Topology-Aided Cross-Layer Fast Handoff Designs for IEEE 802.11/Mobile IP Environments

Chien-Chao Tseng, National Chiao-Tung University
Li-Hsing Yen, Chung Hua University
Hung-Hsin Chang and Kai-Cheng Hsu, National Chiao-Tung University

Abstract

This study first reviews state-of-the-art fast handoff techniques for IEEE 802.11 or Mobile IP networks. Based on that review, topology-aided cross-layer fast handoff designs are proposed for Mobile IP over IEEE 802.11 networks. Time-sensitive applications, such as voice over IP (VoIP), cannot tolerate the long layer-2 plus layer-3 handoff delays that arise in IEEE 802.11/Mobile IP environments. Cross-layer designs are increasingly adopted to shorten the handoff latency time. Handoff-related layer-2 triggers may reduce the delay between layer-2 handoff completion and the associated layer-3 handoff activation. Cross-layer topology information, such as the association between 802.11 access points and Mobile IP mobility agents, together with layer-2 triggers, can be utilized by a mobile node to start layer-3 handoff-related activities, such as agent discovery, address configuration, and registration, in parallel with or prior to those of layer-2 handoff. Experimental results indicate that the whole handoff delay can meet the delay requirement of VoIP applications when layer-3 handoff activities occur prior to layer-2 handoffs.

1. Introduction

Internet Protocol (IP) technology is increasingly adopted as a conventional service platform for both data and speech services. Meanwhile, IEEE 802.11 wireless local area networks (WLANs) have been widely deployed as an infrastructure providing high-speed data services to mobile users. However, offering voice over IP (VoIP) services on WLANs is still considered problematic due to an inherent limitation of the IEEE 802.11 MAC protocol, the very long handoff process.

VoIP service can be provided on WLANs, where mobile nodes (MNs) equipped with IEEE 802.11 network interfaces send streaming IP packets through Access Points (APs) to the Internet. When an MN detects poor link performance (e.g., low received signal strength or signal-to-noise ratio, high frame error rate), the MN may have to change its point of attachment to the Internet from one AP to another to retain its connection. The link-switch process is called a layer-2 handoff, and involves AP probe, authentication, and association phases in 802.11 networks.

Handoff may also involve activities at higher layers. If the handoff entails changing network domains (i.e., an inter-domain handoff), then the MN must acquire a valid IP address by schemes such as Dynamic Host Configuration Protocol (DHCP) in the new network domain. If Mobile IP is adopted for network-layer mobility management, then the MN should change its mobility agent and register accordingly (henceforth called a layer-3 handoff). If Session Initiation Protocol (SIP) is used as an application-layer mobility management method, the ongoing sessions may continue without interruption by allowing the MN to conduct an application-layer handoff (by sending an invite message to re-establish a new communication session with the correspondent host). Both mobility management methods (Mobile IP and SIP) may entail authentication, authorization and accounting (AAA).

The overall handoff latency should be minimized to maintain the desired quality of services demanded by VoIP or real-time multimedia applications. The layer-2 handoff delay has been reduced by exploiting the handoff-to relationship between APs in order to predict a collection of APs with which the MN may re-associate [1, 2, 3, 4]. Handoff-related activities (probing, authentication, etc.) can then be performed prior to handoffs in these APs. However, to accurately predict the next AP (rather than all candidates,) topology information in addition to handoff relationship between APs is needed [4]. This information includes the locations (coordinates) of APs and MNs as well as the MN moving directions.

Higher-layer handoff latency can also be reduced if higher-layer handoff can begin prior to or immediately after a link-layer handoff. To this end, we need cross-layer protocol state information, such as the indication of the occurrence of a layer-2 handoff related event (a layer-2 trigger [7, 10]), and cross-layer topology information, namely, the association between APs and higher-layer entities [8]. This study first reviews some state-of-the-art cross-layer fast-handoff techniques that could be applied to the Mobile IP or WLAN environment. The previous work in [4], which only applies to layer-2 handoff, is then extended by incorporating these cross-layer techniques to minimize the overall layer-2 and layer-3 handoff delay. Finally this design is shown to have very low handoff delay if implemented appropriately.

The rest of this article is organized as follows. Section 2 describes the details of handoffs in IEEE 802.11 and Mobile IP. Section 3 presents existing handoff speedup techniques. Sections 4 and 5 introduce our design and experimental performance evaluations, respectively. The last section concludes this article.

