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User-Oriented Quality Preservation Mechanism in Ubiquitous WiFi Networks

Yuzo Taenaka

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Department of Information Processing
Graduate School of Information Science
Nara Institute of Science and Technology

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Yuzo Taenaka

Thesis Committee:

Professor Suguru Yamaguchi	(Supervisor)
Professor Minoru Okada	(Co-supervisor)
Professor Hiroshi Esaki	(The University of Tokyo)
Associate Professor Youki Kadobayashi	(Co-supervisor)

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ABSTRACT

This dissertation focuses on preserving communication quality experienced by users in WiFi networks. In the near future, WiFi will realize WiFi everywhere (ubiquitous WiFi networks) by integrating coverage area of APs placed by different owners. Moreover, next generation mobile applications, e.g., high definition (HD) multimedia, are also highly demanding; they always require high communication quality. As a result, it will be natural that a mobile node (MN) keeps communication with preserving its own communication quality during movement. Our goal, therefore, is achieving this vision.

First, wireless connectivity has to be strong sufficient for communication (omnipresent sufficient connectivity). WiFi connectivity becomes weaker as distance from an AP is larger. Communication quality also degrades if an AP is additionally placed. Therefore, network provisioning architecture that adapts changes in environments is essential. Next, even if an MN has sufficient connection, its communication quality may be bad due to congestion and radio interference, which is temporary caused by other WiFi devices. Communication quality is also deteriorated by increasing distance between an MN and an AP. Consequently, an MN should preserve communication quality during movement.

This dissertation presents a new paradigm of wireless measurement architecture to adapt changes in surrounding environments. Although one-shot measurement is used in deployment of WiFi networks, it is hard to support ubiquitous WiFi networks in which APs are placed one after another; measurement should be omnipresent. Therefore, our study enables AP to keep measurement over coverage area. On the other hand, an MN should appropriately detect deterioration of communication quality and determine whether carry out handover. In addition, a next AP should provide better communication quality than a current one. Therefore, our study lets MN control AP selection and handover. In AP selection, an MN selects an AP considering actually provided communication quality. In handover, an MN appropriately detects deterioration of communication quality and switches to a better AP. Furthermore, important factors to preserve communication quality are different by communication types. Our study also directs how to detect deterioration of communication quality and how to make an action for two communication types (i.e., bulk transmission and real-time communication), respectively. Through these studies, we finally discuss about our comprehensive contribution and open issues to our goal.

KEYWORDS:

Preservation of communication quality, wireless measurement, access point selection, seamless inter-domain handover, coverage area detection, WiFi network

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1

INTRODUCTION

The WiFi technologies have ever developed with its performance enhancement. After the first protocol design (ALOHA [2]) appears, many wireless network technologies are studied one after another in research area and industry. From the brilliant results, IEEE 802.11 specification [25] was standardized. Since the first standardization, wireless network technologies drastically evolved with performance improvement for the few decades [26, 27, 29], and today IEEE 802.11n specification [24] has been ratified, which brings two hundreds times capacity of the first one. Hence, WiFi has become a promising technology to provide users high performance wireless communication.

Along with such evolution of WiFi technologies, its usage has also been changing. In the early stage of development, it is almost used as a communication network of researchers in laboratories and universities, or at experimentations. After standardization, many consumer products had been manufactured and then WiFi network became to be utilized for normal browsing habits in personal and business, and often employed as a hot spot. Currently, it has been more rapidly and widely spreading in public space such as airports, stations, and various stores, then, a use of WiFi has been also shifting for most client communication over WiFi network toward next generation.

In the near future, WiFi network will be more expanded until urban area, and realize the vision of wireless everywhere (*ubiquitous WiFi networks*) in both private and public spaces. Most WiFi networks today offer only one hop wireless connectivity through each Access Point (AP), which has to be connected by wired links to the Internet. Hence, to achieve ubiquitous WiFi networks within urban area, entire APs have to be wired, which is typically quite expensive and hard to be maintained. As the future technology to provide public wireless connectivity everywhere, wireless mesh network (WMN) based on WiFi technologies has been studied [5, 4, 10]. WMN can extend coverage area in public space without expensive wiring. Since current existing WiFi networks have already covered private spaces and some specific public spaces such as stores, conjunctional use of existing WiFi networks and WMN achieves ubiquitous WiFi networks in both private and public spaces.

Next generation mobile applications are also highly demanding. Users will expect to be able to access the Internet with high definition (HD) video, voice over IP (VoIP) and sharing large files (network storage). These applications always require high communication quality. Moreover, users will anticipate using such applications in mobile situation. Consequently, since mobile nodes (MNs) can have wireless connectivity everywhere, it will be natural that they require to keep communication with preserving their own communication quality everywhere at any time.

Our goal, therefore, is realizing the vision that MN preserve communication quality everywhere at any time in ubiquitous WiFi networks. In the Internet, since the number of end hosts is particularly large, end hosts are given intelligent features to independently deal many processes involved in communication. As a result, the Internet has high scalability and has been proliferating. Then, our study attempts to enhance quality preservation functions at end hosts as much as possible. At first, MNs demand to have sufficient wireless connectivity everywhere (omnipresent strong connectivity). Since wireless connectivity is different even at neighboring location around an AP due to some environmental factors and changes in WiFi condition, controlling coverage area to maintain omnipresent strong connectivity is essential. Our study attempts to achieve omnipresence of wireless measurement through coverage area, and detection of coverage area by seamlessly integrating detected coverage. On the other hand, since many APs are densely placed and each coverage area is relatively small in ubiquitous WiFi networks, an MN has to appropriately choose and utilize an AP with better performance, and preserve its own communication quality when switching a using AP (handover). Additionally, since APs are often belonging to different organizations, inter-domain handover is also necessary to traverse APs with different IP subnets. To solve these problems, our study employes measurement based quality detection in which an AP and an MN individually measure performance metrics, and make an appropriate decision to preserve communication quality.

Table 1.1. Categorized wireless technologies

Category	Example	Communication range	Communication rate
WLAN	IEEE 802.11n	$\sim$ 100 meters	$\sim$ 300 Mbps
WMAN	IEEE 802.16e	$\sim$ 3000 meters	$\sim$ 40 Mbps
WWAN	IMT-2000	$\sim$ 10000 meters	$\sim$ 7.2 Mbps

1.1. Next Generation Wireless Network

Wireless technologies have grown in recent few decades, and currently several wireless network technologies are deployed to supply MNs with the wireless Internet connectivity. This section refers overview of current wireless technologies, and describes target area of this study. After that, details of next generation WiFi network are summarized to address issues for shifting from current situation to the next generation.

Current wireless technologies are classified into four types by the size of communication area that are Wireless Personal Area Network (WPAN), Wireless Local Area Network (WLAN), Wireless Metropolitan Area Network (WMAN), and Wireless Wide Area Network (WWAN). Since WPAN [23] focuses on inter-device or inter-sensor (very short range) communication, it beyonds the scope of this study (mobile computer communication). Particular features of other three types are shown in Table 1.1. WLAN consists of IEEE 802.11 (WiFi) based technology, which communication range is approximately 100 meters. WMAN is referred as IEEE 802.16e technology (Mobile WiMAX) [30]; its communication range is up to approximately 3,000 meters. The last one, WWAN, basically means mobile telecommunication cellular network (IMT-2000) [1] with approximately 10,000-meters of communication range. Note that, WMAN and WWAN technologies are sometimes classified to a same category. From these communication range, WLAN focuses on inside room or specific small area, WMAN intends covering urban area, and WWAN targets widely covering vast area including outside urban area. However, in these wireless technology, communication rate and range are trade-off relation; as communication range is larger, communication rate becomes lower. Therefore, WLAN covering the smallest area brings the highest communication rate.

This dissertation focuses on preserving communication quality experienced by an MN in urban area. Although urban area is basically covered by WMAN and WWAN from Table 1.1, our study intends WLAN (WiFi network). Currently, wireless networks have been already utilized by many applications such as web browsing, electronic mail

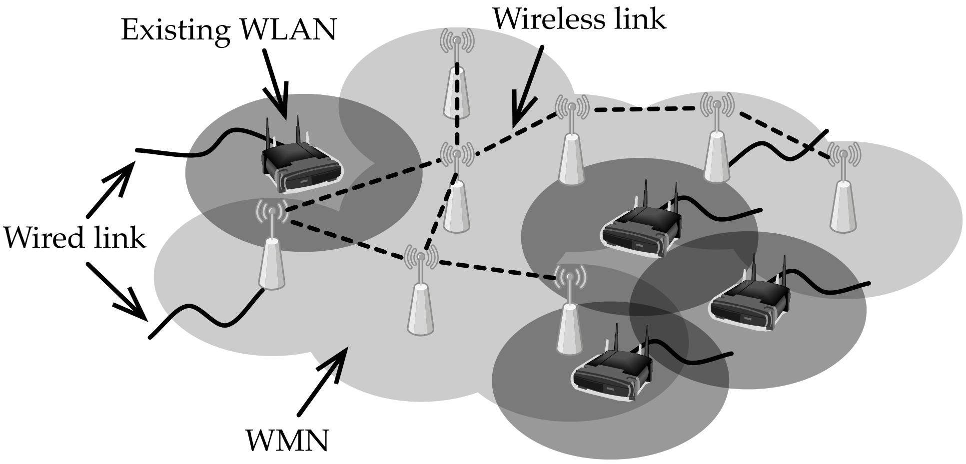


Figure 1.1. Ubiquitous WiFi networks

(email), map, internet radio, and Instant Messanger (IM). Some of them require relative high communication quality to smoothly work their own functions. For instance, browsing web site and reading a map such as Google Earth [21] sometimes require high throughput. To smoothly run them, we choose WLAN among three categories in the table, because it has sufficient communication rate. In the near future, although wireless technologies will be developed with improvement of its performance, applications also will enhance its own functions and demand higher communication quality. In addition, more various applications will be used over wireless network. From this, we can say that wireless technologies covering large area (WMAN and WWAN) will not catch up with the requirements of applications even if they are developed to next generation WMAN and WWAN technologies. On the other hand, WLAN is assumed to enhance its communication rate up to 1 Gbps in IEEE 802.11ac [57] and IEEE 802.11ad [58], which has possibility to meet requirements of next generation applications. Therefore, our study employs WLAN (WiFi network) as a wireless network technology.

Ubiquitous WiFi networks based on WLAN technology expect to consist of two parts as illustrated in Figure 1.1: existing WiFi networks and WMN. Existing WiFi networks mean WiFi networks that are selfishly placed at many locations by different owners; they are already placed at private spaces such as inside houses and specific public spaces such as stores and stations. However, they offer only one hop wireless connectivity through each AP, which has to be connected by wired links to the Internet. In order to realize ubiquitous WiFi networks within urban area, entire APs have to be wired, which is typically quiete expensive, hard to be maintained, and is sometimes impractical. Therefore, existing WiFi networks are hard to realize ubiquitous WiFi networks. As a solution to this, WMN based on WiFi technologies is proposed. WMN is a multi-hop wireless network formed by multiple APs. In WMN, every AP utilizes multiple radios; a subset of them connects with neighboring APs each other to form a multi-hop wireless network in which few of them act as gateway nodes that connect the WiFi network to the Internet; packets are forwarded by multiple APs before reaching the gateway and finally the wired Internet. The other radios provide MNs with wireless connectivity around every AP, which is putted around urban area in place. Then, WMN extends the coverage area without expensive wiring. Consequently, ubiquitous WiFi networks are constructed by complementarily integrating coverage area of each AP in existing WiFi networks and WMN.

In addition, a new paradigm of providing the wireless Internet connectivity has been launched over the world; a typical example is FON [17]. In the primitive style of providing the wireless connectivity, Internet Service Provider (ISP) basically works on both deployment of wireless networks and providing the wireless connectivity. On the other hand, FON provides a system for sharing wireless networks; people become members by agreeing to let FON share their wireless Internet connection. The members of FON can have the wireless Internet connection provided by FON around the world. The particular difference with the primitive style is FON does not deploy any APs; people do it. This style brings a win-win situation, i.e., FON expands its service area, and people connects the wireless Internet everywhere in the world. As a result, FON today has been widely used over the world. In the near future, many APs belonging to Wireless Connectivity Provider (WCP) such as FON will be more placed at many locations by different owners, and sometimes collaboratively construct WMN by following the direction of WCP. Finally, they expect to achieve ubiquitous WiFi networks.

The deployment scheme of WiFi networks expects to change because WiFi networks today have become scattered networks instead of planed networks. The deployment scheme of general wireless networks is originally developed in the area of cellular networks, which radio frequencies (channels) are legally assigned in advance. Therefore, since each carrier of cellular networks occupies some specific channels, cellular networks essentially keep stable condition once they are appropriately designed (deployed). Such traditional deployment scheme is called as the one-shot deployment scheme. Currently, to deploy WiFi networks, the one-shot deployment scheme are also used. However, neighboring WiFi networks sometimes influence each other and then communication quality they supply degrades. This is because APs of WiFi networks are selfishly placed at many locations by different owners because of license-free usage of WiFi networks and its simplicity of installation. Although appearances of other wireless networks are not considered in cellular networks (planed networks), it is necessary in WiFi networks (scattered networks). In addition, the one-shot deployment scheme requires that all APs are owned (can be deployed) by a same owner. This is inapplicable for ubiquitous WiFi networks selfishly deployed by different owners. Therefore, the one-shot deployment scheme is insufficient for ubiquitous WiFi networks. A new deployment scheme to keep adapting to changes in surrounding WiFi condition is expected.

In ubiquitous WiFi networks, MNs will establish communication utilizing next generation applications such as HD video, VoIP, and network storage. They need high communication quality to maintain their own communication. In addition, although they basically require high computing power to appropriately work, in the near future, emerging powerful mobile devices enables MNs to have communication of such applications while they move around. Then, we can assume that many MNs have communication of next generation applications with moving. Consequently, MNs will have communication with preserving its own communication quality everywhere while they move around.

1.2. Design Principle of WiFi Technologies

Before describing details of issues toward next generation WiFi network, we refer to design principle of WiFi technologies. WiFi technologies are emerged as a branch of development in the Internet technologies; it lies on the same design principle with the Internet.

From the beginning, the Internet has been highly demanded to have high scalability, and keep working as communication link at any time (high fault tolerance) even if end or intermediate systems have any troubles; it was designed based on the "end-to-end principle" [55] and the "layering architecture" [48, 12] as depicted in Figure 1.2. The end-to-end principle claims that the processes involved in communication should be performed at endpoint as much as possible, in short, dumb network and intelligent end host. Therefore, since the number of end hosts is the largest in the Internet, the end-to-end principle lets end host have most processes evolved in communication to have high scalability. This is reflected in Internet Protocol (IP) [47] and transport layer protocols such as Transmission Control Protocol (TCP) [49] and User Datagram Protocol

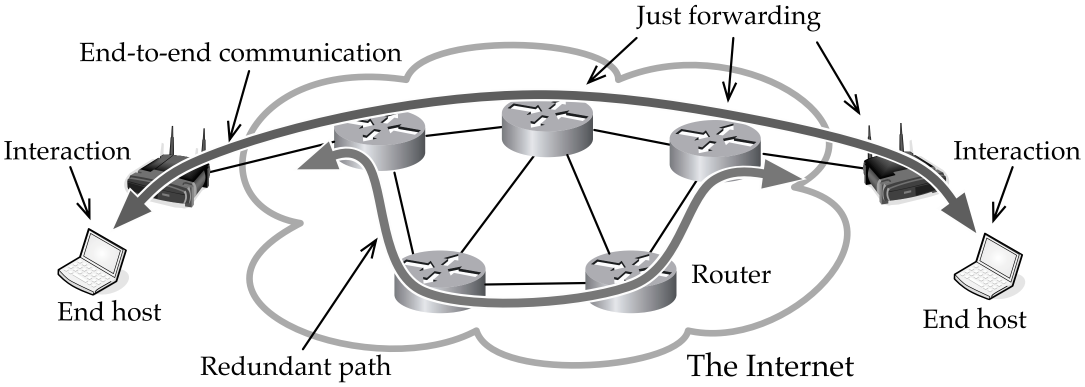


Figure 1.2. The Internet with end-to-end principle and layering architecture

(UDP) [46]. IP essentially carries packets between end hosts (end-to-end packet reachability) in the Internet, and transport layer protocols control end-to-end interaction by its own intelligent feature. For instance, TCP controls end-to-end communication at end host by error detection, retransmission, and flow control. The layering architecture separates responsibility on each part of communication into five layers to hold a high fault tolerance. In fact, the layering architecture makes the Internet only carry packets in contention manner rather than circuite switching. As a result, the Internet does not participate in end-to-end communication. From these, the Internet (IP at layer 3) acts like belt conveyor that just carries packets as they desire without concern about upper layer. Meanwhile, end hosts (transport layer protocols at layer 4) throw packets into the conveyor, and only care about end-to-end interaction. In other words, end hosts do not have to care what and how inside of the Internet is. The Internet, therefore, is able to additionally deploy network facilities in decentralized manner, and hence independently prepare multiple paths between end hosts illustrated as redundant path in the figure. As a result, the Internet is endowed with a high fault tolerance. Currently, contributed by these benefits (separated responsibility with end-to-end principle) in terms of decentralized control and scalability, the Internet is also able to independently keep expanding, and has become the largest distributed system in the world.

WiFi technologies follow the above design principle of the Internet. In WiFi system, APs connect wireless to wired at fringe of the Internet, or are sometimes assumed to form a multi-hop wireless network at last few hops of the Internet by bridging or routing. The difference between bridging and routing is a way of traffic forwarding. Bridging takes place at layer 2 while routing takes place at layer 3. This means that bridging directs frames according to hardware assigned addresses (Media Access Control

(MAC) addresses) while routing makes its decision according to arbitrarily assigned IP addresses. In both cases, every AP works inside network role, hence, it only carries traffics between end hosts without concern about upper layers (upper layer 4) and other systems. Hence, WiFi is essentially same with the Internet except wireless.

The benefit of separated responsibility with the end-to-end principle also contributed in spreading WiFi. It enabled AP to be freely placed without extra facilities in decentralized manner at many locations like the Internet. In addition, since WiFI is essentially same with the Internet, AP can be also a substitute for wired network facilities such as network switches and routers without extra facilites. As a result, WiFi is individually deployed or replaced with existing wired network facility as a last one hop of the Internet. Actually, many APs are selfishly placed at many locations by different owners. Such drastic spread of WiFi network proved that the network design based on separated responsibility with the end-to-end principle is feasible for spreading WiFi in terms of simple installation.

The current Internet containing WiFi network, actually, is not fully operated with separated responsibility with the end-to-end principle. The Internet does not work only on carrying packets between end hosts but has some intelligence features. For instance, many firewalls, load balancers, and Intrusion Prevention Systems (IPSs) are attached in the Internet. They basically inspect headers of IP/transport layer protocols and packet payloads, and sometimes discard packets their own way. In addition, some Internet Service Providers (ISPs) restrict available bandwidth and delay to prioritize some applications by identifying them from forwarding traffic. These came from the Internet as business; to keep profit, some organizations accept extra facilities that control the Internet traffic at expense of the benefit in scalability. However, the Internet remains holding the end-to-end principle in terms of interaction between end hosts; the Internet is looked like conveyor from end host yet. Hence, we can say that the Internet will/should keep holding end-to-end interaction because end-to-end interaction is a benefit for intermediate systems in terms of low load.

In WiFi networks, WLAN switch is used in enterprise WiFi networks to control associating MNs. This also aims to keep profit of an organization. However, since ubiquitous WiFi networks are constructed by many APs deployed by various owners and provided as public wireless connection, common functions such as limiting users' experiences can not be implemented in APs. Any extra facilities also can not be placed or attached to APs. Therefore, the extra procedures related to communication should be done at end hosts of the Internet as much as possible.

1.3. Problem Definition

From the nature of the Internet described in Section 1.2, APs and MNs independently work. It gave the Internet containing WiFi network high scalability but made preservation of communication quality difficult. In other words, since every MN independently transmits packets through a same channel in contention manner and an each AP does not control them, any MNs and any APs do not know how communication quality an MN experiences at next moment. Therefore, in mobile situation, communication quality experienced by an MN is hard to be preserved. Since simplicity installation carried by nature of the Internet is an important factor to more widely spread WiFi networks, our study attempts to preserve communication quality as much as possible based on the design principle of the current Internet.

In ubiquitous WiFi networks, causes of deterioration in communication quality comprise two factors, carrying packets inside network, and packet transmission between MN and AP. Especially, in case of inside network, wireless section has to be considered because the wired section is assumed to have sufficient performance. Moreover, since existing WiFi networks are single hop wireless network (directly connects the Internet by wiring), it does not need to be mentioned; only multihop wireless section of WMN brings deterioration of communication quality. After describing factors that cause deterioration of communication quality, this section presents the essential issue on quality preservation, and how our study attempts to solve it.

In case of carrying packets inside network, it is important that packets that an AP is received from MNs are surely delivered to a gateway connected to the wired Internet and vice versa in WMN. In delivering packets, WMN transports them through multiple wireless links before reaching the gateway. In this way, a wireless link formed between APs delivers lots of packets, which received by multiple APs and many MNs. Consequently, packets forwarded by an AP on a wireless link increase more and more as a wireless link is getting closer to a gateway. From this reason, an wireless link nearly each gateway tends to become bottleneck links due to its bandwidth limitation. Currently, primary research topics to reduce bottleneck links are gateway placement strategies [22, 54], and raising essential bandwidth [13, 38]. However, their objective are exploring efficient placement with limited number of gateways, and enhancement of essential bandwidth in long lossy wireless link. These are minor issues assuming our situation with ubiquitous WiFi networks (APs are densely placed without limited number of gateways).

Therefore, in ubiquitous WiFi networks, deterioration of communication quality is mainly caused by packet transmission between MN and AP. In the end-to-end principle, network is just conveyor to carry packets between end hosts, then, MNs have no choice for intermediate network other than believing that network transports packets as much as possible. Consequently, communication quality at transmission between MN and AP should be preserved; it is important to surely pass all packets between MN and AP as much as possible to preserve communication quality experienced by MNs.

To ensure that an AP receives packets from an MN, wireless connectivity should be omnipresent anytime, and be enough strong for keeping stable communication of an MN. In ubiquitous WiFi networks, an MN always moves around while communicating. Packets have to be smoothly transmitted between an MN and an AP at everywhere. In a real environment, WiFi connectivity basically differs at every location even at neighboring location. This difference occurs due to two reasons: (1) various environmental factors such as fading, and shadowing, and (2) radio interference caused by other APs selfishly placed by different owners. Both of them also independently change at every location; an MN is sometimes hard to transmit packets in mobile situation. As a result, deterioration of communication quality occurs. Although the one-shot deployment scheme traditionally has been used for deployment of WiFi networks, it only solve deterioration due to (1) environmental factors; that of (2) radio interference due to appearances of APs cannot be avoided by the one-shot deployment scheme. In ubiquitous WiFi networks, many APs are freely placed in ubiquitous WiFi networks, i.e., WiFi condition (radio interference) dynamically changes in time series. Then, one-shot deployment scheme cannot adapt the changes (the influence caused by additional APs); the one-shot deployment scheme is not suitable for ubiquitous WiFi networks. Therefore, our study focuses on how to keep controlling coverage area for providing enough connectivity anytime by avoiding deterioration.

Furthermore, since coverage area of every AP with WiFi technology is relatively small, an MN have to traverse many APs. Also, even if an MN has strong connectivity, deterioration of communication quality may occur due to radio interference caused by surrounding WiFi devices and congested condition. Therefore, when traversing APs, an MN have to find out an AP with better performance, and appropriately switch communication on the found AP for avoiding deteriorated APs. During this, an MN is often difficult to transmit packets because processes to search a next AP and re-associate with it are necessary. If the next AP belongs to existing WiFi networks (different IP subnets) described in Section 1.1, an MN additionally needs to obtain a new IP address. It more prevents packet transmission of an MN. So far, to support mobility of an

MN, several schemes based on Mobile IP (MIP) [45, 31] are proposed. However, since these methods basically employ proxy servers, which forward packets, they cannot essentially prevent deterioration of communication quality during handover processes. Therefore, to ensure all packets are smoothly passed to network, our study attempts to solve how to enable MN to surely transmit packets during traversing APs.

1.4. Approach

From the discussion in Section 1.3, our study focuses on two issues: how to keep controlling coverage area for providing enough strong connectivity everywhere (omnipresent strong connectivity), and how to enable MN to surely transmit packets during movement. This section describes approaches to solve these two issues.

First, for the former (omnipresent strong connectivity), our study assumes that most APs belong to WCP and they control their own WiFi networks to maintain strong connectivity throughout ubiquitous WiFi networks. Actually, coverage area of every AP is complementarily integrated over ubiquitous WiFi networks so as to keep sufficient performance everywhere. Ubiquitous WiFi networks consist of many APs selfishly placed by different owners. Through such APs, WCP provides WiFi connectivity. In such situation, the traditional one-shot deployment scheme can not be applied due to different owners (independent management), and dynamic changes in wireless condition. However, controlling APs is essential for realizing ubiquitous WiFi networks (appropriately integrated coverage area) in scattered networks. Then, APs belonging to WCP collaboratively construct ubiquitous WiFi network.

From the principle of the Internet described in Section 1.2, network facilities should work in decentralized manner to have high scalability and fault tolerance. In WiFi networks, all processes to control network also should be done in decentralized manner only by facilities composing themselves. Our study, therefore, employs decentralized mechanism to control coverage area, in which APs collaboratively controls their own coverage area as routers in the wired Internet do.

Processes involved in controlling coverage area are divided into two phases: measurement with coverage area detection, and analysis & improvement of coverage area. To keep controlling coverage area, these processes should be omnipresent inside coverage area. In this dissertation, our study focuses on measurement, which achieves *omnipresent measurement*. To make measurement omnipresent, there are two approaches. One is 3D ray-tracing, which predicts physical propagation based on detailed 3D physical model. The other is primitive measurement. For omnipresent measurement, 3D ray-tracing requires that 3D physical model is always updated, and primitive measurement should be conducted at any time. These approaches impractical in terms of cost. Then, our study propose a new paradigm of measurement. More specifically, each AP autonomically measures communication quality around its own coverage area, and finds out coverage area with desirable communication quality based on measurement results.

The main point of this approach is measurement architecture, which enables an AP to keep measurement over its own coverage area. Since wireless condition differs depending on location and changes due to radio interference, it is important for AP to keep investigating how communication quality is provided at each location inside its own coverage area. These details described in Chapter 2.

On the other hand, for the latter, our study prevents deterioration of communication quality during traversing many APs. Actually, our study attempts to enable an MN to select an AP with better performance, and appropriately switch to a next AP (handover) with preventing deterioration of communication quality. To preserve communication quality during movement as much as possible, our study makes AP selection method and handover method work only at end host. Since APs are placed by different owners in ubiquitous WiFi networks, it is significantly difficult that extra facilities or functions to support AP selection and handover are installed in every AP. Therefore, our study assumes that each MN independently performs AP selection and handover to preserve its own communication quality.

In a real environment, communication quality changes every moment and depending on WiFi condition. Even if an MN has a strong wireless connectivity, communication quality degrades due to congested condition and radio interference caused by surrounding WiFi devices. In such environment, it is important that each MN promptly detects deterioration of communication quality, and immediately takes action to preserve communication quality. In AP selection, an MN has to choose an AP with better performance (without congestion and radio interference) so as to immediately switches communication at deterioration. In handover, an MN has to switch communication to preserve its communication quality. Since importance on preserving communication quality is different with types of communication, our study employs two different mechanisms for two communication types respectively. One is VoIP (real-time communication), which emphasizes delay and packet loss. The other is Hypertext Transfer Protocol (HTTP) [16] (connection oriented bulk transfer), which focuses of total amount of transmitted traffic, in other words, it is sensitive deterioration of wireless condition and stability of communication quality.

Then, the main point of these methods is how an MN detects communication quality of an AP. Our solution is quality detection based on measurement at MN. In AP selection, an MN has to know communication quality provided by an AP in advance. In handover, an MN has to promptly and reliably detect communication quality, and takes an action according to types of communication. The details of AP selection is described in Chapter 3, handover for VoIP and TCP communication are in Chapters 4, and 5, respectively.

1.5. Positions

So far many studies are conducted to preserve communication quality experienced by MNs. This section presents our positions in this research area by referring them. From Section 1.4, our study focuses on preservation of communication quality by two direction in terms of wireless network provisioning and client mobility. Each of them are mentioned respectively.

1.5.1 Wireless Network Provisioning

WiFi networks are significantly effected by surrounding environments, which are classified as physical objects and WiFi conditions. Physical objects such as buildings and walls impact on radio propagation of WiFi network, hence, coverage area of an AP indicates different shape depending on its placed location. WiFi conditions such as radio transmission of other APs and noise are also so. In addition, while physical objects do not so change, WiFi conditions are sometimes change. Therefore, it is indispensable for network provisioning to keep both omnipresent measurement (detecting coverage holes) and improvement of found holes.

Currently, while many studies present detection of the coverage area of WiFi network [51, 9, 7, 53], none have proposed a framework suited for ubiquitous WiFi networks. In ubiquitous WiFi networks, since a new AP is often placed, communication quality of an existing AP around the additional AP degrades due to radio interference when their channel conflict. To adapt such situation, a framework that is able to achieve omnipresent measurement is essential. In [51], authors estimate coverage area by 3D ray tracing, which performs detailed simulation and prediction of physical-layer propagation. Other studies [9, 7, 53] mention about small set of coverage measurements to build parameters of physical-layer propagation. However, they all does not discuss about continuous of measurement, and focuses on one-shot measurement. Then, our study focuses on achieving omnipresent measurement (keep measurement over a coverage area).

Furthermore, to keep strong connectivity sufficient to preserve communication quality, coverage area with desirable communication quality should be detected. However, most studies identify locations where the given performance metric (signal strength) meets a predetermined threshold; it does not indicates communication quality at all. That is, they find an area where an MN can establish an WiFi association. Our study, therefore, focuses on performance metrics, which identify coverage area with desirable communication quality.

1.5.2 Client Mobility

In ubiquitous WiFi environment, since APs are densely placed, an MN switches communication among them during movement. However, even if WiFi connectivity is enough strong for preserving communication quality everywhere, communication quality of an MN degrades by effects of many WiFi devices, which are basically working around the MN. For instance, various mobile WiFi devices and microwave ovens impact on communication quality of WiFi networks due to congestion and radio interference. Since these effects temporary occur during a few period, an MN has to individually detect them and adaptability take an action to preserve its own communication quality. In addition, a next AP to which an MN switches communication may not have better communication quality. Therefore, an MN also has to promptly and reliably start handover and appropriately determine whether a new AP provides better communication quality.

Generally, preservation of communication quality during movement is referred as seamless mobility. The most popular technologies are Mobile IP (MIP) [45, 31] and mobile Stream Control Transmission Protocol (mSCTP) [69]. MIP employed network embedded servers, which behaves as proxies for MNs. That is, servers forwards packets received from other nodes to an MN. However, MIP requires registration of changes in IP address. It can be completed after layer 2 and 3 handover, i.e., processes of AP selection, association, and acquiring an IP address. Consequently, MIP cannot avoid communication Interruption (deterioration of communication quality). On the other hand, mSCTP does not need layer 2 and 3 handover. However, both of them do not discuss about how to appropriately detect deterioration of communication quality (start of handover), and how to confirm communication quality provided by a next AP. Therefore, our study attempts to achieve prompt and reliable detection of deterioration in communication quality and appropriate selection of a better AP during handover.

1.6. Contributions

Our goal is that MNs can selfishly move around urban area with preserving communication quality while communicating in ubiquitous WiFi networks. Toward this goal, our study focuses on preserving communication quality at packet transmission between AP and MN. To ensure that an MN has at least one sufficient wireless connectivity, APs have to complementarily integrate their own coverage. Therefore, our study attempts to control coverage area by detecting coverage area and integrating them based on wireless measurement. Moreover, in such ubiquitous WiFi networks, each MN has to traverse many APs in mobile situation, because coverage area of each AP is relatively small and wireless condition frequently fluctuates. Then, our study attempts to appropriately carry out AP selection and handover without deterioration of communication quality based on measurement based quality detection. Therefore, the primary contribution of this dissertation are as follows:

- Our study clarifies how an AP achieves omnipresent measurement and identifies its own coverage area with desirable communication quality.
- When an MN simultaneously finds multiple APs, how the MN can select one with better performance.
- When an MN moves around, how the MN promptly detects deterioration of its own communication quality.
- When an MN runs procedure of handover, how the MN promptly select a better AP among a new AP and an old one.

1.7. Organization

This chapter first have described the current situation and next generation of WiFi network. Then, our motivation, the essential issues to shift WiFi network from current situation to next generation have been also described based on the nature of the Internet. The rest of this dissertation continues as follows. Chapter 2 detects coverage area with desirable communication quality toward achieving that all APs complementarily construct omnipresent sufficient wireless connectivity through urban area. In Chapter 3, our study enables an MN to select an AP with better performance to traverse in ubiquitous WiFi networks. Chapters 4 and 5 present handover method to preserve communication quality for VoIP and TCP communication, respectively. In VoIP communication, occurrence of packet loss significantly impacts on communication quality. On contrary, in TCP communication, frequent handover and unstable wireless condition have most impact on communication quality. In Chapters 4 and 5, our study considered these characteristics and design how appropriately detect communication quality and take an action. Finally, concluding remarks and future work are presented in Chapter 6.

2

WIRELESS MEASUREMENT ARCHITECTURE TO IDENTIFY COVERAGE AREA

WMN attracts attention to expand the coverage area of public wireless networks into urban scale. Each AP of WMN provides the wireless Internet connectivity to MNs, and relays traffic towards a gateway, which connects the Internet. Hence, by complementarily integrating coverage area of each AP, WMN can provide the ubiquitous client connectivity. In addition, since next generation applications are always claim high communication quality, it is important to put a monitoring infrastructure in place, which can identify *deterioration hole*, where an MN experiences deterioration of communication quality even if associating other APs. It is often created due to obstacles, weather, and temporary interference sources, i.e., it dynamically appears. Then to detect deterioration holes, it is essential to appropriately find out an area with desirable communication quality.

Currently, most researchers focus on coverage holes, where an MN cannot associate any APs, instead of deterioration holes. Then, many studies are conducted to find coverage holes [51, 9, 52, 53, 20, 8]. Coverage holes are generally detected by collecting coverage area of each AP and integrating them. Coverage area of each AP is detected by identifying locations where the given performance metric, i.e., signal strength, meets a conformance threshold. To collect performance metric, two approaches, observation and estimation, are employed. In the observation approach, measurement at every location (*exhaustive measurement*) is manually operated. The estimation approach utilizes 3D ray tracing propagation with detailed 3D physical model [51]. Although both approaches lead to high accuracy of coverage area detection, they are expensive, less scalable in urban-scale WMN, and often impractical due to requiring exhaustive measurement or detailed 3D physical model. Then, to make coverage area detection easy, hybrid approach (combined use of both approaches) is studied [53]. The authors estimate coverage area based on path-loss model and publicly available digital maps, and then refine estimated coverage area based on small number of measurement. However, their estimation needs parameters such as path-loss exponent and shadowing component. However, other study presents that values of such parameters change depending on location [8], i.e., hybrid approach also requires many measurement to configure them. Then, measurement is unavoidable, and is required to be performed as many locations as possible. Hence, it is also essential to increase scalability by eliminating manual operation of measurement.

In order to detect deterioration holes, identification method is same with detecting coverage holes in terms of identifying locations where the given performance metric meets a threshold. However, we have to find out new performance metric with a threshold, because current coverage area detection utilizes signal strength to check whether an MN can associate with it. In addition, signal strength frequently fluctuates depending on time or space. It brings inaccurate estimation of communication quality. Then, performance metric that can accurately detect coverage area with desirable communication quality is needed. In addition, since wireless environment dynamically changes and coverage area also become different. To follow the changes, current coverage area detection needs additional observations and updating estimation parameters. It is expensive, less scalable, and impractical. A monitoring infrastructure, therefore, is required to keep measurement to find changes in wireless environment and update detected coverage area.

Then, to find coverage area with desirable communication quality, a monitoring infrastructure has to satisfy the following three requirements: (i) elimination of manual operation, (ii) measuring performance metric at many locations as much as possible, and (iii) continuous measurement. In this chapter, we present an wireless measurement architecture, which employs AP based measurement to detect coverage area with desirable communication quality. In our proposed architecture, to satisfy (i), wireless measurement is exhaustively performed as many location as possible. Current wireless measurement is manually operated, which makes exhaustive measurement impractical. Therefore, elimination of manual operation is a key challenge in exhaustive measurement. In order to keep measurement, our proposed architecture also continuously performs exhaustive wireless measurement. Through simulation experiment, we can see that our architecture can detect coverage area with desirable communication quality.

