path and the backup paths are denoted $SRTT_p$ and $SRTT_b$, and the BBW values of the primary and backup paths are denoted BBW_p and BBW_b. The $HB.Interval$ is set to 1 s. When hosts compare $SRTT$ values for each path, a margin (ϵ) is employed to adjust the operating point for switching paths. The margin ϵ is a coefficient of the delay comparison, and is greater than one ($\epsilon \geq 1$).

Similarly, a margin (β) is also applied to BWW, representing the coefficient of the bandwidth comparison ($\beta \geq 1$).

The four rules defined to guide the selection of paths for optimum real-time communication performance are as follows.

Rule 1: If only BBW_p satisfies B_R, the mobile host does not switch the primary path.

Rule 2: If only BBW_b satisfies B_R for a period of d seconds, the mobile host switches to the backup path.

Rule 3: If both BBW_p and BBW_b satisfy B_R, the mobile host switches to the backup path according to the satisfaction of one of two conditions over a period of d seconds.
[Condition 1:] $(\beta BBW_p < BBW_b)$
[Condition 2:] $(SRTT_p > \epsilon SRTT_b)$

Rule 4: If neither BBW_p nor BBW_b satisfy B_R, the mobile host switches to the backup path according to the satisfaction of one of two conditions over a period of d seconds.
[Condition 3:] $(\beta BBW_p < BBW_b)$
[Condition 4:] $(SRTT_p > \epsilon SRTT_b)$

The period d serves to define the period in which rules are evaluated for path switching, and should be set sufficiently long to prevent oscillatory switching.

3.3 Simulation and Results

The throughput performance of the proposed PSM is evaluated in simulation involving large fluctuations of the condition of wireless links during handover. The proposed method is implemented on the Network Simulator version 2 (NS-2) [NS2] with an SCTP module [MOD].

3.3.1 Simulation Setting

Figure 4.4 shows the network topology employed for the simulation. The scenario is of mobile host A roaming within an overlap area between an International Mobile Telecommunications-2000 (IMT-2000) network and a Personal Handyphone System (PHS) network. Mobile host A is maintaining real-time communication with fixed host B. Each host supports two different network interfaces (IF1, IF2), with IF1 of the mobile host A to IF1 of fixed host B forming Path 1, and IF2 to IF2 forming Path 2. Each of these paths constitute one SCTP connection. The maximum transmission rate of IF1 for mobile host A is 128 kb/s (PHS), and for IF2 is 384 kb/s (IMT-2000). The transmission rates for the rest of the links are illustrated in Figure 4.4. The application in this scenario is VoIP at 64 kb/s, with unidirectional streaming from mobile host A to fixed host B.

Table 3.1 summarizes the change in bandwidth (BW), link propagation delay (D) and packet loss ratio (PL) in the wireless networks. The protocol parameters are set as follows: $\beta = 2$, $\gamma = 1.2$, $\epsilon = 3$, and $d = 5$.

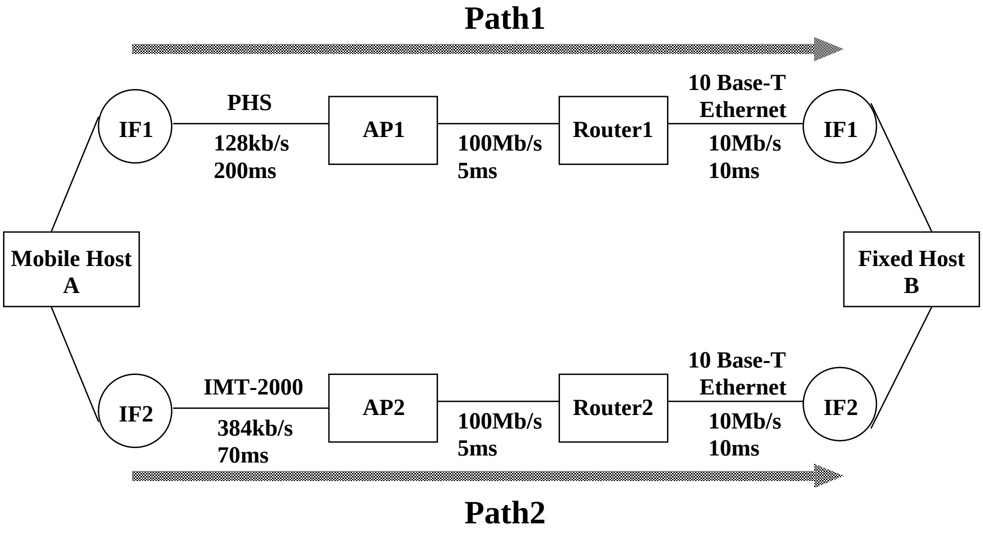

Figure 3.1: Network Topology

Table 3.1: Network Condition

	PHS (Path 1)			IMT-2000 (Path 2)		
Time [s]	BW [kb/s]	D [ms]	PL [%]	BW [kb/s]	D [ms]	PL [%]
0	simulation start					
0.5	128	200	0	384	70	0
20	128	200	0	144	100	1
60	64	300	1	64	120	3
100	32	400	3	64	120	3
300	32	400	3	384	70	1
330	128	200	3	384	70	1
350	simulation end					

3.3.2 Results

Figures 3.2 and 3.3 show the throughput of hosts with and without PSM. Without PSM, the throughput degrades significantly at 100 s due to a decrease in the bandwidth of Path 1 (PHS) to 32 kb/s at that time. However, mobile host A with PSM successfully switches the transmission path to the backup path (Path 2), which provides better performance than Path 1. As a result, mobile host A with PSM is able to maintain the quality of real-time communication by switching the transmission path from Path 1 to Path 2 at about 70 s. This straight-forward comparison demonstrates the effectiveness of the proposed PSM in this situation.

The switching operation is examined in more detail in Figures 3.4 and 3.5, which show the variations in BBW and $SRTT$, respectively. As described in Table 3.1, BBW of Path 1 falls to 64 kb/s at 60 s. As the BBWs of both paths are the same at that time point, mobile host A with PSM is unable to decide which path to select based on the BBW alone. However, the $SRTT$ of Path 1 is larger than that of Path 2 for a period of 5 s (d) to 70 s, at which time mobile host A with PSM switches to Path 2 according to Rule 4.

In this simulation, the average throughput and delay are 43.9 kb/s and 0.574 s for the mobile host without PSM, and 61.7 kb/s 0.364 s for the mobile host with PSM. This corresponds to a 40% improvement in average throughput and a 37% reduction in average delay in this scenario.