2. Handoffs in Layers 2 and 3

2.1 IEEE 802.11 Handoffs

A layer-2 handoff consists of three phases: probe, authentication, and re-association. In the probe phase, an MN discovers available APs by either an active or a passive scan. In an active scan, an MN broadcasts in some channel a *ProbeRequest* message with a particular Service Set Identifier (SSID). If the SSID matches an AP's configuration, then the AP responds with a *ProbeResponse* to the MN, and the MN can therefore be made aware of the presence of the AP. If the MN instead uses a passive scan, then it does not issue any message but listens to *Beacon* messages broadcast periodically by APs on channels of interest.

With AP information obtained from the *ProbeResponse* or *Beacon* message, the MN selects a new AP to camp on based on the measure of received signal strengths. Following the probe phase, the MN performs 802.11 authentication (open system or WEP), and then re-association phases with the new selected AP. In the authentication phase, the MN exchanges 802.11 authentication messages with the AP. In the re-association phase, the MN sends a *ReassociationRequest* to the AP and receives a *ReassociationResponse* replied by the AP. The receipt of the last message concludes the 802.11 handoff process.

As a port-based network access protocol, IEEE 802.1*x* provides authentication and key management under various 802 LAN infrastructures, and is now extensively adopted in 802.11 WLANs to resolve the limitations of WEP. An 802.1*x*-enabled AP acts as an authenticator controlling the MN's access to the Internet. The authenticator communicates with an authentication server that makes authorization decision on the access requests sent by an MN (called a supplicant in 802.1x terms). Either the MN or the authenticator may initiate an 802.1*x* authentication immediately after the re-association phase is completed. If the authentication is successful, then the authentication server sends a pair-wise master key (PMK) to the authenticator, which then initiates an 802.11*i* four-way handshake procedure to synchronize the PMK with the MN and to generate pair-wise temporal keys (PTKs). The 802.1*x* control port of the authenticator is then unblocked for the MN, and the MN can then send and receive messages protected by the PTKs.

2.2 Mobile IP Handoffs

Mobile IP (MIP) [5] is an Internet standards-track protocol that enhances the existing IP protocol to accommodate host mobility. In MIP, a special host called mobility agent (MA) maintains registration information for mobile nodes. When an MN moves away from its home network, the MA located in the MN's home network, called the MN’s Home Agent (HA), tunnels packets for the MN. Tunneled packets are usually, although not always, handled by the MA on the MN's visiting network, called the Foreign Agent (FA). An MN away from its home network can retain its connection to the Internet aided by HA and FA.

MIP provides two care-of address (CoA) options to identify an MN in the visited network, foreign-agent CoA (FA-CoA) and co-located CoA (CCoA) [5]. FA-CoA is generally an IP address of the FA. If an MN registers an FA-CoA with the MN’s HA, then the FA intercepts all tunneled packets destined for the MN, and delivers the de-tunneled packets directly to the MN. If the MN uses a CCoA, which is an IP address belonging to the visited network, then the MN itself receives and handle all tunneled packets.

When an MN detects that the current serving FA (cFA) is no longer accessible, it initiates a layer-3 handoff from cFA to the next FA (nFA). A layer-3 handoff consists of two phases. If FA-CoA is in use, then the MN must first discover nFA and then register with the MN’s HA through nFA (Fig. 1); otherwise, the MN must acquire a CCoA via some external means, such as DHCP, before it can start a registration process.

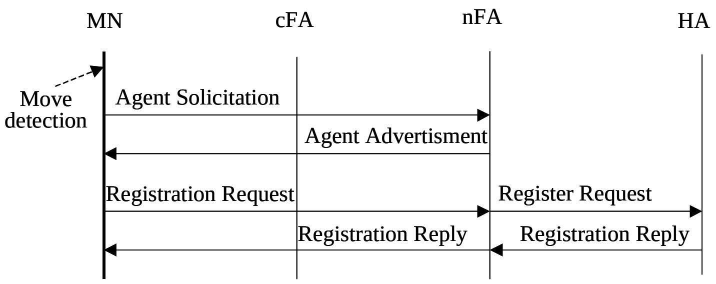

Fig. 1: Mobile IP handoff in the FA-CoA case

- Agent Discovery: This concerns how an MN becomes aware of the presence of nFA. Every MA can be uniquely identified by its *AgentAdvertisement* message. An MN may either listen to *AgentAdvertisement* messages broadcast periodically by nFA, or actively issue an *AgentSolicitation* message to request an advertisement.

- Address Configuration: This concerns how an MN obtains its new CCoA, which is typically achieved by DHCP.

- Registration: This informs the HA of an MN's CoA. If an FA-CoA is in use, then the MN issues a *RegistrationRequest* message to nFA, where the message is then forwarded to the HA. If a CCoA is used, then the MN sends this message directly to the HA. The HA sends a *RegistrationReply* to the MN to confirm the registration. The nFA relays the *RegistrationRequest* if an FA-CoA is in use.

