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Proactive AP Selection Method Considering the Radio Interference Environment

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SUMMARY In the near future, wireless local area networks (WLANs) will overlap to provide continuous coverage over a wide area. In such ubiquitous WLANs, a mobile node (MN) moving freely between multiple access points (APs) requires not only permanent access to the Internet but also continuous communication quality during handover. In order to satisfy these requirements, an MN needs to (1) select an AP with better performance and (2) execute a handover seamlessly. To satisfy requirement (2), we proposed a seamless handover method in a previous study. Moreover, in order to achieve (1), the Received Signal Strength Indicator (RSSI) is usually employed to measure wireless link quality in a WLAN system. However, in a real environment, especially if APs are densely situated, it is difficult to always select an AP with better performance based on only the RSSI. This is because the RSSI alone cannot detect the degradation of communication quality due to radio interference. Moreover, it is important that AP selection is completed only on an MN, because we can assume that, in ubiquitous WLANs, various organizations or operators will manage APs. Hence, we cannot modify the APs for AP selection. To overcome these difficulties, in the present paper, we propose and implement a proactive AP selection method considering wireless link condition based on the number of frame retransmissions in addition to the RSSI. In the evaluation, we show that the proposed AP selection method can appropriately select an AP with good wireless link quality, i.e., high RSSI and low radio interference.
key words: *AP selection, Radio interference, Frame retransmission, RSSI, Multi-homing, WLAN*

1. Introduction

Wireless local area networks (WLANs) based on the IEEE 802.11 specification [1] provide high data transmission and simple, low-cost installation. For this reason, WLANs have been spreading rapidly in both private and public spaces, so that these WLANs will overlap to provide continuous and wide coverage as the underlying basis of ubiquitous networks. In such ubiquitous WLANs, mobile nodes (MNs) can access the Internet from everywhere and at anytime.

In WLANs, an MN requires not only permanent access to the Internet, but also seamless movement between access points (APs) without degradation of communication quality, i.e., seamless mobility is essential. Furthermore, in such ubiquitous WLANs, each AP will independently provide wireless Internet connectivity based on IEEE 802.11 technology. That is, the APs have a different IP subnet due to independent management of different organizations and operators. In such a situation, if a mobility support technology 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 mobility 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 mobility technology is also not realistic. Therefore, it is desirable to provide a seamless mobility technology without modification of APs.

To achieve such seamless mobility, 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 handover. For (2), we proposed a handover management scheme based on the number of frame retransmissions [2]–[4]. In the proposed scheme, an MN is assumed to move between WLANs with different IP subnets. In [2], we first employed multi-homing architecture to prevent a disruption period due to handover processes. That is, since an MN with two WLAN interfaces (a multi-homing MN) can connect to two APs before starting handover, an MN never experiences a disruption period due to handover processes. 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 [5]. 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 [2], even if an MN has two WLAN interfaces 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

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handover. In ubiquitous WLANs, 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 exist in high-density ubiquitous WLANs, 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 WLAN devices.

In the present paper, 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, in this paper, we especially focus on the radio interference caused by packet transmission from other WLAN 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 [2], [6] is extended to introduce our AP selection method, which requires no modification of AP.

The present paper is organized as follows. Section 2 surveys related research for existing AP selection methods. Section 3 describes the proposed proactive AP selection method. In Sect. 4, we then explain an implementation and system parameters used in the proposed AP selection method. Section 5 describes the experimental topology and presents the demonstration in a real environment and screenshots of the prototype system. After introducing our future work in Sect. 6, concluding remarks are presented in Sect. 7.

2. Related Work

So far, there have been numerous discussions on AP selection for improving the communication performance of MNs in WLANs. As described in Sect. 1, in ubiquitous WLANs, 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 [7]–[9], 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 the present paper, we focus on an AP selection method with no modification of an AP, i.e., only an MN is modified.