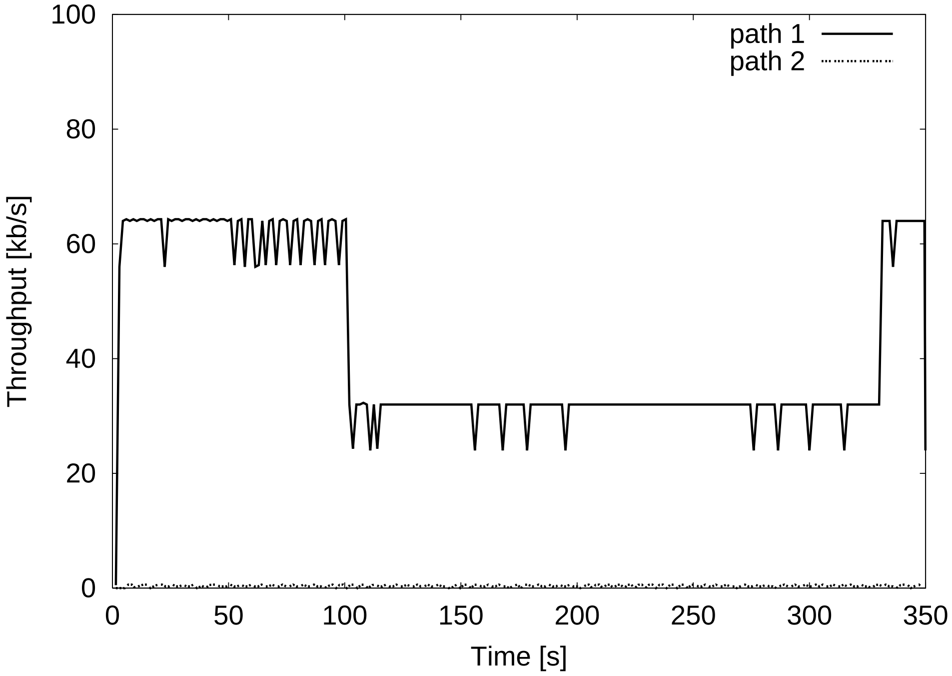

Figure 3.2: Throughput: Without Path Selection Method

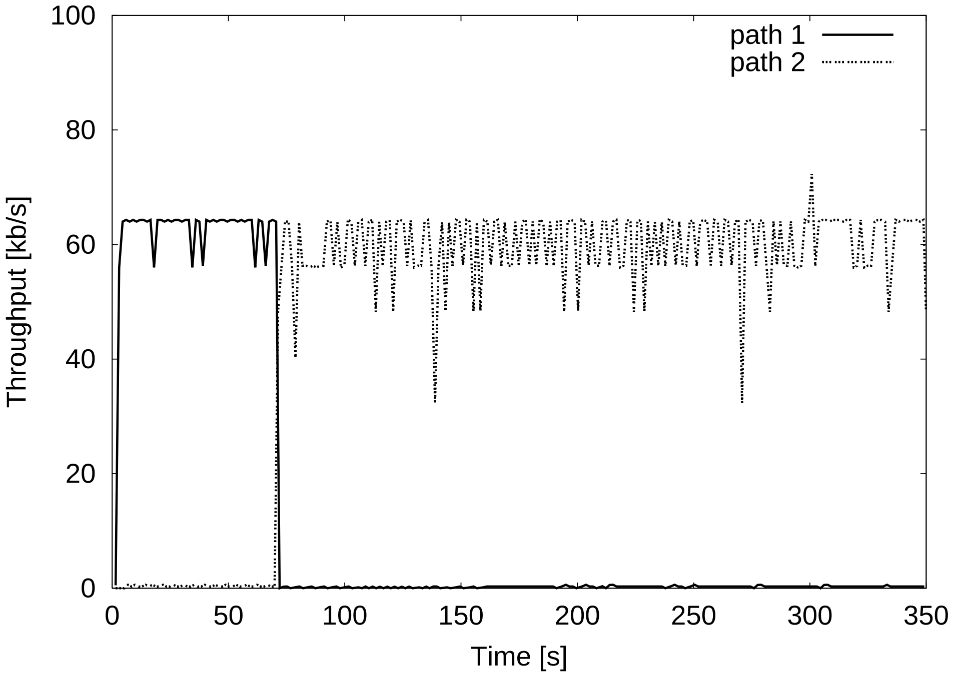

Figure 3.3: Throughput: With Path Selection Method

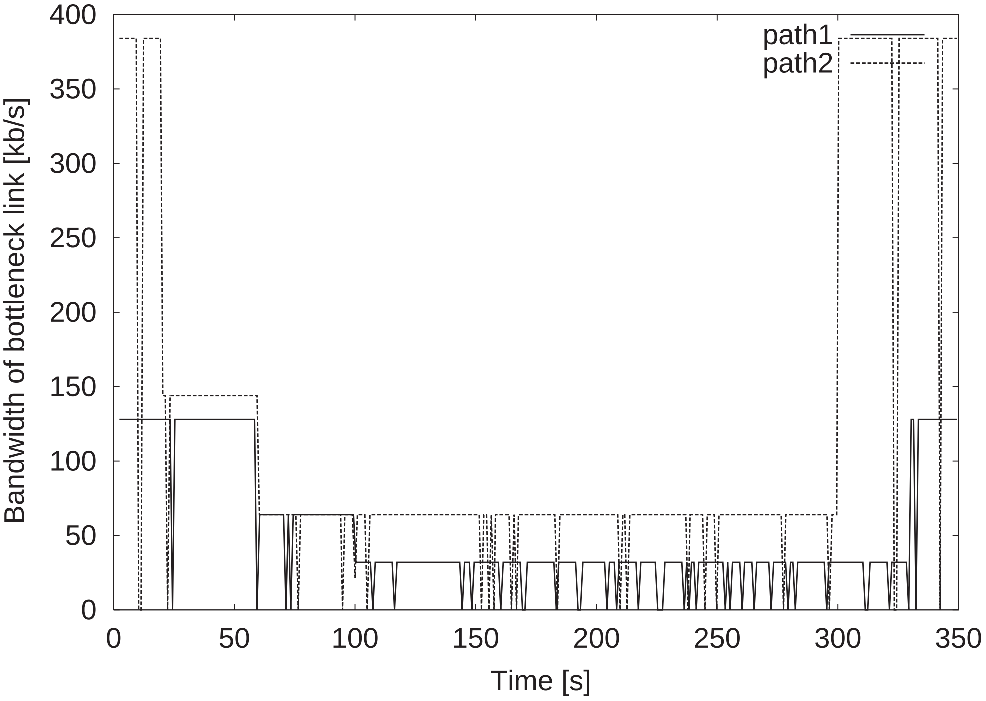

Figure 3.4: Variation in bottleneck bandwidth

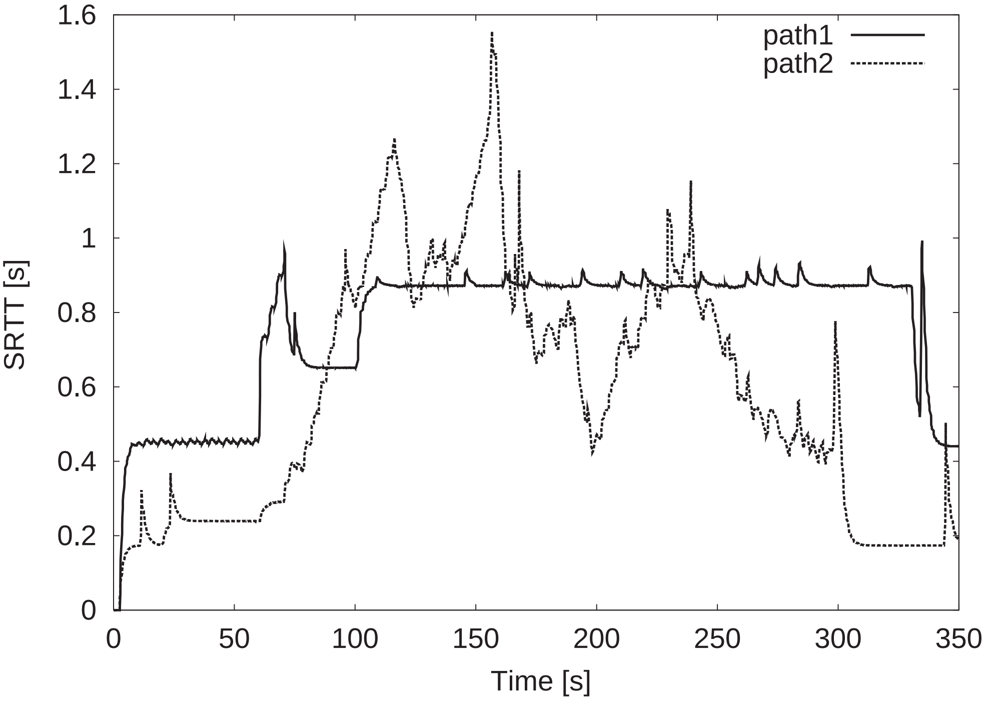

Figure 3.5: Variation in Smoothed RTT

3.4 Summary

A path selection method for coverage overlap areas based on active measurement of path performance was proposed and demonstrated to be effective. The proposed PSM improves network performance for mobile hosts roaming within coverage overlap areas by providing dynamic path selection. This scheme was developed specifically for handover between multiple networks with widely differing coverage area, bandwidth, delay, and packet loss rate. Using a modified SCTP to support real-time communication, path performance is measured using the smoothed round trip time and bottleneck bandwidth measured by a packet pair. The PSM then switches the transmission path according to four rules. Simulation of network performance under conditions of variable congestion demonstrated the effectiveness of the PSM, allowing the path to be switched to a backup path when the primary path could no longer maintain the quality of real-time communication.

Chapter 4

Multi-Path Transmission Algorithm

In future mobile networks, new technologies will be needed to enable a mobile host to move across heterogeneous wireless access networks without disruption of the connection. In the past, many researchers have studied handover in such IP networks. In almost all cases, special network devices are needed to maintain the host's mobility. Moreover, a host cannot move across heterogeneous wireless access networks without degradation of the goodput for real-time communication, although a mobile host with multiple network interfaces can connect to multiple wireless access networks. For these reasons, we consider that a mobile host needs to manage seamless handover on an end-to-end basis. In this chapter, we propose a multi-path transmission algorithm for end-to-end seamless handover. The main purpose of this algorithm is to improve the goodput during handover by sending the same packets along multiple paths, minimizing unnecessary consumption of network resources. We evaluate our algorithm through simulations and show that a mobile host gains a better goodput.

4.1 Introduction

In future mobile networks, Wireless Local Area Network (WLAN) hotspot services will be available at many places including transportation waiting lounges and coffee shops, while cellular services will also exist. Although a cellular service provides a wide coverage area, it is relatively expensive, narrowband, and has unstable connectivity. On the other hand, the WLAN hotspot service is relatively inexpensive, wideband, and has stable connectivity, but its coverage is very limited. In order to improve this environment, we believe new technologies are needed to enable a mobile host to move across heterogeneous wireless access networks that are based on different wireless access technologies and operated by different wireless service providers.

The technology required to maintain a connection during roaming across different networks is called a handover. The major challenge of an effective handover is how to minimize quality degradation such as packet loss and delay. In this chapter, we focus on a seamless handover, to avoid quality degradation that is unacceptable for real-time communications including video streaming and Voice over IP (VoIP).

To accomplish seamless handover, we propose an end-to-end seamless handover mechanism in which a mobile host can roam across heterogeneous wireless access networks. Our approach does not require any special network devices such as the Home Agent (HA) of Mobile IP [CP02a, JPA03]. Instead, the mobile host needs to coordinate with its corresponding host to realize mobility on an end-to-end basis.

In this chapter, we employ the Stream Control Transmission Protocol (SCTP) [SX01, SXM$^+$00] as an end-to-end protocol. SCTP is an appropriate research platform for end-to-end protocols, since it has many functions that have arisen from many years of research in transport protocols. One such SCTP function is multihoming to achieve reliable transport service for VoIP signaling. The multihoming function handles multiple network interfaces for sustaining the reliable transfer of data between two hosts. We make use of this multihoming function for end-to-end seamless handover. However, the current SCTP uses only one of the network interfaces at a time.

Our main contribution in this chapter is to propose a multi-path transmission algorithm. For a seamless handover with minimal consumption of network resources, our algorithm has two modes: single-path transmission mode and multi-path transmission mode. Single-path transmission is the normal mode. If the transmission path becomes unstable, the mode is changed to multi-path transmission to avoid quality degradation. Moreover, if either of the transmission paths becomes stable, the mode returns to single-path transmission to reduce unnecessary consumption of network resources.

This chapter is organized as follows: Section 4.2 describes related work on our end-to-end seamless handover. We give an overview of SCTP and propose a multi-path transmission algorithm in Section 4.3, and evaluate the effectiveness of our algorithm through simulations in Section 4.4. Section 4.5 summarizes the chapter with a description about future work.

4.2 Related Work

Mobile communication technologies in the Internet are being investigated by a number of researchers. Most of this research is classified into network assisting mobility support (NAMS). A list of NAMS is the following: Mobile IP [CP02a, JPA03], Hawaii [RPT$^+$99, CG00], Cellular IP [Val99], and Hierarchical Mobile IP [GJP02]. In NAMS, each mobile host communicates with a network device to handle the location of mobile hosts. Thus, special network devices are needed to maintain states in terms of locations of mobile hosts, causing high deployment and operation costs. This is the reason why some researchers have proposed the notion of end-to-end assisting mobility support (EAMS).

In EAMS, each mobile host coordinates with its corresponding host to maintain mobility of both hosts. Thus, EAMS does not need special network devices to maintain mobility, but needs a special end-to-end protocol. Examples of EAMS are TCP migration [SB00] and Multimedia Multiplexing Transport Protocol (MMTP) [MK01]. TCP migration, which has been proposed by Snoeren et al., is a modification of normal TCP, allowing changes of IP addresses of a mobile host. When a mobile host changes its own IP address, it will send a Migrate SYN packet to notify the change of IP address to its corresponding host. On the other hand, MMTP, which has been proposed by Magalhaes et al., is a novel transport protocol for transferring real-time streaming data on mobile hosts. Due to the nature of wireless links, wireless access networks provide relatively small bandwidth. Therefore, MMTP is designed to aggregate the available bandwidth from multiple channels to create a virtual channel with more bandwidth. However, no existing EAMS supports seamless handover.