2.1. Wireless Measurement Architecture

In this section, we propose the wireless measurement architecture. First, we show overview of our proposed architecture in Section 2.1.1. Then, the structure of our architecture is described in Section 2.1.2. After that, details of our architecture are introduced in Secition 2.1.3.

2.1.1 Overview

In this section, we describe overview of our proposed architecture. In our proposed architecture, to find coverage area with desirable communication quality, we need following three requirements: (i) elimination of manual operation, (ii) executing measurement as many locations as possible, and (iii) continuous measurement. First, to conduct wireless measurement, we need to manually generate some kinds of traffic while collecting performance metric, which is also based on manual measurement. Then, wireless measurement should exclude the two manual operations to increase scalability (Req. (i)). To eliminate manual generation of traffic, we employ network users (MNs), which communicate through WMN, to generate traffic, and, to remove manual measurement, enable AP to measure performance metric. In addition, to achieve exhaustiveness, wireless measurement should be performed at many locations without manual operation (Req. (ii)). We then employ location management by which AP can acquire the location of each MN. From this, AP can record measured performance metric with a location. Consequently, since each MN moves around, performance metric can be collected at many locations. Finally, to adapt changes in wireless condition, wireless measurement should be continuously performed (Req. (iii). In our architecture, our study enables each AP transparently measures performance metric. Lightweight measurement is also employed in order to keep measurement.

Next, we describe the behavior of our proposed architecture. Figure 2.1 shows it. In ubiquitous WiFi networks, we can assume that many MNs move around while communicating with corresponding nodes (CNs), hence, an AP receives many frames from each MN and forwards it toward a gateway AP (and vice versa). In addition, it can be also assumed that each MN can obtain the location of itself. Then, an MN first enters

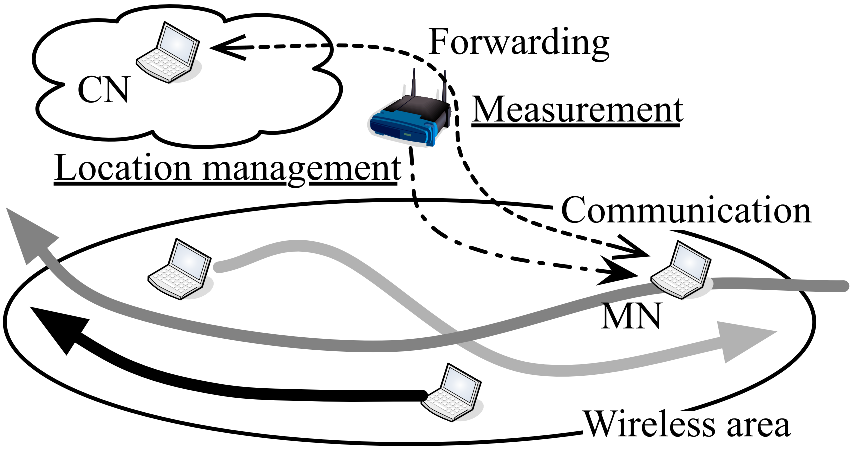


Figure 2.1. Behavior of the proposed architecture

a wireless area and starts communication through the AP. At that time, the AP notices a new MN and then starts monitoring it. During monitoring, the AP periodically acquires the location of the MN by requesting the location from the MN, and keeps it until next acquisition. Moreover, when receiving a frames from the MN, the AP measures performance metric and records it with the location. Therefore, since the MN moves around, the AP can collect performance metric at many locations. Finally, when the MN leaves out the wireless area, the AP detects it and stop monitoring the MN. Since these above processes are kept while the AP works, changes in wireless condition will be also detected.

2.1.2 Structure

In this section, we describe the structure of our proposed architecture. As described in Section 2.1.1, our proposed architecture needs three modules, the node detection module (NDM), the node locating module (NLM), and the measurement module (MM). The NDM checks entering/leaving of MNs in the wireless area, the NLM acquires the location of each MN and finally, the MM measures performance metric.

The relationship between three modules is shown in Figure 2.2. In the proposed architecture, an AP needs the location of an MN at measurement, which acquisition needs a time. Since an AP has to perform measurement and forwarding in real-time, the NLM acquires the location periodically rather than acquisition at measurement. The NDM also runs independent on other modules to check entering/leaving of MNs. Hence, all modules independently work. Then, to exchange information related to existing MNs between three modules, we employ a list, named a *target list*. The target

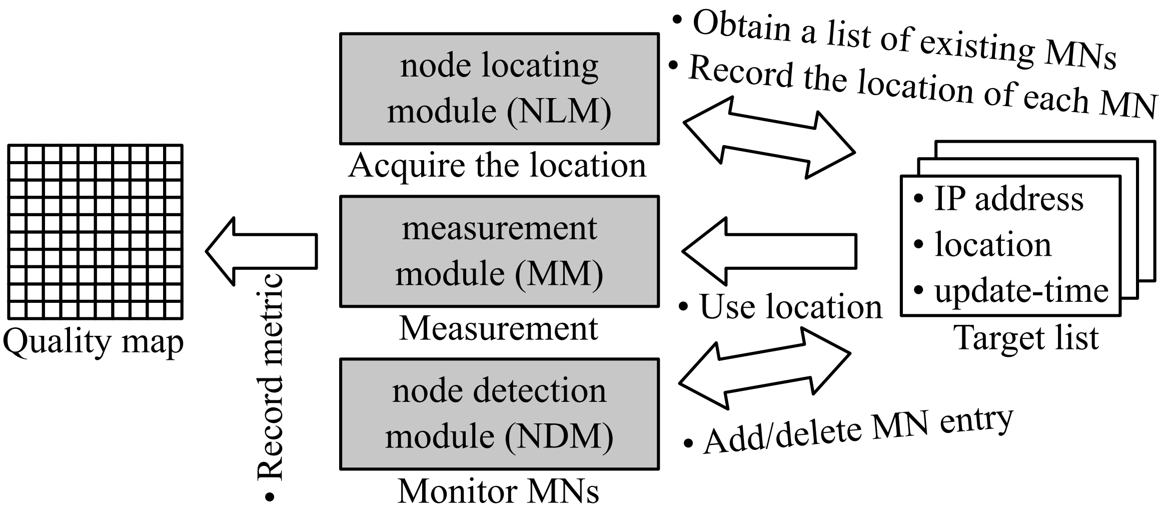


Figure 2.2. Relationship between three modules

list has three fields for each MN: the *address field*, the *location field*, and the *update-time field*. The address field contains the IP address of an MN, the location field is recorded the location, and the update-time field is set to the time when the entry is updated. Utilizing the target list, the NDM finds a leaving, the NLM acquires/keeps a location, and the MM records measured metric. These details are described in Section 2.1.3.

In addition, to record collected metric with a location, we employ a map between performance metric and a location, named a *quality map*. As shown in Figure 2.3, to create a quality map, an AP divides a real world into grid, which is consists of N-meters cells. Note that, in the quality map, an AP is regarded as standing at the center. Then, after measuring performance metric and acquiring a location from the target list, the measured metric is recorded into a cell corresponding to the location.

2.1.3 Detailed Procedure of the Proposed Architecture

The proposed architecture consists of two parts: location monitoring and wireless measurement. In the location monitoring, an AP detects entering/leaving of MN, and acquires the location of each MN. In the wireless measurement, whenever forwarding a frame from/to an MN, an AP measures performance metric, and records it with a location. The node monitoring and the wireless measurement are respectively described in followings.

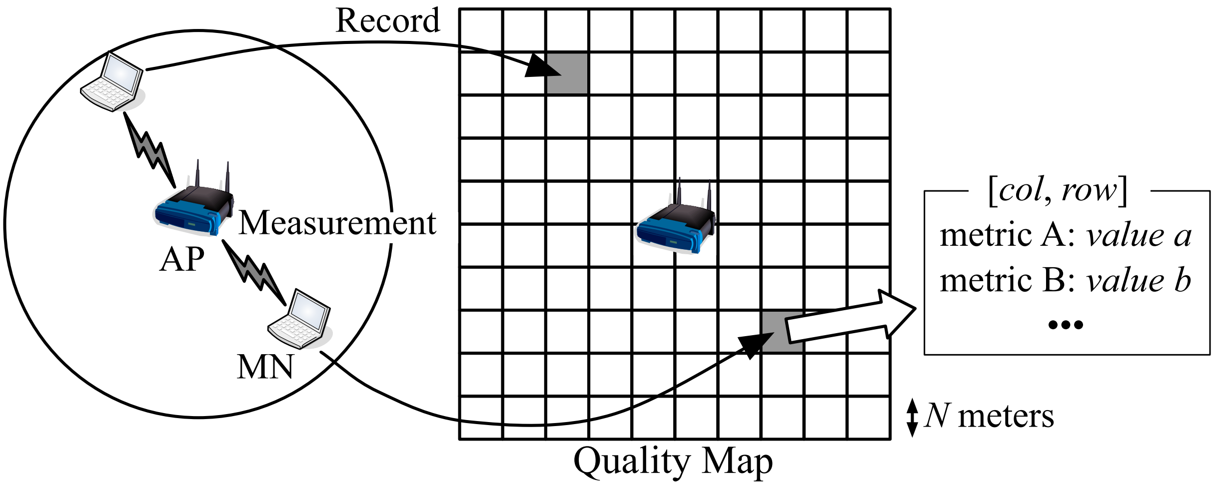


Figure 2.3. Quality Map

Location Monitoring

In the location monitoring, the NDM and the NLM work on holding the location of MNs using the target list. Since, in the proposed architecture, each module independently runs, the NDM adds/deletes an MN entry in the target list, and the NLM periodically acquires the location of each MN listed in the target list. Then, we first introduce the NDM. Figure 2.4 shows the flowchart of the NDM. Since the NDM consists of two process ((a) addition process and (b) deletion process), we respectively describe them.

(a) Addition process: To find a new MN, the NDM always monitors a source IP address of forwarding frames received from MNs. When a new IP address is found, the NDM creates an MN entry in the target list. At that moment, the IP address of the new MN is recorded in the address field, and the update-time field is set to the current time.
(b) Deletion process: To detect leaving of an MN, the NDM periodically executes (b) deletion process at *int* milliseconds interval. In (b) deletion process, the update-time field of the target list is utilized, which contains a time when updating the MN entry. That is, if a given period passes from a time of the update-time field, the NDM removes the MN entry from the target list. Note that, the given period and *int* are set to the same duration with the interval of the NLM to acquire the location.

While the NDM adds/deletes an MN entry in the target list, the NLM periodically acquires the location of each MN listed in the target list by requesting it. Since we assume that all MNs can identify its own location, they need a something to obtain

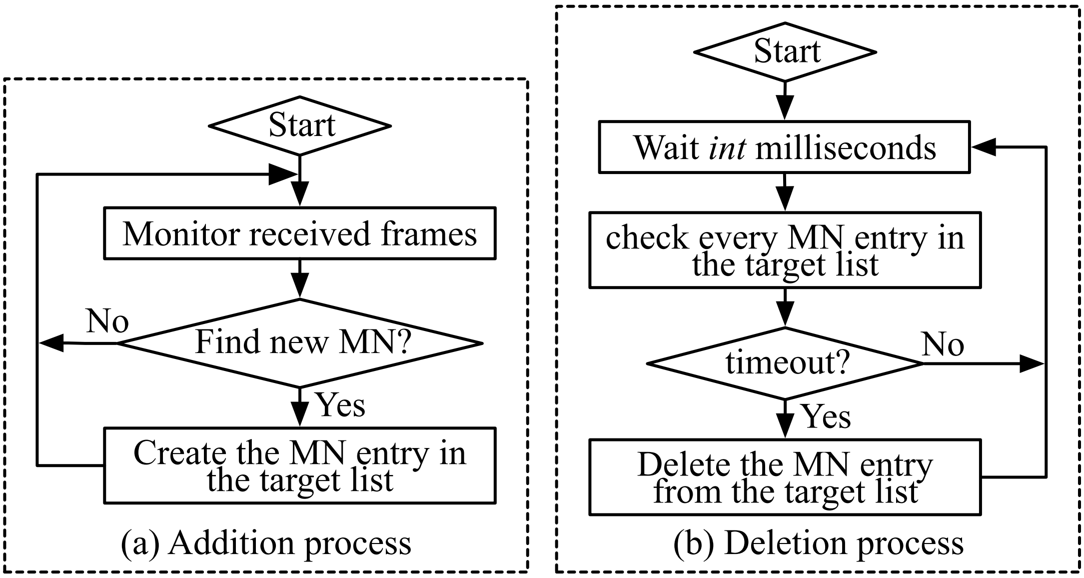


Figure 2.4. Flowchart of the NDM

it. Currently, various location management methods exist and have different characteristics. Then, since they bring complex in evaluation, we do not here concern with difference between location management methods. That is, we assume that all MNs can promptly obtain its own location without measurement error. The flowchart of the NLM is shown in Figure 2.5. To periodically collect location, the NLM runs at predetermined interval. When the NLM is executed, it first obtains the IP address of all existing MNs. After that, the NLM attempts to acquire the location of every MN. To acquire it, the NLM sends every MN a location request to ask the location. Each MN replies it with its own location. If receiving a reply, the NLM registers the received location to the location field, and the update-time field is also set to the current time. Otherwise, the NLM terminates without any update of the target list.

Wireless Measurement

In the wireless measurement, the MM measures performance metrics based on forwarding frames, and then records measured metrics into the quality map according to the location. The flowchart of the MM is shown in Figure 2.6. Whenever a frame is forwarded from/to an MN, the procedure is runed. First, the MM measures performance metric based on forwarding traffic. Then, to record it to the quality map, the MM acquires the location of a source/destination MN. More specifically, the MM finds the MN entry corresponding to the MN in the target list, and obtains the location reg-

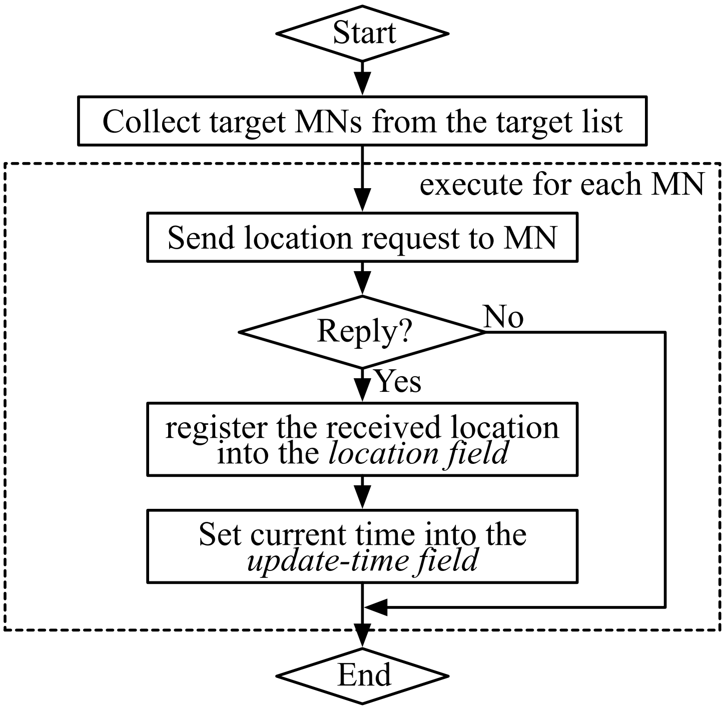


Figure 2.5. Flowchart of the NLM

istered in the location field. If the obtained location is available (it is not empty), the measured metric is recorded into the quality map after the MM converts the location into the coordinate address of the quality map.

In order to keep measurement, the MM has to transparently measures performance metrics. Then, performance metrics that MM can collect are limited because an AP has to forwards frames as soon as possible after receiving them. Consequently, our study selects few performance metrics and discuss about which is appropriately indicates communication quality. This discussion is described in Section 2.2.3.

2.2. Performance Evaluation

In this section, we evaluate the proposed architecture through simulation experiments in which qualnet simulatior 4.0.1 [56] is employed. Since our proposed architecture focuses on detecting coverage area with desirable communication quality, evaluation is performed based on its detection accuracy. Then, we employ simple detection algorithm described in Section 2.2.1. In addition, since it needs criterion, after simulation model is explained in Section 2.2.2, we discuss what performance metric can appro-

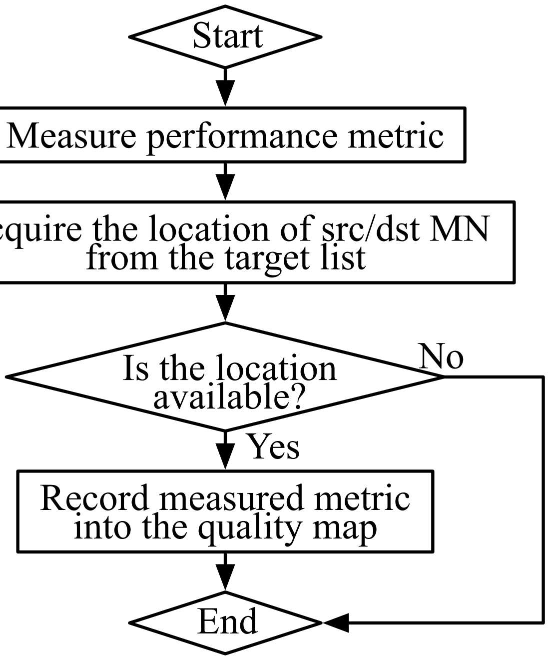


Figure 2.6. Flowchart of the MM

priately detect communication quality and about its threshold in Section 2.2.3. Then, Section 2.2.4 describe evaluation metric to assess performance of simulation results. In the experiments, we examine the difference of effectiveness depending on cell size of the quality map, time series variation, and interval to acquire location in Sections 2.2.5. From these results, as a case study, we find coverage area with an obstacle in Section 2.2.6. Finally, in Section 2.2.7, we examine influence caused by increasing MNs.

2.2.1 Coverage Area Detection Algorithm

To evaluate effectiveness for coverage area detection, an algorithm to detect the coverage area is indispensable. However, so far, no algorithm fits the proposed architecture. We then employ a primitive method to detect coverage area, which uses measured metric in the quality map.

The detection algorithm is shown in Algorithm 2.1. Figure 2.7 illustrates two example coverage areas. First, to find a uniform coverage area (left in Figure 2.7), the algorithm attempts to find a lower and an upper bounds (white circle and triangle in Figure 2.7) in each column from left to right side. Since each cell in the quality map contains performance metric, the algorithm examines whether a cell satisfies a predetermined threshold from the bottom to the top one by one in each column. Every

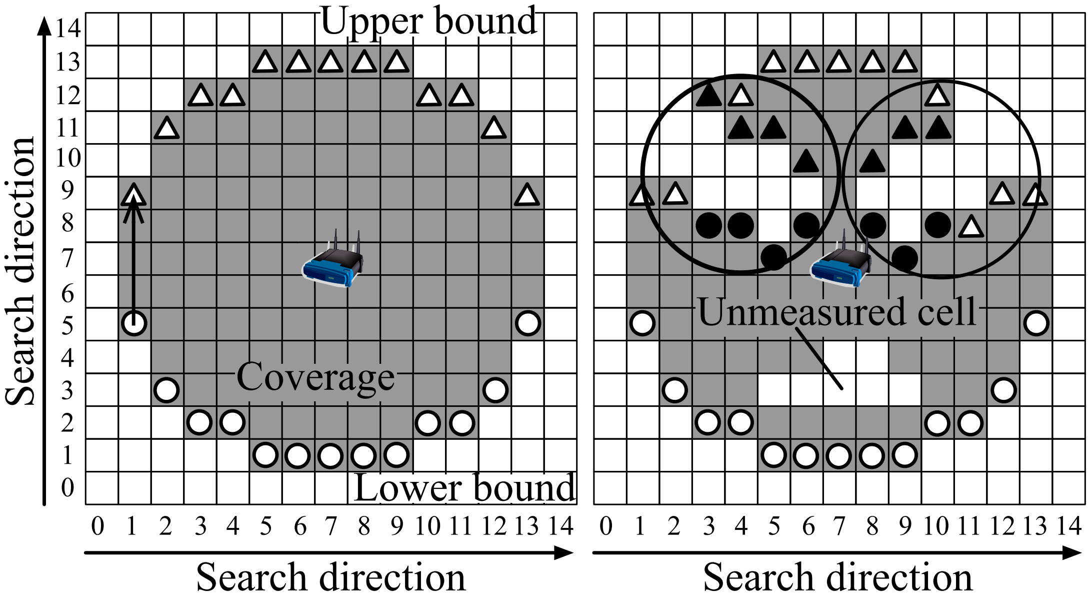


Figure 2.7. An example of coverage area detection

satisfied cell is sequentially inserted a list (*cellList* in Algorithm 2.1), and the first and the last elements of the list are respectively treated as the lower and the upper bounds. For example, in column 1 of the left in Figure 2.7, the cells between 5th and 9th are satisfied cells. Then, the lower and the upper bounds are respectively 5th and 9th. Then, by tracing the lower and the upper bounds, we can detect coverage area with desirable communication quality.

However, an AP does not always obtain quality information in every cell, and its coverage area may dent due to presence of an obstruction; hence, the algorithm needs to be able to find a misshapen shape such as the right map of Figure 2.7. To search a dent of the coverage area, we employ an additional procedure. In the procedure, unsatisfied cells making a dent in coverage area are detected. That is, a lower and an upper bounds (black circle and triangle in Figure 2.7) of sequential unsatisfied cells is collected based on the same process with Algorithm 2.1. In addition, to deal with unmeasured cells, if unmeasured cells are surrounded by satisfied cells, they are also treated as satisfying a threshold, otherwise, they are unsatisfied cells.

Algorithm 2.1 Coverage Area detection procedure

```
$column = row = 0$
while seek all cells do
    if satisfyThreshold($column, row$) then
        insert $row$ into $cellList$
    else if $CellGroup$ != empty then
        $lowerBound$ = firstElement($cellList$)
        $upperBound$ = lastElement($cellList$)
        clear $cellList$
    else if row == $last$ then
        forward $column$; $row = 0$
    end if
    forward $row$
end while
```

Table 2.1. Simulation parameters

Parameters	Value
Simulation area	200 × 200 meters
Traffic	VoIP (G.711)
Mobility	Gauss-Markov model
Wireless std.	IEEE 802.11g (Fixed rate of 54Mbps)
Transmission power	10.1 dBm
Antenna gain	-68 dBm
Fading model	nakagami-ricean model ($k = 4.84$)

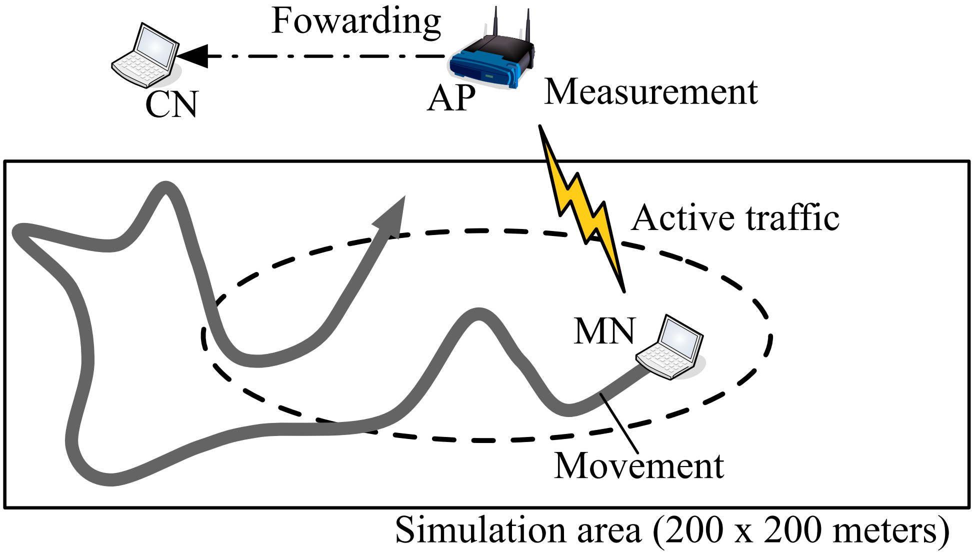


Figure 2.8. Overview of simulation model

2.2.2 Simulation Model

Figure 2.8 illustrates a simulation model. In our experiments, an MN moves depending on a mobility model in the simulation area (200 × 200 meters). Other MNs do not exist in the simulation area. During experiments, the MN communicates with a CN through an AP.

The simulation parameters are listed in Table 2.1. We employ the communication as real-time UDP traffic (Voice over IP (VoIP) with G.711), which sends a 200-byte packet every 20 milliseconds. This is because connection oriented communication cannot be maintained and resumed when the MN enters and leaves the wireless area without any special mechanism. Only an AP are placed in the center of the area, and an MN

Table 2.2. Correlation coefficient with TCP throughput

	RSSI	FRC	FER	PLR
THR	0.69	-0.92	-0.98	-0.76

moves according to the gauss-markov model in which an MN moves at average 1 m/s with maximum 2 m/s. In our simulation, since multi-rate prevent managing communication quality, we employ fixed 54 Mbps of IEEE 802.11g with RTS/CTS. In physical parameters, antenna gain and transmission power are set to -68 dBm and 10.1 dBm according to specification of ORiNOCO AP-4000 [50]. The nakagami-ricean fading model with 4.84 of k factor are also employed as a fading model assuming urban area.

2.2.3 Threshold of Performance Metric

As described in Section 2.2.1, the coverage area detection algorithm examines each cell whether it meets a predetermined threshold. Hence, in this section, we discuss what performance metric is useful to determine communication quality, and about its threshold.

Since the detection algorithm compares a performance metric with a threshold, we first consider which metric is useful to detect communication quality. In WLAN, communication quality is often discussed by application performance, i.e., throughput (THR). Then, in this paper, since measuring THR needs generating special traffic, we attempt to employ a metric, which is useful to estimate THR. To find a useful metric, we perform a preliminary simulations in two scenarios. In the first scenario, an MN is randomly located at the right edge in the simulation area. Then, the MN goes left and right while keeping the VoIP communication. During the experiment, the AP obtains the pair of the location and four metrics, i.e., received signal strength indicator (RSSI), frame error rate (FER), frame retry count (FRC), and packet loss rate (PLR). In the second scenario, the MN makes a TCP communication, and measures THR at every location in a simulation area. From the both results, we make a pair of THR and the measured metrics, as a result, 26,139 pairs are obtained through multiple simulations. Then, their correlation coefficient is shown in Table 2.2. From Table 2.2, we can see that FER has the highest correlation with THR. Therefore, FER is employed as the decision metric of communication quality.

Next, we describe how the threshold of FER is determined. In the paper, since we consider the coverage area without deterioration hole (deterioration of communication

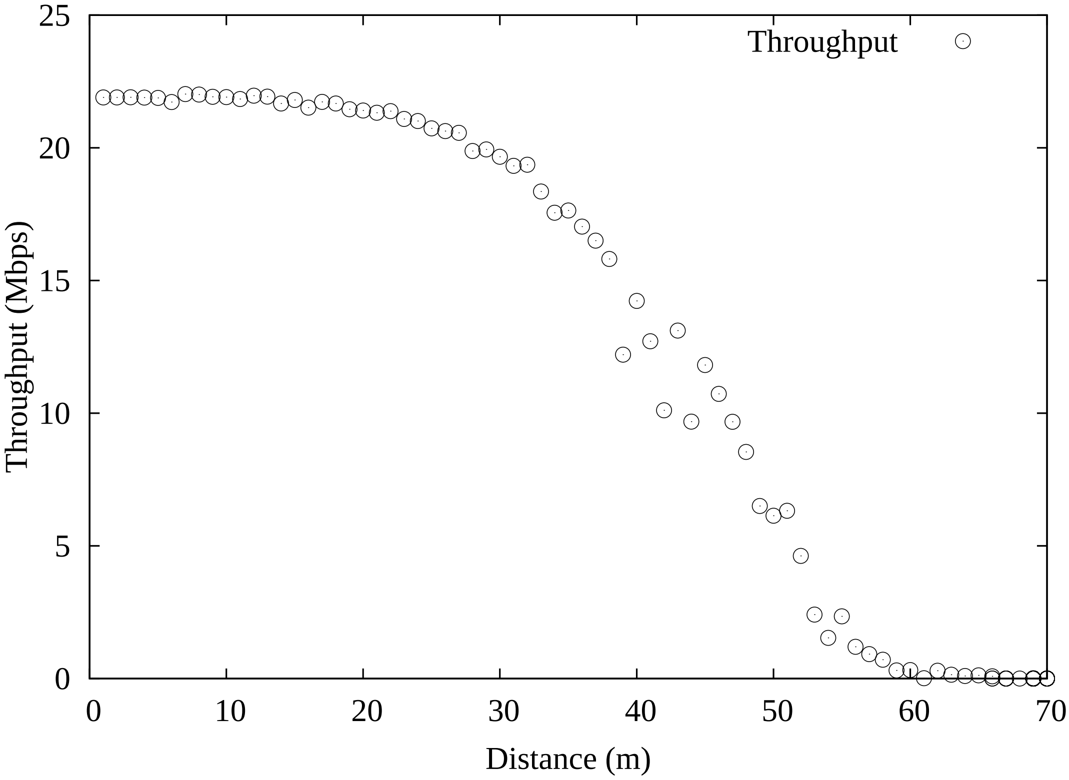


Figure 2.9. Relationship between distance and throughput

quality), we investigate THR according to the distance from an AP, which is indicated in Figure 2.9. To illustrate the figure, we performed simulations in which we measure THR for one minute at every one meter from an AP. In the figure, the THR starts to decrease to 20 Mbps near 30 meters and then drastically falls, hence, the threshold of THR can be defined as 20 Mbps. As for FER, we need to determine the threshold corresponding to 20 Mbps of THR. Then, Figure 2.10 illustrates the relationship between FER and THR using the above preliminary simulation results. From the figure, we can see that THR can be almost maintained over 20 Mbps when FER is less than 10 percent. Therefore, to detect the coverage area with 20 Mbps of THR, the threshold of FER is 10 percent.

As described in Section 2.2.2, we employ UDP (VoIP) instead of TCP due to TCP characteristics, that is, while MN randomly moves in the simulation area, TCP connection cannot be resumed at all once the MN leaves away a wireless area. On the other hand, as UDP is connection-less, an MN continues to send packets even if the MN goes out of the wireless area. Then, in order to investigate the difference between TCP and

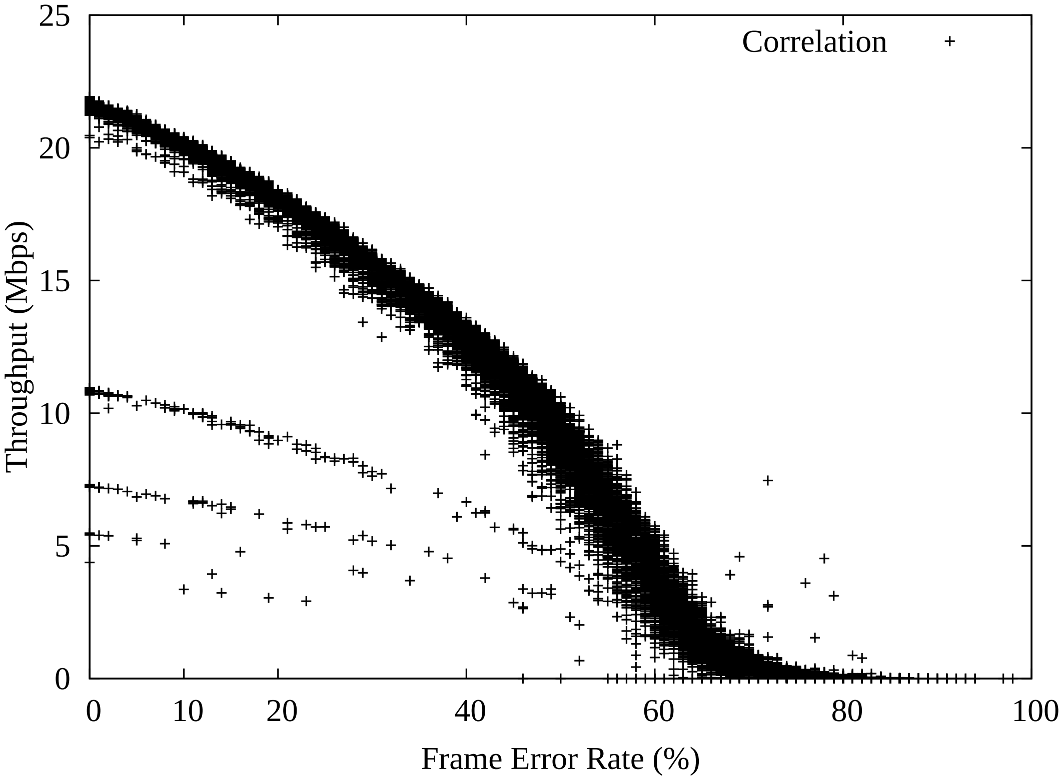


Figure 2.10. Relationship between FER and throughput

UDP, we also perform another simulation experiments. In the simulation, while generating VoIP traffic, as shown in Figure 2.11, an MN regularly moves in turn from the bottom to the top at every one meter in a simulation area. During it, FER is measured at each location. From the results, we found that the detected coverage area is 30.8 meters in radius based on UDP traffic, which is almost same with the distance of 20 Mbps in TCP (see Figure 2.9). So, we can also say that FER does not depend on the transport protocol.

2.2.4 Evaluation Metric

To investigate accuracy of the detected coverage area, we have to compare the detected coverage area with the actual coverage area. Since the qualnet simulator can reproduce the same wireless environment whenever specifying a same seed at a simulation, to create the actual coverage area, we perform a simulation with the same seed and the parameters in advance. In the simulation, as shown in Figure 2.11, the MN regularly moves in the entire simulation area while generating VoIP traffic. Then, the actual

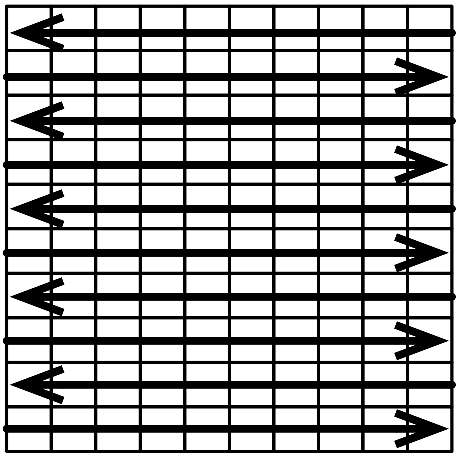


Figure 2.11. Movement pattern

coverage area can be obtained through the simulation area.

To assess accuracy of the detected coverage area, it is compared with the actual coverage area at every 1-meter cell. The comparison result of each 1-meter cell are classified into the following four types: true positive (T_p), true negative (T_n), false positive (F_p) and false negative (F_n). T_p and F_n indicate correct and mistaken detection within the actual coverage area, respectively. T_n and F_p also mean mistaken and correct detection outside the actual coverage area. To investigate accuracy of the detected coverage area based on these types, the F-measure is employed as the evaluation metric. The equations of the F-measure are shown below.

$$F - measure : F_\alpha = \frac{(1+\alpha) \times P \times R}{\alpha \times P + R} \tag{2.1}$$

$$Precision : P = \frac{T_p}{T_p + F_p} \tag{2.2}$$

$$Recall : R = \frac{T_p}{T_p + F_n} \tag{2.3}$$

where α indicates a weight parameter between P and R. P indicates how accurate detected cells contain F_p, whereas R indicates how accurate coverage area is found out. If the coverage area is detected larger than the actual coverage area (overestimation), it leads coverage area holes and/or deterioration holes. Then, to reduce F_p, α is set to 0.5, which weight P twice as much as R. In the F-measure, "1" indicates the best accuracy of detecting the coverage area, and "0" is that the coverage area cannot be detected at all.