In [10], [11], AP selection methods only on an MN were proposed. In [10], 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 [11] 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 [12], [13] proposed methods to avoid such types of degradation. In [12], 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 [9], the modification of an AP is still necessary. On the other hand, [13] 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, which has not yet become widespread. Therefore, in the present paper, we focus on a proactive AP selection method considering the wireless link condition with no modification of APs for inter-domain handover.

3. AP Selection Method

In this section, we describe the proposed AP selection method. We first describe the concept of the proposed method in Sect. 3.1. Then, in Sect. 3.2, we describe the proposed method with flowcharts.

3.1 Overview

In the present paper, we focus on a proactive AP selection for a radio interference environment. In the handover method we proposed in a previous study [6], as described in Sect. 1, a multi-homed MN appropriately switches WLAN interfaces (WIFs) according to wireless link condition. Figure 1 shows an overview of operation between a handover and an AP selection on an MN. An AP selection is per-

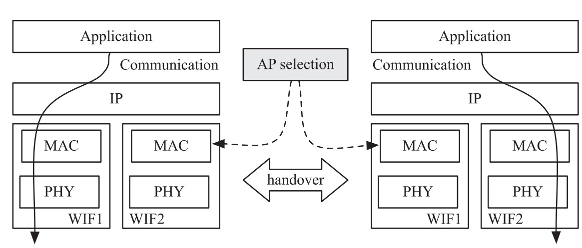


Fig. 1 A handover and an AP selection on an MN.

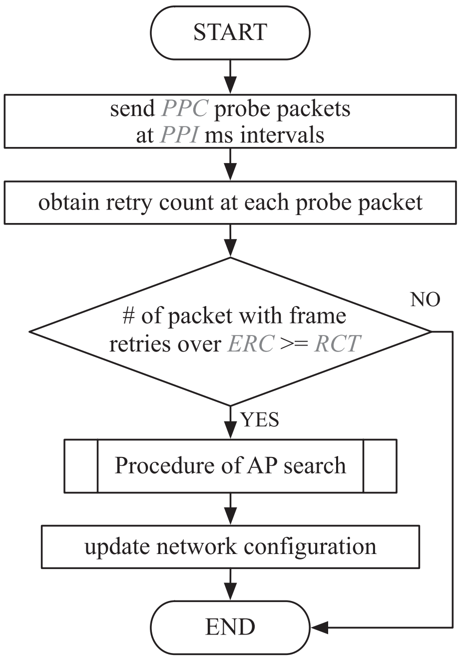


Fig. 2 Flowchart of the AP selection procedure.

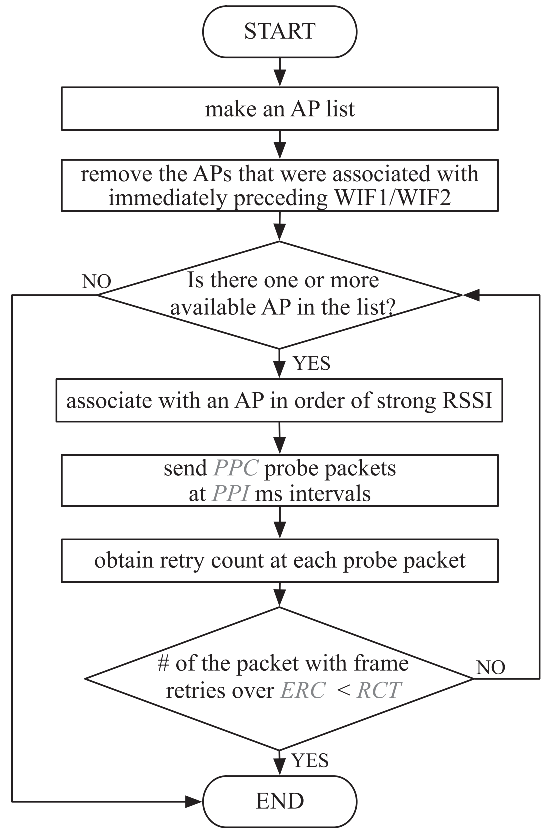


Fig. 3 Flowchart of the AP search procedure.

formed on the WIF2 during communicating through 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 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 Figs. 2 and 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 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 Fig. 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.