A definition of seamless handover appeared in [EN02]: “Ensuring a seamless (or transparent) migration of an element from one domain to another”. The major difficulty of this is how to hide from applications any differences between the service during the migration interval and the normal service. Note that difficulties in seamless handover are also described in the context of the third generation wireless system in [TTL99].

4.3 Multi-Path Transmission Algorithm

First, we define end-to-end seamless handover. Since the conventional terminology of “handover” is assumed as NAMS, the terminological combination of “end-to-end” and “seamless handover” may be confusing. Our definition is this: seamless migration of a mobile host from one network to another in EAMS. Since existing techniques of seamless handover are designed only for NAMS, we need to develop a new technique.

As a key technique, we propose a multi-path transmission algorithm. In our algorithm, a mobile host can switch between multi-path transmission mode and single-path transmission mode to achieve seamless handover with minimal consumption of network bandwidth.

In this section, we describe our multi-path transmission algorithm. First, we explain our motivation for choosing SCTP as the base protocol for end-to-end seamless handover in Section 4.3.1. We then describe modifications to SCTP in Section 4.3.2. Finally, we give a description about our multi-path transmission algorithm in Section 4.3.3.

4.3.1 Motivation for Choosing SCTP

SCTP is a novel transport protocol designed for both reliable and unreliable data transmissions [SXM+00, SX01]. One major advantage of SCTP is its multihoming function. Since this function can handle multiple network interfaces, it will be useful in switching between different wireless network interfaces without closing the connection when one of the wireless links is disconnected. We think the multihoming function will be a basic function to realize seamless handover.

Moreover, an enhancement of SCTP, called ADD-IP [SRX+03], enables a mobile host to dynamically add and/or delete IP addresses without loss of the connection. This function should be used in conjunction with our algorithm. Since our main focus in this chapter is the algorithm, we are not concerned with ADD-IP.

Our terminology related to SCTP is as follows. *Path* is a combination of source and destination addresses. Due to the multihoming function of SCTP, one transport connection may contain multiple paths. Among these paths, *primary path* is the path actively chosen for data transmission. The other paths are called *backup paths.*

4.3.2 Modifications to SCTP

Since the SCTP in RFC2960 provides only reliable data transmission, as does TCP, some modifications for supporting real-time communications are needed by way of implementing unreliable transmission mode. Moreover, to implement seamless handover, we modify mechanisms of failure detection and recovery. Here is a list of modifications to SCTP.

1. Disable the congestion control mechanism and the retransmission mechanism
2. Periodically send HEARTBEAT packets to all paths
3. Change the method of increasing and resetting for the error counter
4. Change the sending interval for HEARTBEAT packets
5. Implement the multi-path transmission algorithm

The first, second and third modifications are for supporting real-time communications. Since the SCTP in RFC2960 is optimized for non-real-time communications, it has a congestion control mechanism and a retransmission mechanism. However, these two mechanisms are obstacles to real-time communication, so that disabling them is the first modification. After the first modification, we also need the second, third and fourth modifications.

In RFC2960, there are two ways of failure detection: a data/acknowledgment packet, and a HEARTBEAT/HEARTBEAT Acknowledgment (HEARTBEAT-ACK) packet. Since we disabled the data packet retransmission mechanism in the first modification, our failure detection mechanism relies only on the HEARTBEAT mechanism. We next explain the HEARTBEAT mechanism.

Hosts periodically send HEARTBEAT packets to each other to investigate reachability. After the corresponding host receives a HEARTBEAT packet, it sends back a HEARTBEAT-ACK packet to the sender host. Since HEARTBEAT packets are only sent to backup paths in RFC2960, the primary path's reachability is not tested by the HEARTBEAT mechanism. Therefore, our modification is that a host sends HEARTBEAT packets to all paths. The second modification is for reachability testing of the primary path.

Moreover, a host maintains parameters called error counters that are a metric of reachability for each path. In RFC2960, the error counter for a path is increased by 1 when data sent through the path is timed out. Conversely, the error counter is reset to 0 when a host receives an acknowledgment packet. However, this condition cannot appropriately give changes of reachability for each path in a wireless access network environment. We then change the method of increasing and resetting the error counter, as the third modification:

- When a host sends a HEARTBEAT packet along the path, the error counter for the path is increased by 1.
- When a host receives a HEARTBEAT-ACK packet along the path, the error counter for the path is reset to 0.

For the fourth modification, we use our HEARTBEAT interval (H) calculation, which is given by

$$H = HB.Interval \times (1 + \delta) \tag{4.1}$$

where $HB.Interval$ is a constant, and δ is a random value, uniformly distributed between -0.5 and 0.5, to reflect a fluctuation of loads in computers and networks.

The fifth modification is our key proposal. We describe it in the following section.

4.3.3 Multi-Path Transmission Algorithm

In this section, we describe our multi-path transmission algorithm for end-to-end seamless handover. In wireless access networks, there are many packet losses which degrade the quality of real-time communication, so that more redundant packet transmission is one possible implementation of seamless handover. However, redundant packet transmission consumes network resources; thus, we need to minimize unnecessary packet transmissions. In order to achieve these two contradictory goals, we provide two modes: a single-path transmission mode and a multi-path transmission mode. The mode will change according to packet loss occurrences in the path for seamless handover, with only a small consumption of network resources.

When the quality of the primary path is degraded significantly, the host switches its transmission mode to the multi-path transmission mode. In this mode, the sender host sends the same packet to two paths simultaneously. One of these is the primary path, and the other is one of the backup paths. If either of the paths becomes stable, the sender chooses the stable path as the new primary path and switches back to single-path transmission.

Figs. 4.1 and 4.2 illustrate pseudo codes which represent a part of our algorithm in sending HEARTBEAT packets and receiving HEARTBEAT-ACK packets, respectively. The algorithm in sending HEARTBEAT packets is executed for each path at every interval of H that is calculated by Eq. (4.1). The timing of execution is different for each path. The algorithm in receiving HEARTBEAT-ACK packets is executed when a host receives a HEARTBEAT-ACK packet.

Our algorithm relies mainly on an error counter as an indicator to switch to the multi-path transmission mode. As we described above, an error counter is a metric of packet loss occurrences for each path. There is a threshold for the error counter called $Path.Max.Retrans$ (PMR), to indicate that the path is inactive due to some network trouble. If the primary path becomes inactive, a host uses one of the backup paths as the primary path. In addition to this threshold, we provide *Multi-Path.Threshold* (MT) as a new threshold. MT is a threshold for the error counter to switch from the single-path transmission mode to the multi-path transmission mode. This process is shown in Fig. 4.1. Note that MT must be smaller than PMR.

To switch back to the single-path transmission mode, we provide a stability counter for each path and *Stability.Threshold* (ST) as, respectively, a new counter and a new threshold. The stability counter is used only in the multi-path transmission mode. The initial value of the stability counter is 0. The stability counter is increased by 1 when two consecutive HEARTBEAT packets are acknowledged. To confirm this, we provide slight modifications to HEARTBEAT and HEARTBEAT-ACK packets to incorporate a sequence number. When the stability counter exceeds ST, which means the path has become stable, the host then switches back to single-path transmission mode, shutting down the operation of the stability counter. The stability counter is maintained in both paths currently in use, choosing the better path when the mobile host switches to single-path transmission mode. The reset condition of the stability counter is when two consecutive HEARTBEAT-ACK packets cannot be received. This process is illustrated in Fig. 4.2.

```
[Primary path]
  send(HB);
  ErrorCount++;
  if (ErrorCount >= MT) {
        mode = MultiPath;
  } else if (ErrorCount >= PMR) {
        state = inactive;
  }

[Backup paths]
  send(HB);
  ErrorCount++;
  if (ErrorCount >= PMR) {
        state = inactive;
  }
```

Figure 4.1: Pseudo Code in Sending HEARTBEAT Packets

```
[All paths]
  receive(HBack);
  if (mode == SinglePath) {
       ErrorCount = 0;
  } else if (mode == MultiPath) {
       ErrorCount = 0;
       if (seqnum == HBack_seqnum - 1) {
            StabilityCount++;
            if (StabilityCount >= ST) {
                 mode == SinglePath;
            }
       } else {
            StabilityCount = 0;
       }
  }
  seqnum = HBack_seqnum;
```

Figure 4.2: Pseudo Code in Receiving HEARTBEAT-ACK Packets

4.4 Simulation Experiments

In this section, we do simulation experiments to get some basic evaluations. The base simulator used to implement our algorithm is the Network Simulator version 2 (NS-2) [NS2] with SCTP module [MOD]. In Section 4.4.1, we give a description of our simulation models, including the mobile scenario and network topology. We then show the simulation results of our algorithm in Section 4.4.2. In Section 4.4.3, we show another simulation results using parameters selected in Section 4.4.2.

4.4.1 Simulation Setting 1

Since our objective is seamless handover, we consider the following scenario as shown in Fig. 4.3. Mobile host A has two different wireless network interfaces: IMT-2000 as a cellular service and IEEE 802.11b as a WLAN hotspot service. At first, mobile host A is only within the IMT-2000 service area. After the simulation starts, it moves towards the WLAN Hotspot service area. Time lines of all the simulations follow Fig. 4.3. The simulation start time is 0 s. Between 15 s and 45 s, mobile host A is within the overlapping area. The simulation ends at 60 s.

We next show our network topology in Fig. 4.4. Mobile host A communicates with corresponding fixed host B. These hosts have two network interfaces, IF1 and IF2, respectively. IF1 of mobile host A and IF1 of fixed host B form Path1. Similarly, IF2 of mobile host A and IF2 of fixed host B form Path2. Both paths are contained by one SCTP connection. The network capacity of IF1 of mobile host A is 384 kb/s due to the assumption of IMT-2000, whereas that of IF2 is 11 Mb/s due to the assumption of 802.11b. On the other hand, since both network interfaces of fixed host B are assumed to be Ethernet, the network capacity is 10 Mb/s. The moving speed of mobile host A is walking velocity. When mobile host A enters the overlapping area of two wireless access networks, the packet loss rate of IF1 increases linearly whereas that of IF2 decreases linearly as a function of time, as illustrated in Fig. 4.3. Our assumed application is real-time video streaming at a rate of 300 kb/s. The streaming is uni-directional from mobile host A to fixed host B.