In comparison, since the cell size of our experiment is changed from 1 to 10 meters,

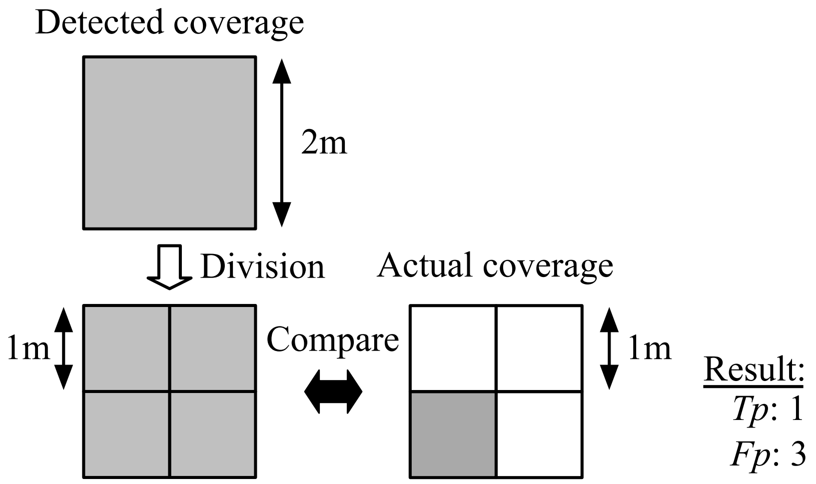


Figure 2.12. Examples of comparison

we need to consider the way to compare with the actual coverage area. Then, each cell in an experimental result is divided into 1-meter cells as shown in Figure 2.12. In the case of 2-meters cell, we regard each cell as containing four 1-meter cells with the same detected result, and make a comparison at each 1-meter cell.

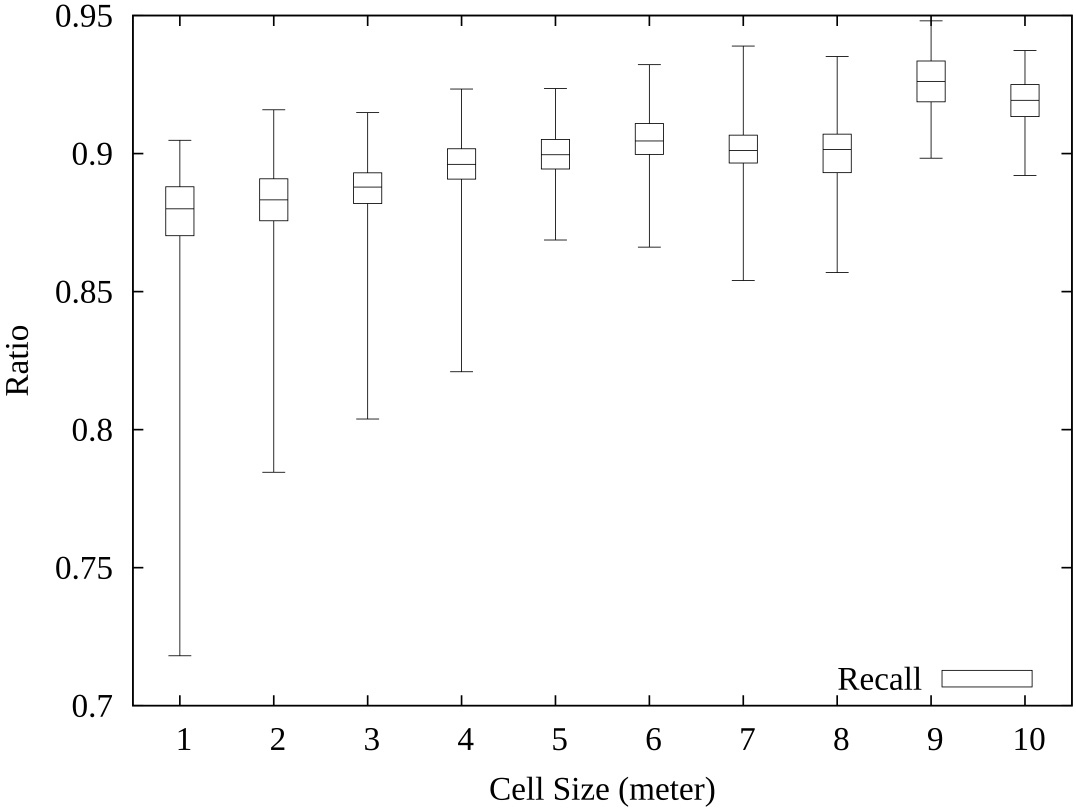
2.2.5 Investigation of Parameters and Detection Accuracy

In this section, we evaluate effectiveness of our architecture depending on a cell size (N meters) of the quality map, time series variation and an interval of the acquiring location. For each experiment, we simulate 100 times with different movement patterns.

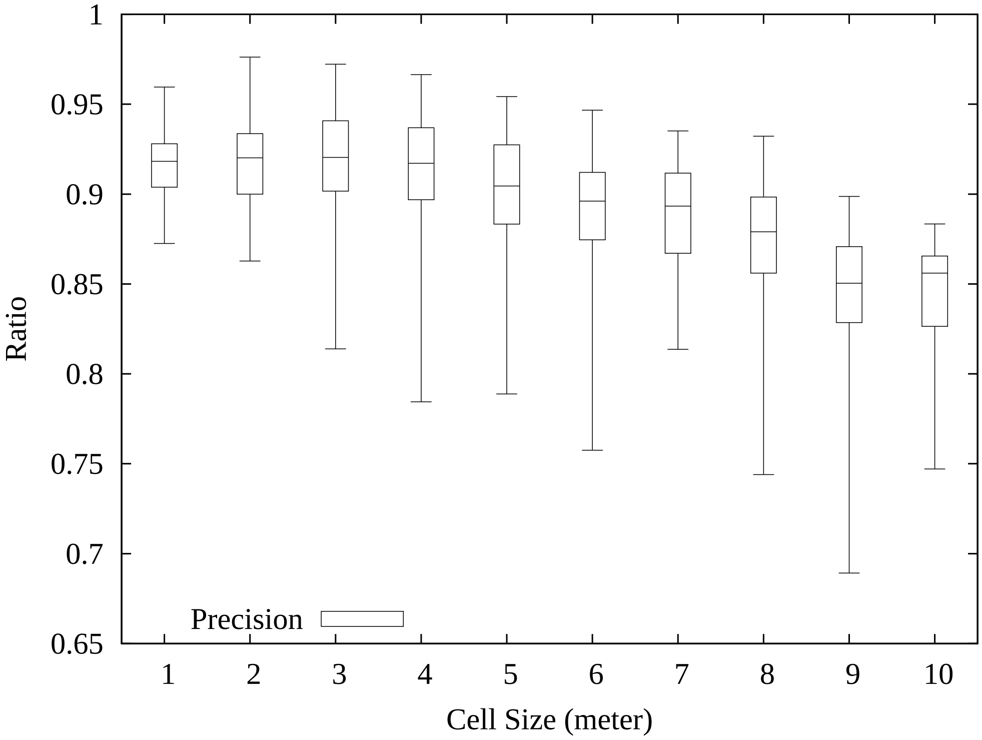
Investigation of Cell Size

As described in Section 2.1.2, our architecture employs a quality map that consists of N-meters cells. Since coverage area detection is performed at each cell, cell size is an important factor. Then, we evaluate detection accuracy depending on cell size, and find the value of the cell size (N) carrying out the reasonable detection accuracy. Note that, in the simulation, the MN keeps moving during 10 hours and the location acquisition interval is set to 50 milliseconds to avoid that the recorded location includes the error due to it.

First, Figure 2.13 indicates recall of detected coverage and precision of detected cells. Recall is calculated by equation 2.3, and indicates how accurately find coverage area depending on cell size, whereas precision ratio is calculated by equation 2.2,



(a) Recall of detected coverage area



(b) Precision of detected cells

Figure 2.13. Accuracy of detected coverage

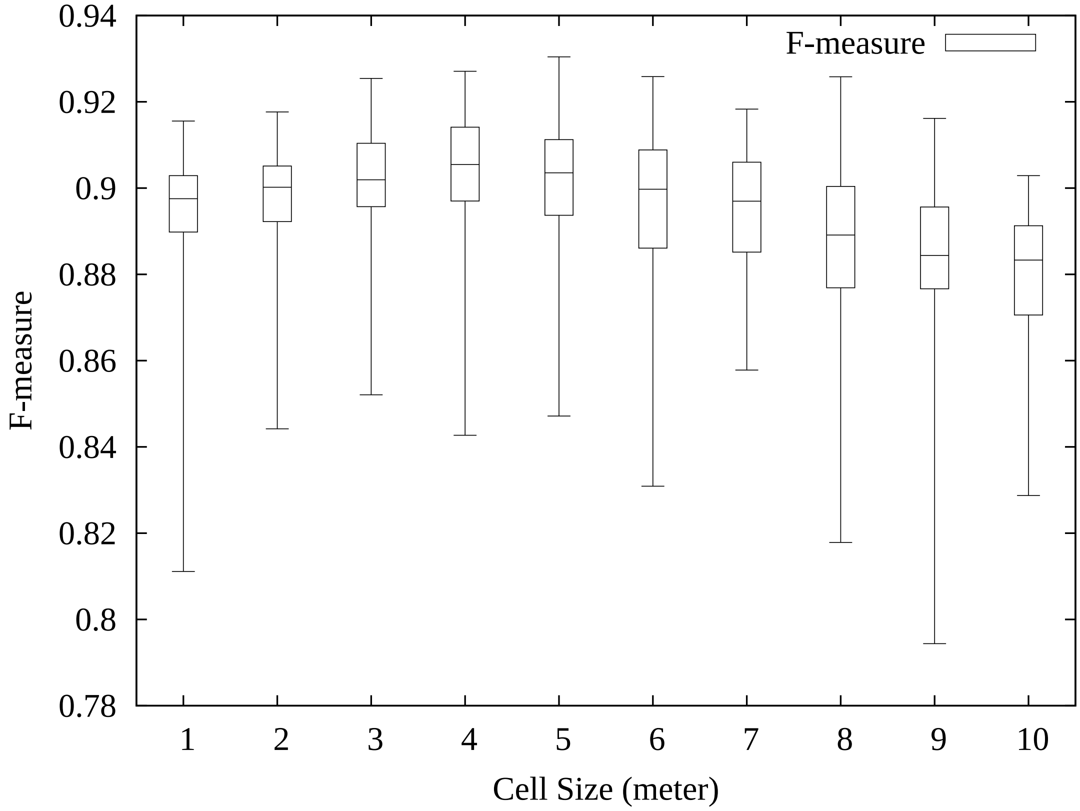


Figure 2.14. F-measure with each cell size

and means how amount of correctly detected cells is included in detected cells. From Figure 2.13(a), recall becomes larger as cell size is larger. Generally, larger cell size brings more accurate measurement result, because more lots of packets are transmitted in a larger cell. On the other hand, in Figure 2.13(b), precision falls with cell size. Since coverage area detection based on each cell, error often occurs due to different cell granularity between actual coverage and detected coverage. Therefore, we can see that recall and false detection have trade-off relationship depending on cell size.

To balance the trade-off relationship, our study investigate detected coverage area by the F-measure. Figure 2.14 shows F-measure for each cell size. We can see that the F-measure grows with cell size until 4-meters cell, and then keep falling. This behavior caused by trade-off relationship described above. Note that, our study more focuses on reducing F_p (overestimation), therefore, F-measure tend to be better when coverage area is underestimated. Then, since 4-meters cell indicates best value of the F-measure, 4-meters or 5-meters cell have possible to be best values in cell size.

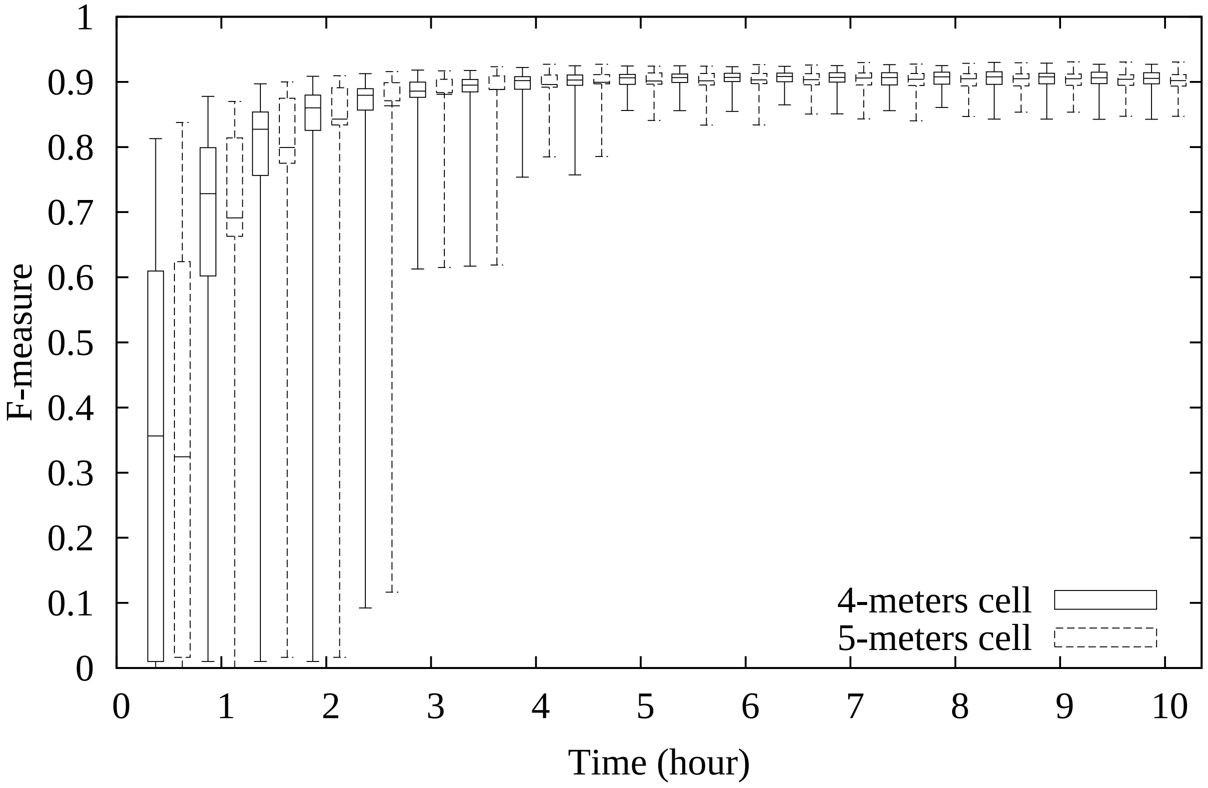


Figure 2.15. Time series variation of the F-measure

Investigation of the Time Series Variation

Since our architecture depends on communication of MN, it is important to investigate how different the detected accuracy changes in time series, and how long does it take until detection accuracy reaches the result of Section 2.2.5. Then, since Section 2.2.5 indicates that 4-meters or 5-meters cell leads better result, this section attempts to compare them in time series, and find the duration needed to converge on the result of Section 2.2.5. The simulations are performed in the same parameters and scenario with Section 2.2.5

Figure 2.15 shows time series variation of the F-measure for 4-meters and 5-meters cell, respectively. In these graphs, the F-measure is calculated at each 30 minutes. This figure indicates that the F-measure converges with increase of the simulation duration in 4-meters and 5-meters cell. Compared 4-meters cell with 5-meters cell, the F-measure only shows little difference variation in time series. In shorter duration (less than 2.5 hours), since the moved distance is a short and total amount of transmitted

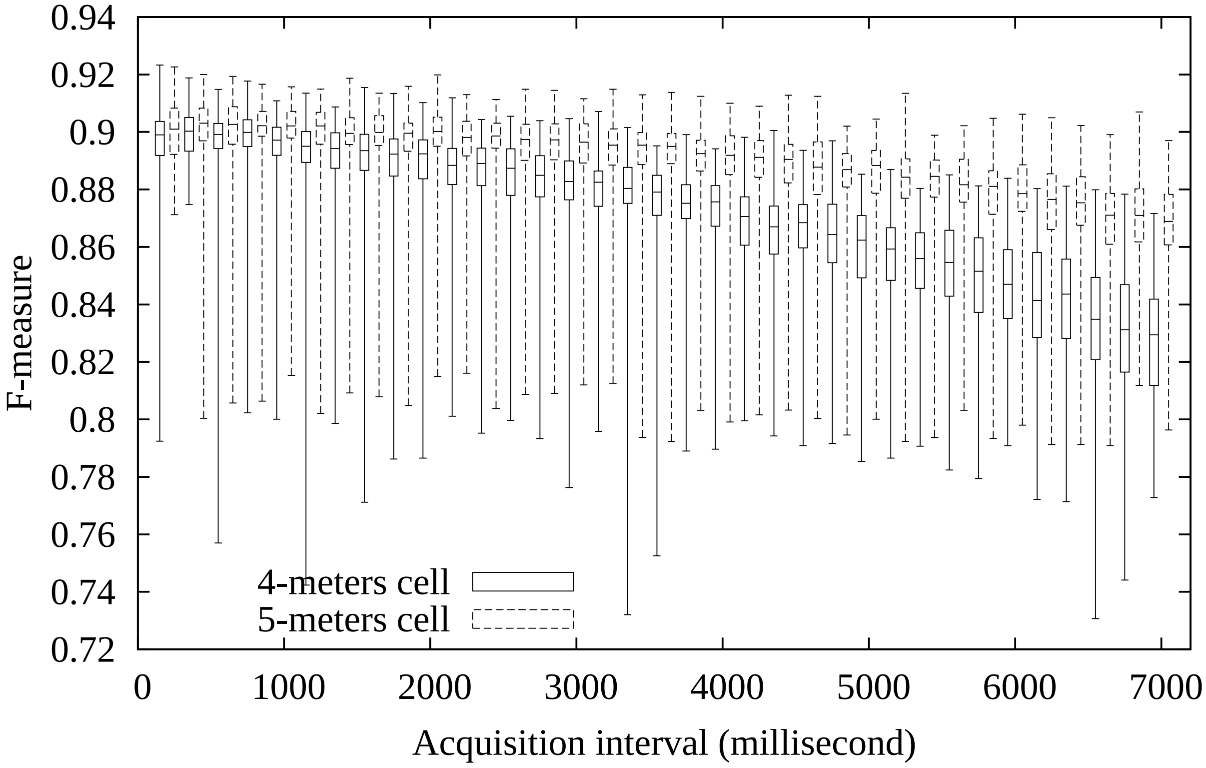


Figure 2.16. The F-measure with the execution interval of the location manager

packets in each cell is a little, the F-measure widely distributes. After 2.5 hours, the F-measure starts to reduce the distribution and finally it converges at approximately 5 hours later. Then, we can see that 5 hours is sufficient to detect the coverage area based on a single MN.

Investigation of the location acquisition Interval

In our architecture, the location of each MN is periodically obtained by the NLM, and registered into the location field of the target list, which is used to record measured metric. Then, detection accuracy degrades if measured metric is registered into an improper cell. This section evaluates impact of the location acquisition interval on the F-measure, and attempts to find the reasonable interval, which does not prevent detection accuracy. Note that, in this experiment, the simulation is runed for 5 hours as investigated in Section 2.2.5.

Our study investigate the variation of the F-measure depending on the execution interval. Figure 2.16 shows the F-measure with interval for 4 and 5-meters cell re-

Table 2.3. Results of coverage area with obstacles

	Minimum	Median	Maximum	Average
Recall	79.5%	82.3%	84.3%	82.2%
Precision	95.0%	96.9%	97.2%	96.7%

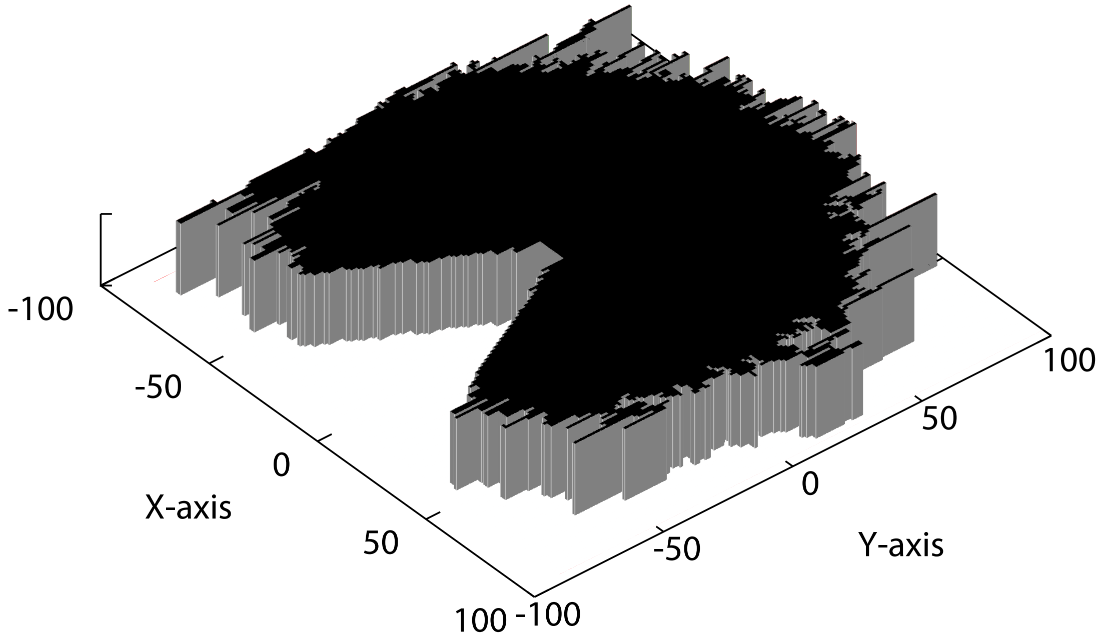
spectively. In the figure, the F-measure is indicated at every 200 milliseconds on the interval. In both cells, the F-measure gradually decreases as the interval grows in time. However, the F-measure of 5-meters cell degrades more slowly than that of 4-meters cell. This is because, as cell size becomes larger, the possibility that measured metric is recorded in an improper cell is smaller. From the above results, we can say that 5-meters cell is better than 4-meters cell, hence, we employ 5-meters cell as the cell size in the following section. In addition, we also employ 1000 milliseconds as the location acquisition interval because in 5-meters cell the F-measure starts to degrade at nearly 1000 milliseconds.

2.2.6 Case Study: Obstacle Detection

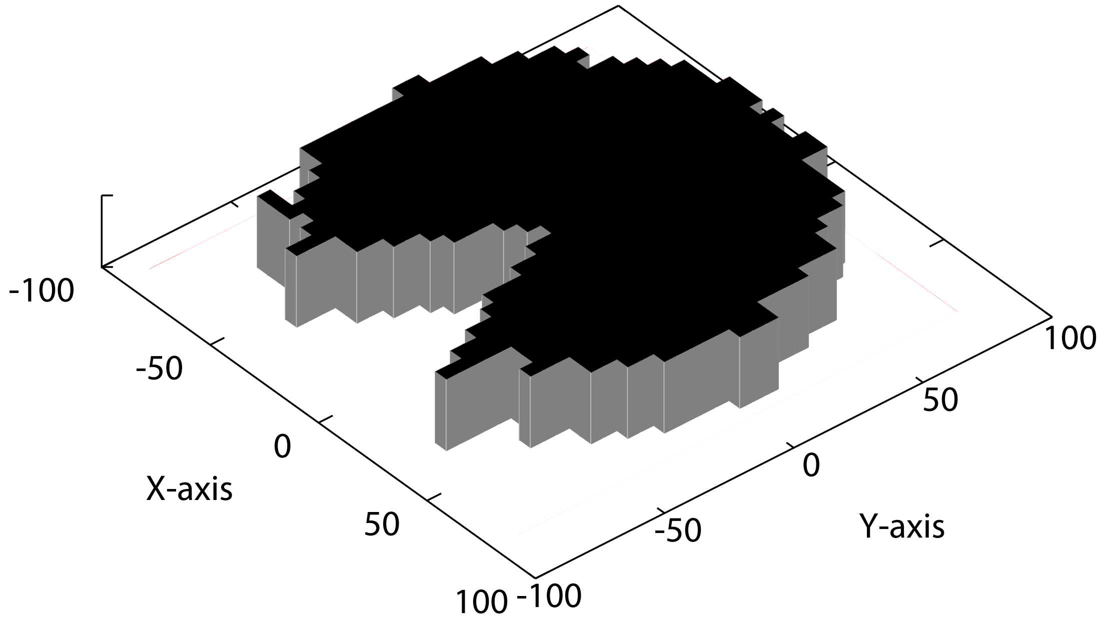
In this section, we show simulation results with an obstacle. In the simulation model, This simulation follows the parameter settings in Table 2.1 except an obstacle. In addition, in configurable parameters, our study sets the cell size and the acquisition interval of the location to 5 meters and 1,000 milliseconds, respectively, based on the results in the previous section. Note that, the simulation is performed for 5 hours in simulation time, and executed at 100 times. The AP is located at (0, 0) of the simulation area in this experiment. Our study then puts an obstacle of 10-meters width, 3-meters height and 0.5-meters thickness at (0, -10) in the simulation area.

Table 2.3 shows minimum, median, maximum, and average values of recall and false rate in an obstacle scenario. From the table, our proposed architecture detects approximately 82 percents of coverage area. In addition, approximately 97 percents of detected coverage area is F_p; in short, detected coverage area does not so contain mistaken of detection, because 100 percent of precision indicates that the detected result does not contain F_p. From these, we can see that our architecture tends to underestimate coverage area, i.e., detected coverage area becomes smaller than the actual coverage area.

Figure 2.17 shows the actual coverage area and the detected coverage area. Note that these figures show the result of the median values of Table 2.3 in 100 simulations.



(a) Actual coverage area



(b) Detected coverage area

Figure 2.17. Coverage area with obstacle

From Figure 2.17(a), we can see that the coverage area has a dent shape, i.e., a locations where the MN cannot obtain the predetermined communication quality, due to the obstacle. On the other hand, from Figure 2.17(b), our proposed architecture can detect the dent shape as well as does the correct dataset. Comparing Figure 2.17(b) with Figure 2.17(a), we can see that our proposed architecture underestimates coverage area.

To maintain communication quality in ubiquitous WiFi network, it is important that the coverage area of all AP are appropriately integrated. However, our architecture unable to avoid containing detection error because of employing asynchronous procedure between the wireless measurement and the location management. We need to balance between overestimation and underestimation. Then, from the viewpoint of achieving omnipresent sufficient communication quality, utilizing the overestimated coverage area brings deterioration holes; hence, underestimation is relatively preferred. Therefore, from the above result, we can say that our architecture can detect the reasonable coverage area to maintain communication quality because the $Precision$ is closer to 1 than the $Recall$.

2.2.7 Dependency on multiple MNs

In this section, we additionally investigate the performance of our proposed architecture with multiple MNs. In the above experiments, we investigated characteristics of our architecture and evaluated detection accuracy based on a single MN. However, we assume that our architecture can simultaneously utilize multiple MNs to measure communication quality in the access area. Then, we attempt to investigate the dependency of our architecture on multiple MNs. In the experiments, we set the cell size, the execution interval of the location manager, and the simulation duration to 5 meters, 1000 milliseconds, and 5 hours, respectively. Other simulation parameters are the same with the values of Table 2.1.

Figure 2.18 shows the relationship between the F-measure and the number of MNs. From the figure, we can see that all values of the F-measure is nearly value. In short, we can say that the F-measure does not changes depending on the number of frame retransmissions.

We next investigate how the F-measure changes depending on time series in presence of multiple MNs. Figure 2.19 shows the time series variation of the F-measure. In the figure, median values of simulation results are utilized. From the figure, we can see that the F-measure faster grows as the number of MNs increases. In case of a single MN, it takes 5 hours to reach the result of Figure 2.14. On the other hand, at two MNs,

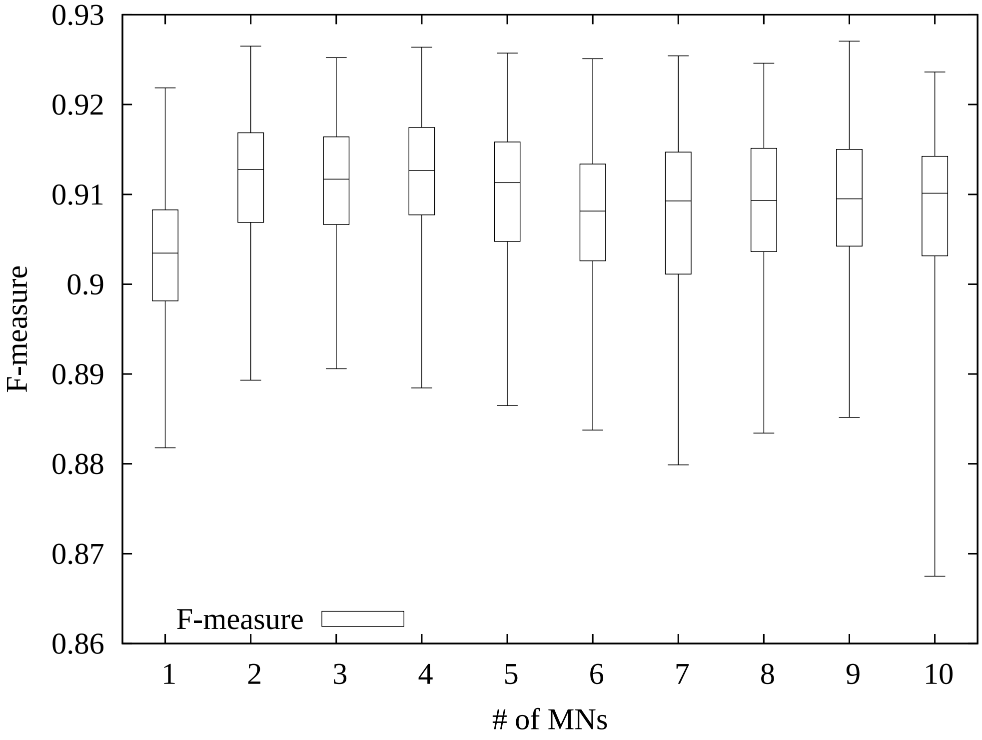


Figure 2.18. F-measure with the number of MNs

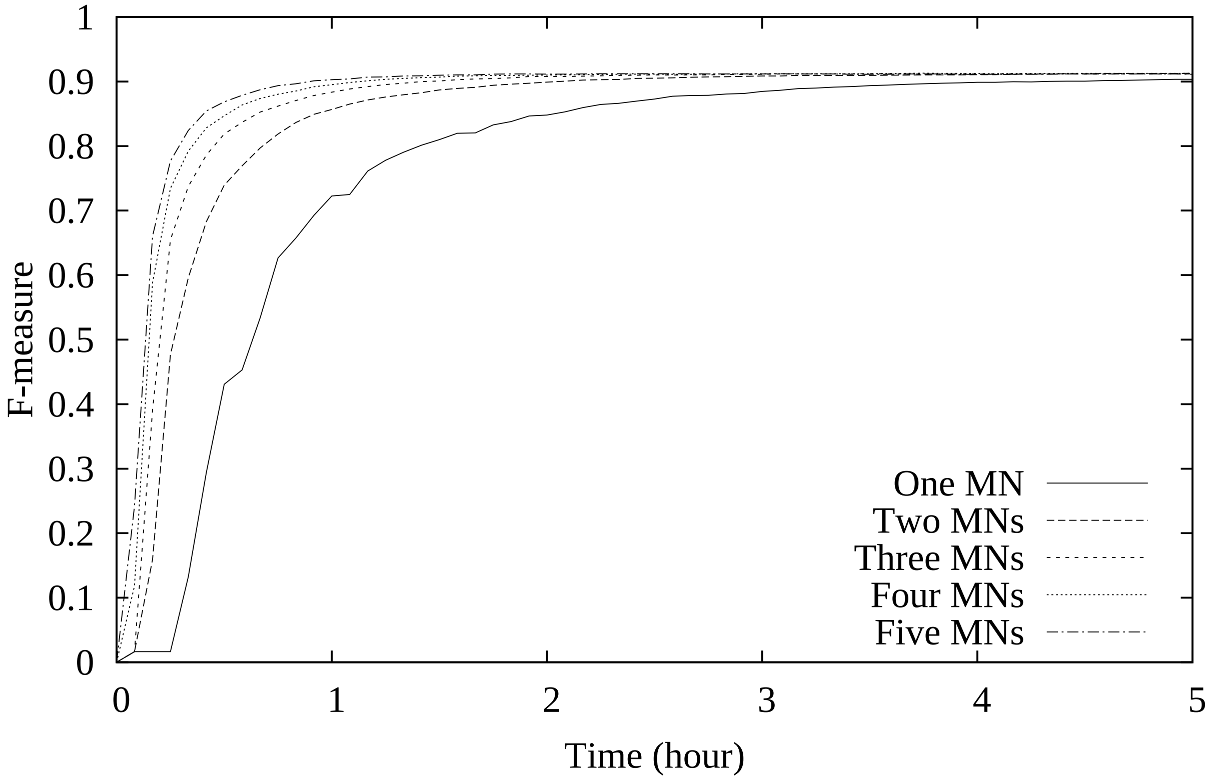


Figure 2.19. Time series variation of the F-measure with multiple MNs

it needs approximately only 2.5 hours. In addition as shown in Figure 2.19, in three MNs, it takes approximately only 1.5 hours. Then, the growth time of the F-measure is simply proportional to the number of MNs. Therefore, we can say that the coverage area can be detected more rapidly without degradation of the detection accuracy by employing multiple MNs.

2.3. Summary

In ubiquitous WiFi network, it is essential to appropriately integrate coverage area so that an MN has sufficient wireless Internet connectivity everywhere. In other words, detection and improvement of deterioration holes are essential. In this chapter, our study presents wireless measurement architecture to identify coverage area with desirable communication quality intending to detect deterioration holes. Although coverage area is currently detected by identifying locations where an MN can associate with an AP based on signal strength, our study tackles a new paradigm of coverage area detection, i.e., identifying locations where an MN has sufficient wireless Internet connectivity. Moreover, in order to detect coverage area, manually operated measurements are indispensable so far even if coverage estimation approach is took. Our proposed measurement architecture overcomes it, and holds high scalability by enabling AP to autonomically conduct measurement.

Through the simulation experiments, our study explores performance metrics that an AP appropriately detects communication quality inside its own coverage area. As a result, we can see that FER is the most suitable for it. Then, after our proposed architecture is examined in various parameters to find a suitable value, our study attempts to detect coverage area in the presence of an obstacle as a case study. From the results, we can say that an AP can find out coverage area with desirable communication quality using the proposed architecture. In addition, we can also see that its accuracy is independent on the number of MNs.

3

SELECTING AN AP WITH BETTER PERFORMANCE

In ubiquitous WiFi network, an MN requires not only permanent access to the Internet, but also preservation of communication quality whenever an MN communicates. Furthermore, in ubiquitous WiFi network, many APs will independently provide wireless Internet connectivity based on IEEE 802.11 technology. That is, the APs may have a different IP subnet due to independent management of different organizations and operators. In such a situation, if a support technology for preserving communication quality is developed and standardized for APs in the future, it will be difficult to replace all APs, which have been spreading, with new APs that support such technology. Moreover, since existing APs may not be able to accept such technologies due to restrictions such as lower CPU performance or less memory, update of APs' software for supporting the technology is also not realistic. Therefore, it is desirable to provide quality preservation mechanism without modification of APs.

To achieve preservation of communication quality, the following two requirements must be satisfied: (1) selection of an AP with better performance from among multiple candidate APs and (2) preservation of communication quality during traversing APs (seamless handover). For (2), we proposed a handover management scheme based on the number of frame retransmissions [33, 66, 32]. In the proposed scheme, an MN is assumed to move between APs with different IP subnets. In [33], we first employed multi-homing architecture to prevent a disruption period due to handover processes. That is, since an MN with two WiFi interfaces (WIFs) (a multi-homing MN) can connect to two APs before starting handover, an MN never experiences a disruption period due to handover processes. Although multi-homing architecture requires two physical WIF, existing WIF drivers allows to create multiple virtual wireless interfaces (VWIFs) based on single physical WIF. Since each VWIF is looked like physical WIF from a operating system, every MN essentially equips two WIFs. Next, to properly switch the two associating APs based on each wireless link quality, the number of frame retransmissions was introduced as an indicator for detecting the wireless link condition. Although the Received Signal Strength Indicator (RSSI) is generally used as an indicator of a wireless link quality, we showed that the RSSI is insufficient to detect wireless link condition because it is incapable of detecting the degradation of communication quality due to radio interference [67]. On the other hand, we showed that the number of frame retransmissions could promptly and reliably detect the performance degradation due to reduction of the RSSI and radio interference. Therefore, the proposed handover management method based on the number of frame retransmissions can preserve communication quality during a handover.