4. Implementation and System Parameters

In this section, we explain the implementation of the proposed AP selection method. Section 4.1 describes the present implementation. We then discuss the configurable system parameters of the proposed AP selection in Sect. 4.2.

4.1 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 WLAN interface 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 WLAN interface (P/N: 40Y7028) employing an Atheros chipset. In addition, in the proposed method, since we focus on a multihomed MN, i.e., an MN equipped with two WIFs, a WIF of a PC card type (corega WLCB54AG2) is prepared as another WIF.

As described in Sect. 1, 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 4 shows the architecture of the proposed AP

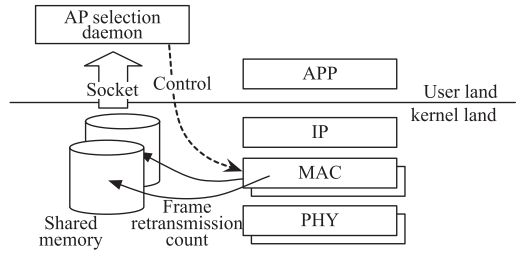


Fig. 4 Architecture of the AP selection.

selection method on an MN. Note that our AP selection method is implemented as an extension of on the prototype system described in [6]. In [6], 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 Fig. 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.

4.2 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 Sect. 3.2, 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 [5], 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 [5]. We investigated the relationship between communication quality and frame retransmissions due to the reduction of the RSSI and radio interference. As shown in Fig. 5, we used an indoor experimental environment to investigate it. Note that, in the experiment, the MN commu-

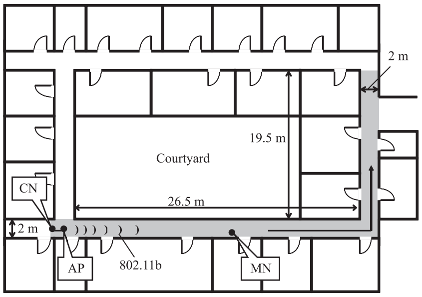


Fig. 5 Indoor experimental environment (investigation of wireless link quality over a distance).

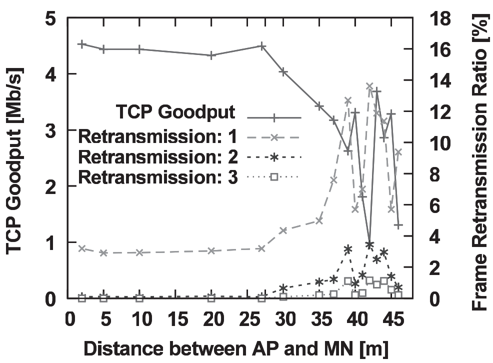


Fig. 6 TCP goodput and frame retransmission ratio (FTP) over a distance.

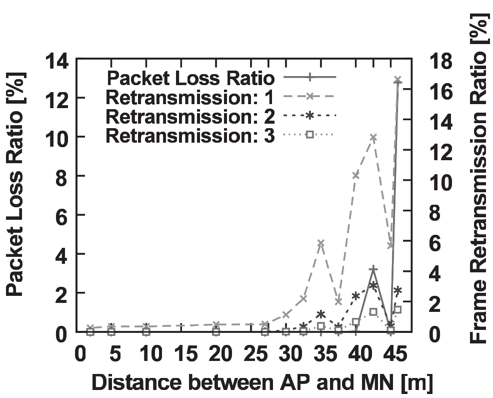


Fig. 7 Packet loss ratio and frame retransmission ratio (VoIP) over a distance.