The process for an MN detecting that cFA is no longer accessible is called move detection. MIP specifies two move detection principles, the advertisement expiration and the network prefix change. Each *AgentAdvertisement* in MIP carries an advertisement lifetime. If the lifetime of the most recently received advertisement expires, then the MN may assume that cFA is unreachable, which generally leads to long move detection delays, as MIP suggests that the advertisement lifetime should be long enough to tolerate three consecutive losses of advertisements. Alternatively, if the MN receives an *AgentAdvertisement* with a network prefix different from that of the MN's current CoA, then the MN may deduce that cFA is unreachable, leading to long move detection delay as the MN can receive nFA's advertisement only after a layer-2 handoff.

3. Handoff Speedup Techniques

Figure 2 illustrates the whole layer-2 plus layer-3 handoff delay. Many studies have attempted to reduce the delay in different activity sections and thereby speeding up the handoff process.

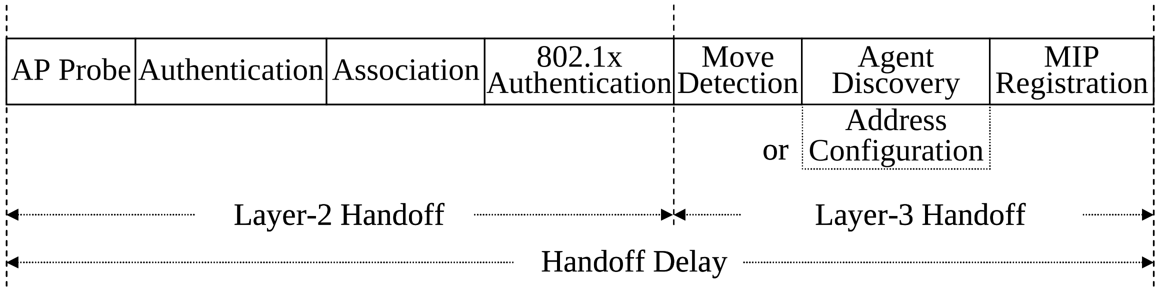

Fig. 2: Total Handoff delay

3.1 AP probe delay

Mishra et al. [6] have noted that the probe phase delay significantly contributes to the layer-2 handoff latency, and recommended using neighbor graphs [1] to capture the handoff-to relationship between APs; the MN only needs to probe the APs that are neighbors of the current AP. An AP is a neighbor of another AP only if a handoff from the latter to the former has occurred recently. Neighbor graphs thus only capture temporal handoff-to relationships.

3.2 Association Delay

A neighbor graph can also be used to lower the re-association delay by caching security information before the handoff begins, where security information is needed to establish secure communication channels between APs [2].

3.3 802.1*x* Authentication Delay

A neighbor graph was also used to decrease IEEE 802.1*x* authentication delay between an MN and an authentication server by pre-distributing key material to the candidate set of APs with which the MN may re-associate [3].

3.4 Move Detection Delay

A cross-layer design shortening the move detection delay naturally leads to the notion of layer-2 (L2) triggers. An L2 trigger is a layer-2 signal that informs a layer-3 entity of particular events before or after a layer-2 handoff [7]. Two types of layer-2 triggers, *pre-handoff trigger* and *post-handoff trigger*, are defined according to the timing of the occurrence.

A pre-handoff trigger occurs before a layer-2 handoff, while a post-handoff trigger indicates the completion of a layer-2 handoff. In IEEE 802.11, a pre-handoff trigger may be conditioned on the execution of the probe phase, which only takes place when an MN detects poor link performance. A candidate post-handoff trigger can be a “link up” event that occurs in an AP or MN after an MN successfully completes the re-association phase.

Wu et al. [8] used the post-handoff trigger in an MN to realize move detection, thereby eliminating the move detection delay.

3.5 Agent Discovery Delay

Wu et al. [8] also presented the use of neighbor lists to shorten the agent discovery delay. Entries of a neighbor list store IP addresses of MAs associated with neighbor APs, one for each neighbor AP. On the occurrence of a post-handoff trigger, an MN looks up its neighbor list for *n*FA's IP address, to which it then directly issues a registration request.[1]

3.5 Registration Delay

Handoff latency can be further improved with pre-handoff triggers instead of post-handoff triggers, as an MN could commence a layer-3 handoff even *before* the layer-2 handoff is completed, as revealed by pre-registration or early registration in Malki's low-latency handoff proposal for Mobile IP [7][2]. While this proposal allows both types of L2 triggers to be used, pre-handoff trigger is more appropriate than post-handoff triggers for pre-registration.