Selection of an AP with better performance from among multiple candidate APs, however, remains unresolved. For example, in the method proposed in [33], even if an MN has two wireless interfaces (WIF) to eliminate a disruption period due to handover process, there is no guarantee that the MN can select an AP with better performance for a handover. In ubiquitous WiFi networks, the MN may find multiple candidate APs at one time and needs to select an appropriate AP from among them. At this time, if an AP of good quality is not selected appropriately, the communication quality may degrade after a handover. In the current general AP selection, an MN selects an AP based on the strongest RSSI. However, since numerous APs and MNs will densely exist in ubiquitous WiFi network, radio interference, which degrades communication quality, occurs frequently due to both the lack of the number of channels and heavy traffic in the AP. Thus, in order to achieve seamless mobility, it is essential that an AP selection consider not only RSSI reduction but also radio interference caused by other wireless devices.

In this chapter, we propose a new proactive AP selection method based on RSSI and frame retransmissions and then demonstrate the experimental results of a prototype system. The proposed AP selection method enables an MN to select an AP with better performance taking radio interference into consideration by exploiting the number of frame retransmissions in addition to the RSSI. Note that, we especially focus on the radio interference caused by packet transmission from other wireless devices. Therefore, the proposed method is designed to avoid degradation of communication quality due to collisions between hidden terminals and/or simultaneous transmission from neighboring MNs. Furthermore, our handover management system [33, 61] is extended to introduce our AP selection method, which requires no modification of AP.

This chapter is organized as follows. Section 3.1 surveys related research for existing AP selection methods. Section 3.2 describes the proposed proactive AP selection method. In Section 3.3, we then explain an implementation and system parameters used in the proposed AP selection method. Section 3.4 describes the experimental topology and presents the demonstration in a real environment and screenshots of the prototype system. After introducing our future work in Section 3.5, concluding remarks are presented in Section 3.6.

3.1. Related Work

So far, there have been numerous discussions on AP selection for improving the communication performance of MNs in WLANs. In ubiquitous WiFi network, since an MN must be able to freely connect with all APs for an inter-domain handover, it is desirable that an AP is not modified in order to maintain compatibility with existing APs. Almost all existing AP selection methods [3, 60, 18], however, necessitate some modifications of APs, e.g., additional information is needed in the beacon frame transmitted from the AP. Moreover, the modification needs to be implemented in both an AP and an MN. Such approaches have focused on the enhancement of communication performance in some limited areas where a network operator can manage the all APs. However, if the modified APs are introduced into ubiquitous WLANs, MNs without the modification may not be able to connect to the modified APs or obtain sufficient performance for AP selection. Thus, in this paper, we focus on an AP selection method with no modification of an AP, i.e., only an MN is modified.

In [68, 42], AP selection methods only on an MN were proposed. In [68], the proposed method measures potential uplink/downlink bandwidth by exploiting beacon frames. However, the experiments were carried out under low noise conditions only, and their effectiveness under radio interference conditions have not been investigated. On the other hand, although the method proposed in [42] selects an AP with the best quality using active scanning, the authors did not focus on periodical AP selection. Continuous selection of an AP with better performance is essential for inter-domain handover in ubiquitous WLANs.

In ubiquitous WLANs, communication quality on MNs could degrade due to radio interference and hidden mobile nodes. A number of studies [19, 15] proposed meth-

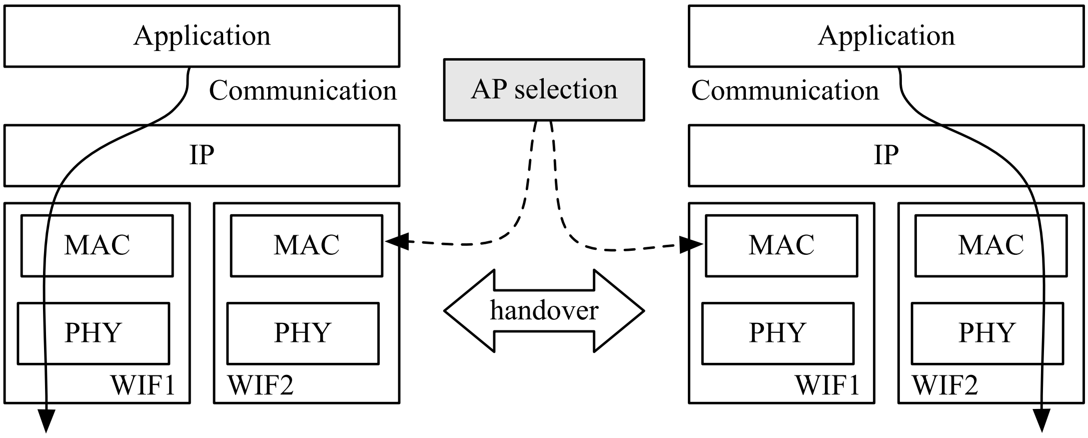


Figure 3.1. A handover and an AP selection on an MN

ods to avoid such types of degradation. In [19], the authors showed the communication performance under radio interference and proposed an AP selection scheme considering radio interference. However, as this scheme is an extension of [18], the modification of an AP is still necessary. On the other hand, [15] explained that the effects from hidden mobile nodes severely impacts throughput degradation. In the method proposed herein, although modification of an AP is unnecessary, the method is applied to only IEEE 802.11e [28], which has not yet become widespread. Therefore, in this chapter, we focus on a proactive AP selection method considering the wireless link condition with no modification of APs for inter-domain handover.

3.2. AP Selection Method

In this section, we describe the proposed AP selection method. We first describe the concept of the proposed method in Section 3.2.1. Then, in Section 3.2.2, we describe the proposed method with flowcharts.

3.2.1 Overview

In this dissertation, our study focus on a proactive AP selection for a radio interference environment. In the handover method, our study proposed in a previous study [61], a multi-homed MN appropriately switches WIFs according to wireless link condition. Figure 3.1 shows an overview of operation between a handover and an AP selection on an MN. An AP selection is performed on the WIF2 during communicating through

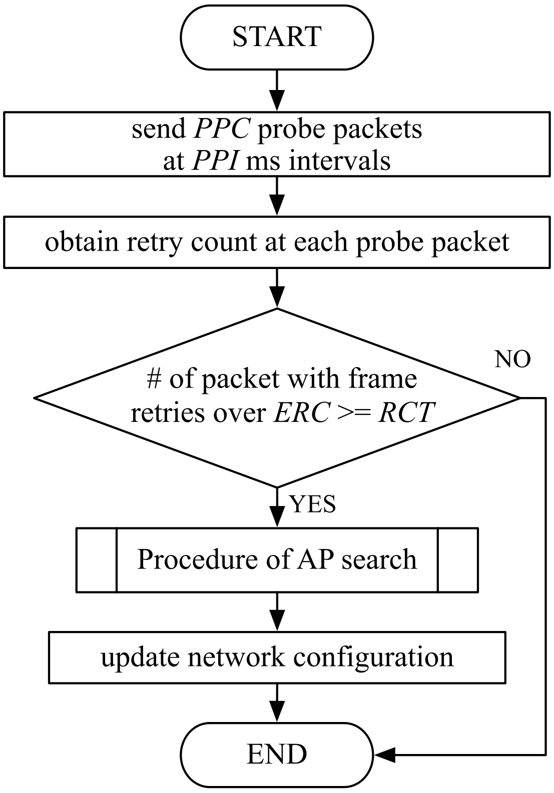


Figure 3.2. Flowchart of the AP selection procedure

the WIF1. On the other hand, after a handover, since the communication switched to the WIF2, the AP selection is next executed on the WIF1. That is, the AP selection is executed on an idle interface.

3.2.2 Details of the AP Selection Method

In this section, we describe the proposed AP selection method. The AP selection method is divided into two main parts: the AP selection procedure and the AP search procedure, as shown in Figures 3.2 and 3.3, respectively. In both figures, *words in italic font* denote the system parameters in the proposed AP selection method. In the AP selection procedure, an MN periodically investigates the wireless link condition of an associating AP and decides whether the wireless link has sufficient wireless link quality. On the other hand, in the AP search procedure, an MN scans candidate APs and selects an AP with better performance from among them if the wireless link quality of the selected AP degrades. Hence, MN starts the AP search procedure only when it detects the degradation of the communication quality by exploiting the number of

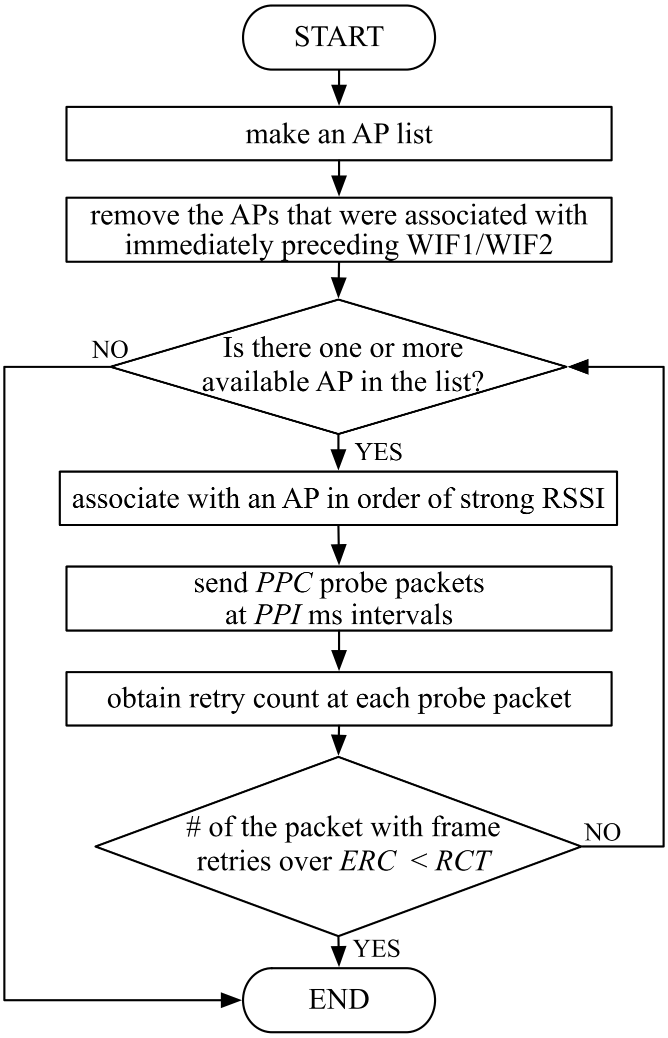


Figure 3.3. Flowchart of the AP search procedure

frame retries. That is, MN does not start the AP search procedure even when the RSSI degrades unless the frame retries increases.

In this section, in order to clarify the proposed AP selection method, we assume that an MN with two WIFs (the WIF1 and the WIF2) first communicates through the WIF1, and the WIF2 associates with an AP with better performance at this time. Hence, the AP selection procedure is executed on the WIF2. Initially, the MN starts a timer to control the AP selection procedure, i.e., the AP selection procedure is periodically executed at each AP Selection Execution Interval of *APSEI* seconds based on the timer. This is because an MN needs to periodically investigate the wireless link condition of the associating AP in order to detect changes in the wireless link quality due to the movement of the MN and radio interference. If the AP selection method is not periodically executed, an MN unfortunately maintains the association with the AP until its wireless link quality clearly degrades, similarly to an AP selection based on the RSSI. This causes severe degradation of the communication quality at handover. When the AP selection procedure is executed, the WIF2 sends probe packets to the AP at constant intervals. The Probe Packet Count (*PPC*) denotes the number of probe packets for one AP, and the Probe Packet Interval (*PPI*) indicates the sending interval of probe packets. After sending all of the probe packets, the MN obtains the number of frame retransmissions for each probe packet. If the number of probe packets that experienced frame retransmission is greater than the Experienced Retransmission Count (*ERC*) is less than the Retransmission Count Threshold (*RCT*), the MN decides that the AP has good wireless link condition and maintains selecting the AP as an AP with better performance for a handover. After selecting an AP with better performance, the procedure terminates and the MN executes the AP selection procedure again after *APSEI* seconds.

In contrast, if the number of probe packets that experience frame retransmission is greater than *ERC* exceeds *RCT*, i.e., the AP associated with the WIF2 is not an AP with better performance, an AP search procedure is executed. As shown in Figure 3.3, in the AP search procedure, the MN first makes a list of all candidate APs detected by the WIF2, and removes the APs currently associated by the WIF1/2 from the list. Note that, to make the list, the MN utilizes the information cached by the Linux OS. In our approach, to efficiently find an AP with better performance, our proposed method first checks the RSSI of candidate APs because the RSSI can be easily and passively obtained than the number of frame retransmissions. That is, it does not need both establishment of the association with APs and the packet transmission of probe packets. Therefore in our proposed scheme, after sorting the candidate APs based on the strength of the RSSI, the MN investigates the APs by exploiting the number of frame retransmissions in order of high RSSI. If not sorting, the MN may transmit unnecessary packets to an AP with low performance (low RSSI) not to an AP with good performance (high RSSI). Hence, creation of an AP list based on RSSI prevents the unnecessary packet transmissions and shortens the detection time as much as possible. In the flowchart, if the number of packets that experienced more than *ERC*-times frame retries exceeds *RCT*, our proposed scheme detects that the wireless condition of the selected AP degrades and then the investigation is repeated in order of high RSSI until finding an AP with better performance. If an AP with better quality cannot be found, the MN retries the AP search at the next AP selection, i.e., after *APSEI* seconds. After finishing these procedures, the MN can select an AP with low radio interference and strong RSSI.

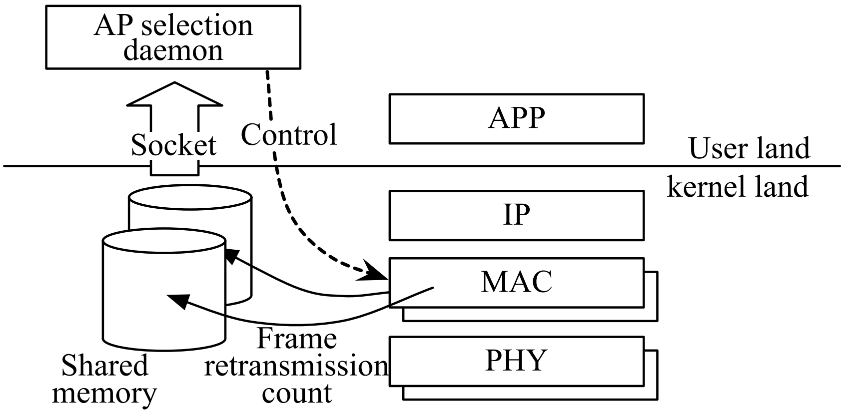


Figure 3.4. Architecture of the AP selection

3.3. Implementation and System Parameters

In this section, we explain the implementation of the proposed AP selection method. Section 3.3.1 describes the present implementation. We then discuss the configurable system parameters of the proposed AP selection in Section 3.3.2.

3.3.1 Implementation

In this section, we describe the details of our implementation. We first explain the implementation environment. We employed CentOS 4.3 with Linux kernel version 2.6.9 as an operating system and a madwifi driver as a WIF driver. Note that the madwifi driver can obtain the number of frame retransmissions per packet on an Atheros chipset. In order to obtain the number of frame retransmissions, we select a laptop PC (ThinkPad X60) with a built-in WIF (P/N: 40Y7028) employing an Atheros chipset. In addition, in the proposed method, since we focus on a multi-homed MN, i.e., an MN equipped with two WIFs, a WIF of a PC card type (corega WLCB54AG2) is prepared as another WIF.

The proposed AP selection method requires no modification of an AP. That is, the proposed AP selection method only requires modification of an MN. Figure 3.4 shows the architecture of the proposed AP selection method on an MN. Note that our AP selection method is implemented as an extension of on the prototype system described in [61]. In [61], the prototype system uses a shared memory to collect the number of frame retransmissions. A handover manager on the transport layer then obtains the number of frame retransmissions from the shared memory and controls the execution of handovers based on the information. That is, the shared memory connects the transport layer with the MAC layer (cross-layer architecture). In the cross-layer mechanism used herein, whenever a data frame is successfully transmitted, i.e., an MN receives an ACK frame on the MAC layer, the modified madwifi driver writes the number of frame retransmissions to the shared memory. The shared memory is allocated for each WIF and forms a ring buffer for storing the number of frame retransmissions. As depicted in Figure 3.4, since our AP selection mechanism works as a daemon process in userland, we also implement a socket to obtain the number of frame retransmissions in the shared memory from userland applications. Moreover, since the AP selection mechanism cooperates with the proposed handover management system, we also implement a function to control the execution of handovers during the AP selection process.

3.3.2 System Parameters

In this section, we discuss the values of the five system parameters *PPC*, *PPI*, *ERC*, *RCT*, and *APSEI* used to control AP selection. As described in Section 3.2.2, the proposed AP selection method employs active measurement to investigate the wireless link condition of each candidate AP and then selects an AP with better performance based on the measurement results. However, since we employ active measurement in the proposed AP selection method, we need to reduce the network load due to measurement and improve the precision of the measurement results as much as possible. In a previous study [67], we investigated the relationship between communication quality and frame retransmissions in a real environment. We then explore the suitable values of the system parameters through a review of the results.

We summarize the experimental results obtained in a previous study [67]. We investigated the relationship between communication quality and frame retransmissions due to the reduction of the RSSI and radio interference. As shown in Figure 3.5, we used an indoor experimental environment to investigate it. Note that, in the experiment, the MN communicates with the corresponding node (CN) through the AP. Figures 3.6 and 3.7 show the variation of communication quality and frame retransmission with the increase of the distance between the AP and the MN in FTP and VoIP communications, respectively. Note that, in the figures, "Retransmission: *X*" denotes the occurrence of *X* frame retransmissions. The results show that the number of frame retransmissions increases just before the degradation of the TCP goodput in FTP and the increase of packet loss in VoIP, as the MN moves away from the AP. Furthermore, as depicted in Figure 3.8, we also investigated how the communication quality and

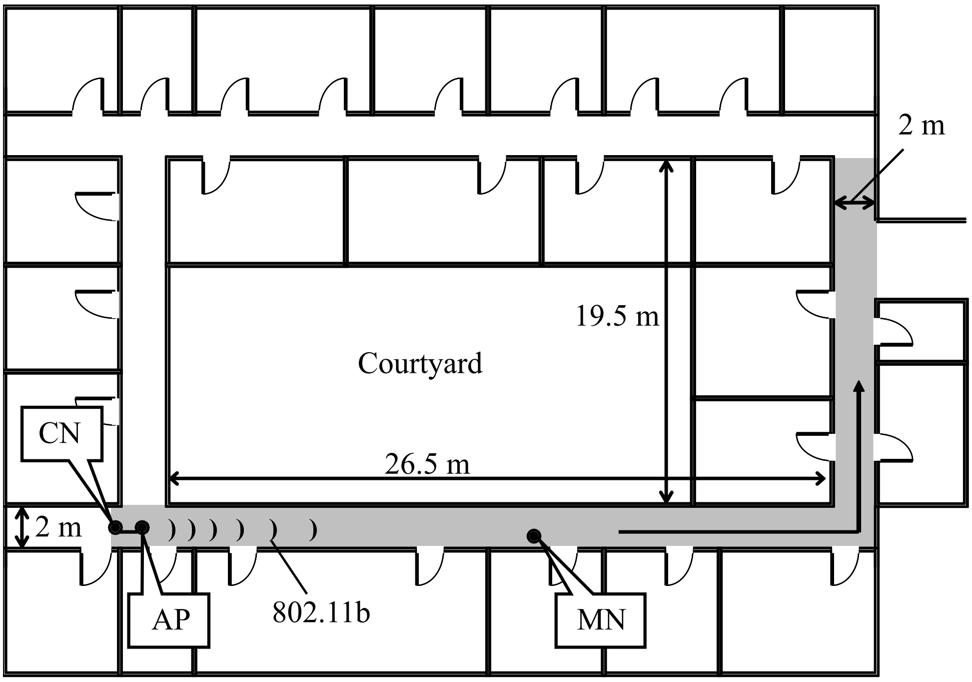


Figure 3.5. Indoor experimental environment (investigation of wireless link quality over a distance)

frame retransmission change under radio interference. That is, since communication on a channel is influenced by traffic on neighboring three channels due to spread spectrum of IEEE802.11b, we investigated its influence. In the experiment, the channel of the AP1 is fixed at 14 ch[1], and the MN1 communicates with the CN1 through the AP1 during the experiments. In contrast, the channel of the AP2 varies from 11 ch to 14 ch in each experiment. To evaluate the influence of radio interference, we then considered the following two cases: (a) without data transmission (only beacon message) and (b) with data transmission. That is, the MN2 does not communicate with the CN2 during communication of the MN1 in (a), whereas the MN2 downloads a large data file from the CN2 through the AP2 during communication of the MN1 in (b). From Figures 3.9 and 3.10, we can see that the number of frame retransmissions increases with the increase of radio interference, while the communication quality degrades.

We discuss the system parameters based on the above results. We first consider the measurement time and measurement precision for estimating the condition of one AP. *PPC* and *PPI* are the system parameters related to measurement time. *PPC* denotes the number of probe packets for one AP, and *PPI* denotes the sending interval of probe

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[1] The 14 ch is only available in Japan.

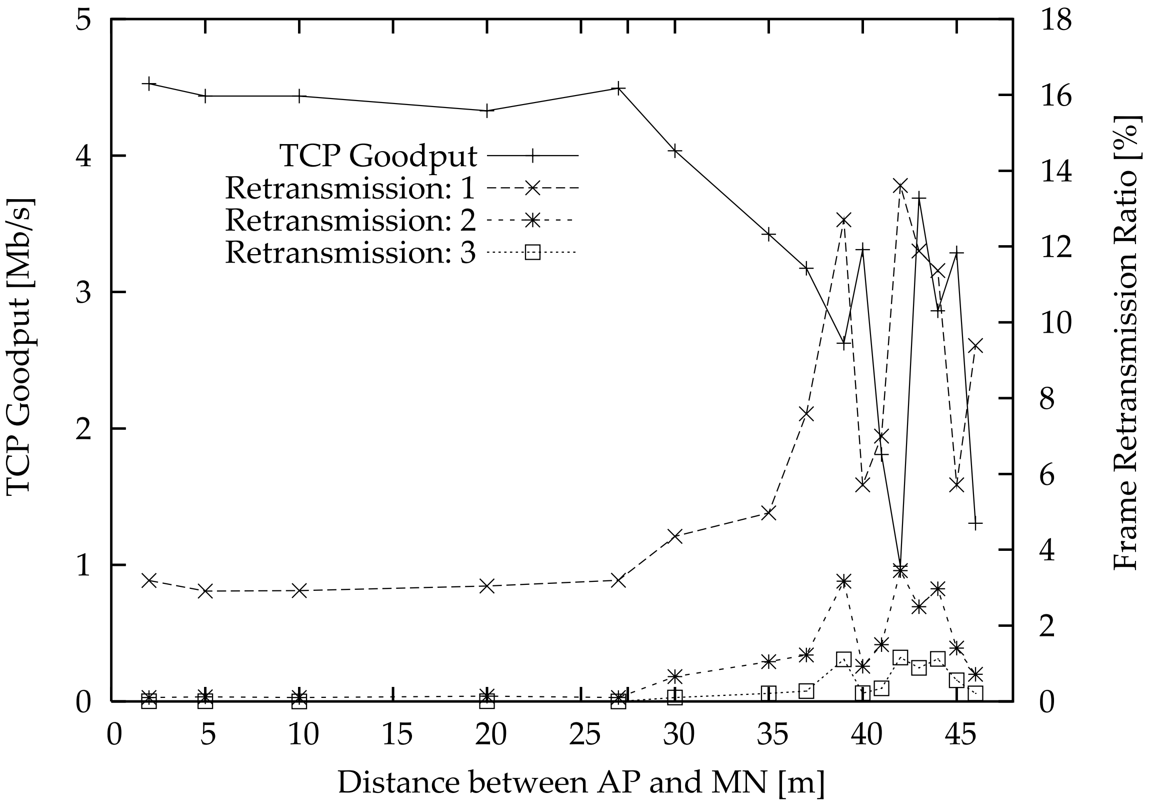


Figure 3.6. TCP goodput and frame retransmission ratio (FTP) over a distance

packets. In *PPC*, as the number of probe packets for one AP increases, the measurement precision is improved. However, the increase in measurement traffic also causes increases in the network load and measurement time. On the other hand, if probe packets are limited, the measurement may be inaccurate. Thus, we need to reduce the number of probe packets as much as possible, while maintaining the measurement quality. Then, in order to obtain the wireless condition as accurately as possible by few probe packets, we set the size of the probe packets to 1,500 bytes because larger packets are more susceptible to radio interference than smaller packets. Note that we intend to investigate the condition of one AP within one second because the RSSI is usually calculated every second in order to smooth its value. That is, our proposed method can detect the radio interference more than one second. In IEEE 802.11b with a fixed rate of 11 Mb/s and RTS/CTS, it takes approximately 2.3 ms to successfully complete transmission of a 1,500-byte packet without frame retransmissions. On the other hand, it takes approximately 12.7 ms to handle a 1,500-byte packet as a lost packet after three frame retransmissions. From the result, in order to complete the measurement of one

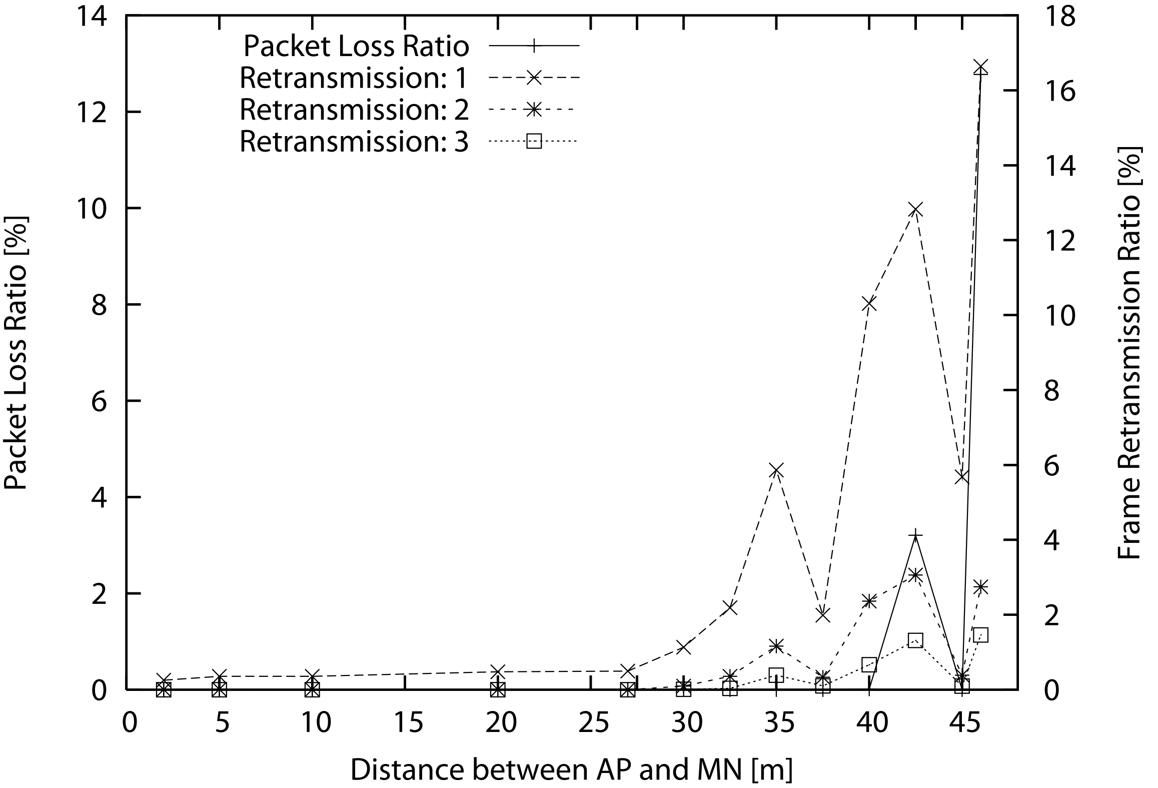


Figure 3.7. Packet loss ratio and frame retransmission ratio (VoIP) over a distance

AP within one second, the number of probe packets should be set to less than 78 (= 1000 / 12.7). Then, the sending interval of probe packets should be shortened as much as possible. Considering the transmission time of 2.3 ms, the sending interval should be set to at least 3 ms. If the interval is set to be shorter, e.g., 1 ms, probe packets are likely to be queued in the buffer of MN. Therefore, *PPC* and *PPI* are set to 50 and 3 ms, respectively.

We next describe *ERC* and *RCT*. *ERC* is the threshold for the number of frame retransmissions that a probe packet experienced, and the proposed method counts probe packets over *ERC* as probe packets with frame retransmissions. On the other hand, *RCT* is the threshold for the number of probe packets with frame retransmissions for evaluating the wireless link condition of one AP, and the AP is decided to have poor wireless link quality when the number of probe packets exceeds *RCT*. First, in *ERC*, Figures 3.6 and 3.7 show that one retransmission provides the best correspondence to the degradation of communication quality, as compared with two and three retransmissions. Thus, in order to appropriately detect the wireless link condition, *ERC* is set

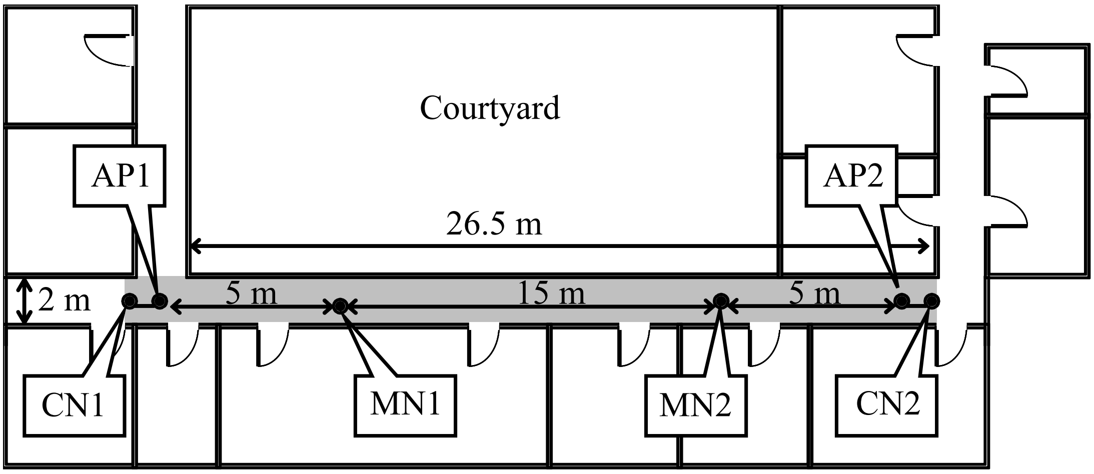


Figure 3.8. Indoor experimental environment (investigation of wireless link quality for radio interference)

to one. We then consider the value of *ERC*. Figures 3.6 and 3.7 show that the communication quality starts to drastically degrade just after the rate of one retransmission exceeds 6%, and Figure 3.6 shows that one retransmission always occurs at a rate of approximately 4%. Moreover, Figure 3.10 shows that the communication degradation is suitably detected by one retransmission of greater than 4%. Hence, *RCT* is set to 3, i.e., 3 is divided by 50, which is the number of probe packets an MN sends to each AP and is equal to 6%.

Finally, we consider the execution interval of the proposed AP selection method. In the present paper, since we assume that users (MNs) move at walking speed, the wireless link condition of each AP varies depending on spatial and temporal changes. Hence, we need to execute the proposed AP selection method at an appropriate interval. *APSEI* denotes the execution interval to run the AP selection method. If *APSEI* is set to a larger value, the communication quality at the selected AP may abruptly degrade when an MN executes a handover. On the other hand, if AP selection is frequently executed with a smaller *APSEI*, the network load increases dynamically. Here, we assume that users move at an average speed of 1 m/s. In this case, from Figures 3.6 and 3.7, we can see that the term, which is from the start of degradation of wireless link quality to the start of degradation of communication quality, is approximately five seconds. That is, it is the duration until communication quality degrades (at approximately 35 seconds) after the number of frame retransmissions increases (at approximately 30 seconds). Therefore, To detect the starting point of the degradation, *APSEI* is set to five seconds. Through the above consideration, in the present paper, we set the

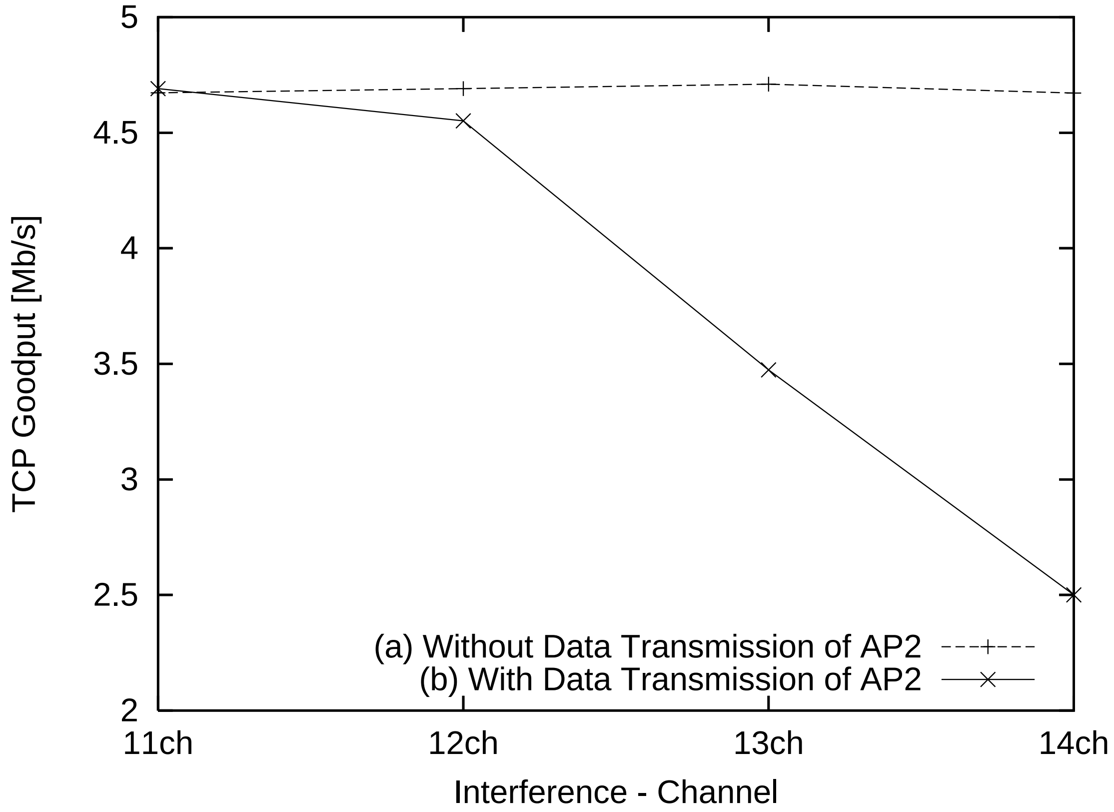


Figure 3.9. TCP goodput performance

system parameters to $PPC = 50$, $PPI = 3$, $ERC = 1$, $RCT = 3$, and $APSEI = 5$. Note that we can say that this configuration is also adaptable to outdoor environment from the results in our previous study [67].

3.4. Experiment

This section explains the experimental results obtained in a real environment in order to demonstrate the effectiveness of using the number of frame retransmissions as a criterion for AP selection and demonstrate the behavior of this implementation. First, in Section 3.4.1, we describe the experimental environment, including the facilities and the experimental topology and scenario. Then, in Section 3.4.2, we demonstrate the system behavior of the AP selection method with the proposed handover method. After that, we evaluate the performance of the proposed method in Section 3.4.3.