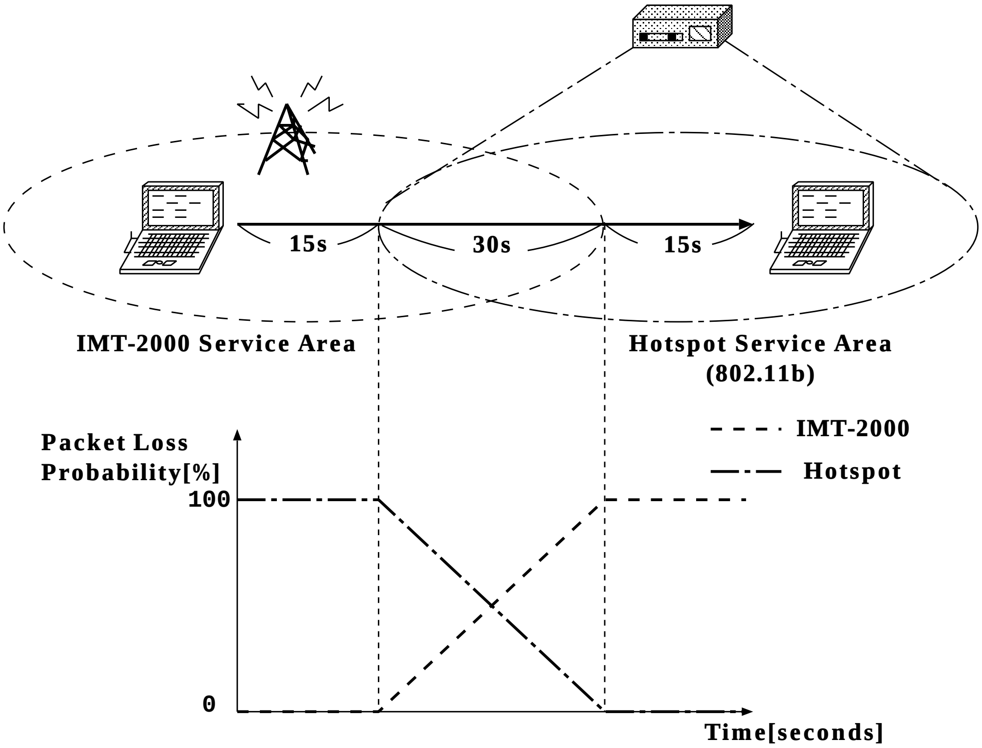

Figure 4.3: Mobile Scenario

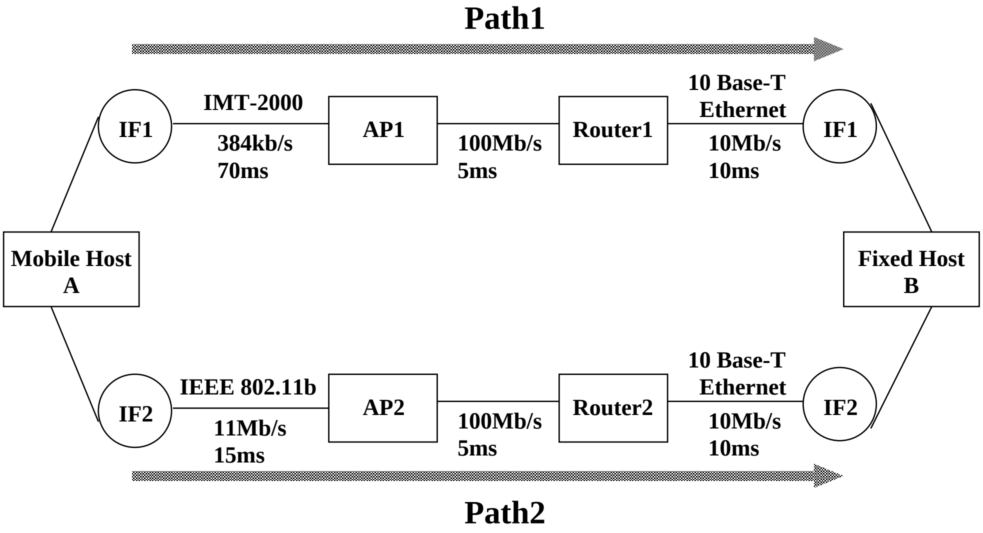

Figure 4.4: Network Topology

4.4.2 Results

In this section, we give some simulation results including parameter selection and performance comparisons. First, we select parameters for SCTP with the Multi-path Transmission Algorithm (MTA). These parameters are selected according to requirements. We then compare performance between SCTP with MTA and SCTP without MTA.

Parameter Selection for SCTP with MTA

As listed in Table 4.1, SCTP with MTA has three parameters, $HB.Interval$, MT and ST. Moreover, it has three important performance metrics: goodput, total multipath transmission period, and communication overhead caused by data packets and/or HEARTBEAT packets. In this section, we investigate the relationship among these parameters and performance metrics, and discuss parameter selection.

We first would like to determine $HB.Interval$, to simplify the rest of the discussion. The communication overhead caused by HEARTBEAT packets can be calculated from the following equation,

$$\text{Overhead} = \frac{\text{HEARTBEAT packet size} \times 8}{HB.Interval}, \tag{4.2}$$

where the HEARTBEAT packet size is a constant 60 Bytes. Therefore, this metric is only affected by the $HB.Interval$. If we choose 0.1 s as the $HB.Interval$, the communication overhead for each path becomes 4.8 kb/s, which is unlikely to be an acceptable value.

Fig. 4.5 shows goodput as a function of ST. The MT value is set to 3. Goodput is the total number of bytes received by the receiver when a mobile host is in the overlapping area. The purpose of this figure is to find a good value for the $HB.Interval$. From Fig. 4.5, we can see that a small value for the $HB.Interval$ gives us high goodput. For example, if we select 0.3 s as $HB.Interval$ value, this results in a communication overhead of 1.6 kb/s for each path. This would be acceptable in the IMT-2000 environment at a rate of 384 kb/s. Note that the simulation results listed in this section are average values from 100 experiments for each set of parameter values.

We then select values for MT and ST. First, we investigate the relationship between these parameters and performance metrics. Figs. 4.6 and 4.7 show goodput and total multi-path transmission period as a function of ST when the $HB.Interval$ is set to 0.3

s. From Figs. 4.6 and 4.7, goodput is high when MT is set to 1, but the communication overhead is also high due to a long multi-path transmission period. Moreover, as ST increases, goodput becomes high, but the communication overhead also becomes high. We explain the reason for this relationship. If MT is small, the mobile host switches to multi-path transmission mode as soon as the primary path becomes unstable. This makes goodput higher, but the communication overhead also increases. On the other hand, if ST is small, the mobile host switches back to single-path transmission mode as soon as one of the paths becomes stable even for a moment. This makes the communication overhead low, but also makes goodput low. Also, the number of mode changes increases as shown in Fig. 4.8. That is, MT and ST should be determined in consideration of a tradeoff between goodput and the communication overhead. In this chapter, we also focus on reducing the communication overhead. To decrease the communication overhead, we select 3 as MT.

We next try to optimize ST to minimize the communication overhead. For example, if we keep the total multi-path transmission period within 15 s, the range of ST from 1 to 9 satisfies the condition in Fig. 4.7. In another example, if we keep the total multi-path transmission period within 10 s, the range of ST from 1 to 4 satisfies the condition. To achieve high goodput, we select 4 if wish to keep the total multi-path transmission period within 10 s.