An MA in Malki's proposal [7] needs to acquire the advertisements of neighbor MAs prior to MN's handoffs. When a pre-handoff trigger occurs in an MN, the MN asks for *n*FA's advertisement by sending a *ProxyRouterSolicitation* to *c*FA (notably, the MN does not yet have a direct link with *n*FA), which returns a *ProxyRouterAdvertisement*, i.e., nFA's Agent Advertisement. The MN can then initiate pre-registration by sending a *RegistrationRequest* through *c*FA to *n*FA. With this pre-registration method, layer-3 handoff parallels layer-2 handoff, significantly reducing the overall handoff latency. Preliminary analytical results indicate that the pre-registration method outperforms traditional MIP with route optimization [10].

3.6 Cross-Layer Topology Information

Previous low-latency layer-2 handoff schemes [1-4] do not use much topology information — they generally consider only the handoff-to relationship of AP. However, to facilitate higher-layer handoffs, the definition of topology information should be extended to incorporate cross-layer information such as the association

---

[1] Notably, the IP address alone is not sufficient for all registrations. Therefore, the contents of neighbor list should be extended to include all relevant information that ought to be retrieved from Agent Advertisements.

[2] This proposal considers both pre-registration and post-registration methods to achieve low-latency handoff. However, this study focuses on the pre-registration case.

between APs and higher-layer entities.

In the pre-registration scheme mentioned above, an MN must learn of *n*FA’s IP address before pre-registration. Hence, the following information must be available to the MN:

- AP topology, which provides not only handoff-to relationship among APs (provided by the neighbor graph) but also the physical locations of APs (which could be local or global coordinates). If AP topology information is implemented in a distributed fashion [2], then the MN can acquire it from the current AP. Alternatively, the MN may request the topology information from a designated location server [4].
- The location and the moving direction of the MN, which is for an accurate estimate of the next AP. An MN can learn of its current location and moving direction by GPS (Global Positioning System) or any indoor location technique [11].
- The association between APs and MAs (cross-layer information for estimating the next FA to which the next AP belongs). The AP/MA association should be configured and maintained at the network side, since such information is network-dependent. An MN can obtain associations similar to how it acquires AP topology information. AP topology information can also be combined with AP/MA association, as with the neighbor list [8] mentioned above.

Application-layer handoffs also benefit from such a topology-based cross-layer design. Specifically, the association between APs and SIP proxy servers or AAA servers may be maintained. The association information rarely changes, as network topology is nearly static, and can therefore be gathered offline. This information allows not only simple pre-caching and pre-registration, but also pre-authentication and pre-reinvitation.

For instance, Kwon et al. [9] discussed using Diameter protocol to authenticate MNs during MIP registration. They proposed Shadow Registration which can be applied to both MIP and SIP to reduce the time taken to process inter-domain handoff. The key idea is to establish the security association between an MN and authenticators (APs), and between the MN and foreign AAA servers in neighbor domains prior to handoffs. However, little has been considered on how to determine the set of candidate authenticators and the associated AAA servers. This study proposes that the association information can be used to make an MN or a network-side server aware of the set of candidate authenticators and the associated AAA servers.

4. Topology-Aided Cross-Layer Design for Fast Layer 2/3 Handoff

As indicate earlier, layer-2 triggers and cross-layer topology information are essential to speedup MIP handoffs. The following paragraphs present a protocol design incorporating both techniques. The protocol uses pre-handoff triggers for agent discovery or address configuration prior to layer-3 handoffs, and applies post-handoff triggers to eliminate the move detection delay. We assume that there is an independent location association server (LAS), which maintains location information, handoff-to relationships, and AP/MA or AP/DHCP association for a set of APs.

LAS can be implemented either as a stand-alone server or as an add-on software module at MAs, DHCP Proxies, or RADIUS servers. The information maintained by LAS is assumed to be manually configured, since such information rarely changes in most cases. However, LAS can also include a function that periodically collects relevant information from associated entities. The contents of LAS can be duplicated or hierarchically organized, as DNS (Domain Name Service) servers are typically treated, to distribute processing loads.

4.1 Use of Foreign-Agent CoA

The proposed protocol broadly comprises three phases, neighbor request, agent pre-discovery, and pre-registration (Fig. 3).