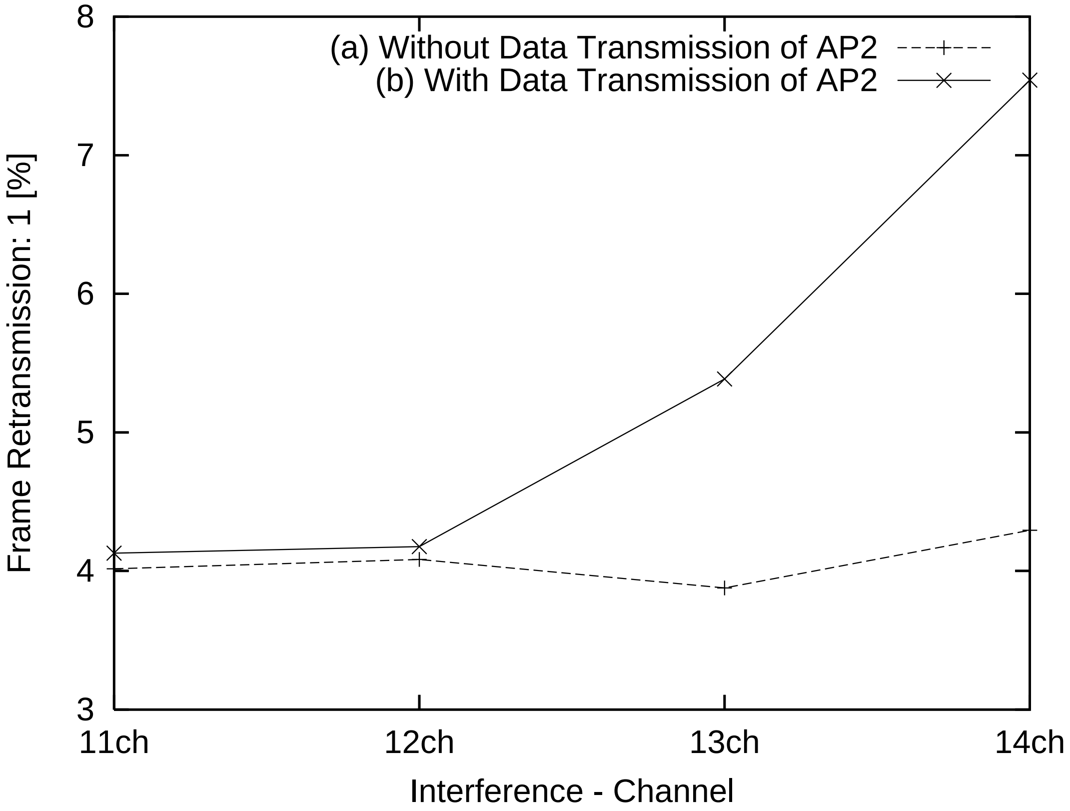


Figure 3.10. Frame retransmission ratio

3.4.1 Experimental Environment

Figure 3.11 shows the experimental topology. In the experiment, we use four laptop PCs, one router, and three APs. The four laptop PCs consist of a multi-homing MN, a corresponding node (CN), and two PCs for generating radio interference. The router has four different IP subnets and connects directly to the CN and three APs via Ethernet cables. The AP selection method is installed in both the MN and the CN. Note that, although the implementation contains not only the proposed AP selection method but also a handover management system, the CN only helps the MN in executing a handover, i.e., the CN does not use the AP selection method. The other two laptop PCs, shown at the bottom of Figure 3.11, are directly associated with each other through a wireless peer-to-peer network, and they use iperf to generate radio interference between the MN and each AP. The two laptop PCs are referred to as JAM PCs. Since the AP selection method needs no modification on APs, we also use the ready-made APs: ORiNOCO AP-600 of proxim and two ORiNOCO AP-4000 of proxim. These APs are

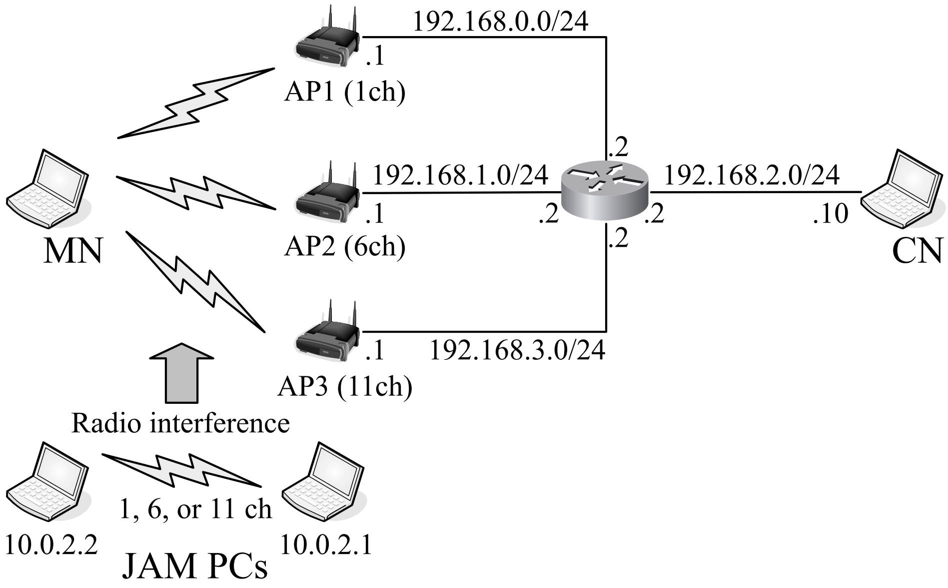


Figure 3.11. Experimental topology

configured to a fixed rate (11 Mb/s) of IEEE 802.11b, i.e., auto rate fallback (ARF) is not used, because the occurrences of frame retransmission dynamically changes due to the change in coding schemes at the physical layer if we employ the ARF. Therefore, in the present paper, we do not focus on the ARF environment. Furthermore, as shown in Figure 3.11, each AP belongs to a different IP subnet so that the multi-homing MN has two different IP addresses. Note that, in this experiment, we placed the MN, the APs, and the JAM PCs as illustrated in Figure 3.12.

3.4.2 Demonstration

In this section, we demonstrate the proposed method with the handover scheme proposed in [61]. The MN first associates with the AP1 and the AP2 through the WIF1 and the WIF2, respectively, and then communicates with the CN through the WIF1 by VoIP (G.711 codec). That is, the MN and the CN alternately send 200-byte packets at 30-milisecond intervals. In order to demonstrate the effectiveness of using the number of frame retransmissions as a criterion for an AP selection, the MN is fixed near three APs during the experiment. After the MN starts to communicate with the CN, the JAM PCs disturb the communication by radio interference. When the MN performs handover to another AP, the JAM PCs also change the channel to another channel with which the MN currently communicates and continue to disturb the communication.

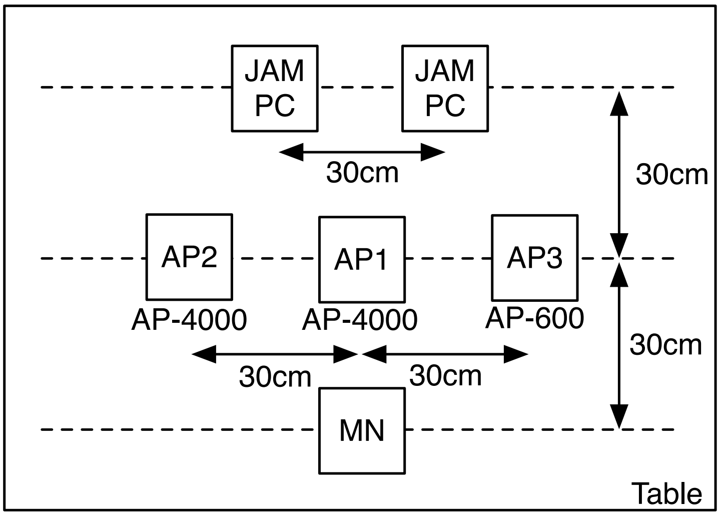


Figure 3.12. Detailed placement of facilities

That is, in the demonstration, AP selection is executed after handover process. In order to show the behavior of handover and AP selection, we also capture traffic data by tcpdump and the output of the iwconfig command. We obtain the sent packet count from traffic data captured by tcpdump and the associating AP with each WIF from the output of the iwconfig command. Here, we explain one result in ten experimental results, because other results also have almost the same behaviors.

Figure 3.13 illustrates which AP is used by each WIF. The x-axis indicates the time sequence, and the y-axis indicates that the cumulative packet count succeeded in transmitting through each WIF. That is, as an increase in the cumulative packet count indicates that the WIF communicates through an AP, we can see the execution point of handover. Moreover, the AP associated with each WIF is distinguished by three points. Note that, in the graphs, the shadowed area shows the radio interference period for each AP.

In Figure 3.13, packet capture begins when the MN starts to communicate with the CN. The WIF1 and the WIF2 of the MN associate with the AP1 and the AP2, respectively, and then communicate with the CN through the AP1 (WIF1). At this time, since the WIF2 is idle, the AP selection method is executed on the WIF2. However, since the channel used by the WIF2 is stable, the WIF2 maintains an association with AP2. On the other hand, in the AP1, the JAM PCs disturb the communication through the AP1 by radio interference. The interference is from approximately 25 seconds to approximately 55 seconds. As a result, the MN executes a handover, i.e., the MN switches the communication path from the WIF1 to the WIF2 at 28.3 seconds. Then, the MN

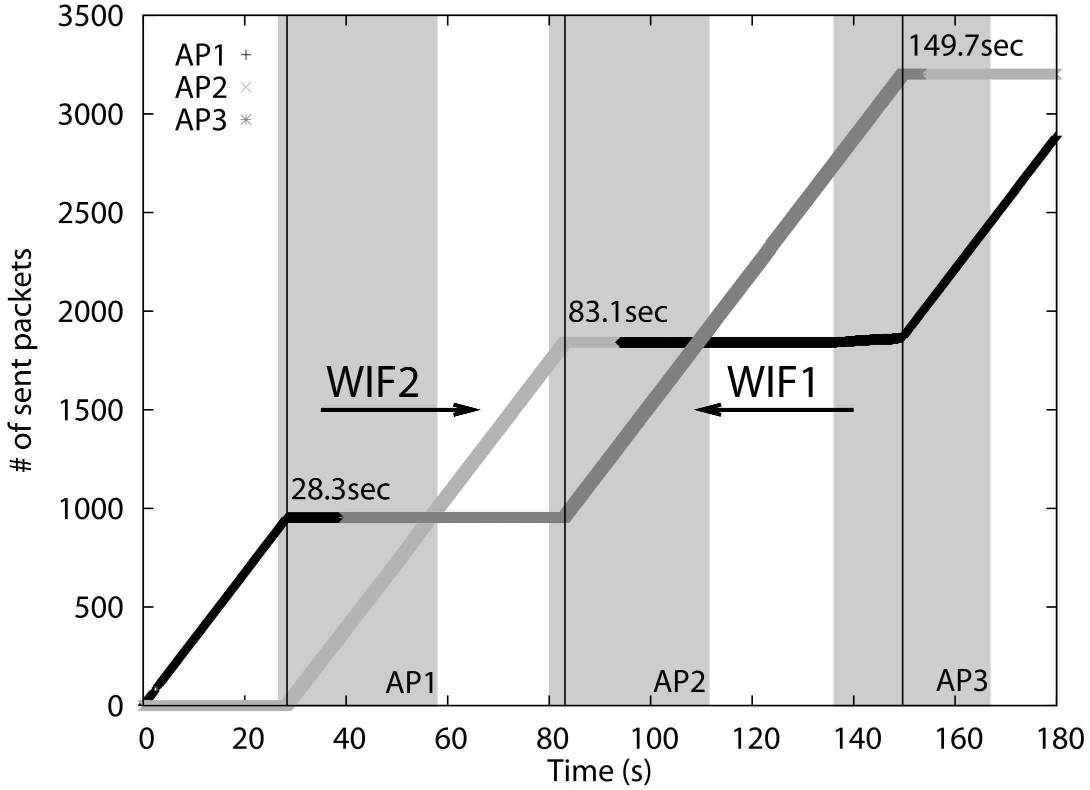


Figure 3.13. selected AP and sent packet count

starts to run an AP selection procedure on the WIF1. From the results of an active scanning, the WIF1 selects the AP3 as an AP with better performance at approximately 40 seconds, because the AP1 now has radio interference from the JAM PCs, i.e., the wireless link quality of the AP1 is degraded. Next, we again generate radio interference with the AP2 at approximately 80 seconds. The communication path of the MN is then switched to the AP3 of the WIF1, and the WIF2 selects the AP1 after executing the proposed AP selection method and avoids radio interference with the AP2. Finally, we also disturb the communication through the AP3 using the JAM PCs at approximately 135 seconds. As a result, the handover is executed at 149.7 seconds based on our previous proposed handover management scheme. After that, our proposed AP selection method actually runs on an idle WIF (WIF1) and selects the AP2 with non-interference as an AP with better performance. Therefore, the MN can select the AP with better performance. In addition, the proposed AP selection method and the handover mechanism work cooperatively.

In Figures 3.14 and 3.15, we show the behavior of the RSSI for each WIF. These results are obtained from the output of the iwconfig command during an experiment.

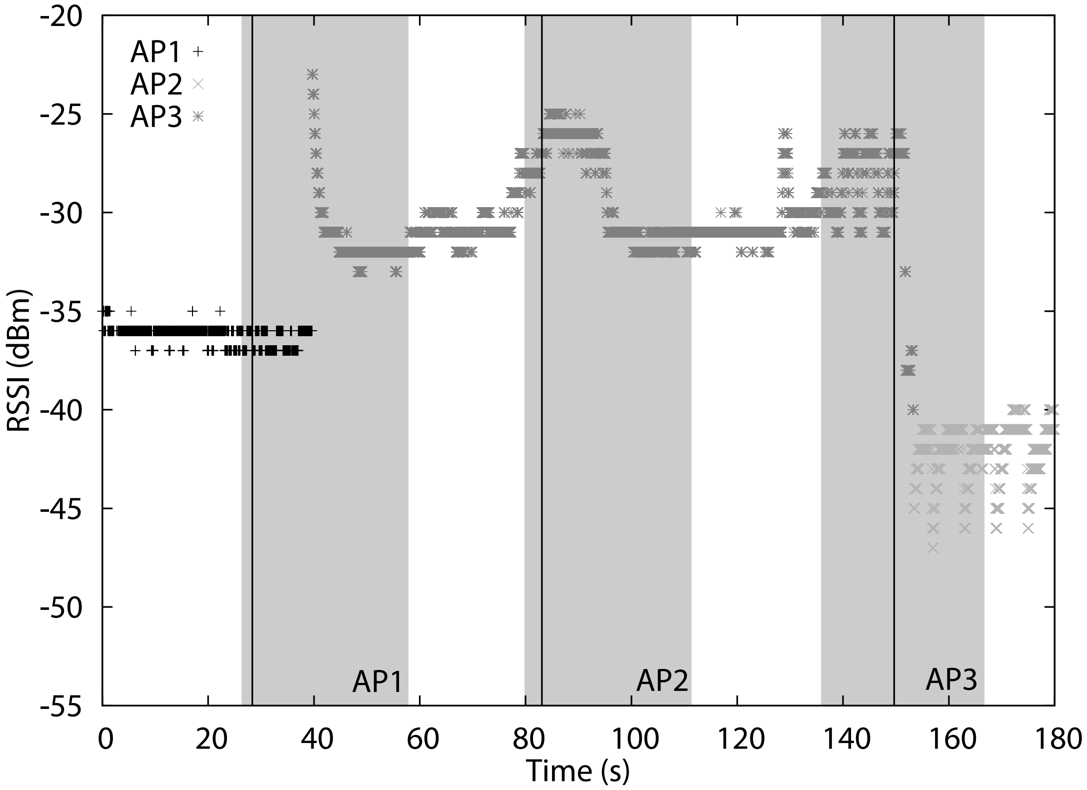


Figure 3.14. RSSI on the WIF1

Note that, the difference of the RSSI obtained from both the WIF1 and WIF2 for the same AP depends on some physical factors, such as antenna position. As shown in Figure 3.13, the first handover is finished at approximately 28 seconds. On the other hand, Figures 3.14 and 3.15 show that the MN can smoothly communicate through the WIF2, even though the RSSI of the WIF2 is smaller than the RSSI of the WIF1. Moreover, even if the RSSI is weak, the MN can also select an AP with better performance, which has no radio interference. For example, at approximately 150 seconds, WIF1 switches its association from the AP3 to the AP2, which has a lower RSSI than the AP3 (see Fig. 3.14). These results reveal that by using the number of frame retransmissions, the MN can escape as necessary from the AP disturbed by radio interference. Therefore, selecting an AP with better performance in ubiquitous WiFi network, the number of frame retransmissions is a potentially effective metric for the selection of an AP with a good wireless link condition.

In Figure 3.16, we present two screenshots of the implementation of the experiment. In Figure 3.16(a) shows that the MN executes a handover to the WIF2 (ath1). In Figure 3.16(b), after the handover, the WIF1 (ath0) selects the AP3 as an AP with better

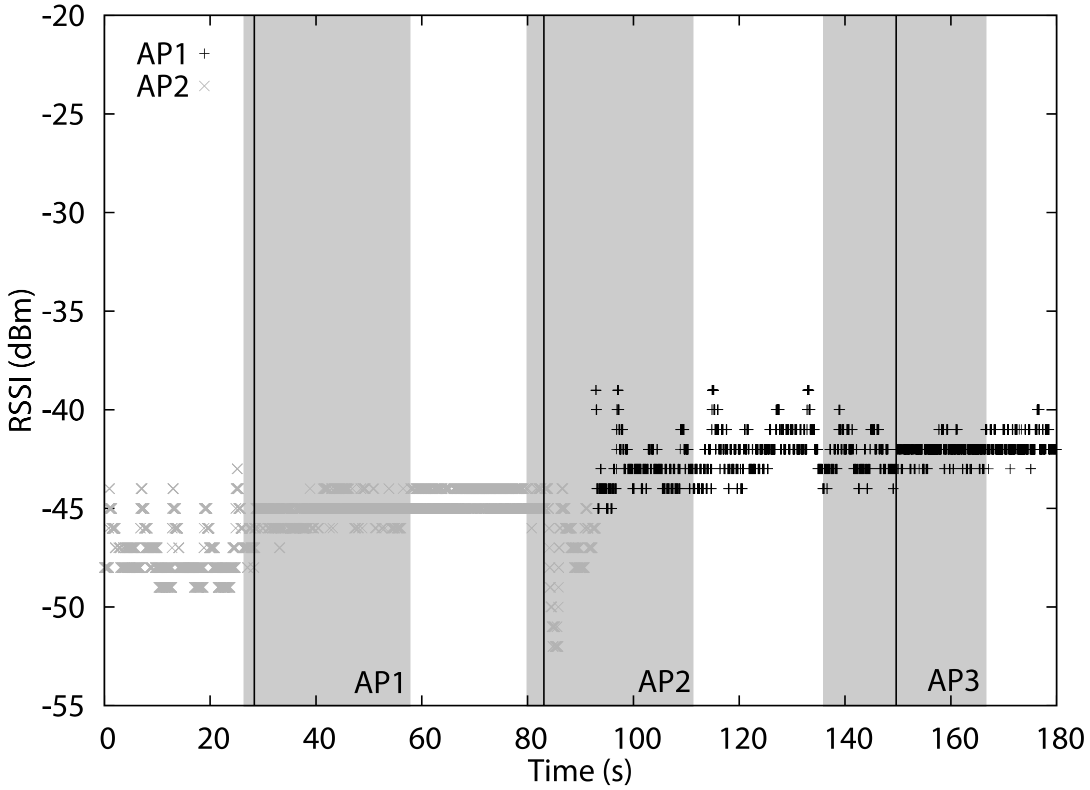


Figure 3.15. RSSI on the WIF2

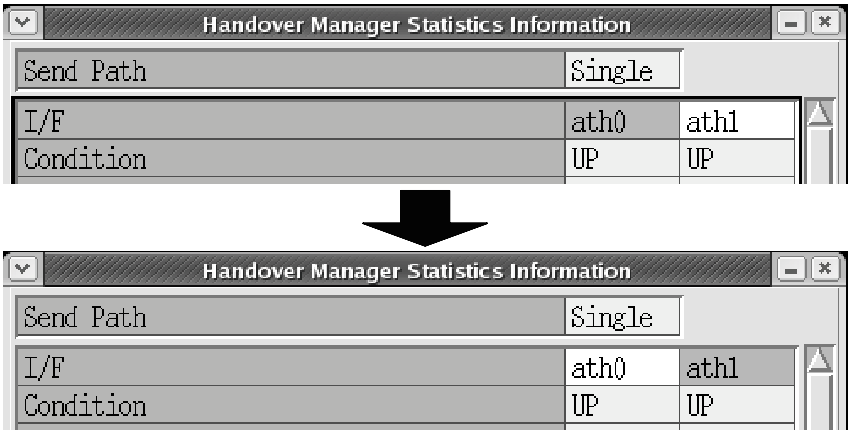
performance, thereby avoiding radio interference with the AP1.

3.4.3 Performance Evaluation

In Figure 3.13, after radio interference occurs, there are delays until the MN selects an AP with better performance. In addition, each value of the delays differs each other. Therefore, in this section, we evaluate the processing time of the proposed AP selection method through actual experiments.

In order to evaluate the processing time, we use the environment described in Section 3.4.1 and generate radio interference in the same way in order to make the MN perform AP selection. In this experiment, in order to precisely evaluate only the processing delay of AP selection, we perform ten experiments without the effect of the handover mechanism. That is, we generate radio interference by the JAM PCs to the idle WIF with no communication. During the experiment, we also collect traffic data captured by tcpdump and the output of the iwconfig command.

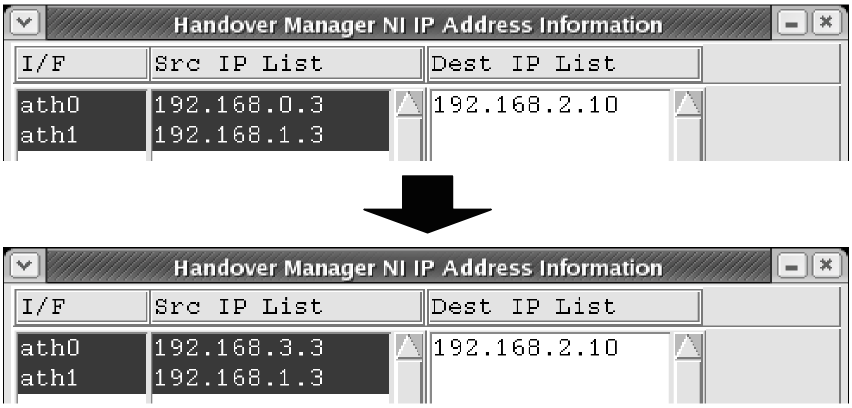
The processing time from the occurrence of radio interference to the completion of



Send Path	Single	
I/F	ath0	ath1
Condition	UP	UP

Send Path	Single	
I/F	ath0	ath1
Condition	UP	UP

(a) The MN changes a WIF to the WIF2 (ath1) for communication (executing a handover)



I/F	Src IP List	Dest IP List
ath0	192.168.0.3	192.168.2.10
ath1	192.168.1.3	

I/F	Src IP List	Dest IP List
ath0	192.168.3.3	192.168.2.10
ath1	192.168.1.3	

(b) The WIF1 (ath0) changes an association to the AP3 (192.168.1.3)

Figure 3.16. Screenshots of the implemented system

the AP selection is divided into the detection delay, which is the period from the occurrence of the radio interference to the start of the AP selection, and the processing delay of the AP selection method. Note that the processing delay contains a period of active scanning. Then, we show the experimental values of the detection delay and the processing delay sorted in order of increasing magnitude in Table 3.1(a), and the minimum, average, and maximum values of these delays are shown in Table 3.1(b). These results show that the detection delay is widely distributed between 1.60 and 19.03. This is because the occurrence of frame retransmissions depends on the timing of the collision with packets transmitted by the JAM PCs. Even in the environment in which two MNs disturb communication, the MN can detect degradation of communication quality in less than 20 seconds, and usually in less than 12 seconds (see Table

Table 3.1. Detection and processing delay

(a) Experimental values listed in order of magnitude

Detection delay	Processing delay
1.60 s	1.98 s
2.22 s	2.16 s
2.99 s	2.38 s
3.41 s	7.37 s
5.93 s	7.59 s
7.09 s	8.27 s
7.85 s	8.33 s
10.80 s	8.36 s
11.67 s	8.51 s
19.03 s	8.58 s

(b) Minimum, average, and maximum values

	Minimum	Average	Maximum
Detection delay	1.60 s	7.26 s	19.03 s
Processing delay	1.98 s	6.35 s	8.58 s

3.1 (a)). Note that, from Figures 3.6 and 3.7, since the area of sufficient communication quality is greater than 20 square meters, the proposed AP selection scheme can be used for walking speeds. On the other hand, the processing delay is distributed between 1.98 and 8.58 seconds. The processing delay consists of the time required to send probe packets and the processing time of the proposed AP selection method (Figures 3.2 and 3.3). Since the time required for sending probe packets is not so large due to the limitation on frame retransmission, the processing time of the method impacts the processing delay. In particular, in the proposed method, making an AP list in Figure 3.3 requires a significant amount of time, which results in increased processing delay, because the MN must sense the beacon frame of each AP for a while before making the AP list. Although the proposed method requires such a delay, the proposed AP selection method, which employs not only the RSSI but also frame retransmission, works effectively in the presence of radio interference.

3.5. Future work

In this chapter, we showed that our proposed method can select an AP with better performance with high RSSI and low radio interference. However, to adapt the method to more realistic environments, the following problems remain. We here describe them as the future work.

a) APs with Auto-Rate Fallback (ARF): In the present experimental environment, we disabled ARF function because it makes our basic evaluation complex. However, since almost APs enable it in a real environment, we intend to study the influence of various ARF algorithms in order to demonstrate practical use in actual ubiquitous WiFi network.

b) Network load: Since our proposed method employs an active scan to collect the number of frame retransmissions, it may contribute to network load. In the present configuration, 50 probe packets with 1,500-byte size are sent in 3-milliseconds interval at every 5 seconds, that is the network load generated by one MN is 120 ($= (8 \times \frac{50\times 1500}{5})/1000$) kbps. As the network load increases depending on the number of MNs, it is important to reduce network traffic of probe packets. To solve the problem, we consider the following approach. An MN can capture frames sent by another MN even if the frames are not destined for itself. As proposed in [43], a representative MN among MNs associating with an AP sends probe packets. Then, MNs around the representative MN detect condition of an AP based on the captured frames. Thus, this approach has a possibility to be able to reduce the network load.

3.6. Summary

In this chapter, in order to select an AP with better performance from among multiple candidate APs in ubiquitous WiFi network, we proposed a proactive AP selection method based on frame retransmissions and the RSSI. In an AP selection based on only the RSSI, an MN cannot always select an AP with better performance in ubiquitous WiFi network, because the RSSI alone cannot detect the degradation of wireless link quality due to radio interference. We therefore used the number of frame retransmissions as an index for detecting radio interference in addition to the RSSI and then proposed an AP selection method for the proposed handover management system. Moreover, to evaluate its effectiveness in a real environment, we also implemented the proposed AP selection method on a prototype system. Experimental results in a real environment revealed that an MN could avoid an AP disturbed by radio interference and select the AP with a good wireless link condition due to the number of frame retransmissions. Therefore, we consider that the number of frame retransmissions has potential as an effective metric to select an AP with low radio interference.

4

HANDOVER METHOD FOR VOIP COMMUNICATION

In ubiquitous WiFi network, MNs can access the Internet from everywhere and at anytime, and VoIP is expected to become one of major application, i.e., a post-cellular phone. In such situation, delivering VoIP in ubiquitous WiFi network is a challenging issue because VoIP is a delay and packet loss sensitive application.

In ubiquitous WiFi network, the coverage of each AP is relatively small and each AP independently provides the wireless connectivity, i.e., they have a different IP subnet due to independent management of different operators. Then, an MN has to maintain VoIP communication during traversing many APs with different IP subnets. To achieve such seamless mobility, (1) selection of an AP with better performance (AP selection method), and (2) maintaining VoIP communication during handover (inter-domain handover method) are required.

To satisfy (1), our study proposed a new AP selection method [62], which described in Chapter 3. In [62], our study employed the number of frame retransmissions as a selection index in addition to traditional received signal strength indicator (RSSI) because frame retransmissions is useful to grasp accurate wireless link quality [67]. On the other hand, to achieve (2), our study also proposed a handover method based on the number of frame retransmissions and showed the performance evaluation through simulation experiments [32].

In ubiquitous WiFi networks, the VoIP communication quality is likely to degrade due to (a) intermittence by the handover processes of layer 2 and 3, and (b) inappropriate handover initiation. In our previous study [32, 33], to eliminate (a), we employed a multi-homing architecture. That is because a multi-homing MN can simultaneously associate with two access points (APs) using two WLAN interfaces (WIFs) before handover initiation, thereby preventing terminating communication at the handover. Next, to improve (b), we employed the number of frame retransmissions as a new handover trigger because frame retransmission can promptly and reliably detect degradation of wireless link quality in [67]. Since, in the proposed method, the handover manager (HM) on transport layer controls handover to maintain end-to-end communication, we applied a cross-layer architecture between transport layer and MAC layer in order to detect the occurrence of frame retransmissions on MAC layer. Although we demonstrated effectiveness of the proposed method through simulation experiments, any existing studies did not mentioned about its implementation design (multi-homing and cross-layer dealing with the number of frame retransmissions), which has a practical use in a real system. We also had not mentioned about implementation design in a real system yet, and additionally feasibility and effectiveness of the method in a real environment are unclear.

In this chapter, our study designs and implements the proposed handover method with the following three features: a handover trigger of frame retransmissions, cross-layer architecture and multi-homing architecture on a Linux OS, and then show a practical use of our system through experiments using our prototype system.

This chapter is organized as follows. Section 4.1 surveys related work. Section 4.2 outlines our prior proposed method. Section 4.3 describes design and implementation of our proposed method. In Section 4.4, this chapter shows the communication performance of the proposed prototype system to clarify its practical use in a real wireless environment. Concluding remarks are presented in Section 4.5.

4.1. Related Work

So far, to achieve an inter-domain handover, several handover methods such as Mobile IP (MIP) [45, 31] and Fast Handover for Mobile IPv6 (FMIP) [36] have been studied. In MIP, two network embedded servers, namely Home Agent (HA) and Foreign Agent (FA), behave as proxies for MNs. During the communication between an MN and a CN, these HA and FA basically forward all packets received from the CN to the MN. When performing a handover, i.e., associating with a new AP, the MN needs to notify its own change in the IP address to both of the HA and the FA. As a result, MIP can conceal the change in the MN's IP address, and then communication can be maintained even with the change in IP address due to handover. However, since the MN cannot receive or send any packets while processing layer 2 and 3 handover, even recent enhanced schemes [34, 41] cannot completely eliminate the communication interruption. Furthermore, MIP inherently necessitates extra network facilities such as the HA and the FA for achieving inter-domain handover. Therefore, it is difficult to expand them into ubiquitous WiFi networks because each AP is independently managed by different organizations and operators. Also, updating all existing APs for support of this additional function is extremely difficult. Thus, it is desirable to provide an end-to-end inter-domain handover without extra facilities and modification of APs.

To achieve inter-domain handover based on end-to-end principle, handover should be controlled on layer 4 or higher layers, because end-to-end communication is managed on layer 4. That is, layer 3 or lower layers cannot handle handover in end-to-end. The mobile Stream Control Transmission Protocol (mSCTP) [69] and Media Optimization Network Architecture (MONA) [35] have been proposed as an end-to-end based handover method. The mSCTP is the mobile extension of the Stream Control Transmission Protocol [59], and an MN supports mulit-homing to handle two or more wireless interfaces. Although mSCTP can avoid an inherent communication interruption of layer 2 and 3 handover processes by utilizing this multi-homing architecture, the prompt and reliable detection of wireless link quality degradation is not concerned. Thus, some essential issues such as an appropriate handover trigger and handover initiation still remain. Furthermore, mSCTP is a new standard track of transport protocol that does not support real-time traffic. On the other hand, MONA also has a function for multi-homing and can handle both real-time and non real-time communications. However, MONA does not focus on the handover management.

In an implementation of cross-layer architecture, several researchers study on cross-layer architecture. However, some papers are based on simulation and analytical results, and then they do not mention its implementation design and its practical use [70, 40]. On the other hand, although other papers propose cross-layer architecture on a real system, their cross-layer architectures did not treat the frame retransmissions on MAC layer at all [11, 65]. In addition, since each layer asynchronously processes to send packets, an implementation design of cooperative cross-layer is essential.

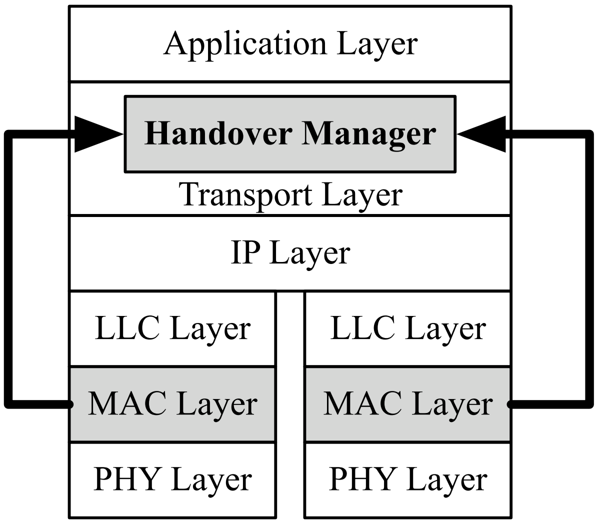


Figure 4.1. Cross-layer architecture

4.2. Handover Management Method for VoIP

This section outlines the seamless VoIP handover method proposed in our previous work [33]. In the previous work, we classified requirements for seamless handover into the following three: (i) prompt and reliable detection of degradation in wireless link quality, (ii) elimination of communication interruption due to inherent handover processes of layer 2 and 3, and (iii) selection of a better WLAN. First, to satisfy (i), we employed the number of frame retransmissions as a handover trigger. Frame retransmissions inevitably occur before a packet loss in wireless networks. We then showed that the number of frame retransmissions is effective as a handover trigger to detect the degradation of communication quality [67].

To satisfy (ii), we next employed a multi-homing architecture, which enables a MN with two WIFs to simultaneously associate with two APs of different IP subnets before handover initiation. Consequently, since the layer 2 and 3 handover processes can be executed before break of current communication due to handover, a multi-homing MN can switch to a candidate (next) AP without a handover processing delay and a communication interruption.

In (iii), an HM selects a WLAN with better quality among associated two WLANs to avoid a handover to an AP with poor communication quality. Since an HM needs to compare communication quality of both APs for selection of a better one, the number of frame retransmissions is here also employed as a comparison index. Then when performing handover, an MN starts to transmit duplicated packets over both two APs;

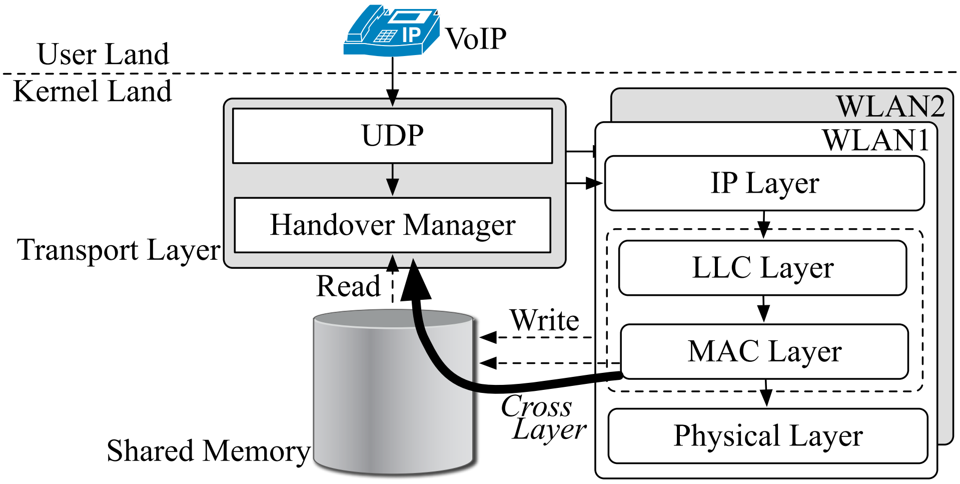


Figure 4.2. Design of cross-layer architecture

that is, the MN switches to multi-path transmission. During multi-path transmission, an HM investigates the wireless link quality of both APs based on the number of frame retransmissions and selects a better one. After that, it backs to single-path transmission through the selected AP.

In this way, although the handover is managed by the HM on transport layer, (i) and (iii) are achieved based on the number of frame retransmission obtained from MAC layer. Therefore, we employed a cross-layer architecture to connect MAC layer to transport layer, as shown in Figure 4.1. Based on this architecture, the HM carries out seamless inter-domain handover while switching between single-path transmission and multi-path transmission based on frame retransmissions.