Table 4.1: Simulation Parameters for SCTP with MTA

HB.Interval	0.1, 0.3, 0.5s
Multi-Path.Threshold	1, 2, 3
Stability.Threshold	1–10

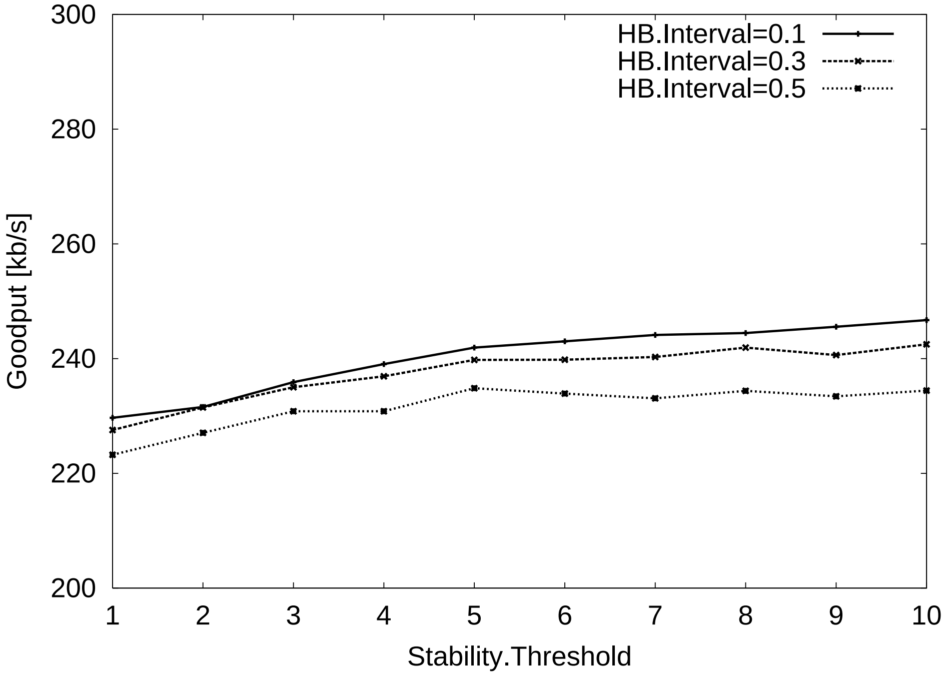

Figure 4.5: Goodput versus *Stability.Threshold* and *HB.Interval*

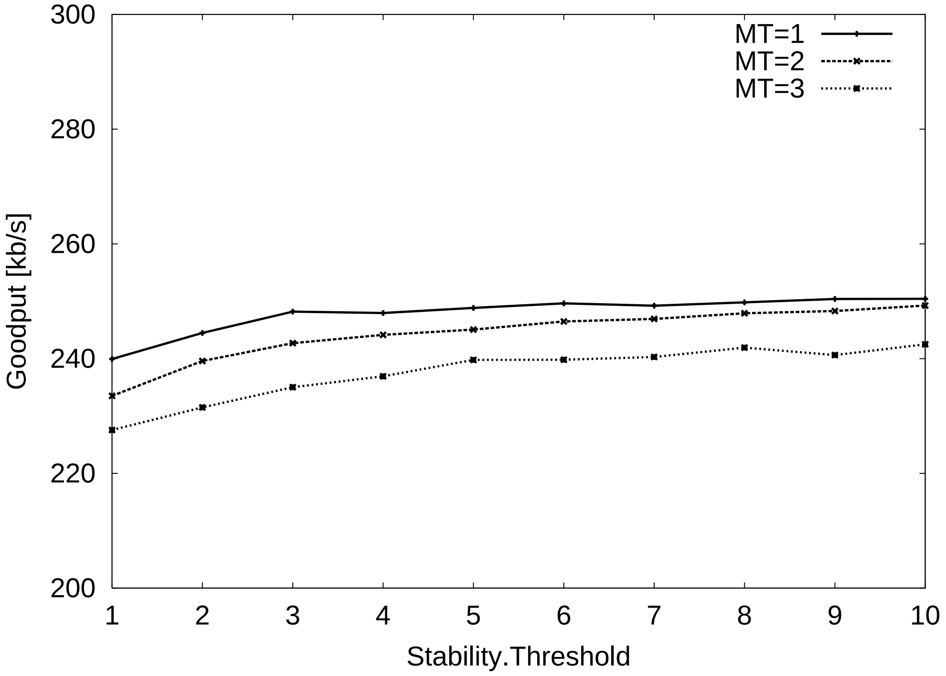

Figure 4.6: Goodput versus *Stability.Threshold* and *Multi-Path.Threshold*

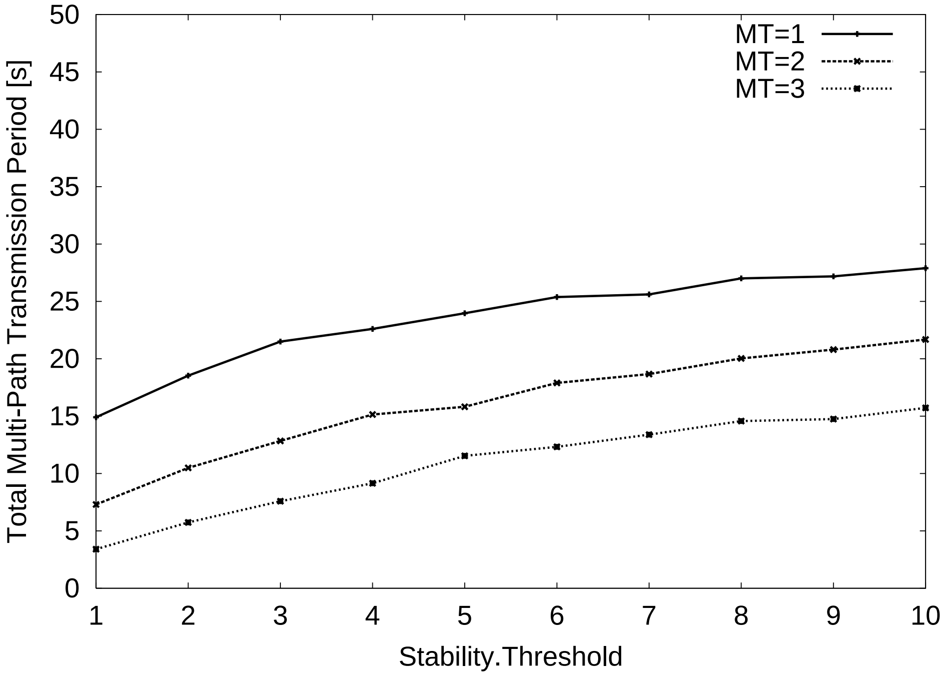

Figure 4.7: The Total Multi-Path Transmission Period versus $Stability.Threshold$ and $Multi\text{-}Path.Threshold$

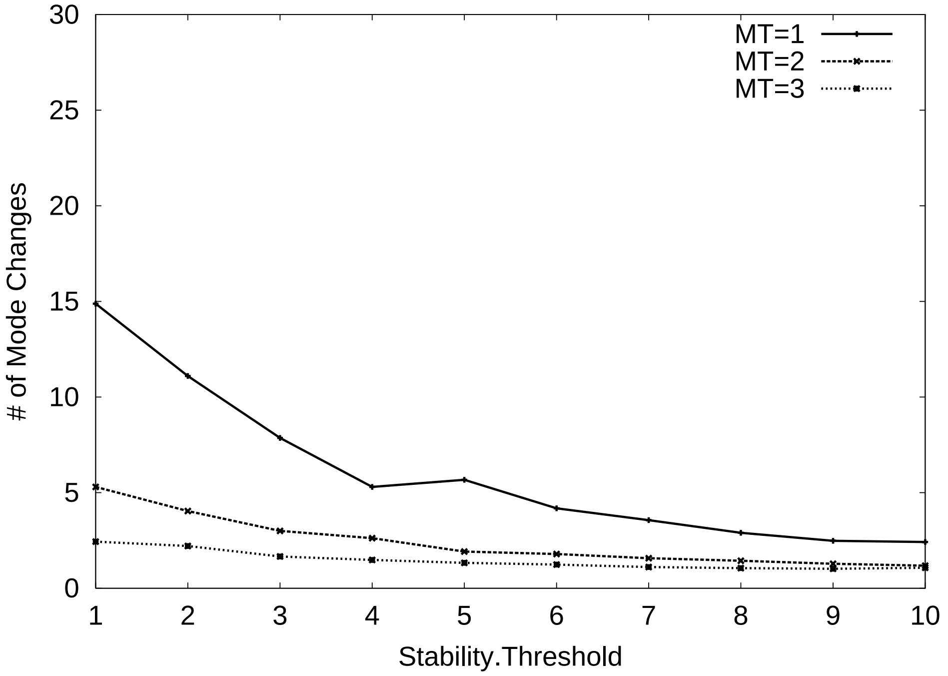

Figure 4.8: The Number of Mode Changes versus *Stability.Threshold* and *Multi-Path.Threshold*

Comparisons

We compare goodput for SCTP with and without MTA. Table 4.2 shows the parameter values for SCTP with and without MTA. The parameter value for SCTP with MTA follows the results of parameter selection in the previous section. On the other hand, in SCTP without MTA, we similarly choose 0.3 s as $HB.Interval$. Then, we choose 3 as PMR, which is the threshold to switch to a backup path, because MT in our algorithm achieves the function of PMR.

Figs. 4.9, 4.10, 4.11 and 4.12 illustrate throughput and goodput performance of SCTP with and without MTA, respectively. Fig. 4.9 shows there is a time period when both paths are sending packets, while Fig. 4.11 does not have such a period. As a result, goodput performance of SCTP with MTA is better than that of SCTP without MTA. The average goodput of SCTP with MTA is 236.9 kb/s, and that of SCTP without MTA is 218.5 kb/s. The difference between these two values is about 18 kb/s. One thing we would like to emphasize is that Fig. 4.12 includes a period in which goodput is drastically decreased, to less than 100 kb/s, which is not an acceptable performance. On the other hand, SCTP with MTA shows that goodput is kept high (i.e., more than 150 kb/s) at almost all times in Fig. 4.10.