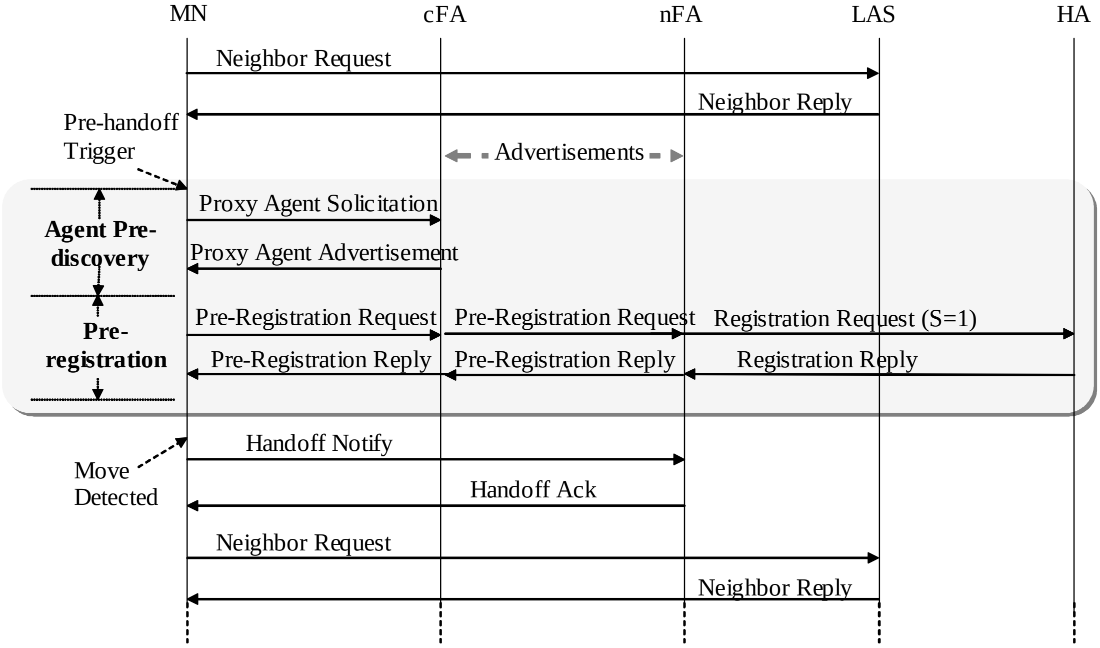

Fig. 3: Message flow for the FA-CoA case

Neighboring MAs periodically exchange their advertisements in the proposed design. After an MN has registered successfully in the visited network, the MN sends a *NeighborRequest* to LAS to request topology-related information. The LAS replies to the MN with a *NeighborReply*, which contains a list of all neighboring APs with their locations and associations with MAs. With this information and MN's current location plus the direction of movement, the MN can determine the neighbor AP that is most likely to be the next serving AP, and the corresponding *n*FA on the occurrence of a pre-handoff trigger. The MN then starts agent pre-discovery by sending a

ProxyAgentSolicitation to *c*FA, requesting *n*FA's advertisement. *c*FA returns the requested information via a *ProxyAgentAdvertisement*.

ProxyAgentSolicitation/Advertisement can be skipped if *NeighborReply* also contains *n*FA's advertisement. To this end, the contents of LAS should include advertisements of associated MAs.

An MN obtains its CoA after the agent pre-discovery phase. If the layer-2 handoff is not yet completed, the MN may wait for a post-handoff trigger and then attempt registration. This option eliminates the agent discovery latency, but not the registration delay.

Alternatively, the MN may directly initiate the pre-registration phase after the agent pre-discovery phase, by encapsulating a *RegistrationRequest* that ought to be sent to HA in a *Pre-RegistrationRequest* and sending the *Pre-RegistrationRequest* to *c*FA. *c*FA then forwards the *Pre-RegistrationRequest* to nFA, where the *RegistrationRequest* is decapsulated and sent to the HA. When the *RegistrationReply* sent by the HA is received by *n*FA, nFA encapsulates it in a *Pre-RegistrationReply* and sends the *Pre-RegistrationReply* to *c*FA. *c*FA then forwards the *Pre-RegistrationReply* to the MN.

When the MN receives a post-handoff trigger revealing the completion of a layer-2 handoff, the MN sends a *HandoffNotify* to inform *n*FA of its arrival. The MN may then start a new neighbor request phase to acquire new topology-related information.

Like the pre-registration proposal [7], this design has the benefit of allowing a layer-3 handoff in parallel with a layer-2 handoff, significantly shortening the overall handoff latency. Moreover, the proposed design allows the completion of a layer-3 handoff even *before* that of a layer-2 handoff, completely eliminating layer-3 handoff latency.