4.3. Implementation Design

The main concepts of the proposed method are the following three: cross-layer architecture to pass the number of frame retransmissions obtained from MAC layer to transport layer, frame retransmissions as a handover trigger, and multi-path transmission to reduce packet losses during handover. In [33], although we demonstrated the effectiveness of the proposed method through simulation experiments, we did not demonstrate nor evaluate the feasibility of implementation. This section clarifies the implementation design of the proposed method. Section 4.3.1 explains how to exploit cross-layer architecture, which enables an HM on transport layer to obtain the number of frame retransmissions from MAC layer. The mechanism to control a handover

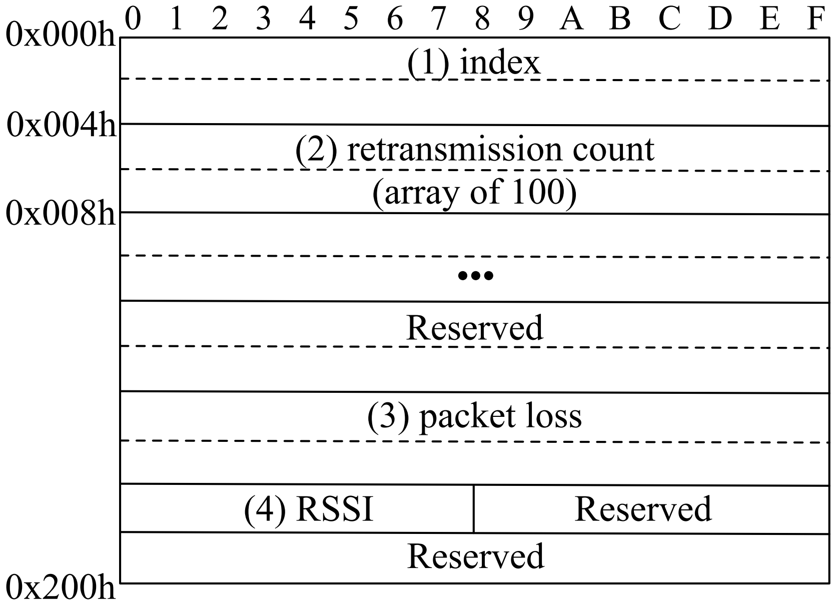


Figure 4.3. Structure of shared memory

execution is described in Sections 4.3.2. In Section 4.3.2, an operation to switch to multi-path transmission and an operation by which to return to single-path transmission are explained based on the number of frame retransmissions. Then, Section 4.3.3 mentions an utilization of MONA.

4.3.1 Cross-layer Architecture between Transport Layer and MAC Layer

As mentioned in Section 4.2, an HM on transport layer obtains the number of frame retransmissions from MAC layer. This section explains how to pass the information on MAC layer to the HM.

Although, in the previous study [33], the number of frame retransmissions is directly passed from MAC layer to the HM every transmission of each frame, we found that it actually causes significant deterioration of kernel performance due to frequent interruptions in a Linux OS. Then, our study proposes an asynchronous process between the HM and MAC layer. In our design, as illustrated in Figure 4.2, to avoid deterioration of of the kernel performance, MAC layer writes the number of frame retransmissions into a shared memory, and the HM retrieves the number of frame retransmissions from the shared memory. In our implementation, since MN employs two WIFs, shared memory is allocated for each WIF.

Figure 4.3 illustrates the structure of the shared memory. The shared memory consists of four regions: (1) index, (2) retransmission count, (3) packet loss count, and (4) RSSI. Whenever MAC layer detects the successful transmission of data frame by receiving an corresponding ACK frame, it records the number of frame retransmissions into (2) retransmission count region. The retransmission count region consists of an array containing 100 elements and is used as a ring buffer to store the number of frame retransmissions therein. At that time, MAC layer also writes the array position into (1) index region and the value of RSSI into (4) RSSI region, respectively. When the number of frame retransmissions exceeds the predetermined retransmission limit (generally, four or seven), the data frame is treated as a lost packet. Then, the value of (3) packet loss region is increased by one in addition to (2) retransmission count region. Note that, to control handover, only (1) index region and (2) retransmission count region are utilized. (3) packet loss count region and (4) RSSI region are used for the evaluations in Section 4.4.2.

4.3.2 Procedure of our proposed HM

In the proposed method, an MN attempts to perform a seamless handover while switching between multi-path transmission and single-path transmission according to the number of frame retransmissions. To control the switch, the HM has two switching procedures: switching from single-path transmission to multi-path transmission and vice versa. As mentioned in Section 4.3.1, MAC layer cannot directly notify the number of frame retransmissions to the HM. In addition, VoIP communication requires prompt detection of degradation in communication quality. Thus, in our implementation design, handover decision is executed at sending each frame. That is, whenever the HM on transport layer attempts to send packets received from an application, it can execute a switching procedure based on current transmission condition, i.e., occurrence of frame retransmissions. Switching procedures (switching from single-path transmission to multi-path transmission and vice versa) are described as following.

Switching to Multi-path Transmission

The MN usually communicates by single-path transmission. Once the number of frame retransmissions exceeds the Multi-Path Threshold (MP_TH) in the HM, the HM switches to multi-path transmission in order to prevent packet loss and to investigate the quality of each wireless link.

Figure 4.4 shows a flowchart of switching to multi-path transmission. The flowchart is divided into two parts: (a) reading the information from the shared memory, and

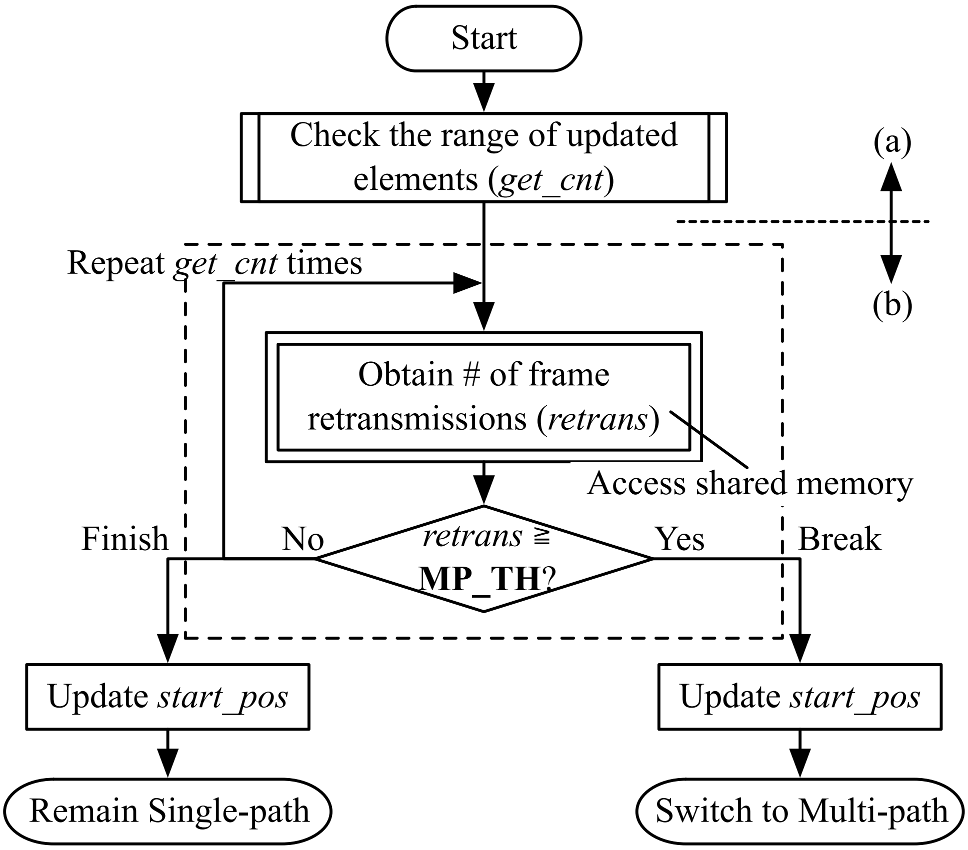


Figure 4.4. Switching to multi-path transmission

(b) switching to multi-path transmission according to wireless link quality. In the flowchart, *italic letters* indicate variable parameters and **bold letters** indicate system parameters.

In (a), since the HM and MAC layer asynchronously work, some frames may be already sent when the HM checks the number of frame retransmissions, i.e., the HM needs to check some past frame retransmissions. Then, the HM checks the range of elements (*get_cnt*) updated in (2) retransmission count region after the previous execution. This procedure is illustrated in Figure 4.5. In this procedure, two position indexes are employed; *start_pos* indicates an array position where the HM starts to obtain the number of frame retransmissions in (2) retransmissions count region, whereas *end_pos* means the latest array position, which is written by MAC layer. To check *start_pos*, this process first checks whether this process is an first-time execution. If so, *start_pos* is set to 0. Otherwise, *start_pos* is already set to the value of the latest obtained array position at the previous execution (see last process in Figure 4.4). On the other hand,

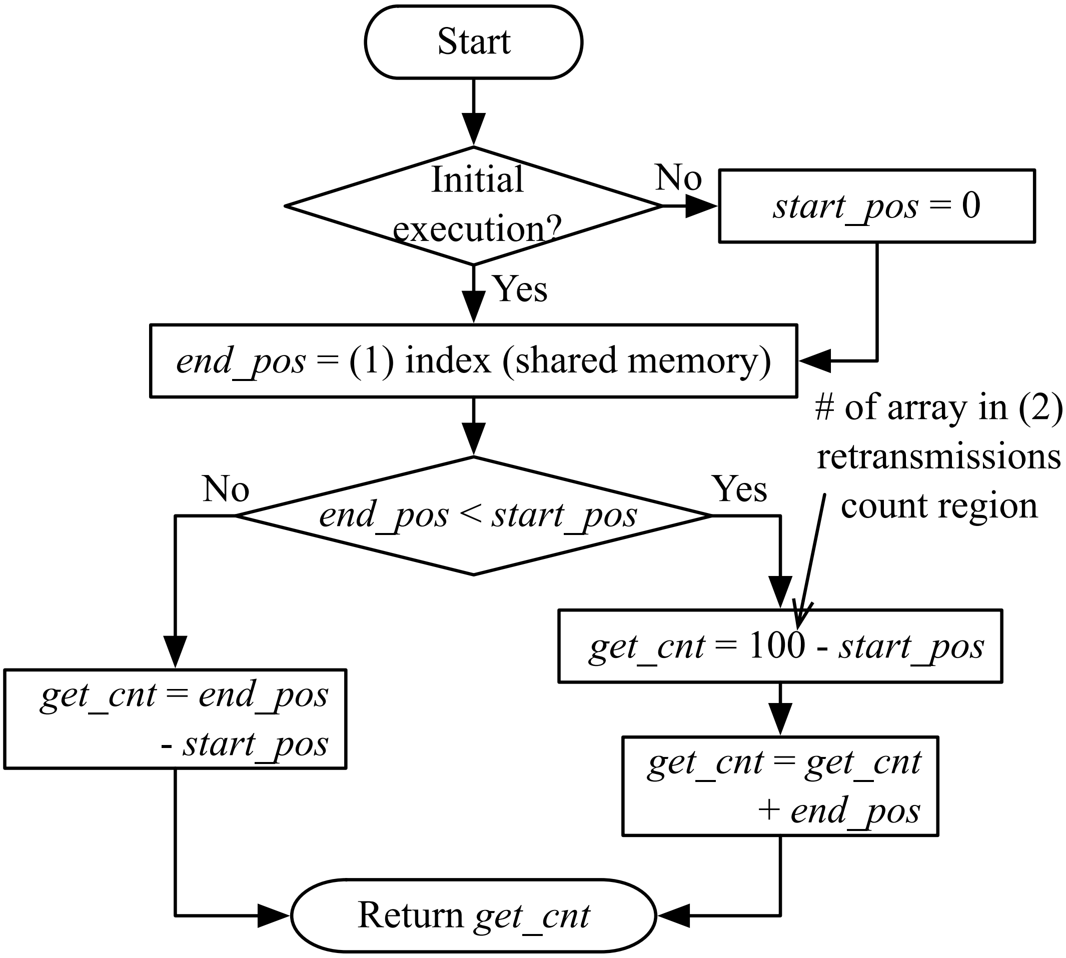


Figure 4.5. Calculation of the range of updated elements

end_pos is set to the value of (1) the index region in shared memory. Therefore, updated elements are detected from the difference between *start_pos* and *end_pos*. Note that, since (2) retransmissions count region is ring buffer, *start_pos* could be larger than *end_pos* and thus the process calculates the actual written number.

In (b), the HM compares the number of frame retransmissions with the MP_TH *get_cnt* times. In this comparison, if the number of frame retransmissions obtained from (2) retransmission count region exceeds MP_TH, the HM immediately escapes from the loop and switches to multi-path transmission. Otherwise, the HM obtains the next element in (2) retransmission count region and continues to compare it with with MP_TH. If the all elements do not exceed MP_TH, this process is finished. Then, in order for next execution, *start_pos* is set to $end\_pos + 1$.

Switching to Single-Path Transmission

In multi-path transmission, since an MN sends the same data frames through two WLANs, the network traffic load increases. Thus, an MN needs to return single-path transmission and select a WLAN with better quality as soon as possible in order to reduce the extra network traffic. In order to investigate each wireless link quality in multi-path transmission, the HM utilizes the number of frame retransmissions as in the case of single-path transmission. the HM compares the number of frame retransmissions on each WIF with the predetermined Stability Count Threshold (SC_TH). If the number of frames sequentially experiencing frame retransmissions less than SC_TH exceeds the Single Path Threshold (SP_TH), the HM decides that the wireless link quality is stable for communication and switches back to single-path transmission of the WLAN.

Figure 4.6 shows an switching operation to single-path transmission. In (c), the HM first calculates the range of updated elements in (2) retransmission count region for each WLAN, same as in the case of single-path transmission operation described in Section 4.3.2. The HM then executes a loop to obtain the number of frame retransmissions of each WLAN from shared memory for *get_cnt* times. In this loop (d), the HM continuously compares the number of frame retransmissions with the SC_TH for each WLAN at *get_cnt* times. At this time, if the number of frame retransmissions is smaller than SC_TH, *SC_IF* is incremented by one. Otherwise, *SC_IF* is reset to 0 because the HM decides that wireless link is still unstable. After the loop, the HM updates *start_pos* for the next execution and compares *SC_IF* of each WLAN with SP_TH. If *SC_IF* exceeds SP_TH, the HM switches to single-path transmission of a WIF corresponding to the *SC_IF*. Otherwise, the HM continues multi-path transmission.

4.3.3 Utilization of MONA

In our implementation, our study employs MONA [35] as a base system enabling an MN to handle multiple IP addresses. Moreover, our study also utilizes MONA to synchronize current transmission mode between both end-hosts. Therefore, our proposed method can prevent termination of VoIP communication due to inter-domain handover. Since the MONA is implemented between IP layer and transport layer (on layer 3.5), an additional header (basic/optional header) is inserted between IP header and UDP header. The basic header is used to handle multiple IP addresses, and the optional header is used to adapt the dynamic events such as addition and deletion of IP address. For example, when an IP address is added or deleted, address information

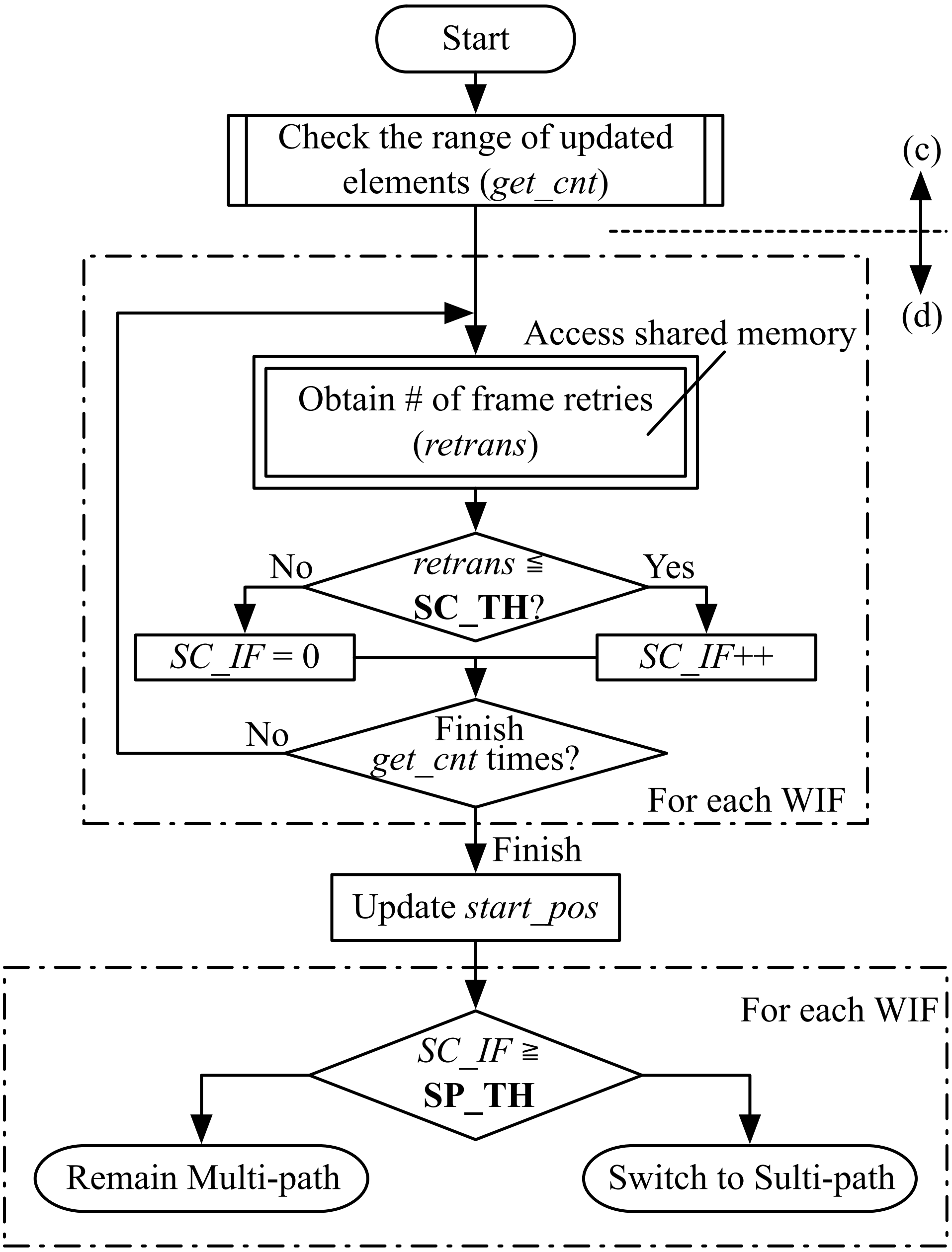


Figure 4.6. Switching to single-path transmission

is recorded in the optional header and exchanged between end nodes. In this way, location management can be achieved.

Moreover, both multi-path (MP) flag and interface flag in the basic header to control bi-directional path switching are introduced. If the MN sets the MP flag according to the deterioration of wireless link quality, the CN also switches to multi-path transmission. That is, from the MP flag, the CN can detect the request for multi-path transmission from the MN. On the other hand, the interface flag indicates which WIF is currently used for communication. That is, the CN changes the destination IP address (i.e., active WIF of the MN). In this way, the additional header of MONA enables an MN to notify their changes. Then, the performance of the CN is especially related to a base system, i.e., MONA. Therefore, in this paper, degradation of communication quality by the CN is beyond the scope of our present study. Note that, other methods that provide a same function (handling multiple IP addresses and synchronizing some status between end hosts) can be applied to our handover method.

4.4. Implementation & Performance Evaluation

In order to show the performance of our prototype system, this section compares the proposed method (FMT: Frame retransmission-based handover method with Multi-path Transmission) with three comparative handover methods in two practical environments, and then evaluate the effectiveness of two features (a handover trigger of frame retransmissions and multi-path transmissions) of FMT. In the evaluation, our study employs two experimental environments, i.e., non-interference and interference environments. Finally, through these experiments, our study confirms whether the last feature (cross-layer architecture to notify the number of frame retransmissions) appropriately works.

We first describe the implementation facilities in Section 4.4.1, and then describe the three comparative handover methods in Section 4.4.2. Section 4.4.3 explains the experimental model and parameter settings. Section 4.4.4 shows basic performance of the four methods in a non-interference environment and Section 4.4.5 evaluates the practical performance of four methods in an interference environment to show the effectiveness of two features.

4.4.1 Implementation Environment

This section describe our implementation environment. First, both end-hosts (an MN and a CN) are implemented in the CentOS 4.3 (Linux kernel version 2.6.9) on Lenovo ThinkPad X60 (CPU: Core Duo 1.66 Ghz Memory: 512 MB). In the MN, to obtain the number of frame retransmissions from a WIF, the madwifi driver [39] that can extract the number of frame retransmissions from an Atheros chipset is employed. Then, for multi-homing, the MN employs a built-in WIF (P/N: 40Y7028) and a PC card WIF (ORiNOCO 802.11 a/b/g Combo Card Gold). To control handover, and HM is implemented in both the MN and the CN. Cross-layer architecture between the HM and MAC layer described in Section 4.3.1 is implemented only on the madwifi driver of the MN.

4.4.2 Comparative Handover Methods

As mentioned in Section 4.3, the prototype system realizes a handover trigger of frame retransmissions and multi-path transmission based on cross-layer architecture for achieving seamless handover. However, general handover methods employ received signal strength as a handover trigger and change over the communication by single-path transmission only. To evaluate the effectiveness of our prototype system (FMT), our study then additionally implements the following three comparative methods: Frame retransmission-based handover method with Single-path Transmission (FST), Signal strength-based handover method with Single-path Transmission (SST), and Signal strength-based handover method with Multi-path Transmission (SMT). The details of them are described in following.

FST utilizes frame retransmissions as a handover trigger, and switches an active AP without multi-path transmission. In FST, when the number of frame retransmissions per packet on the active WIF reaches a retransmission-based handover threshold (RBH_TH), the MN directly switches the communication to another WIF without multi-path transmission. Since the difference between FMT and FST is only transmission mode during handover, our study investigates the effectiveness of multi-path transmission by their comparisons.

SMT and SST employ signal strength as a handover trigger. The difference between SMT and SST is utilization of multi-path transmission, i.e., only SMT employ multi-path transmission. In the SMT, when the received signal strength is lower than a signal-based multi-path threshold (SBM_TH), the MN switches to multi-path transmission. After that, when the received signal strength of either WIF exceeds a signal-based

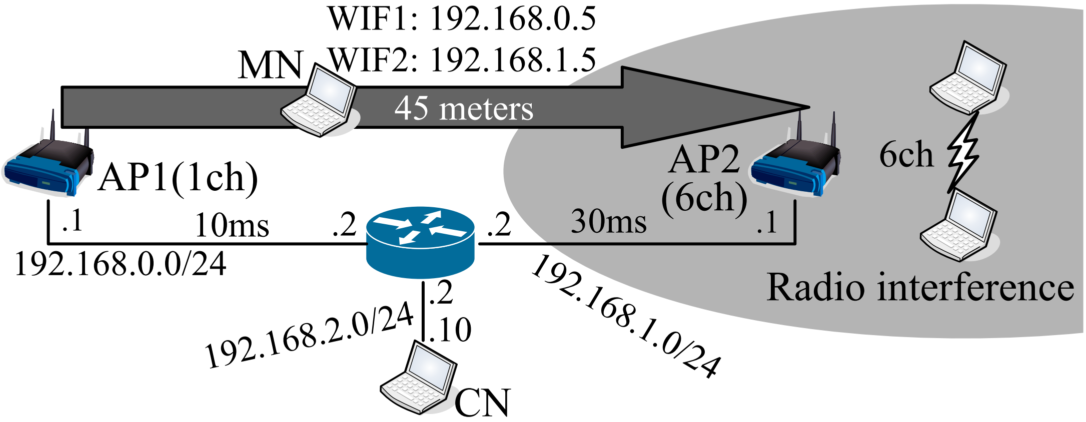


Figure 4.7. Experimental topology

Table 4.1. Values of thresholds

Method	Parameters		
FMT	MP_TH = 3	SP_TH = 2	SC_TH = 1
FST	RBH_TH = 3	—	—
SMT	SBM_TH = 32	SBS_TH = 38	—
SST	SBH_TH = 32	—	—

single-path threshold (SBS_TH) indicating that the condition of the WIF is stable, the MN switches back to single-path transmission using the WIF. Since SMT differs in handover trigger by FMT, our study investigates the effectiveness of frame retransmission-based handover by comparing FMT with SMT. On the other hand, in the SST, when the received signal strength on an active WIF is lower than a signal-based handover threshold (SBH_TH), the MN directly switches the communication to another WIF without multi-path transmission. We investigate the effectiveness of both frame retransmission and mutli-path transmission-based handover by comparing FMT with SST.

4.4.3 Experimental Model and Parameter settings

This section first describes experimental environment. In the experiments, our study employs a non-interference and an interference environments. In the non-interference environment, our study focuses on the basic performance of the proposed method. On the other hand, our study investigate practical performance in the interference environment. In both environments, experimental topology is almost same except radio interference facilities. Figure 4.7 shows the experimental topology and facilities.

In the experimental topology, our study employs seven PCs, which are an MN, a CN, two APs, a router, and two radio-interference nodes. The router belongs to three different IP subnets and directly connects to the CN and the two APs. Since our study assumes that the ubiquitous WiFi networks consist of many APs managed by different operators (belongs to different networks), our study sets the different path delay to the CN, i.e., the path delay through the AP1 is set to 10 ms and that through AP2 is to 30 ms to reproduce realistic environment. This is because path delay between end hosts basically differs depending on belonging networks in the Internet. Note that, the delays are intentionally added at the router using dummynet with the built-in firewall software (ipfw) of FreeBSD [64]. The two APs are constructed by two same laptops (HP nx6120) with a PC card WIF (ORiNOCO 802.11a/b/g Combo Card Gold) in which Fedora Core 6 with madwifi driver is installed. Then, both APs are configured as Master mode of the madwifi driver to stand as an AP. In wireless settings, the data rate is fixed to 11 Mb/s of IEEE 802.11b, i.e., auto rate fallback (ARF) is disabled, because the occurrence of frame retransmission dynamically changes due to the change in coding scheme by ARF at the physical layer. These APs are placed in 45 meters apart away from each other. In the MN and the CN, the three comparative handover methods are installed in addition to our proposed method. To easily intend to perform handover, our study adjusts the transmission power of both APs to 2 dBm. On the other hand, the transmission power of MN is also configured with 1 dBm because it is generally smaller than that of AP. Only in an interference environment, to disturb communication between the MN and the AP2, the two radio-interference nodes directly communicate with each other (ad-hoc communication) in the same channel with the AP2 (6 ch). Note that the radio-interference nodes are only used in the experiment in Section 4.4.5.

Next, our experimental scenario is described. First, in our experiments, since our study focuses on the communication performance during handover, the two WIFs are assumed to associate with two APs in advance. That is, WIF1 associates with the AP1, and vise versa. Then, after starting to capture the traffic by tcpdump [63], the MN walks from the AP1 to the AP2 while communicating with the CN using VoIP (G.711). When it arrives just under the AP2, capturing the traffic stop. Note that our study has nine experiments for each evaluation to sample a median result.

As mentioned in Section 4.4.2, the four-handover methods have several thresholds for handover. Table 4.1 shows the values for the thresholds. The values of MP_TH and SP_TH are set based on our simulation results in [32]. The RBH_TH is set to the

Table 4.2. Packet loss for four methods in non-interference environment

	FMT	FST	SMT	SST
Maximum	11	9	3	22
Minimum	0	0	0	6
Average	4.7	3.8	0.3	11.7
Median	5	3	0	8

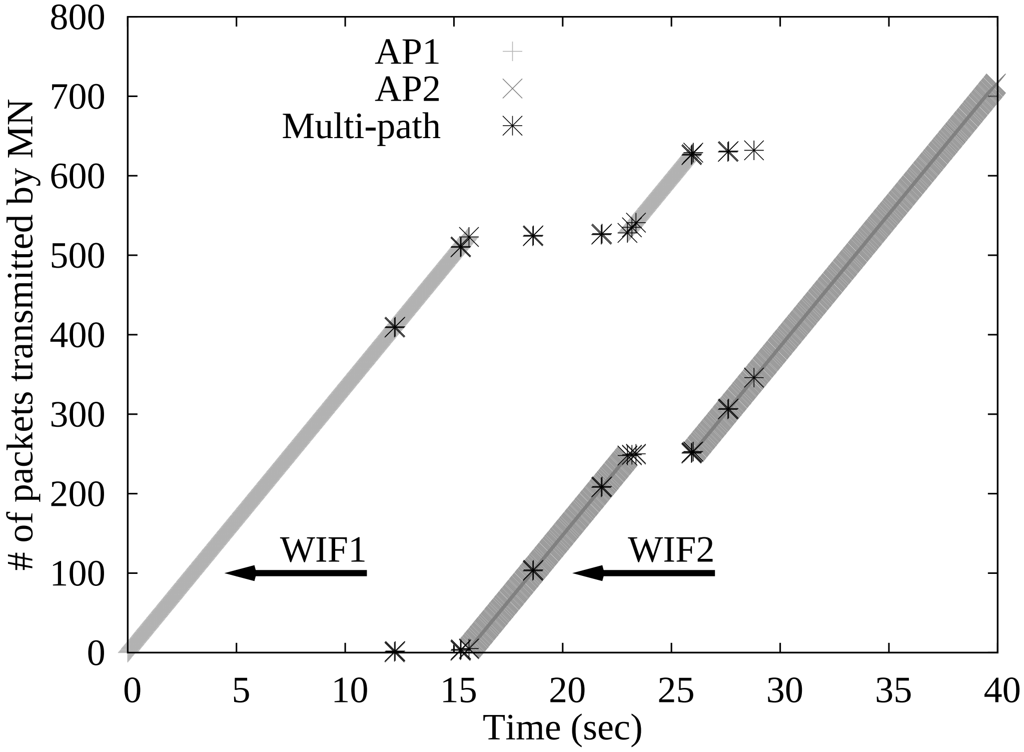
same value with MP_TH because both MP_TH and RBH_TH are triggers for handover initiation. On the other hand, to set the thresholds for signal-based handover methods (SMT and SST), our study investigated the values of signal strength that are equivalent to MP_TH and SP_TH in the preliminary results. Then, from the measurement, our study obtains the relationship between the number of frame retransmissions and the value of signal strength as shown in Table 4.1. Note that, the value of signal strength is the value extracted from inside value of the madwifi driver.

4.4.4 Non-Interference Environment

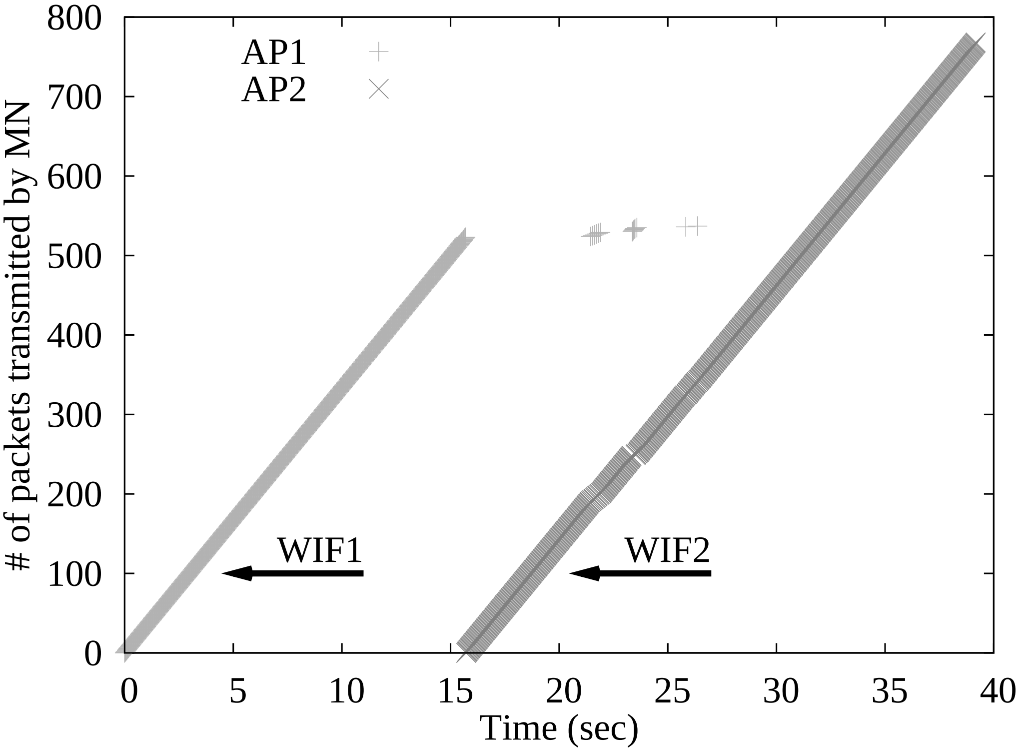
In this section, our study evaluates the basic characteristics of the four methods in a non-interference environment. We first show the behavior for each handover method in Figures 4.8. These graphs illustrate the number of packets transmitted by an MN over time. Points of AP1 and AP2 indicates the timing of packets sent by single-path transmission, and Multi-path marks the timing of packets sent by multi-path transmission. Note that these graphs show the results of the median values in nine experiments. From Figures 4.8(a) and 4.8(b), our study can see that the FMT and the FST carry out handover at about 15 seconds according to the change of wireless link condition. On the other hand, in Figures 4.8(c) and 4.8(d), the SMT and the SST frequently switch communication paths because signal strength cannot detect the wireless link condition appropriately. In particular, the SMT has quite a long multi-path transmission period, thereby consuming more wireless resources than other methods.

Next, our study investigates packet loss during handover. Table 4.2 shows the number of lost packets from the MN to the CN in the four methods throughout the experiment. In this experiment, since both APs provide good communication quality, frequent handover does not bring so much packet losses at SST. Then, all methods can maintain good communication quality throughout the duration of the experiment.

In the four methods, since the FMT and the SMT employ multi-path transmission to compare both wireless link condition and to reduce packet loss during handover,

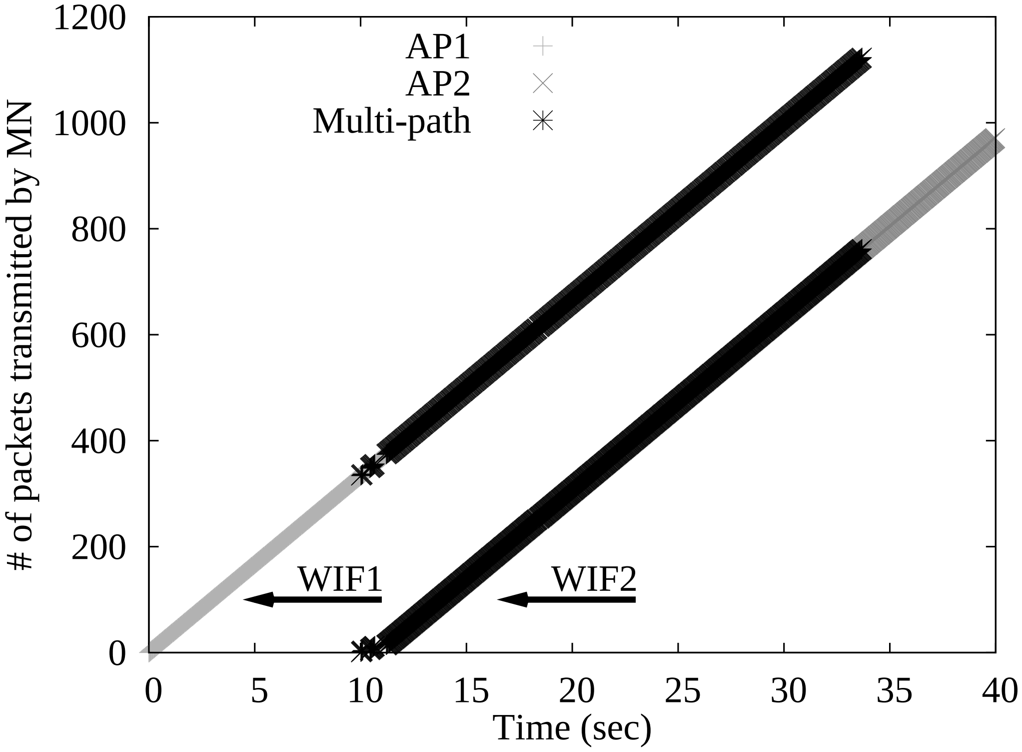


(a) FMT

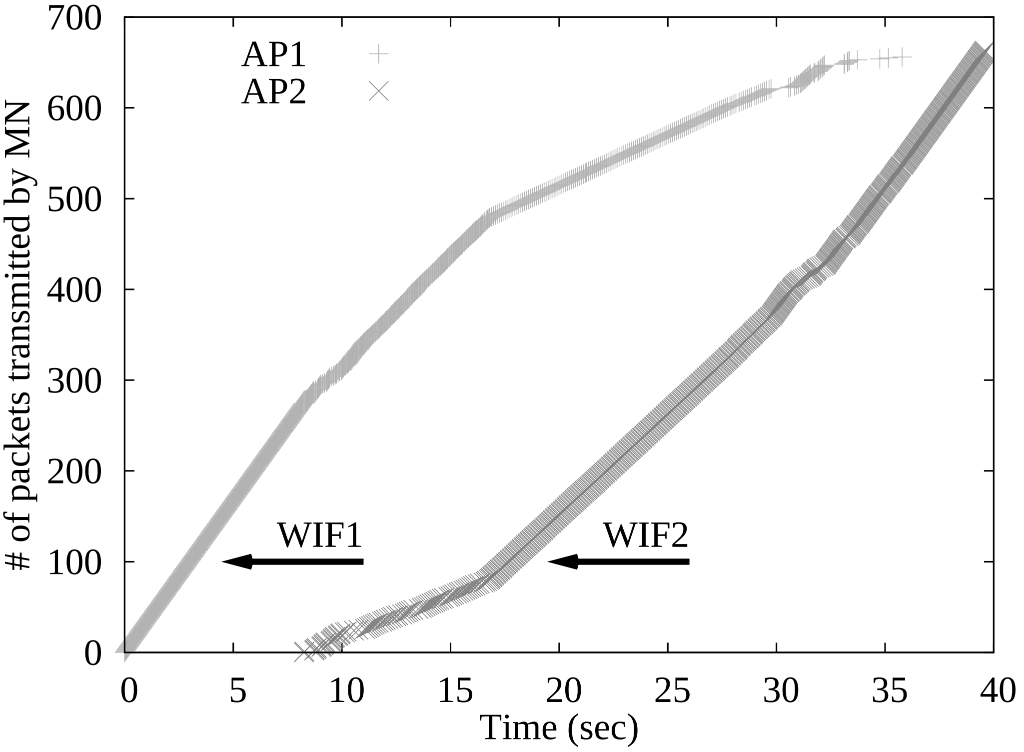


(b) FST

Figure 4.8. Behavior of four methods in non-interference environment



(c) SMT



(d) SST

Figure 4.8. Behavior of four methods in non-interference environment (Contd.)