Table 4.2: Selected Parameter Values for SCTP with and without MTA

SCTP with MTA

HB.Interval	0.3
Multi-path.Threshold	3
Stability.Threshold	4

SCTP without MTA

HB.Interval	0.3
Path.Max.Retrans	3

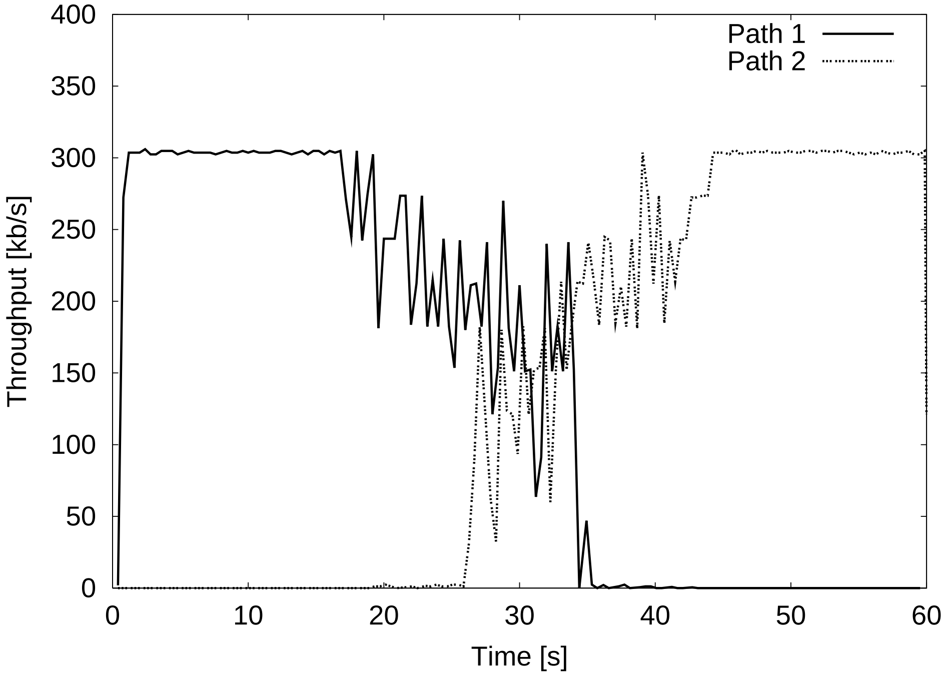

Figure 4.9: Throughput Performance of SCTP with MTA

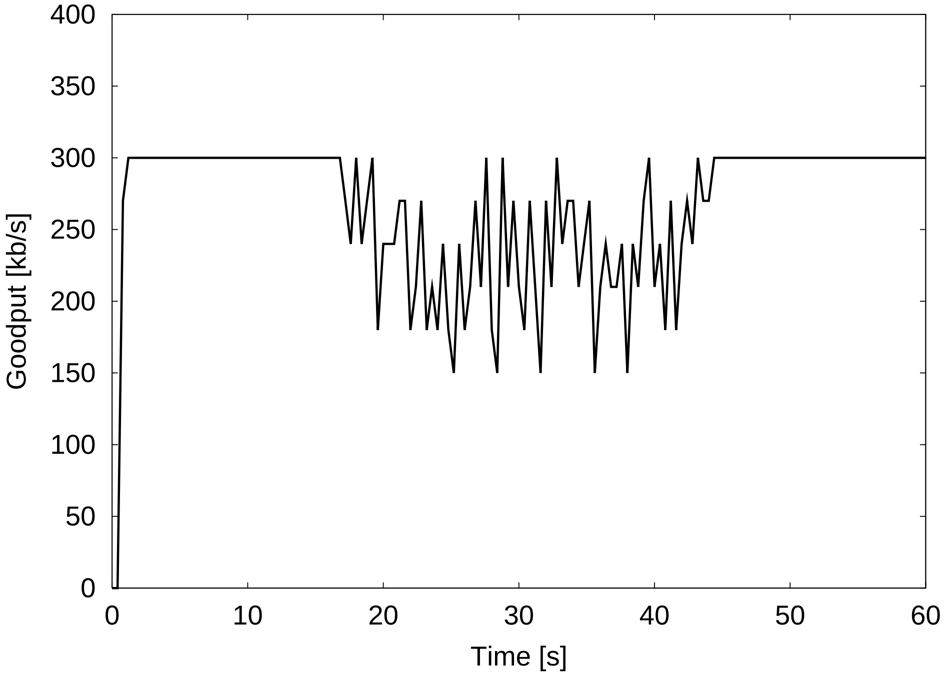

Figure 4.10: Goodput Performance of SCTP with MTA

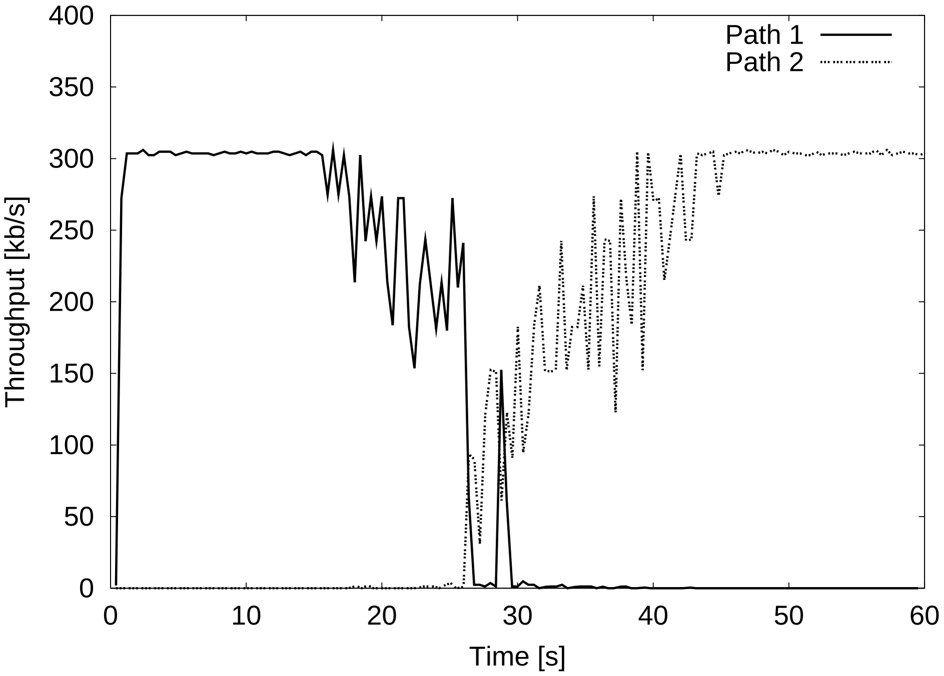

Figure 4.11: Throughput Performance of SCTP without MTA

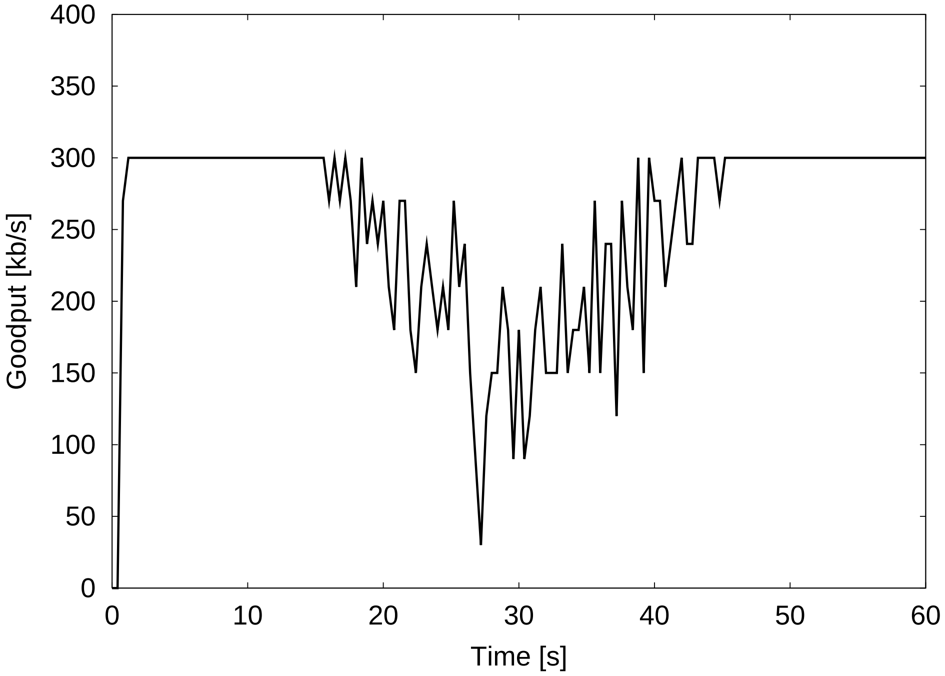

Figure 4.12: Goodput Performance of SCTP without MTA

4.4.3 Simulation Setting 2

Next, we consider a different scenario from section 4.4.1, as shown in Fig. 4.13. The whole WLAN Hotspot service area is included in the IMT-2000 Service Area. Since mobile host A is in the WLAN Hotspot service area, it can connect to both services. At first, mobile host A uses the WLAN Hotspot service area. After the simulation starts, mobile host A moves out of the WLAN Hotspot service area. We do three kinds of simulation. In the first simulation, the connection to the WLAN Hotspot service area is suddenly lost at 15 s (Simulation A). In the second and third simulations, packet loss probability increases between 15 s and 20 s (Simulation B), or between 15 s and 25 s (Simulation C). Our network topology is the same as in Fig. 4.4, and we employ the parameters selected in section 4.4.2.

From Figs. 4.14 and 4.15, we can see that mobile host A switches to another path within 1 s when the path is lost suddenly, because mobile host A can detect the network trouble within $MT \times HB.Interval$. Thus, although the communication is interrupted for a moment, it is not lost. In Figs. 4.16, 4.17, 4.18, and 4.19, when mobile host A detects the network trouble, mobile host A switches to multi-path transmission to prevent degradation of goodput. As a result, mobile host A can keep high goodput.