The HA can start tunneling packets to *n*FA as well as *c*FA even before the layer-2 handoff is completed. In MIP, an MN can register multiple CoAs by setting the S bit (the Simultaneous Binding flag) in a *RegistrationRequest*. The advantage of simultaneous binding is its *bi-casting* ability. That is, the HA can encapsulate and send packets simultaneously to all registered CoAs. If this option is enabled in the proposed scheme, the MN can start collecting packets by sending a *HandoffNotify* to *n*FA as soon as the link to the new AP is established.

4.2 Use of Co-located CoA

Every subnet is assumed to contain a DHCP Proxy. In addition to conventional DHCP functionality, the DHCP Proxy can allocate a CoA and perform Duplicate Address Detection (DAD) and Proxy ARP (Address Resolution Protocol) on behalf of a remote MN (an MN not in the current subnet). The DHCP Proxy can also encapsulate and decapsulate *Pre-RegistrationRequest* and *Pre-RegistrationReply* messages, respectively. In this case, LAS keeps AP/DHCP Proxy association rather than AP/MA association.

Figure 4 shows a message flow involving both address pre-configuration and pre-registration. As in the FA-CoA case, an MN sends a *NeighborRequest* to LAS to request topology-related information once it has been registered successfully. On the occurrence of a pre-handoff trigger, the MN determines MN’s most probably next serving AP and the corresponding DHCP Proxy (i.e., *n*DHCP Proxy) based on location information. The MN then starts address pre-configuration by exchanging Proxy DHCP messages with the *n*DHCP Proxy. Proxy DHCP messages are similar to regular DHCP messages (Discovery, Offer, Request, Ack), but aim to request a valid CoA in the next network domain rather than in the client's (i.e. the MN's) current domain.

After an MN acquires its CoA, the MN may request registration after a post-handoff trigger or immediately initiate pre-registration. The pre-registration process is similar to that of the FA-CoA case, except that *Pre-RegistrationRequest*/*Reply* messages are now encapsulated and decapsulated at the *n*DHCP Proxy rather than at *n*FA. When *n*DHCP Proxy receives a *HandoffNotify* sent by the MN, it stops performing Proxy ARP and DAD defense for the MN.

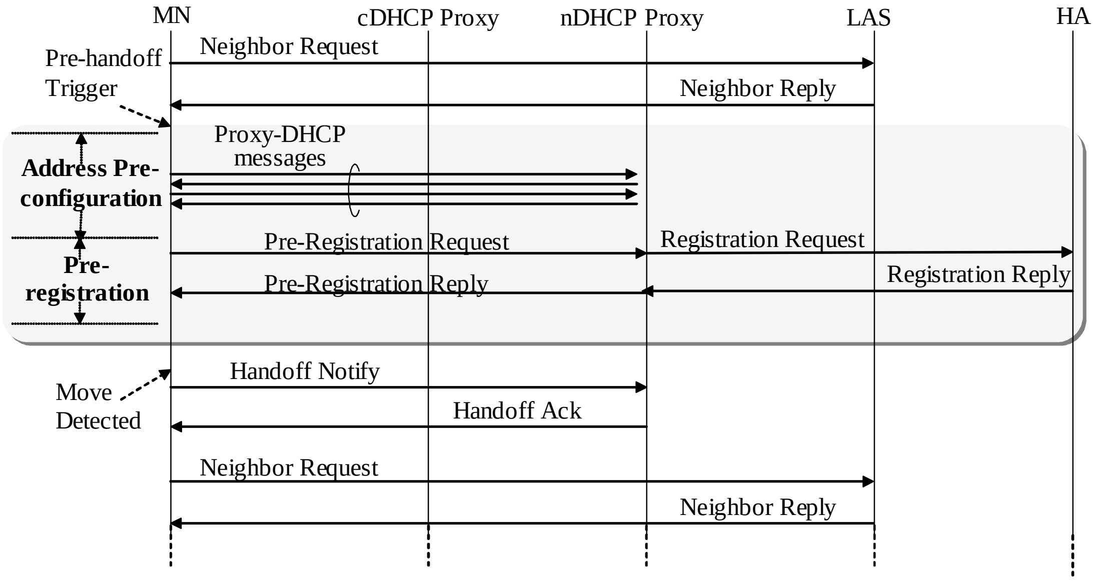

Fig. 4: Message flow for the CCoA case

5. Performance Evaluation

We conducted experiments to measure handoff delays and lost packets when using CCoAs. In each experiment, either an MN or a corresponding node (CN) generated packets at a constant rate (one per 20 ms). The destination of the packets was the MN (CN) if the CN (MN) was the message source. A sequence of packets was lost during the handoff period. The time when the last packet was received before a handoff, and the time when the first packet was received after the handoff, were both recorded. The handoff delay was measured as the time difference between these two instants. The number of lost packets during the handoff period was also measured.