Table 4.3. Multi-path transmission ratio in non-interference environment

	FMT	SMT
Maximum	2.1 %	57.0 %
Minimum	0.4 %	34.1 %
Average	1.3 %	50.7 %
Median	1.2 %	53.5 %

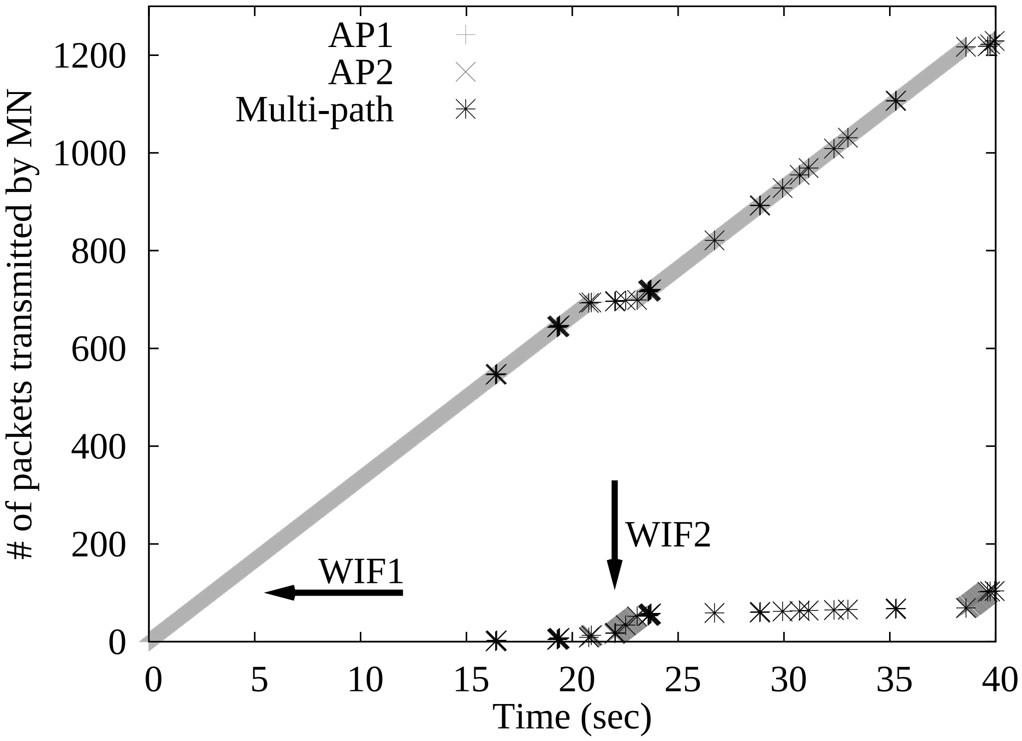
the network load inherently increases by transmission of redundant packets. Table 4.3 describes the multi-path transmission ratio for the FMT and the SMT. From the table, we can see that the redundant packets of the FMT are extremely smaller than those of the SMT. Hence, the FMT barely affects the network. On the other hand, in the SMT, almost half the packets are sent in multi-path transmission. Therefore, our study can demonstrate that the FMT can appropriately utilize multi-path transmission.

4.4.5 Interference Environment

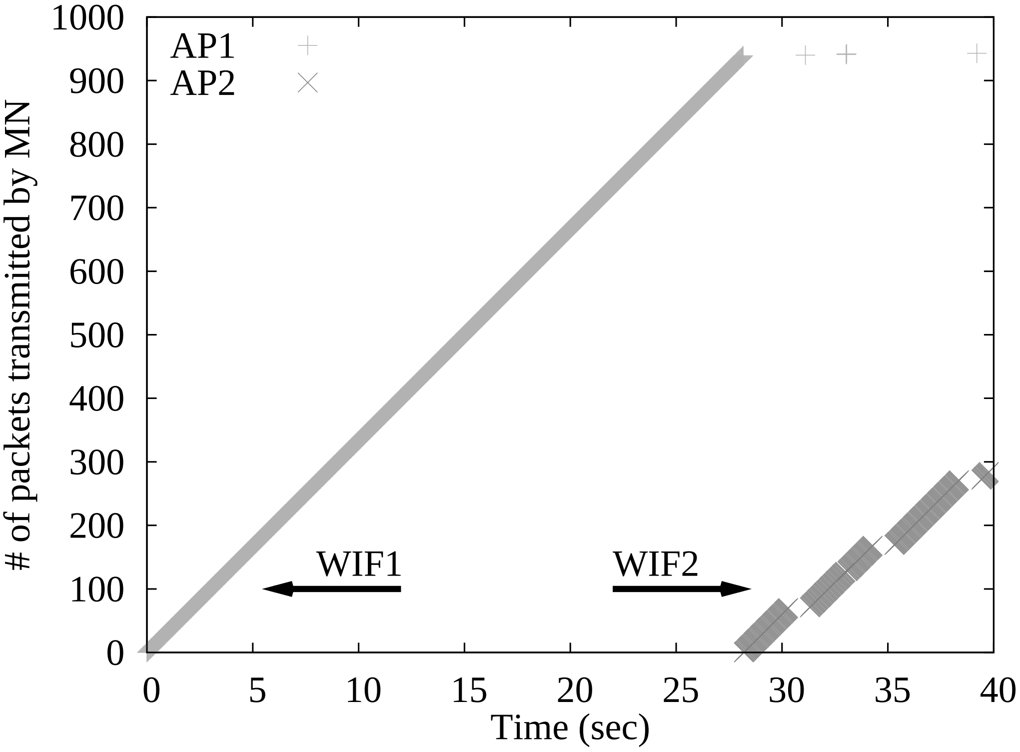
In Section 4.4.4, our study investigated the basic characteristics in a stable environment, i.e., non-interference environment. However, in a practical environment such as ubiquitous WiFi networks, communication quality of an MN is likely to be affected due to radio interference caused by other WLAN devices. To evaluate the effectiveness of our prototype system from two point of view (multi-path transmission and a handover trigger of frame retransmissions), our study investigates communication quality in an interference environment. Note that radio interference is generated as illustrated in Figure 4.7.

The handover behaviors of the four methods are shown in Figures 4.9. Here, our study also shows the median results in nine experiments as well as Section 4.4.4. In this environment, as the AP2 is affected by radio interference, the MN had better use the AP1 as much as possible. Thus, compared with the results in Section 4.4.4, we can see that the MN tends to send packets through the AP1 during the experiments in all methods.

Next, our study investigates network load caused by multi-path transmission. Table 4.4 shows maximum, minimum, average, and median values of the multi-path transmission ratio. From the table, we can remark that redundant packets of the SMT are significantly larger than those of the FMT. Hence, while the SMT cannot appropriately detect the change in the wireless link quality by using signal strength, the FMT

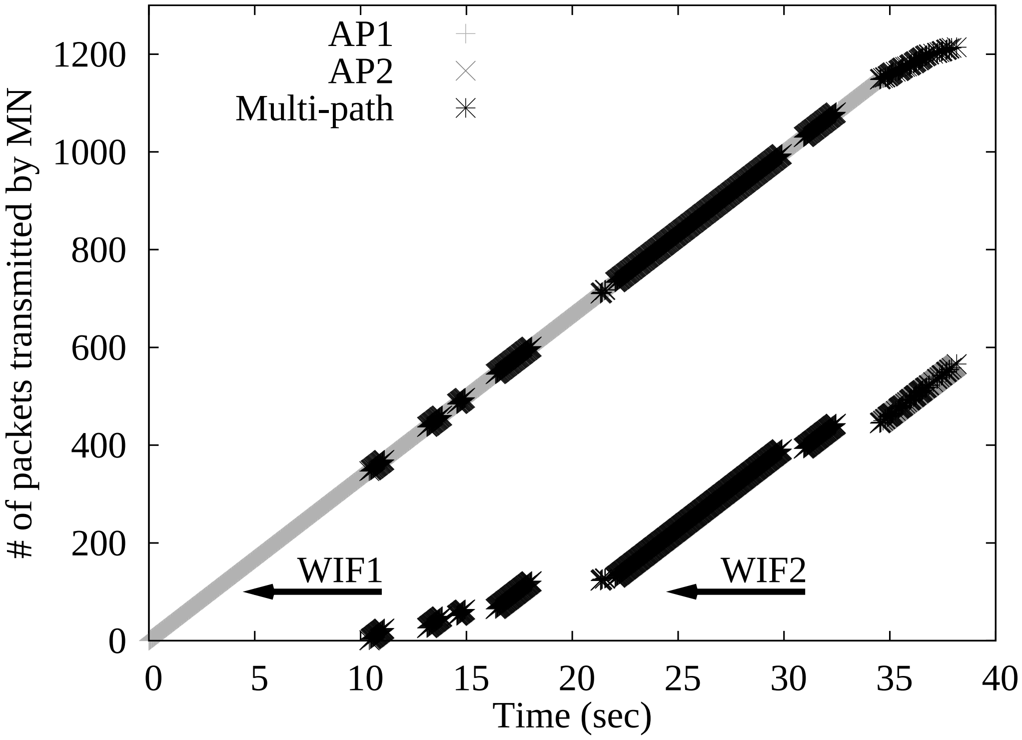


(a) FMT

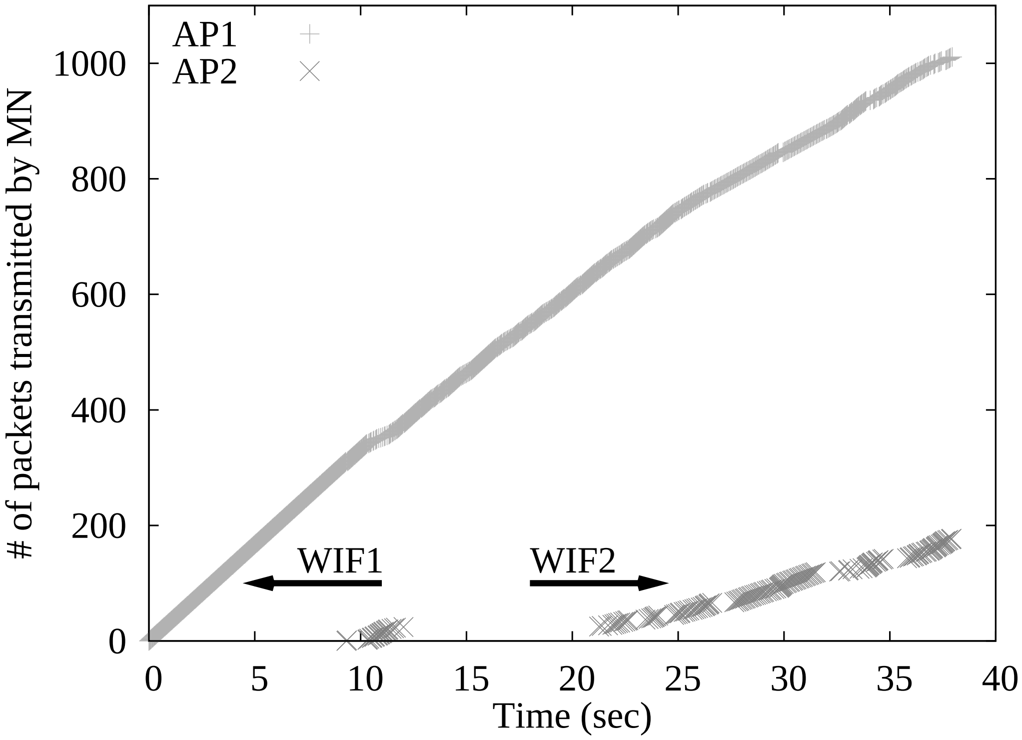


(b) FST

Figure 4.9. Behavior of four methods in interference environment



(c) SMT



(d) SST

Figure 4.9. Behavior of four methods in interference environment (Contd.)

Table 4.4. Multi-path transmission ratio in interference environment

	FMT	SMT
Maximum	4.1 %	43.3 %
Minimum	1.0 %	25.0 %
Average	1.9 %	35.5 %
Median	1.7 %	38.2 %

Table 4.5. Packet loss for four methods in interference environment

	FMT	FST	SMT	SST
Maximum	70	181	53	214
Minimum	16	61	17	175
Average	48.3	109.7	33.6	193.6
Median	49	101	30	193

can promptly and reliably detect it by using frame retransmissions.

We next describe communication quality of the four methods. Table 4.5 shows the number of lost packets transmitted from the MN to the CN. From Table 4.5, the number of lost packets in all methods drastically increases at every methods due to the influence of radio interference, and difference among four methods becomes drastically large. From the result, our study arrives at the following two conclusions. One is that multi-path transmission (FMT and SMT) obviously contributes to reduction of packet losses during handover. The other is that frame retransmissions can more promptly and reliably detect the changes in wireless link condition than signal strength. In the former, the methods with multi-path transmission demonstrate better performance than the methods only with single-path transmission. Actually, in the average, the number of lost packets for the FST (109.7 packets) is more than twice that for the FMT (48.3 packets), and is more than three times that for the SMT (33.6 packets). Furthermore, SST shows the worst performance. In the network load's point of view, multi-path period of the FMT is up to 4.1 % at most. That is, it is extremely smaller than that of the SMT (43.3 %). From the results, we can conclude that multi-path transmission can avoid packet loss during handover. Especially, the FMT can utilize multi-path transmission more effectively. On the other hand, in the latter, since packet loss of the FST (109.7 packets) is smaller than that of the SST (193.6 packets), frame retransmissions can promptly and reliably detect changes in wireless link condition than signal strength.

Table 4.6. Two types of lost packets

(a) Lost packets over wireless link

	FMT	FST	SMT	SST
Maximum	67	112	7	110
Minimum	5	37	1	36
Average	42.0	76.4	3.8	57.6
Median	36	71	4	50

(b) Lost packets by packet reordering

	FMT	FST	SMT	SST
Maximum	14	69	47	164
Minimum	1	0	13	86
Average	6.3	33.2	29.8	136.0
Median	5	24	28	134

In these experiments, the occurrence of packet loss is classified into the following two reasons: deterioration of wireless link quality due to various factors such as radio interference, bit error, and collisions, and irregular arrival of packets (packet reordering). In a real-time application, a receiver generally processes packets in arrival order. However, since a multi-homing MN always sends packets during handover while switching transmission paths, the CN does not surely receive packets in sequence due to the different delays among two paths. That is, the CN may receive decayed packets for a real-time application. Our study then investigates in detail the two types of lost packets.

Table 4.6 shows the numerical results for the two types of lost packet. Tables 4.6(a) and 4.6(b) show lost packets over wireless link and by packet reordering, respectively. Note that since Tables 4.6(a) and 4.6(b) are independently analyzed, the numerical results of Table 4.6 do not much the results of Table 4.5. From Table 4.6(a), we can see that the FMT and the SMT can avoid packet loss over wireless link by multi-path transmission. As shown in Table 4.4, as the SMT has the longest multi-path transmission period, it provides the best performance in terms of the amount of packet losses. However, in terms of network load, we can also say that the FMT utilizes multi-path transmission more effectively than the SMT while limiting the additional network load up to 4.1 %.

In Table 4.6(b), the SST has the largest number of lost packets caused by packet reordering. The packet reordering increases with the number of handovers due to the ping-pong effect. In such a case, as the transmission delay of each packet frequently changes due to the different delay of the two paths, they do not meet in order of sequence number. Then, although the SMT also cannot appropriately carry out handover, it can reduce the number of lost packets by multi-path transmission more than the SST. Hence, from the results of the FMT and the SMT, we can remark that frame retransmissions as a handover trigger can promptly and reliably detect changes in wireless link condition. On the other hand, the FMT can avoid packet loss by multi-path transmission, thereby showing the best performance. From the above results, we can conclude that a handover trigger of frame retransmissions and multi-path transmission are extremely effective for maintaining VoIP communication quality during inter-domain handover.

4.5. Summary

In the present paper, our study designed and implemented a prototype system based on our proposed method and evaluated the effectiveness in two practical environments. Our proposed method has three features: a handover trigger of frame retransmission, cross-layer architecture, and multi-path transmission during handover. Although their effectiveness and performance in a real environment depend on the implementation design, any existing studies including our previous work did not discuss about their implementation. Therefore, our study actually designed implementation of a prototype system on a Linux OS in this paper.

The key concepts of the prototype system are collection of the number of frame retransmissions in the wireless interface driver, shared memory to pass the number of frame retransmissions (exploiting a cross-layer architecture), and transmission control of sending packets at transport layer (multi-path transmission). We then examined the effectiveness of our prototype system in two practical environments, i.e., non-interference and interference environments.

As a result, we confirmed that shared memory (cross-layer architecture) works fine to operate handover, and frame retransmission can more promptly and reliably detect wireless link condition than signal strength, and multi-path transmission can reduce packet loss during handover. Therefore, we can conclude that the prototype system is extremely effective in a practical (interference) environment.

As the future work, the following issue will be studied. In this paper, our study does not employ the rate adaptation (multi-rate) function of IEEE 802.11. However, in the actual environment, the almost APs employ it. For this, we have already studied on the effects on communication performance through the simulations [44]. Therefore, our study will design its implementation considering the rate adaptation function in more realistic environment.

5

HANDOVER METHOD FOR TCP COMMUNICATION

In the ubiquitous WiFi networks, since coverage of each AP is relatively small and APs arranged in the close proximity tend to be managed by different operators (i.e., each AP belongs to different IP subnet), MNs need to traverse many APs with different IP subnets during the communication period. In addition, with the consideration of compatibility with the current Internet, traditional TCP-based applications such as file transfer (FTP) and E-mail will continue to be frequently used even in the mobile environment. Thus, MNs demand seamless mobility while traversing many WLANs. To achieve such seamless mobility, we need the following operations: (i) selection of an AP with better performance (AP selection method), and (ii) preservation of TCP connection and communication quality during traversing APs (inter-domain TCP handover method). To satisfy (i), we proposed a new AP selection method based on the number of frame retransmissions [62]. In [62], we employed combined use of the number of frame retransmissions and received signal strength indicator (RSSI) as a selection criterion, because the number of frame retransmissions is better to precisely grasp wireless link quality of an AP [67]. Then, we evaluated the effectiveness of our proposed AP selection method through experiments in a real environment.

Inter-domain TCP handover method that can preserve not only TCP connection and but also its communication quality is necessary to achieve (ii). So far, although many handover management schemes based on Mobile IP [45, 31] can maintain TCP connection, TCP performance significantly degrades in response to both the increase of disconnection period and the drastic change in the communication condition **after the**

handover (through the new AP). Moreover, with the start of handover operation delays, the wireless link quality is deteriorated due to the increase in the distance between an MN and an AP, and thus frame loss frequently occurs. From this, TCP performance is drastically degraded due to the frequent packet losses *before the handover* (through the old AP). Therefore, to maintain communication quality during inter-domain handover, a new TCP handover management method that can preserve communication quality independent of change in communication conditions around the handover is essential.

In our prior work [66], we have studied a TCP handover method to solve the above problems. In [66], we employed the number of frame retransmissions as a handover trigger because the preliminary experiments in [67] demonstrated that frame retransmission appropriately detects degradation in wireless link quality. Then, to eliminate the disconnection period, we also utilized multiple TCP connections with multi-homing MN. Since multi-homing MN can simultaneously associate with two APs, it establishes two connections through different APs and then switches data transmission among them according to changes in the communication condition. Note that, in the paper, the current connection is called as an *active connection*, another one is called as an *alternative connection*. Although we had demonstrated its effectiveness through simulation experiments, an implementation design in a Linux OS, and its practical use in a real environment have not been clarified yet. In addition, the previous work did not consider several issues for applying the proposed method into a real operating system and environment: for instance, how to establish of an alternative connection, how to manage two TCP connections, and how to adapt the fluctuation of wireless condition should be considered.

In the present paper, we propose a design of our proposed method employing a cross-layer architecture and a multi-homing MN, and implement on an Linux OS. After that, we evaluate its effectiveness in a real environment. The main contributions of the study is how an MN treats fluctuation of wireless condition in a real environment because communication quality highly depends on stability of wireless condition. Furthermore, since repetition of handover due to wireless fluctuation causes significant performance deterioration especially in TCP communication, how the MN reliably starts handover is also proposed in the present paper.

5.1. Related Work

So far, to achieve inter-domain handover, many handover methods based on Mobile IP (MIP) [45, 31] have been studied. In MIP, two servers, namely Home Agent (HA) and Foreign Agent (FA), behave as proxies for MNs. During the communication between an MN and a Corresponding Node (CN), these HA and FA basically forward all packets transmitted from the CN to the MN. Therefore, when the IP address of the MN is changed due to the inter-domain handover, the MN needs to notify its own change in the IP address to both of the HA and the FA. By this operation, MIP can conceal the change in the MN's IP address to the CN; that is, TCP communication can be maintained even with the inter-domain handover. However, the MN cannot receive and send any packets during layer 2 (association with a new AP) and layer 3 (acquisition of the IP address). Although the recent enhancement of MIP [34, 41] try to eliminate the communication interruption at the handover, complete elimination is extremely difficult. Moreover, as MIP inherently necessitates extra network facilities such as the HA and the FA for achieving inter-domain handover, implementing them into ubiquitous WiFi networks or updating all existing APs for supporting this additional function are extremely difficult due to their independent management. Thus, providing a seamless mobility without extra facilities and modification of APs, that is, end-to-end approach, is desirable.

Since end-to-end communication is managed on layer 4, handover should be controlled on layer 4 and upper layers so as to achieve end-to-end handover. In such an end-to-end handover management, the mobile stream control transmission protocol (mSCTP) [69] has been proposed. In mSCTP, an MN has a capability of multi-homing (having multiple IP addresses simultaneously). Then, the CN and the MN choose one path as the primary path as a result of message exchanges each other. If communication quality of the selected primary path degrades, the MN notifies the CN of switching a primary path and then performs a handover to one of secondary paths. However, although mSCTP can completely avoid communication interruption due to layer 2 and 3 handover processes by utilizing multi-homing function, discussions about the quick and reliable detection of degradation in wireless link quality and selecting a better path are at preliminary stage. Furthermore, because mSCTP is a new transport protocol, it cannot treat the majority of existing applications employing TCP protocol. That is, existing applications are enabled to perform an inter-domain handover without any modifications of them self.

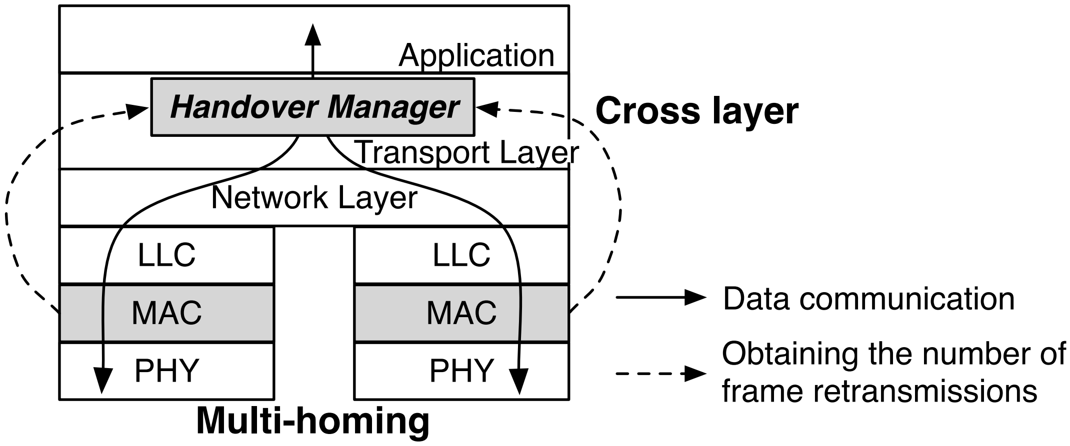


Figure 5.1. Our proposed architecture

5.2. Inter-Domain TCP Handover Management Method

In this section, we outline an inter-domain TCP handover management method proposed in our previous work [66]. In the previous work, we classified requirements for achieving seamless TCP handover into the following three: (1) handover must be initiated based on a quick and reliable detection of deterioration in wireless link quality, (2) communication interruption at handover must be eliminated, and (3) a better WLAN must be selected. Then, we employed a cross-layer and a multi-homing architecture, as shown in Figure 5.1.

In Req. (1), to avoid degradation of communication quality, handover should be started before communication quality actually degrades. In our proposed method, the Handover Manager (HM) on the transport layer obtains the number of frame retransmissions on the MAC layer through the cross layer architecture, and controls handover based on the information. In WLAN, as a frame is treated as a packet loss after experiencing the predetermined number of retransmissions (four or seven times), the number of frame retransmissions is useful to detect degradation in wireless link quality beforehand. Note that, in [67], we showed that the number of frame retransmissions can promptly and reliably detect a wireless link quality degradation. On the other hand, the frame retransmission can apply to selection of better WLAN at handover (Req. (3)). Since the communication condition of the next WLAN may be still severe condition more than a current one, the HM has to carefully decide handover timing by comparing the number of frame retransmissions of both WLANs. Finally, to satisfy Req. (2), we utilize multiple TCP connections with multi-homing architecture. In the multi-homing architecture, an MN is equipped with two WLAN interfaces (WIFs), thereby associating with two APs (paths) simultaneously. Thus, MN can switch data transmission without any communication interruption due to the inherent handover processes on layer 2 and 3.

Next, we describe the handover processes in detail. First of all, we assume that a multi-homing MN with two WLAN interfaces (WIF1 and WIF2) initially communicates with a CN using the WIF1, which is associated with the WLAN1. Meanwhile, another interface (WIF2) searches for a WLAN with better communication quality, and then associates with the WLAN2 before handover by using our AP selection method [62]. The HM keeps monitoring of the primary WLAN1, and carries out a handover if once the number of frame retransmissions of one packet exceeds the predetermined threshold. Then, the MN switches to multi-path transmission mode and notifies the CN of the change in its transmission mode. After receiving the notification, the CN starts parallel transmission using two WLANs. More specifically, the CN sends two data packets with different sequence number, which are transmitted over each WIF one by one, to prevent duplicated packets as much as possible at the MN. Then, the MN sends back an ACK packet corresponding to a received data packet through the associated WLAN. The MN finally selects the WLAN with the better performance by comparing the number of frame retransmissions experienced by the ACK packet on both WLANs. As a result of the comparison, the MN returns to single-path transmission mode over a WLAN with smaller retransmissions, and then the MN notifies the CN of the change in its own transmission mode.

5.3. Implementation Design

In this section, we design our implementation on a Linux OS based on the proposed method described in Section 5.2. In our HM, a handover is executed by switching data transmission from an active connection to an alternative connection. To successfully execute handover, our design mainly consists of two phases as shown in Figure 5.2: *handover preparation* and *handover process*. In handover preparation, an alternative connection is established, and a handover is initiated when the wireless link of active connection is deteriorated. On the other hand, in the handover process, the process for switching data transmission among two connections is carried out. First, Section 5.3.1 describes the structure of our HM. We then explain details of the handover preparation and the handover process in Sections 5.3.2 and 5.3.3 respectively.

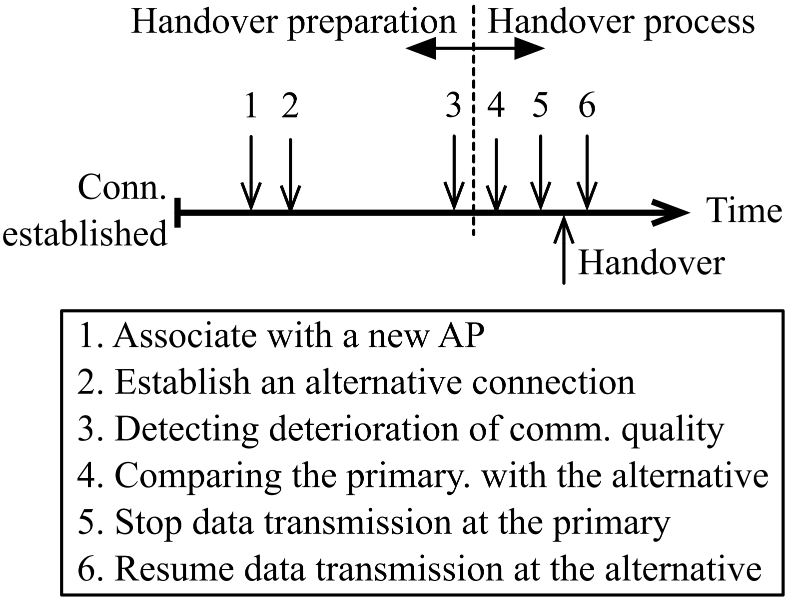


Figure 5.2. Time-series procedure of our implementation design

5.3.1 Structure of HM

Figure 5.3 shows the structure of our HM at an MN. We divides the required functions into four, and each function is designed as a module of Linux kernel: the Connection Manager (CM), the Beacon Watchdog (BW), the TCP Controller (TC), and the Layer2 Prober (L2P). The CM controls handover (selects an better AP) and manages all modules to execute handover. More specifically, the CM bridges messages exchanged between the BW and the TC. The BW monitors each WIF condition and exploits the cross-layer architecture to notify the change in the connection state such as availability of new WLAN (Link-up) and deterioration of link quality of current WLAN (Link-alert) from the MAC layer to the transport layer. After receiving Link-up message, the TC prepares an alternative connection for performing a handover anytime. Finally, the L2P sends probe packets to select a better AP more accurately. Note that, in our HM, the handover preparation process starts when the TC receives Link-up or Link-alert from the BW through the CM (arrow A in Figure 5.3). Then, after receiving a reply from the TC, the CM terminates control process of an alternative connection (Link-up) or selects a better AP for handover (Link-alert) (arrow B in Figure 5.3). On the other hand, in an CN, although the same HM is employed, the BW and the L2P are not necessary at all, and then the function of other modules are limited, i.e., the HM of a CN just executes handover by following the direction received from the MN side.
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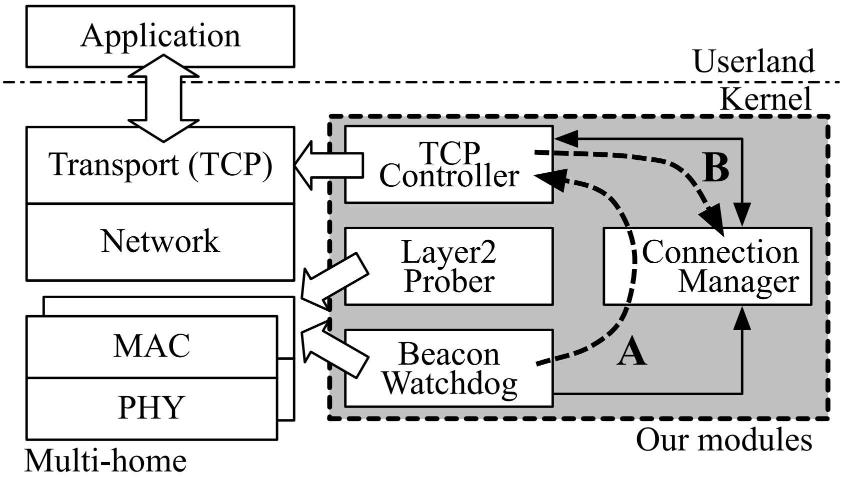


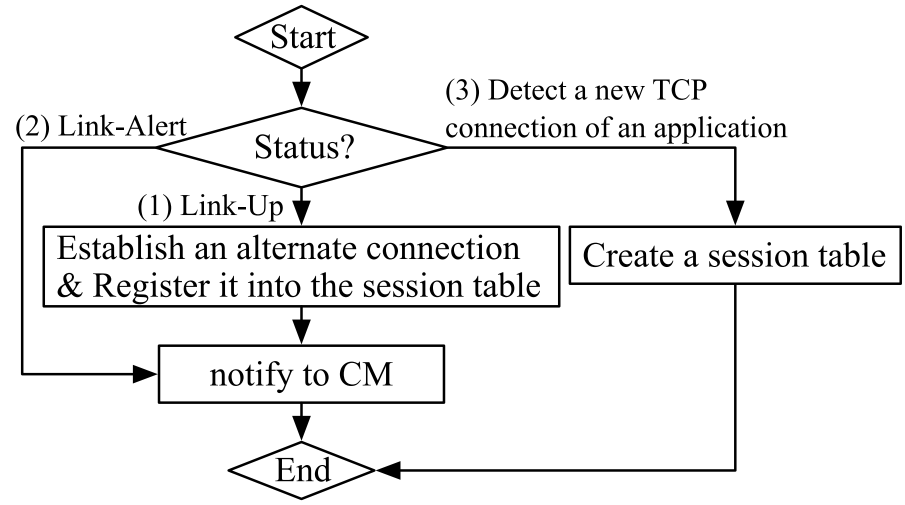
Figure 5.3. Structure of HM

5.3.2 Handover Preparation

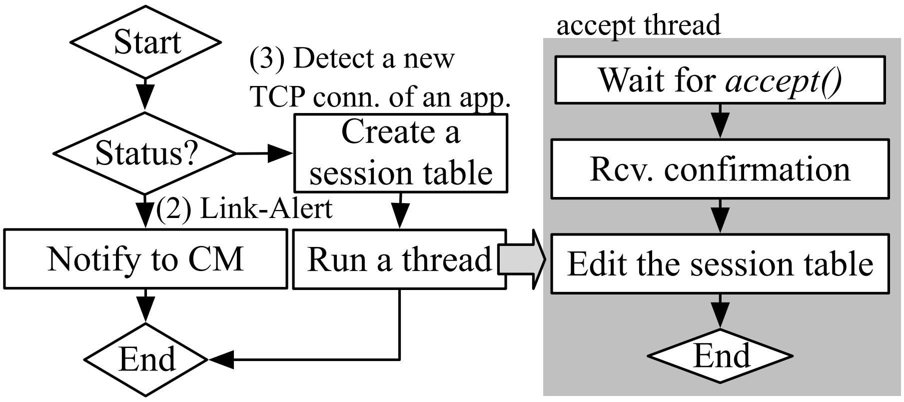
In the phase of the handover preparation, the HM establishes an alternative connection when other WLAN is available (Link-up), and initiates a handover when link quality of active connection is deteriorated (Link-alert). We respectively describe how to establish an alternative connection and how to initiate a handover in Section 5.3.2, and 5.3.2.