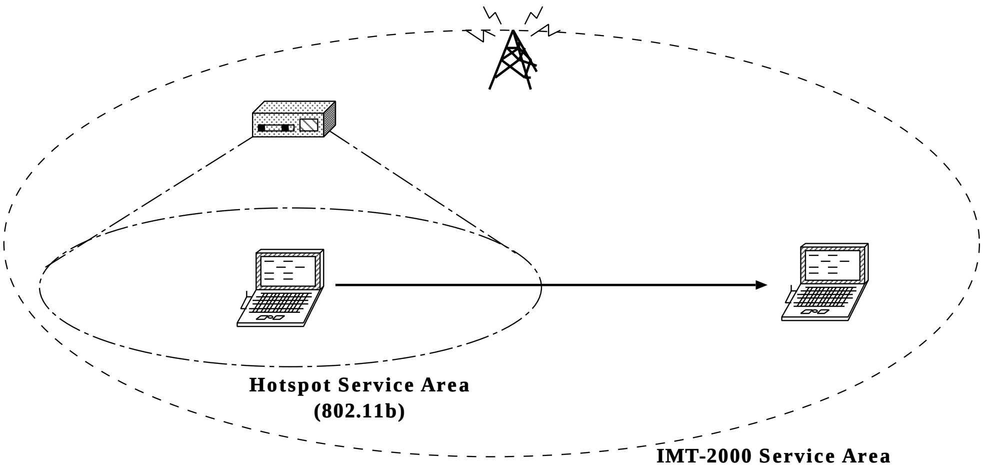

Figure 4.13: Mobile Scenario 2

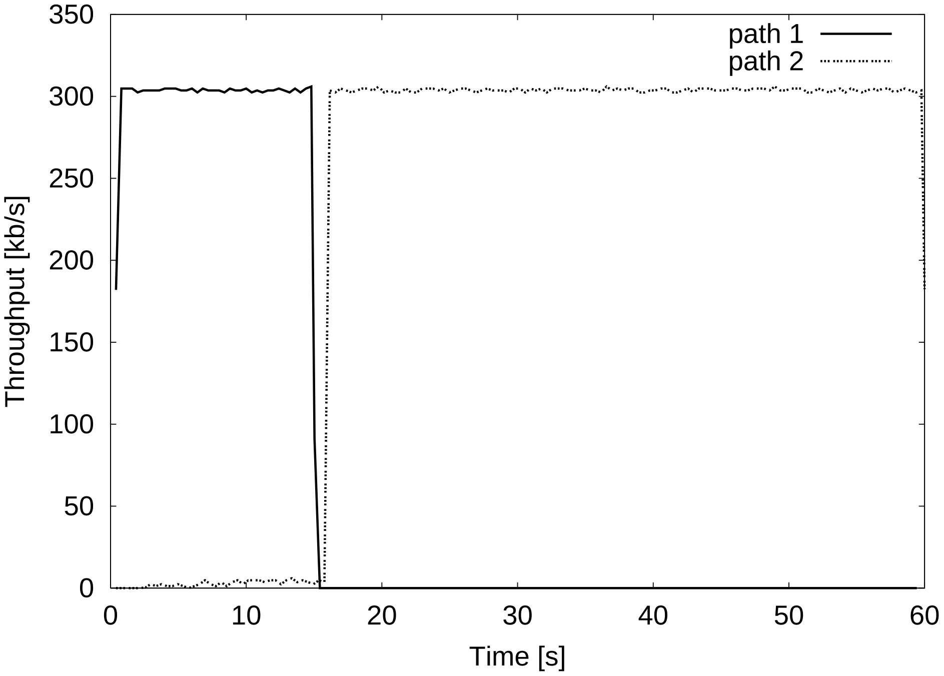

Figure 4.14: Simulation A: Throughput

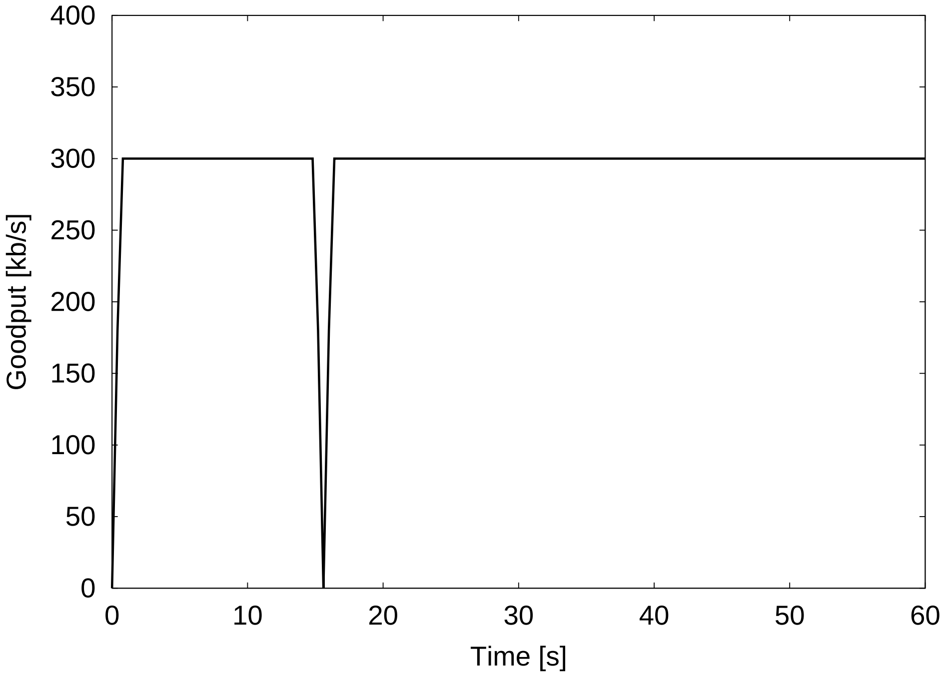

Figure 4.15: Simulation A: Goodput

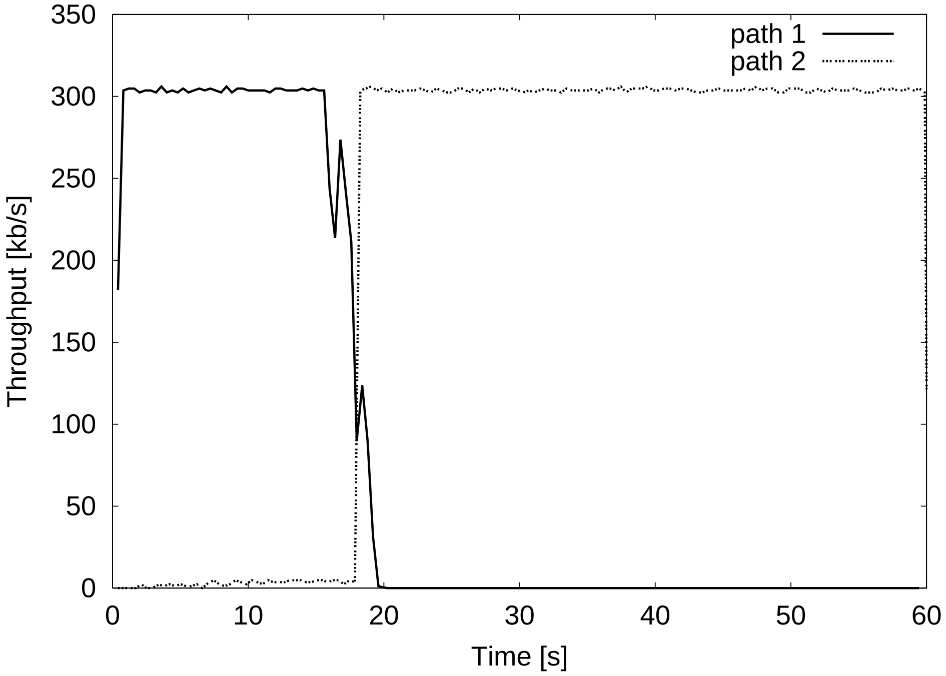

Figure 4.16: Simulation B: Throughput

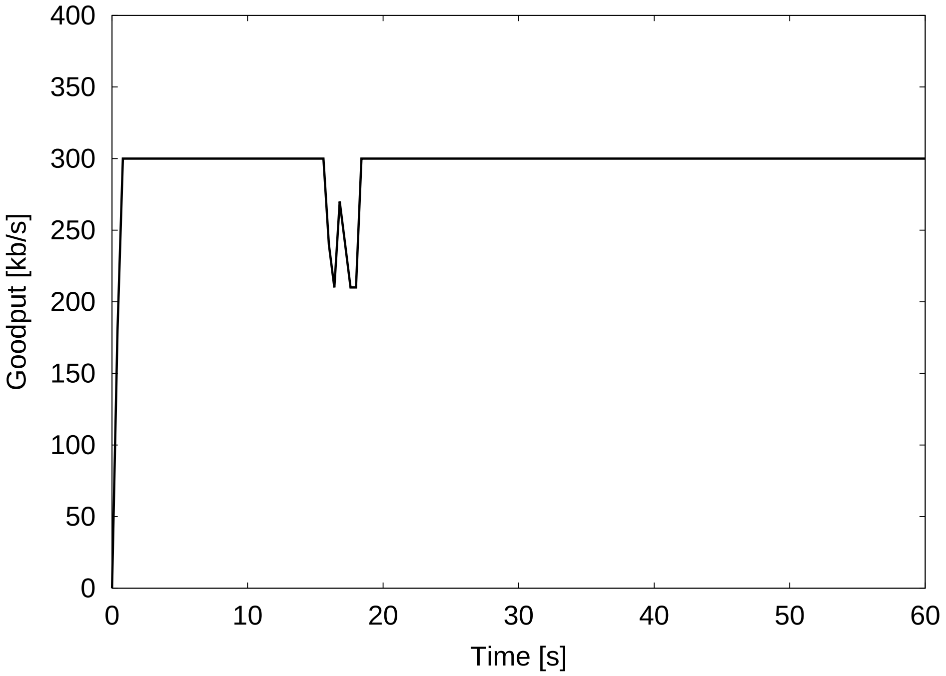

Figure 4.17: Simulation B: Goodput

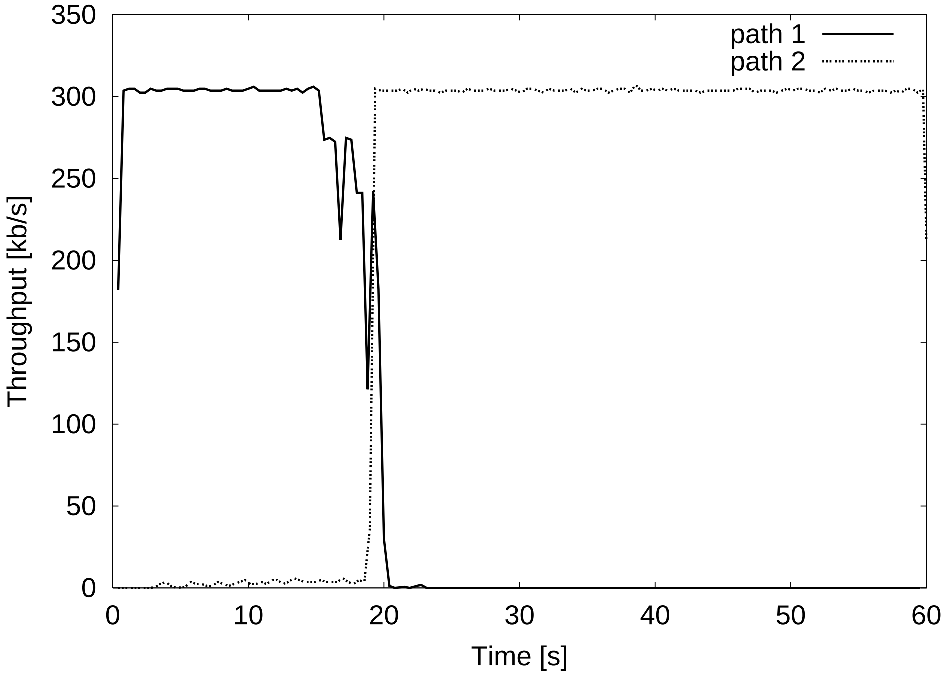

Figure 4.18: Simulation C: Throughput

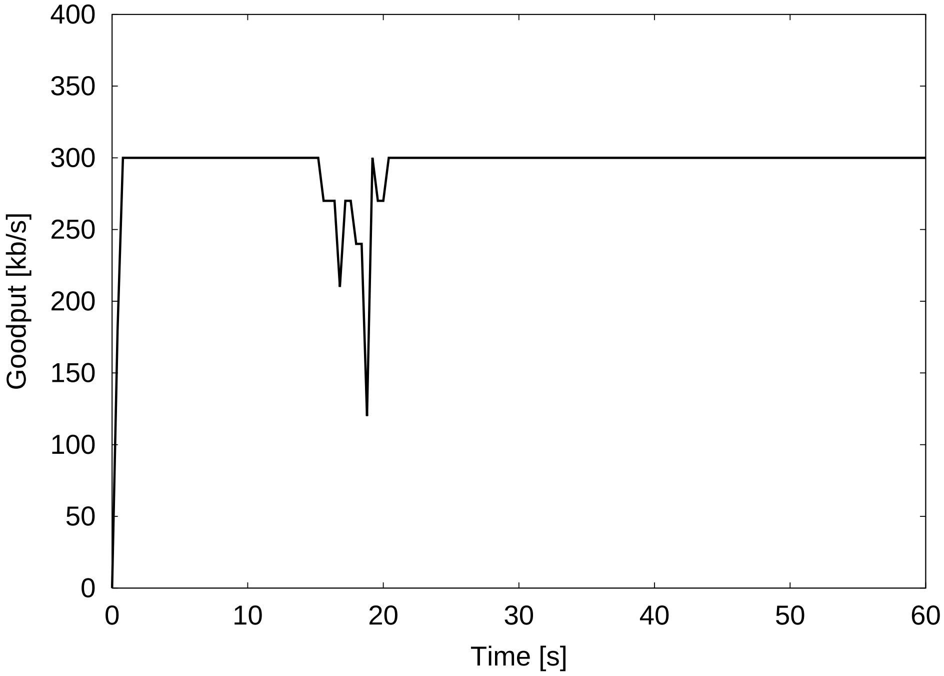

Figure 4.19: Simulation C: Goodput

4.5 Summary

In this chapter, we have proposed a multi-path transmission algorithm (MTA) for end-to-end seamless handover across heterogeneous wireless access networks. The aim of the MTA is to improve goodput during handover by implementing an end-to-end assisting handover. To realize our algorithm, we have modified SCTP, which can handle multiple network interfaces. In the MTA, there are two modes: single-path and multi-path transmission modes. If a mobile host detects that the network condition of the primary path has become unstable, it switches to multi-path transmission mode to avoid quality degradation, and sends the same packets to multiple paths simultaneously. After that, if either of the transmission paths becomes stable, the mobile host switches back to single-path transmission mode to reduce unnecessary consumption of network resources. Through simulations, we have selected the parameters of our algorithm, and derived a set of recommend values. Finally, we have shown that our multi-path transmission algorithm gives us high goodput while limiting unnecessary consumption of network resources.