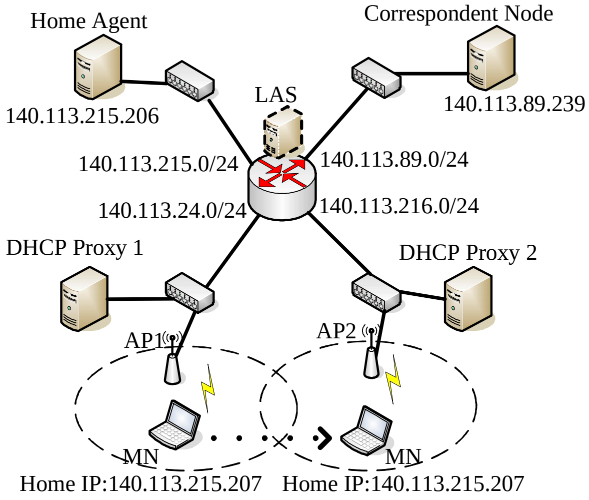

Fig. 5: Experimental setup

Figure 5 shows the experimental setup. Dynamics MIP, which was originally developed at Helsinki University of Technology, was used as an MIP implementation. CCoA was assumed to be used in the MN. The MN was equipped with two identical Intersil prism2-based IEEE 802.11b wireless interfaces, and was located in a place where it could associate with either AP1 or AP2. The experimental procedure was as follows.

1. Before handoff, associate one of the MN’s interfaces (Interface 1) with AP1, and the other (Interface 2) with AP2. Configure Interface 1 with a CoA through DHCP Proxy 1.
2. Start generating and transmitting packets.
3. Detach the CoA of Interface 1.
4. Configure a new CoA for Interface 2 through DHCP Proxy 2.
5. Perform MIP registration.

This procedure only measured layer-3 handoff delay, and did not consider pre-configuration or pre-registration. Step 3 emulated breaking the link to AP1. Because Step 4 was carried out immediately after Step 3, no move detection delay occurred. Additionally, this procedure did not consider the erratic layer-2 handoff delay.

The procedure was changed slightly to measure the layer-3 handoff delay with address pre-configuration. A CoA was additionally configured in Step 1 for Interface 2 through DHCP Proxy 2. Step 4 was then skipped. To measure layer-3 handoff delay with both address pre-configuration and pre-registration, the MN additionally enabled bi-casting by performing a simultaneous registration for the CoA of Interface 2 with the HA in Step 1. Steps 4 and 5 were completely skipped, since neither address configuration nor registration was needed. Table 1 summarizes the obtained results, where each value was measured based on ten experimental results.

Table 1: Means and standard deviations of handoff delay and the number of lost packets with different settings

Setting Metrics		Address configuration + Registration	Address pre-configuration + Registration	Address pre-configuration + Pre-registration
Handoff delay	MN sending to CN	Avg. 3416 ms Std. 1188.1	Avg. 85 ms Std: 41.7	Avg. 48 ms Std: 23.5
	CN sending to MN	Avg. 2463 ms Std. 914.2	Avg. 88 ms Std. 39.1	Avg. 43 ms Std. 15.7
Num. of lost packets	MN sending to CN	Avg. 166 Std. 58.6	Avg. 3 Std. 2.1	Avg. 1 Std. 1.2
	CN sending to MN	Avg. 121 Std. 46.8	Avg. 3 Std. 1.7	Avg. 0 Std. 0.0
Needed L2 trigger		Post-handoff	Pre-handoff, Post-handoff	Pre-handoff, Post-handoff
Needed location/topology information			AP location, MN location,	AP location, MN location,

		AP/DHCP Proxy association	AP/DHCP Proxy association
Other technique needed			simultaneous binding

According to this table, the original layer-3 handoff delay was unacceptable for VoIP applications. The handoff delay with address pre-configuration was only around 85ms, which may still be unacceptable for time-critical applications due to the high variation. Using address pre-configuration plus pre-registration, the handoff delay dropped further to around 45ms with low variation. Such results should meet the delay requirement of VoIP applications.

The number of lost packets in each setting generally agreed with the handoff delay. The original MIP incurred a loss of more than 100 packets. This number fell to 3 when using address pre-configuration, and to 0 or 1 with pre-registration.

6. Conclusions

We have reviewed several cross-layer techniques that aim to reduce handoff delays in IEEE 802.11/Mobile IP environments. Among these, a post-handoff layer-2 trigger successfully eliminates the link-switch detection delay. Conversely, a pre-handoff layer-2 trigger can be used as a signal to execute layer-3 handoff-related activities prior to the associated layer-2 handoff. An MN may use cross-layer topology together with its location and direction of movement to determine the next serving AP and the associated FA or DHCP server to speedup both layer-2 and layer-3 handoffs.