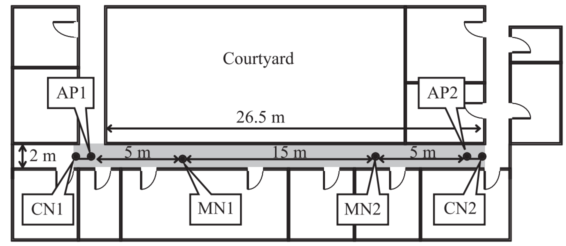


Fig. 8 Indoor experimental environment (investigation of wireless link quality for radio interference).

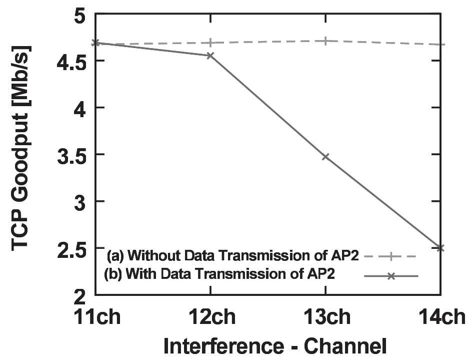


Fig. 9 TCP goodput performance.

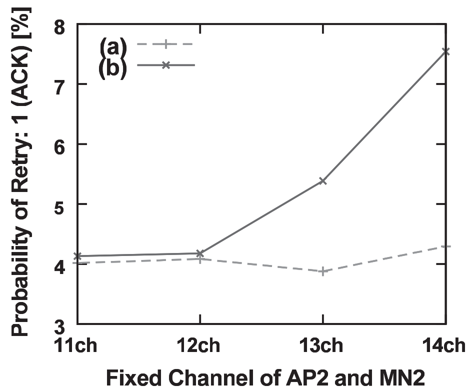


Fig. 10 Frame retransmission ratio.

nicates with the corresponding node (CN) through the AP. Figures 6 and 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 Fig. 8, we also investigated how the communication quality and 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[†], 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 Figs. 9 and 10, we can see that the number of frame retransmissions increases with

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

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 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 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*, Figs. 6 and 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 to one. We then consider the value of *ERC*. Figures 6 and 7 show that the communication quality starts to drastically degrade just after the rate of one retransmission exceeds 6%, and Fig. 6 shows that one retransmission always occurs at a rate of approximately 4%. Moreover, Fig. 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 Figs. 6 and 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 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 [5].

5. 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 Sect. 5.1, we describe the experimental environment, including the facilities and the experimental topology and scenario. Then, in Sect. 5.2, 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 Sect. 5.3.

5.1 Experimental Environment

Figure 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

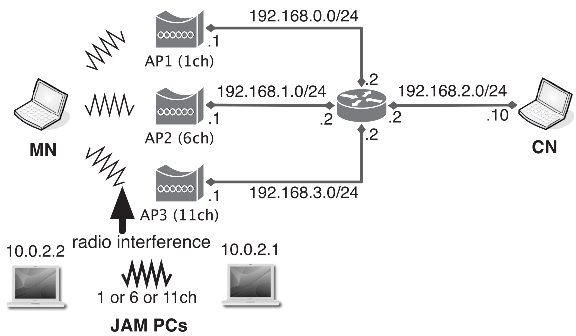


Fig. 11 Experimental topology.

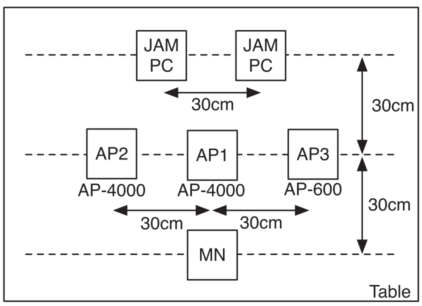


Fig. 12 Detailed placement of facilities.

of Fig. 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 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 Fig. 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 Fig. 12.

5.2 Demonstration

In this section, we demonstrate the proposed method with the handover scheme proposed in [6]. 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. 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 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 colors: the AP1 is red, the AP2 is green, and the AP3 is blue. Note that, in the graphs, the background color shows the radio interference period for each AP.