Chapter 5

Conclusions and Future Work

5.1 Lessons Learnt

The main theme of this dissertation is how a mobile host moves across different wired and wireless networks while keeping real-time communication quality on an end-to-end basis. The Internet is currently built on a number of different wireless and wired networks, and these networks are expanding and beginning to overlap. A mobile host with multiple network interfaces, i.e., multi-homed hosts, demands to move across these different networks without losing the communication. To achieve this, there are two approaches: Network Assisting Mobility Support (NAMS) and End-to-end Assisting Mobility Support (EAMS). In NAMS, each mobile host communicates with some special network devices to maintain a mobile host's mobility. On the other hand, in EAMS, each mobile host needs special end-to-end protocols for maintaining its mobility, although it does not need any special network devices. NAMS has some unappealing characteristics: limited performance and additional complexity for the network. Thus, we employ EAMS to manage a host's mobility. Moreover, from a different point of view, we introduced solutions for mobility management at each layer. To manage a host's mobility on an end-to-end basis, it is appropriate to propose new methods at the transport layer. We employed SCTP with DAR, as a research platform, to enable a mobile host to move across different networks without losing communication.

In this dissertation, to provide methods to enable a mobile host to move across different networks, we first proposed an adaptive selection algorithm to select a network with good condition in Chapter 3. A mobile host needs to know a bottleneck link bandwidth to keep a required bandwidth for real-time communication. In wireless networks, the link between a mobile host and its base station tends to be a bottleneck link. To investigate the bottleneck link bandwidth, a mobile host sends two probe packets consecutively and calculates bottleneck link bandwidth from the difference between the two packets' arrival time. In addition, to further improve the quality of real-time communication, a mobile host measures Round Trip Time (RTT). A mobile host decides whether or not to use a network from these metrics. As a result, a mobile host can move across different networks while maintaining quality of real-time communication.

In addition, we proposed a Multi-path Transmission Algorithm (MTA) to improve goodput during vertical handover. In this algorithm, when a mobile host detects that the network condition of the data-transmitting path becomes unstable, the transmission mode is switched to multi-path transmission mode to avoid quality degradation, and the mobile host sends the same packets to multiple paths simultaneously. After that, when either of the data-transmitting paths becomes stable, the mobile host switches back to single-path transmission mode to reduce unnecessary consumption of network resources. A mobile host with MTA can move across different networks while maintaining quality of real-time communication.

In this dissertation, we show that it is possible to solve vertical handover with keeping real-time communication quality on an end-to-end basis using a multihoming function. A transport layer protocol that provides a multihoming function, as SCTP does, is a natural candidate for supporting such a host's mobility management. Hereafter, to achieve complete mobility management, many mobility management methods need to supplement the shortcomings of individual mobility management methods.

5.2 Summary of the contributions

This dissertation has made a number of contributions to the area of mobility management, especially vertical handover. We summarize the major contributions in this section.

- The necessity of a multihoming function

  The Internet is built on a number of different wireless or wired networks. If a mobile host has multiple network interfaces (i.e., is a multi-homed host), it can connect to the Internet, any time and anywhere. Moreover, a mobile host with a multihoming function which handles multiple network interfaces (i.e., many IP addresses) demands to move across these different networks without losing communication. This function is needed to move between different wireless and wired networks without connection closure.

- Vertical handover on an end-to-end basis

  Currently, solutions on network layer protocols, such as Mobile IP, are believed the most suitable protocol for a host's mobility management. However, in host's mobility management on a network layer, a mobile host needs special network devices to continue communication in the network. These approaches have some unappealing characteristics: limited performance and additional complexity for the network architecture. Because of this, we proposed vertical handover on an end-to-end basis at the transport layer, which is the lowest layer to support end-to-end services. This does not need any special network devices to enable a mobile host to move across different wireless and wired networks.

- Path selection using active measurements

  To keep better real-time communication quality, a mobile host needs to select a path with good condition in multi-homed networks. However, although each network has different features in terms of bandwidth, packet loss, delays and jitters, a mobile host does not have any methods to select a path with good condition. We have proposed a path selection method to switch to a path with good condition using active measurements: bottleneck bandwidth and Round Trip Time (RTT). A mobile host selects a path with good condition according to four rules which compare bottleneck bandwidth and RTT on each path.

- Improvement of goodput within multi-homed networks

  A mobile host connects to wireless and wired networks. At this time, if a network which is used to transmit data becomes unstable, the mobile host needs to keep real-time communication quality. In this case, the mobile host wants to use another network effectually. To improve goodput within multi-homed networks, we proposed that a mobile host sends redundant packets to a corresponding host. If the mobile host detects that the network condition of the data transmitting path becomes unstable, it sends the same packets to multiple paths simultaneously. After that, when either of the data transmission paths becomes stable, the mobile host sends packets to only that path which is stable, to reduce unnecessary consumption of network resources. This proposed method improves goodput with minimal communication overhead in unstable multi-homed networks.

5.3 Future Work

- Location management
  To connect to mobile hosts, location management technology is important. At present, Mobile IP is the appropriate protocol for location management technology. In Mobile IP, whenever a mobile host changes an IP address, it informs its Home Agent of the change. However, some researchers have reported problems about preparation of Home Agent and Home Address, and about firewalls [IIOT98]. Although another approach, although Dynamic Domain Name System (Dynamic DNS) [ETRB97], could be used, Dynamic DNS also has some problems about update intervals, security and scalability.

- Cooperation with other layers
  In this dissertation, a mobile host makes use of active measurement of a transport layer to investigate network condition. However, in wireless networks, almost all unstable points are wireless links between a mobile host and its base station. To detect changes in network condition sensitively, a mobile host needs to make use of radio wave strength. Cooperative measurement of a transport layer and the signal strength of a physical layer enables mobile hosts to detect changes in network condition sensitively.

- Cost
  In some networks, a mobile host must pay a charge for every packet. When a mobile host moves across various kinds of networks, users want to keep such expenses to a minimum. For example, although WLANs such as hotspot services are cheap, cellular services are relatively expensive. A method to keep expenses low while maintaining communication quality is needed, so that a mobile host can set up preferences to use a low-expense network. According to this preference

and the network condition, a mobile host needs to be able to move across these different networks.

- Routing
  In the current architecture, a mobile host must send packets through a default gateway. Once a mobile host selects a default gateway, it keeps using the default gateway until either it changes the default gateway or the default gateway is disconnected. However, in a multihoming environment, since they connect with multiple networks, hosts need to have a mechanism to automatically switch a default gateway to send packets.

- Authentication
  To enable a mobile host to move across different networks, some problems about authentication and security [VN03] must be overcome. Service providers' billing and authentication systems are sometimes incompatible. This means that two otherwise compatible implementations using different handover methodologies may not be able to communicate.

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Appendix A

List of Publications

A.1 Journal

1. Shigeru Kashihara, Katsuyoshi Iida, Hiroyuki Koga, Youki Kadobayashi and Suguru Yamaguchi, “Multi-path Transmission Algorithm for End-to-End Seamless Handover across Heterogeneous Wireless Access Networks,” IEICE Transaction on Communication, March 2004 (To appear).

A.2 International Conference

1. Toshiyuki Kubo, Shigeru Kashihara, Katsuyoshi Iida, Youki Kadobayashi and Suguru Yamaguchi, “Path Management of SCTP to Eliminate Single Point of Failure in Multihoming,” Proceedings of IEEE 5th International Conference on Advanced Communication Technology (ICACT2003), pp. 135–139, Phoenix Park, Korea, January 2002.

2. Shigeru Kashihara, Katsuyoshi Iida, Hiroyuki Koga, Youki Kadobayashi and Suguru Yamaguchi, “Multi-path Transmission Algorithm for End-to-End Seamless Handover across Heterogeneous Wireless Access Networks,” Proceedings of 5th International Workshop on Distributed Computing (IWDC2003), Lecture Notes in Computer Science (LNCS), Calcutta India, December 2003 (To appear).

3. Shigeru Kashihara, Takashi Nishiyama, Katsuyoshi Iida, Hiroyuki Koga, Youki Kadobayashi and Suguru Yamaguchi, “Adaptive Selection among Heterogeneous

Wireless Access Networks for End-to-end Handover," Proceedings of The 2004 International Symposium on Applications and the Internet(SAINT2004), Tokyo Japan, January 2004 (To appear).

4. Shigeru Kashihara, Katsuyoshi Iida, Hiroyuki Koga, Youki Kadobayashi and Suguru Yamaguchi, "Wireless Access Network Selection Algorithm Using Layer 4 Measurement," IEEE Semiannual Vehicular Technology Conference (Submitted).

A.3 Domestic Conference

1. Shigeru Kashihara, Katsuyoshi Iida, Hiroyuki Koga, Youki Kadobayashi and Suguru Yamaguchi, "End-to-End Seamless Handover using Multi-path Transmission Algorithm," Proceedings of Internet Conference 2003, October, 2003.

A.4 Technical Report

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