This study has demonstrated how to integrate these techniques to reduce the overall handoff delay. The experimental results show that the handoff delay meets the delay requirement of VoIP applications if the MN can first perform both address configuration and registration.

Acknowledgment

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC 94-2213-E-009 -005 and NSC 94-2219-E-009 -006.

References:

[1] M. Shin, A. Mishra, and W. Arbaugh, “Improving the Latency of 802.11 Hand-offs Using Neighbor Graphs,” *ACM Mobisys*, 2004.

[2] A. Mishra, M. Shih, and W. Arbaugh, “Context Caching Using Neighbor Graphs for Fast Handoffs in a Wireless Network,” *IEEE INFOCOM*, 2004.

[3] A. Mishra, M. H. Shin, N. L. Petroni Jr., T. C. Clancy and William A. Arbaugh, “Proactive Key Distribution Using Neighbor Graphs,” *IEEE Wireless Commun Mag.*, vol. 11, no. 1, Feb. 2004, pp. 26-36.

[4] C.-C. Tseng, K.-H. Chi, M.-D. Hsieh, and H.-H. Chang, “Location-based Fast Handoff for 802.11 Networks,” *IEEE Commun. Letters*, vol. 9, no. 4, 2005, pp. 304-306.

[5] Charles Perkins, “IP Mobility Support,” Tech. Rep. RFC 2002, IETF, Oct. 1996.

[6] A. Mishra, M. Shih, and W. Arbaugh, “An Empirical Analysis of the IEEE 802.11 MAC Layer Handoff Process,” *ACM Computer Communications Review*, vol. 33, no. 2, April 2003.

[7] K. El Malki et al., “Low latency handoffs in Mobile IPv4,” Internet Draft, Aug. 2005.

[8] J. C.-S. Wu, C.-W. Cheng, N.-F. Huang, and G.-K. Ma, “Intelligent Handoff for Mobile Wireless Internet,” *Mobile Networks and Applications*, vol. 6, 2001, pp. 67-79.

[9] T. T. Kwon and M. Gerla, “Mobility Management for VoIP Service: Mobile IP vs. SIP,” *IEEE Wireless Commun. Mag.*, vol. 9, no. 5, Oct. 2002, pp. 66-75.

[10] H. Fathi and R. Prasad, “Mobility Management for VoIP in 3G Systems: Evaluation of Low-Latency Handoff Schemes,” *IEEE Wireless Commun. Mag.*, vol. 12, no. 2, Apr. 2005, pp. 96-104.

[11] K. Pahlavan, X. Li, and J.-P. Makela, “Indoor Geolocation Science and Technology,” *IEEE Commun. Mag.*, vol. 40, no. 2, Feb. 2002, pp. 112-118.

Biography

CHIEN-CHAO TSENG (cctseng@csie.nctu.edu.tw) is currently a professor in the Department of Computer Science at National Chiao-Tung University, Hsin-Chu, Taiwan. He received his B.S. degree in Industrial Engineering from National Tsing-Hua University, Hsin-Chu, Taiwan, in 1981; M.S. and Ph.D. degrees in Computer Science from the Southern Methodist University, Dallas, Texas, USA, in 1986 and 1989, respectively. His research interests include Wireless Internet, Handover Techniques for Heterogeneous Networks, and Mobile Computing.

LI-HSING YEN (lhyen@chu.edu.tw) received his B.S. (1989), M.S. (1991), and Ph.D. (1997) degrees in computer science, all from National Chiao Tung University, Taiwan. He was an Assistant Professor (1998-2003) and has been an Associate Processor since 2003 at the Department of Computer Science and Information Engineering, Chung Hua University, Taiwan. His current research interests include mobile computing, wireless networking, and distributed algorithms.

HUNG-HSIN CHANG (hhchang@csie.nctu.edu.tw) received the B.S. and M.S. degree in Computer Science and Information Engineering from the National Chiao-Tung University, Taiwan, R.O.C., in 1990 and 1995. He is currently working toward the Ph.D. degree in Computer Science and Information Engineering from the National Chiao-Tung University. His current research interests include design and analysis of wireless network, Internet communications, and personal communications network.

KAI-CHENG HSU (mojahsu@gmail.com) received the B.S. degree in Computer Science and Information Engineering from the National Chiao-Tung University, Taiwan, R.O.C., in 2004 and is currently working toward the M.S. degree in the same department. His research interests include design and analysis of wireless networks, Internet communications, and mobile computing systems.