Preparation of an alternative connection

To achieve a seamless inter-domain TCP handover anytime, the MN establishes an alternative connection immediately when a new WLAN is available (Link-up). An alternative connection is established as following four steps. The BW, the TC, and the CM collaboratively work to establish it as described in Section 5.3.1, and the flowcharts of the TC and the BW and the CM are respectively shown in Figures 5.4, 5.5, and 5.6.
1. Detection of a new active connection: First, when an application in the MN side establishes a TCP connection with a CN through the WIF1, the TC of MN side creates a session table to treat multiple (active and alternative) TCP connections (see (3) in Figure 5.4(a)). The session table records pointers to socket structure of an active and an alternative connections. Note that, in the session table, the TCP connection first created is registered as an active connection. On the other hand, the TC of CN side also creates a session table in the same way with MN side when application establishes a connection. After that, the TC of CN side runs a new thread, namely accept thread, which



(a) MN side



(b) CN side

Figure 5.4. Flowchart of TC at each end host

calls *accept()* function and waits for an establishment of an alternative connection, (see (3) in Figure 5.4(b)).

2. Detection of Link-Up: The BW periodically monitors each WIF condition to find new association, as shown in Figure 5.5. When a new WLAN becomes available, the BW notifies the CM of it and the MN associates the WIF2 with the new WLAN. Note that, since frequent monitoring leads to high system load in a Linux OS. The BW employs a periodical monitoring at t_int-milliseconds interval.

3. Establishment of an alternative connection: Since the CM behaves as a bridge between the BW and the TC (arrow A in Figure 5.3), it forwards the notification from the BW to the TC (see (i) in Figure 5.6(a)). After receiving the notification of Link-up, the TC of MN side establishes an alternative connection with the TC of CN side (see

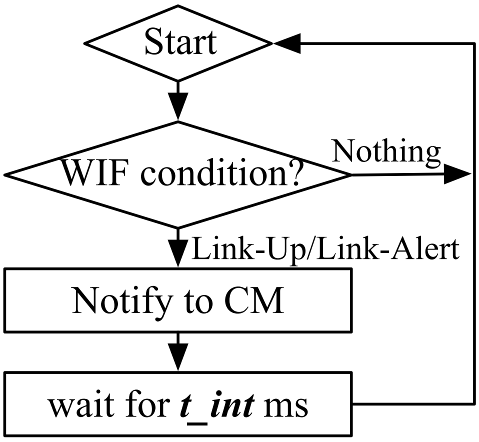


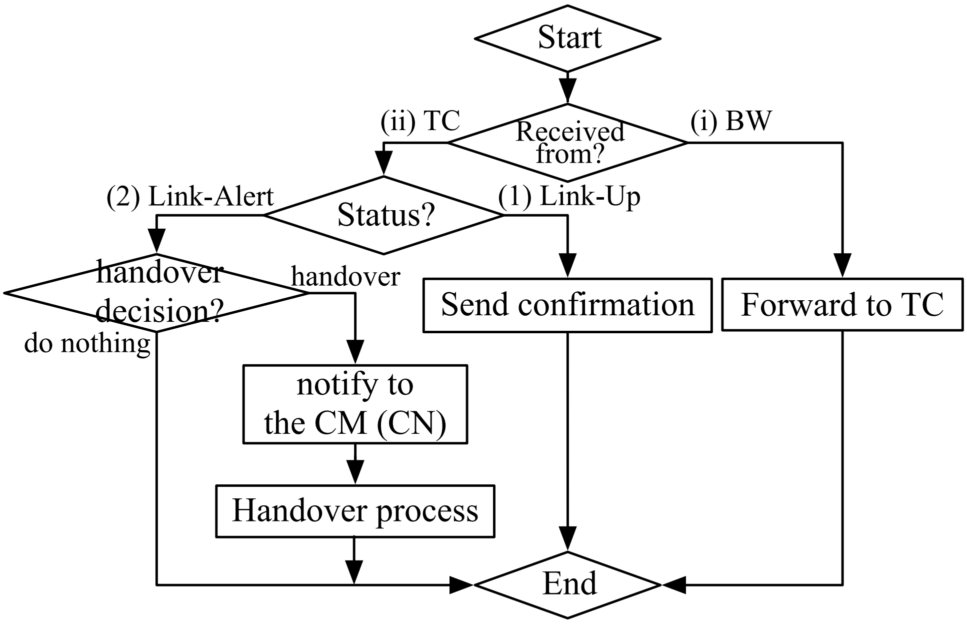
Figure 5.5. Flowchart of BW

(1) in Figure 5.4(a)), and registers the established connection as the alternative one in the session table. Then, the TC informs the CM of the completion of the registration (arrow B in Figure 5.3).

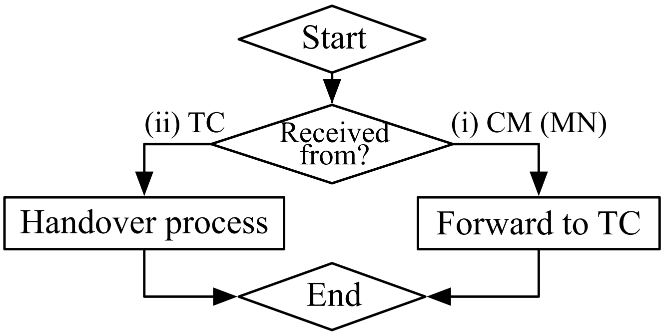
4. Finishing a preparation: After receiving a notification from the TC, the CM of MN side sends a confirmation message through the alternative connection (see (1) in Figure 5.6(a)) to notify a completion of establishement for the alternative connection to the TC of CN side. On the other hand, in the TC of CN side, when a new TCP connection is established (see in Figure 5.4(b)), *accept()* function returns and the TC waits for receiving a confirmation message through the established connection as in the MN side. After receiving it from the CM of MN side, the TC registers the connection as the alternative one in the session table.

Handover Initiation

After the BW detects Link-alert, the CM performs handover process to select a better AP. Our previous work [66] employed the number of frame retransmissions as the handover trigger, and detects Link-alert if once a packet experiences retransmissions more then predetermined threshold. In a real environment, since wireless condition frequently fluctuates and thus the number of retransmissions increases abruptly, we should explore a new and stable criteria. In our study, we employ new two parameters to absorb the fluctuation: $c\_retryThresh$ and $c\_retryAlert$. More specifically, when the number of packets experiencing more than $c\_retryThresh$ frame retransmissions exceeds $c\_retryAlert$, the BW on the MN detects Link-alert, and notifies Link-alert to the CM after once notifying it to the TC (arrows A and B in Figure 5.3).



(a) MN side



(b) CN side

Figure 5.6. Flowchart of CM at each end host

After detecting Link-alert, to select a better AP during handover, our previous work employed the multi-path transmission in which the CN transmits different data packets through each WLAN. Then, the MN sends back an ACK packet through the received path. After this parallel transmission, the MN selects a better AP by comparing the number of frame retransmissions experienced by one ACK packet on both WLANs. However, since TCP performance highly depends on stability of wireless link condition, selection of the AP based on only one ACK packet might lead frequent handovers (ping-pong effect). Thus, in our HM, we newly employ the retransmission ratio (RR) as the selection criterion, which is calculated for *t_retry* seconds just before detecting Link-alert in order to carefully select a better AP.

$$\mathrm{RR} = \frac{\text{Number of } \textbf{retransmitted} \text{ frames}}{\text{Number of } \textbf{transmitted} \text{ frames}} \tag{5.1}$$

The RR is calculated by the BW and is informed with Link-alert to the CM. Then, the CM selects a better AP for handover by comparing RRs from both WLANs. If the RR of the alternative connection is smaller, the CM judges the condition is stable and executes a handover. Otherwise, the current active connection is maintained. When performing a handover, the CM of MN side notifies start of a handover to the CM of CN side. After receiving the notification, the CN also starts the handover process.

To improve the accuracy of selecting a better AP, parameter settings should be necessary. For instance, small number of transmitted packets during *t_retry* degrades the accuracy of the RR. As a result, we employ the L2P, which intentionally sends probe packets to calculate the accurate RR. In the L2P, if the number of transmitted packets through an alternative connection is less than predetermined $c\_l2probe$, ($c\_l2probe$ − # of transmitted packets) ICMP packets of $s\_l2probe$ bytes are sent through the alternative connection.

5.3.3 Handover Process

In an inter-domain handover, preservation of TCP connection and communication quality at a handover is important. First, to maintain TCP connection, when deciding start of a handover, the HM in the transport layer switches data transmission from an active connection to an alternative one. In our study, applications are not aware of inter-domain handover because the HM on the transport layer implicitly switches the TCP connections. That is, existing applications can be used without any modification. Second, to quickly restart the communication after the handover, we employ the

Bandwidth Delay Products (BDP) as the *ssthresh* of the alternative connection after a handover. The details of handover process are described following step by step.

The HM need to appropriately switche data transmission from the active connection to the alternative one based on the session table (actually, HM switches a pointer to socket structure allocated to each connection). For this, we develop the MDL-functions, which run instead of *sock_common_recvmsg()* and *inet_sendmsg()* functions in the Linux kernel. When start of handover is decided, the HM attempts to switch data transmission to the alternative connection. However, since TCP provides completely reliable communication, in an actual OS, the HM surely needs to move packets queued in the send buffer of the active connection to that of the alternative one while perfectly preventing lost packet at handover. Then, the HM marks the current active connection as suspend, and the TCP retransmission timer is then cleared. At that time, since active connection does not exist (only the suspend and the alternative connections), the MDL-functions temporally interrupt the packet transmission until one of connections in the session table becomes active. In addition, to effectively increase TCP performance after a handover, the HM employed the BDP as *ssthresh* of the alternative connection. The BDP is calculated based on the RTT and the bandwidth between the MN and the CN when an alternative connection is established. The RTT and the bandwidth are measured by sending three packets through the alternative connection. Note that, RTT is calculated from the first packet and bandwidth is calculated from the second and third packets transmitted back-to-back. Finally, the alternative connection is marked as active, and the MDL-functions resume transmitting packets through the active connection. However, since the CN cannot identify the packets transmitted through new active connection, the CN may not deconstruct single byte-stream appropriately. In other words, since TCP identifies data based on its sequence number, the CN cannot identify received packets after handover. From this reason, to transfer single byte-stream using multiple connections at a handover, the HM need to synchronize the TCP sequence number of two connections before marking the alternative connection as active.

5.3.4 System Parameters

In this section, we discuss the value of six system parameters used in the proposed implementation: t_int, $c\_retryThresh$, $c\_retryAlert$, t_retry, $s\_l2probe$, and $c\_l2probe$. As described in Section 5.3.2, the proposed method performs handover based on the number of frame retransmissions. Since our focus is on preservation of TCP communi-

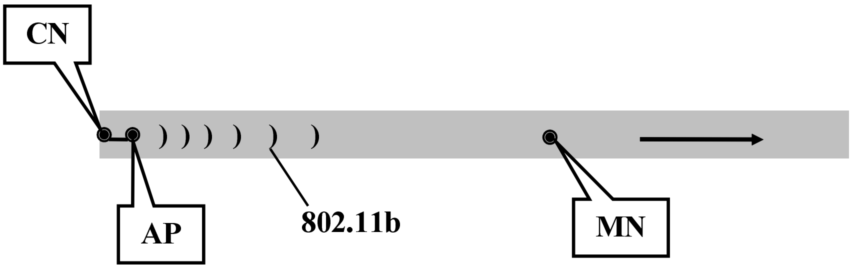
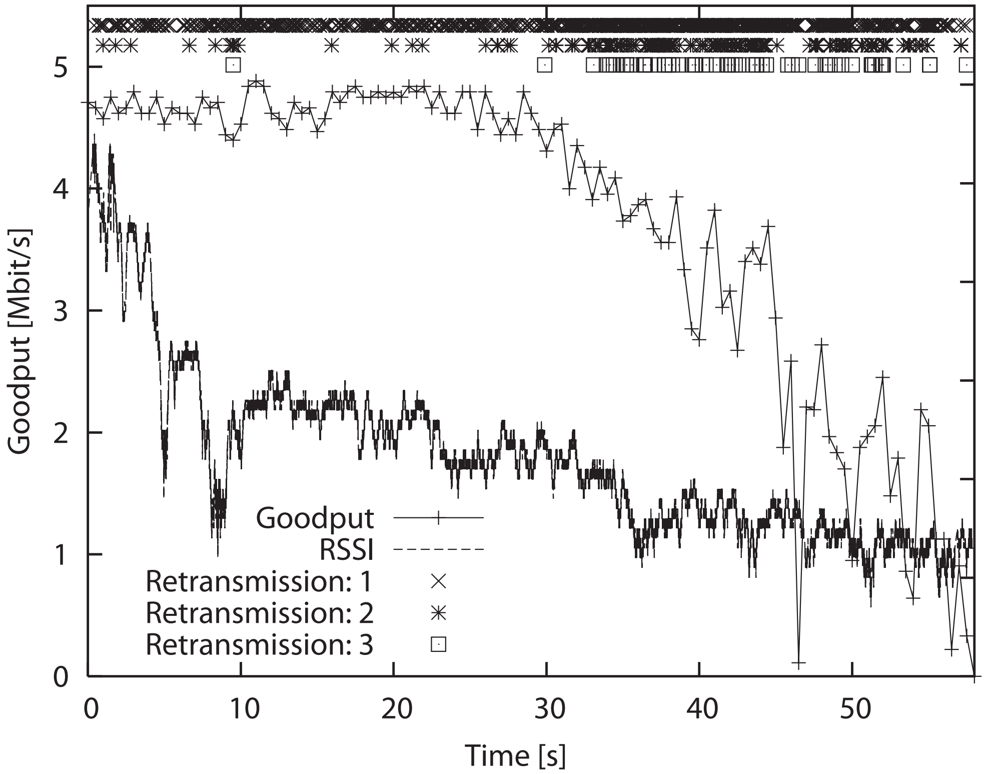


Figure 5.7. Experimental environment

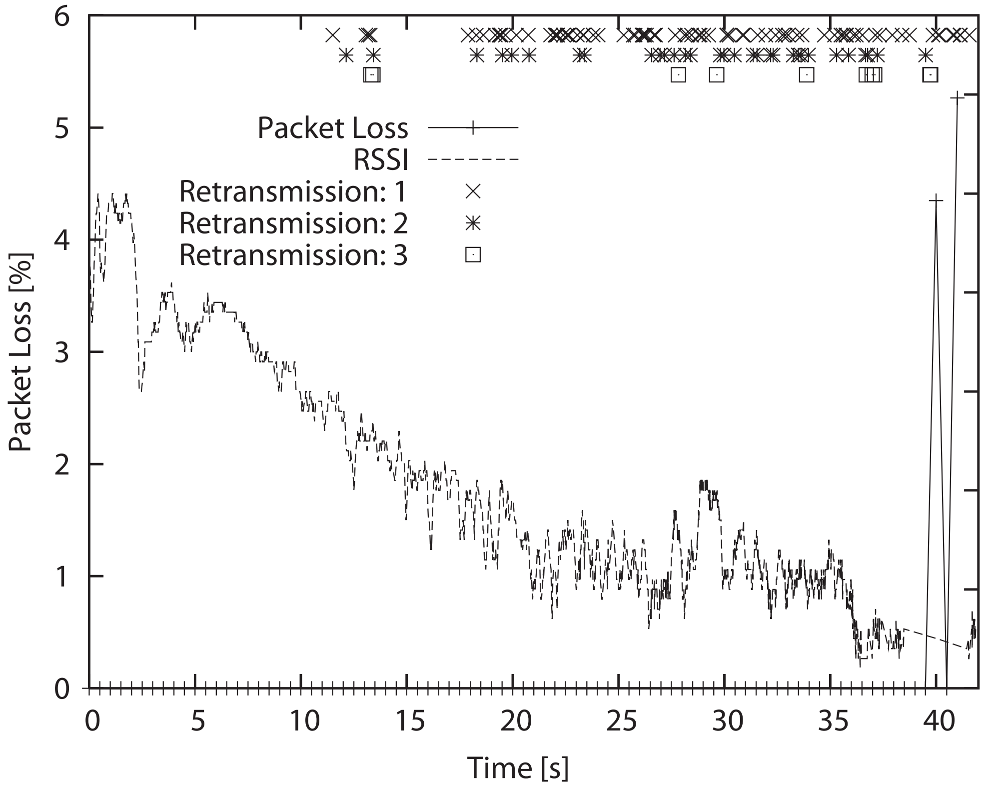
cation quality during traversing APs, appropriate configuration of system parameters is essential for achieving it. That is, we need to alleviate degradation of communication quality caused by handover as much as possible by appropriate setting system parameters.

First of all, we consider the monitoring cycle of the BW, *t_int*. In the BW, each WIF is monitored at *t_int*-millisecond interval. In our prototype, we appropriately set *t_int* to reduce the monitoring load while detecting quality degradation. In general WLAN system, AP broadcasts a beacon frame every 100 milliseconds and the status of WIF is changed based on the beacon message. Thus, from this, we use 100 milliseconds as *t_int*.

We next consider the parameters related to handover trigger, i.e., *c_retryThresh* and *c_retryAlert*. In our handover method, the BW notices the quality degradation (Link-Alert) when the number of packets experiencing more than *c_retryThresh*-times frame retransmissions exceeds *c_retryAlert*. In TCP communication, it is important to avoid frequent handover (ping-pong effect), because a TCP goodput degradation is unavoidable when resuming communication at a handover, hence, to avoid ping-pong effect, Link-Alert should be detected when wireless link quality clearly degrades. In a previous work [67], we investigated the relationship between communication quality and frame retransmissions in a real environment. We then explore the suitable values of the system parameters from the results. In [67], we employed fixed 11 Mbps of IEEE 802.11b with RTS/CTS, and two communications, FTP and Voice over IP (VoIP) of G.711 codec (200-bytes packet every 20 milliseconds). Figures 5.7 shows the experimental environment. In the experiment, the MN moves away from the AP at a walking speed (approximately 1 m/s) while communicating with the CN, which directly connects with the AP. Figures 5.8 indicates the experimental results with FTP and VoIP in time series. In the figures, "Retransmission: *n*" denotes the occurrence of *n*-times frame retransmissions. The results show that frame retransmission occurs



(a) FTP



(b) VoIP

Figure 5.8. Experimental result with movement

before degradation of the TCP goodput in FTP and increase of packet loss in VoIP. In particular, three-times retransmissions frequently happen when the degradation is clearly started. Then, to avoid ping-pong effect, three is suitable for *c_retryThresh*. We can also see that three-times retransmissions occur even at a stable communication quality (see approximately 10 seconds in Figure 5.8(a)) and then bursty happens just before the degradation, hence *c_retryAlert* must be more than two. Moreover, in VoIP experiment (Figure 5.8(b)), we can also find two occurrences of three-times retransmissions at approximately 13 seconds even when communication quality never degrades. On the other hand, since a packet size of FTP is greatly larger than that of VoIP, we can suppose that three-times retransmissions tend to occur more frequently in FTP communication, hence, it is preferred to employ *c_retryAlert* of three.

Next, we describe *t_retry*. As for *t_retry*, we use 5 seconds. Since we assume that an MN moves at a walking speed and performs a handover in an overlap area between a current AP and a neighbor AP after detecting degradation of communication quality. In order to carefully execute a handover, i.e., to confirm the next AP provides higher communication quality, the MN compares communication quality of both APs based on RR for *t_retry* period after detecting Link-Alert when starting handover is decided. With consideration of fluctuation of wireless communication condition, longer *t_retry* is preferable. On the other hand, if too long *t_retry* value is employed, start of handover is delayed because *t_retry* period contains a period when communication quality is better. Thus, *t_retry* should be set to the period for degradation of communication quality. In Figure 5.8(a), goodput begins to decrease at approximately 28 seconds and clearly degrades (three-times retransmission frequently occurs) at approximately 33 seconds. As a result, the difference period (5 seconds) should set as *t_retry*.

Finally, we consider a probe packet size, *s_l2probe*, and probe packet counts, *c_l2probe*. Probe packets (*s_l2probe*-bytes packets) are sent when the number of sent packet via an alternative connection is less than *c_l2probe* until exceeding it. In order to obtain the accurate RR of an alternative connection as much as possible, a larger number of probe packets is preferred, while reducing amount of probe packets to reduce network load. In our previous work [62], we can estimate communication quality based on 50 probe packets. Then, in this paper, we also use 50 packets for RR calculation as *c_l2probe*. In addition, we set the size of a probe packet (*s_l2probe*) to 1,500 bytes because 1,500-byte packet is commonly used for FTP communication.

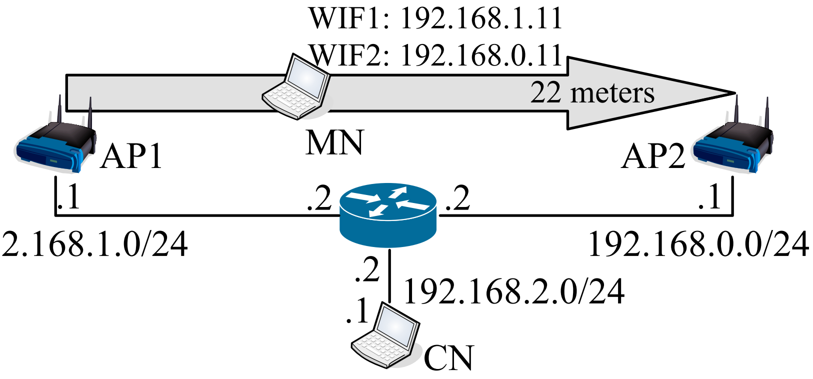


Figure 5.9. Experimental Environment

5.4. Implementation and Experimental Results

In this section, after details of implementation and experimental environment are described, experiments of the prototype system is conducted in a real environment. In the experiment, our study is examined whether the prototype effectively detects deterioration of communication quality, and whether it maintain a TCP connection.

5.4.1 Implemental and Experimental Environment

Since the proposed method controls inter-domain handover based on the end-to-end principle, we implement the HM into an MN and a CN (end hosts) only. We employed a ThinkPad X40 from IBM (CPU: Pentium M 1.6 Ghz, Memory: 1.5 GB) as the MN, and Inspiron 500m from DELL (CPU: Pentium M 1.4 Ghz, Memory: 1 GB) as the CN. For the multi-homing MN, the MN is equipped with a PC card-type WIF (ORiNOCO 11a/b/g Combo Card) in addition to a built-in type WIF (P/N: 93NP4266). Both the MN and the CN are installed with a Cent OS 4.5 with version 2.6.9 of Linux kernel. To obtain the number of frame retransmissions, the MN employed the modified WIF driver based on madwifi driver [39].

To examine the performance of our prototype in a real environment, we employ the experimental environment illustrated in Figure 5.9. The distance between the AP1 and the AP2 is fixed at 22 meters. Two Linux-based computers with madwifi driver are used as the AP1 and the AP2, which belong to different IP subnets. These APs are configured as Master mode of the madwifi driver to stand as an AP, and adjust the signal power to small value (7 dBm) in order to easily make the MN perform a handover. Note that the MN is configured with signal power of 7 dBm to perform a

Table 5.1. Handover-period and average goodput

	Minimum	Median	Maximum	Average
Handover period	2.03 Mbps	2.42 Mbps	3.56 Mbps	2.63 Mbps
Total	5.98 Mbps	6.04 Mbps	6.11 Mbps	6.05 Mbps

Table 5.2. Total number of more than 3 retransmissions until handover

	Minimum	Median	Maximum	Average
Retransmissions ≥ 3	14	18	32	20

handover. Each AP is configured as fixed 11 Mbps of IEEE 802.11b without RTS/CTS. That is, auto-rate fallback (ARF) is not employed because the occurrence of frame retransmission dynamically changes depending on the change in coding schemes at the physical layer if the ARF is activated. As a system parameters of our implementation, we employed the values described in Section 5.3.4, i.e., $t\_int = 100$ milliseconds, $c\_retryThresh = 3$ times, $c\_retryAlert = 3$ packets, $t\_recry = 5$ seconds, $s\_l2probe = 1500$ bytes, and $c\_l2probe = 50$ packets. For FTP communication, the CN stands as http server using Apache HTTP Server [6], and the MN downloads a 1-GB file from the CN using curl [14]. In the experiment, the MN first starts to communicate with the CN by downloading a file through the AP1 associated with the WIF1. After 5 seconds, the MN detects Link-Up of the WIF2, and an alternative connection is established. Then, the MN starts to move from the AP1 to the AP2 at a walking speed and performs a handover between them. Note that, the experiment is executed at nine times to examine the average performance during a handover.

5.4.2 Experimental Result

Table 5.1 shows maximum, minimum, median, and average value of the handover-period and the average goodput based on nine experiments. The handover-period goodput means the amount of transmitted bits during one second after handover starts, whereas the average goodput indicates the averaged goodput during experiment. From the table, we can see that communication interruption is less than one second, and decrease of goodput is suppressed at most one third. On the other hand, from the average goodput, we can say that the MN can prevent degradation of communication quality because we employ 11 Mbps of IEEE802.11b. We next shows the number of frames experiences more than 3 retransmissions before handover in Table 5.2. From

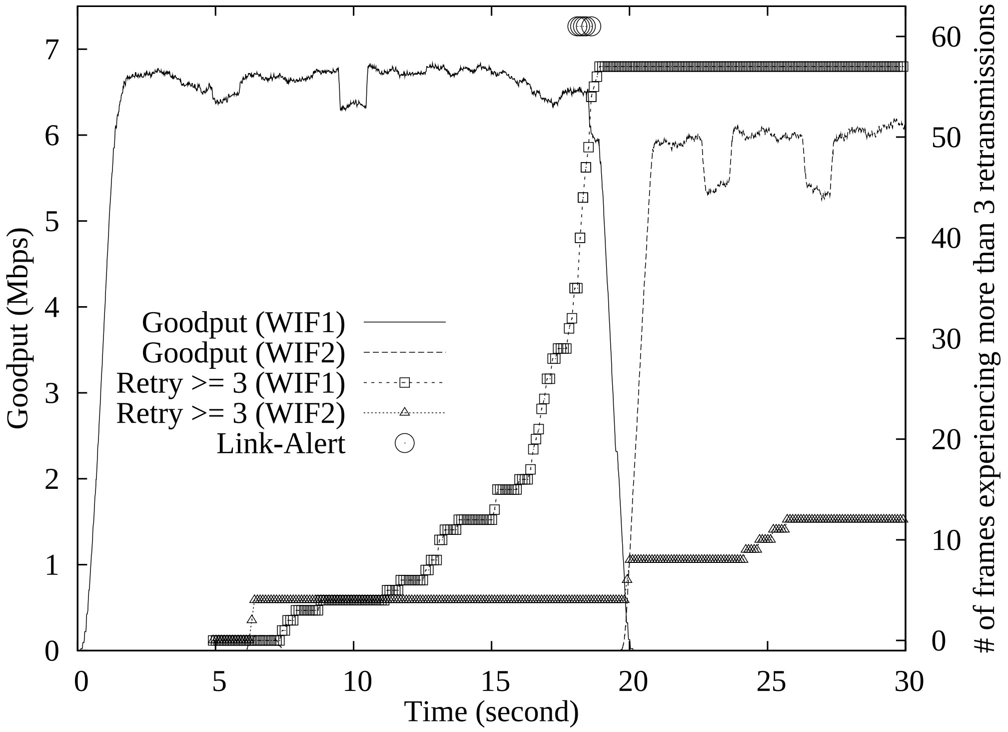


Figure 5.10. Experimental result

the table, we can see that frame retransmissions more than 3 times often occur before handover because, in our implementation, Link-Alert is not detected as long as it happens more than 3 times (*c_retryAlert*) during 100 ms (*t_int*). We next shows time series variation of goodput, and occurrence of more than 3 frame retransmissions with Link-Alert in Figure 5.10. Note that, this graph shows the result of the median values in the handover-period goodput among nine experiments. From this figure, we can also see that more than 3 retransmissions sometimes occurs before handover starts. Then, at approximately 20 seconds, Link-Alert is detected and handover is executed because more than 3 frame retransmissions frequently occurs, i.e., wireless link quality starts to degrade. From this, our prototype can reliably decides a start of handover before TCP performance degrades. In addition, after performing a handover, retransmissions through WIF2 happens less frequently than that through WIF1. From this, we also say that our prototype can appropriately select an better AP.

5.5. Summary

In this paper, we designed and implemented the TCP handover method into a Linux OS to achieve an inter-domain TCP handover in a real environment. The differences between the previous study [66] and this study are following two points: employing an actual OS, and experiment in a real environment. That is, to maintain TCP communication in an actual OS, the HM must correctly manage two TCP connections and control a transmission of a single-byte stream among them. In addition, since a real environment brings fluctuation of wireless condition, the HM must adapt it. For the former, we employed the session table with the MDL-functions to control a transmission of a single-byte stream, moving queued packets among two connections, and sequence number synchronization among two connections for identifying a packet consistently around a handover. To overcome the latter, we employed new handover criterion (more than $c\_retryThresh$-times frame retransmissions exceeds $c\_retryAlert$) and the RR as a criterion to carefully select an better AP. The prototype, finally, was examined through an experiment in a real environment. From the result, we could confirm that it appropriately performed a handover while maintaining communication quality and avoiding degradation of communication quality, thereby showing that it has a practical use.

As the future work, we have an issue: adaptation to multi-rate WLAN. In a real environment, there are various APs with different ARF algorithm. Then, we intend to study the influence of multi-rate WLAN in order to achieve practical use in actual ubiquitous WiFi environment.

6

CONCLUSION AND FUTURE WORK

6.1. Summary of the Dissertation

In this dissertation, we first described the vision of future WiFi network (ubiquitous WiFi netowork), our motivation, and the goal of our study, which is realizing that an MN keeps communication at any time during moving in ubiquitous WiFi network. Then, we also introduced our approaches to reach our goal. Actually, to achieve the goal, it is essential that communication quality experienced by an MN is preserved at any time independent on location. In other words, packet transmission between MN and AP should be surly reached. For achieving this, we classified requirements into followings: (1) omnipresence of sufficient wireless connectivity, and (2) preservation of communication quality during movement of MN. After that, as solution to these requirements, we made each MN individually preserve its own communication quality, and also made network autonomically control its own coverage area for achieving omnipresence of sufficient wireless connectivity.

According to the above solution, our study first tackled omnipresence of sufficient wireless connectivity in Chapter 2. In fact, our study assumes that all APs individually detect their own coverage area, sharing detected coverage area through APs, and finally appropriately integrate coverage area until sufficient wireless connectivity everywhere. In Chapter 2, based on this assumption, our study presents wireless measurement architecture to identify coverage area with desirable communication quality, and evaluates its effectiveness through simulation experiment. Although coverage area is currently detected by identifying locations where an MN can associate with an AP based on signal strength, our study aims a new paradigm of coverage area detection, i.e., identifying locations where an MN has sufficient wireless connectivity. Then, in the simulation experiments, we can see that FER (frame error rate) is useful that an AP identifies communication quality corresponding to a location inside coverage area. Finally, the measurement architecture achieves that an AP autonomically detects communication quality inside its own coverage area, and identifies locations with desirable communication quality.

Next, to achieve preservation of communication quality experienced by an MN, we additionally divide issues into following two: (a) selection of an AP with better performance from among multiple candidate APs, and (b) preservation of communication quality during traversing multiple APs. Even in ubiquitous WiFi network, an MN unfortunately experiences deterioration of communication quality due to two factors; one is deterioration of wireless connectivity by getting distance from currently used AP longer. Second is radio interference due to packet transmission of other WiFi devices. In such situation, in order to avoid deterioration of communication quality, an MN has to select an AP with better performance as a next one. Therefore, an MN has to know how communication quality is obtained by an AP in advance, which was tackled in Chapter 3. To select a better one, not only sufficient connectivity but also congestion condition are important. Moreover, to prevent deterioration of communication quality, an MN has to find a better one beforehand. Then, our study employed the number of frame retransmissions with received signal strength (RSSI) for selection index, and MN with dual interface (multi-homing MN). That is, the idle WiFi interface (WIF) selects an AP with better performance by the number of frame retransmissions and RSSI. Note that, since obtaining the number of frame retransmission needs packets transmission, the proposed method sends some probe packets to a candidate AP for the investigation. Through the experiments in a real environment, we showed that the proposed AP selection method selects an AP with better performance avoiding radio interference.

After selecting an next AP, an MN switches communication to the next one (handover) at which an MN should preserve its own communication quality. Since our study employed multi-homing MN, switching an AP can be seamlessly done. The essential issues are when an MN starts handover, and whether an MN can preserve its communication quality on a next AP. Our study solves them by employing the number of frame retransmissions as both handover criterion and comparison index of communication quality between the current AP and the next one. That is, they mean that how an MN appropriately detects communication, and how an MN compare communication quality of both APs. However, what an MN focuses on differs depending on applications. For instance, real-time application focuses on packet loss and delay.

Then, our study separately introduces handover method for VoIP and TCP.

In Chapter 4, our study focused on preserving VoIP communication. Since VoIP communication focuses on packet loss and delay, our study designed implementation so that an MN can promptly detect changes in wireless condition. Actually, an MN investigates communication quality at each frame transmission, and starts handover when the number of frame retransmissions experienced by one frame exceeds a threshold. Moreover, to avoid packet loss when switching an AP, our study employed multi-path transmission in which an MN sends same packets over two WIF. The MN also compares condition of both APs by collecting the number of frame retransmissions during it, and then switches a better one. Finally, our study shows that the method appropriately executes handover in a real environment.

On the other hand, in Chapter 5, our study presented a handover method focusing on TCP communication. Since TCP communication is sensitive to stability of wireless condition, our study utilize a new threshold to carefully detect changes in communication quality. That is, changes in communication quality is detected when the number of n frame retransmissions occurs more than m during t. Note that, n, m, and t are predetermined parameters. Additionally, to carefully determine whether handover starts, RR (retransmission ratio) was employed. If RR of the next AP is larger than current one, handover is executed. From these mechanism, our study achieves handover focusing on stability of wireless condition.

6.2. Future Work

This dissertation is a milestone for my research on preserving communication quality experienced by MN. To progress my research, following points should be solved in next steps.

- Performance metrics effective in a real environment

  In wireless measurement architecture, our study investigated architectural characteristics of our proposed architecture. The performance metrics used in Chapter 2 are only evaluated in simulation. Since simulator especially utilizing wireless has a long way for realistic environment [37], our study has to explore performance metrics effective in a real environment.

- Analysis method of measured performance metrics

  Currently, in our wireless measurement architecture, measured performance metrics are stored as averaged value. Furthermore, our study assumes that every MN transmits frames in same signal strength. However, WiFi condition frequently fluctuate in a real environment and signal strength to transmit frames are different by terminal types. Our study has to consider how to treat the difference in a real environment in order to appropriately detect providing quality.

- Collaboration between APs

  To achieve ubiquitous WiFi networks, coverage area information every AP has should be distributed between APs to appropriately integrate them. Since measured performance metrics are updated in real-time, network load become higher if distributing all information. In addition, to integrate coverage area, an AP may need information of coverage area only around itself. Therefore, distribution scheme that control distribution frequency and distribution scope is essential.

- Adaptation of other WiFi specification and configuration

  Our study currently assumes specific WiFi technology (IEEE 802.11g and IEEE 802.11b) with fixed rate. In wireless measurement architecture, since an AP transparently conducts measurement, communication performance of applications is estimated by frame error rate. In AP selection and handover, our study also employed thresholds of the number of frame retransmissions to detect communication quality based on measurement results in specific wireless specification and configuration. In both cases, if WiFi specification changes, values of almost thresholds change. The scheme to adapt changes in WiFi specification and configuration is essential.

6.3. Future Direction

This dissertation focuses on preservation of communication quality experienced by MN in terms of achieving ubiquitous WiFi networks with required communication quality. Toward ubiquitous WiFi networks, our study works on measurement architecture, which enables AP to keep on observing communication quality at many location inside coverage area. This architecture runs at individual AP. To control coverage area, anyone has to collect measurement results and take an action to improve deterioration of communication quality. However, central controller is impractical because many WCPs spread WiFi access, and many people personally provides WiFi access in the near future. Therefore, to achieve ubiquitous WiFi networks, researchers should consider decentralized control of coverage area. For Instance, distribution platform of measurement result and collaborative decision making should be discussed.

Furthermore, our study assumes that all APs collaboratively work on achieving ubiquitous WiFi networks. However, some of them are actually uncooperative. For instance, APs belonging to business rivals of WCP will not cooperate each other, and many APs are personally managed without cooperation. In such situation, communication quality corresponding to each location cannot be enough obtained, and controlling coverage area becomes hard. Then, a mechanism or incentive to increase cooperation APs should be discussed.

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