

# A Cross-Layer Partner-Based Fast Handoff Mechanism for IEEE 802.11 Wireless Networks

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## Abstract

In wireless/mobile networks, users freely and frequently change their access points while they are communicating with other users. To support the mobility of mobile nodes, Mobile IPv6 (MIPv6) is used to inform the information of mobile node's home address and current care-of-address (CoA) to its home agent. MIPv6 suffers from a long delay latency and high packet losses because MIPv6 does not support micromobility. A Hierarchical Mobile IPv6 (HMIPv6) is proposed which provides micromobility and macromobility to reduce handoff latency by employing a hierarchical network structure. In this paper, we propose a cross-layer partner-based fast handoff mechanism based on HMIPv6, called the PHMIPv6 protocol. Our PHMIPv6 protocol is a cross-layer, layer-2 + layer-3, and cooperative approach. A cooperative node, called a partner node, is adopted in the PHMIPv6 protocol. A new layer-2 trigger scheme used in the PHMIPv6 protocol accurately predicts the next AP (access point) and then invites a cooperative partner node in the area of the next AP. With the cooperation of the partner node, the CoA can be pre-acquired and duplicate address detection (DAD) operation can be pre-executed by the partner node before the mobile node initializes the handoff request. The PHMIPv6 protocol significantly reduces the handoff delay time and packet losses. In the mathematical analysis, we verified that our PHMIPv6 protocol offers a better handoff latency than the MIPv6, HMIPv6, and SHMIPv6 protocols. Finally, the experimental results also illustrate that the PHMIPv6 protocol actually achieves performance improvements in the handoff delay time, packet loss rate, and handoff delay jitter.

**Index Terms:** Cross-layer, mobility, handoff, hierarchical mobile IPv6, partner, WLAN.

## I. INTRODUCTION

A variety of Internet protocol (IP)-based wireless access technologies have been developed for various needs; one important need is to provide seamless service switching (handoff) for a mobile node (MN) during an IMS (IP Multimedia Subsystem) service session between various access networks, where IP convergence has led to the co-existence of several IP-based wireless access technologies and the emergence of next generation technologies. Seamless mobility in converged IP-centric networks provides uninterrupted services in pervasive/ubiquitous environments. Many studies have attempted to minimize

the data loss rate and delay time during switching so that users do not experience significant interruptions during handoff.

Network environments using IP-based access networks such as public WLAN services are increasing, and the next generation of network environments is naturally moving toward IPv6-based networks [20]. In such environments, when a mobile node moves and attaches itself to another network, it needs to acquire a new IP address. With this change of IP address, none of the existing connections to the mobile node can deliver the data to the correct endpoint.

Because no existing wireless network technology can simultaneously provide high bandwidth, low latency, low power consumption, and wide-area data service to a large number of mobile users [11], Mobile nodes (MNs) must consider the *mobility* issue. An MN may move out of its current wireless base station's (BSs) convergence area, but the signal strength will decrease. To maintain connectivity, the MN is forced to seek and access the network through another BS. It is possible that more than one BS is available simultaneously, or if the loading of the connected BS has reached its capacity, the MN may choose to switch to another access BS to achieve better performance for the current session.

A general handoff problem among WLAN environments is the lack of immediate upper-layer awareness when the lower layer has performed a handoff to a new access point (AP) in a different subnet. It usually takes several seconds for the upper layer to detect MN movement and complete the DAD (duplicate address detection) and registration procedures. Many micromobility designs and lower layer-supported protocols [2][5][6][7][8][12][15] have been proposed, but there is still room for further improvements. The layer 2 handoff latency [13] is divided into probe, authentication, and reassociation delay times. The probe delay occupies a large amount of the entire layer-2 handoff latency. Many studies have attempted to reduce the probe delay in order to significantly reduce the layer-2 handoff latency. The layer-3 handoff latency includes the rendezvous time, DAD time, and binding update time [10]. For HMIPv6-based protocols, the DAD duration time occupies a large amount of the layer-3 handoff latency. Existing studies have attempted to reduce the DAD time in order to significantly reduce the layer-3 handoff latency [1][10][11]. Efforts are made in this work to develop a cross-layer protocol to reduce the total handoff latency of layer-2 and layer-3.