In Fig. 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 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 Figs. 14 and 15, we show the behavior of the RSSI

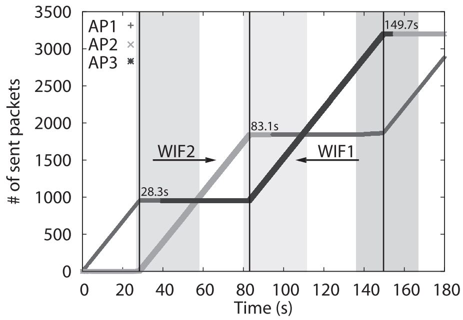


Fig. 13 selected AP and sent packet count.

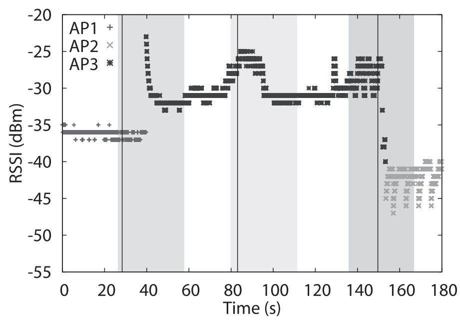


Fig. 14 RSSI on the WIF1.

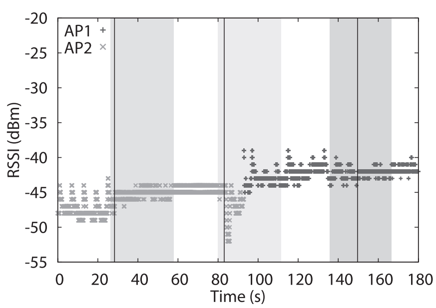
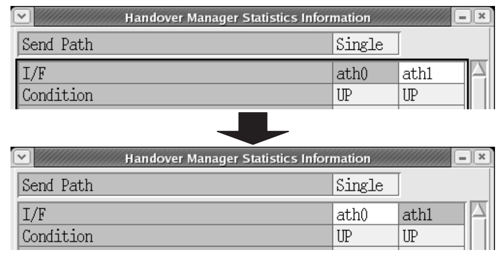
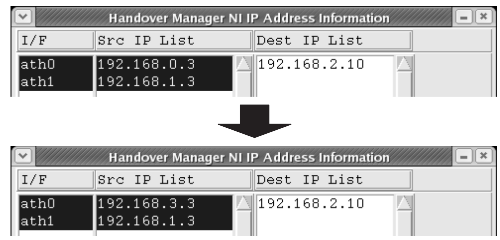


Fig. 15 RSSI on the WIF2.

for each WIF. These results are obtained from the output of the iwconfig command during an experiment. 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 Fig. 13, the first handover is finished at approximately 28 seconds. On the other hand, Figs. 14 and 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. 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 WLANs, the number of frame retransmissions is



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



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

Fig. 16 Screenshots of the implemented system.

a potentially effective metric for the selection of an AP with a good wireless link condition.

In Fig. 16, we present two screenshots of the implementation of the experiment. In Fig. 16 (a) shows that the MN executes a handover to the WIF2 (ath1). In Fig. 16 (b), after the handover, the WIF1 (ath0) selects the AP3 as an AP with better performance, thereby avoiding radio interference with the AP1.

5.3 Performance Evaluation

In Fig. 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 Sect. 5.1 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 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

Table 1 Detection and processing delay.

(a) Experimental values listed in order of magnitude

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

(b) Minimum, average, and maximum values

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

magnitude in Table 1 (a), and the minimum, average, and maximum values of these delays are shown in Table 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 1 (a)). Note that, from Figs. 6 and 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 (Figs. 2 and 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 Fig. 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.

6. Future work

In the present paper, 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 WLAN environment.

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 (= $(8 \times \frac{50\times1500}{5})/1000$) 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 [14], 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.

7. Conclusion

In the present paper, in order to select an AP with better performance from among multiple candidate APs in ubiquitous WLANs, 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 WLANs, 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.

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