To support the mobility of mobile nodes, Mobile IPv6 (MIPv6) [1][6] is used to inform the information of its home address and current care-of-address (CoA) to its home agent. MIPv6 suffers from a long delay latency and high packet losses because MIPv6 does not support micromobility. The Hierarchical Mobile IPv6 (HMIPv6) [17] is proposed to provide macromobility and micromobility to reduce handoff latency by employing a hierarchical network structure, as shown in Fig. 1. In this paper, we propose a cross-layer partner-based fast handoff mechanism based on HMIPv6, called the PHMIPv6 protocol. Our PHMIPv6 protocol is a cross-layer, layer-2 + layer-3, and cooperative approach. A cooperative node, called a partner node, is adopted in the PHMIPv6 protocol. A new layer-2 trigger scheme used in the PHMIPv6 protocol

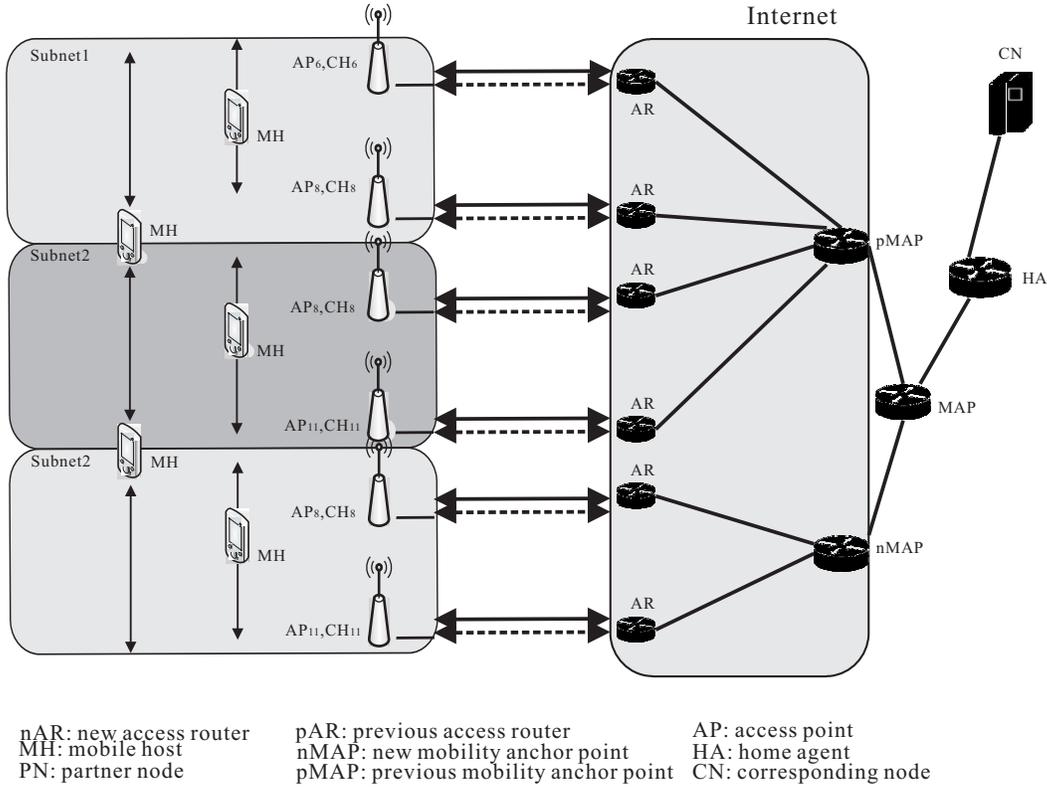


Fig. 1. Micro-mobility and macro-mobility for handoffs.

accurately predicts the next AP (access point) and then invites a cooperative partner node in the area of the next AP. With the cooperation of the partner node, the CoA can be pre-acquired and duplicate address detection (DAD) operation can be pre-executed by the partner node before the mobile node initializes the handoff request. The PHMIPv6 protocol significantly reduces the handoff delay time and packet losses. In the mathematical analysis, we verified that our PHMIPv6 protocol offers a better handoff latency than the MIPv6, HMIPv6, and SHMIPv6 protocols. Finally, the experimental results also illustrate that the PHMIPv6 protocol actually achieves performance improvements in the handoff delay time, packet loss rate, and handoff delay jitter.

The rest of this paper is organized as follows. Section II discusses related work. Section III describes the system architecture and basic ideas. Our proposed PHMIPv6 protocol is presented in section IV. To illustrate the performance achievement, a mathematical analysis is conducted, and simulation results are examined in Section V. Finally, section VI concludes this paper.

## II. RELATED WORK

Mobility support in IPv6, called the Mobile IPv6 or MIPv6 protocol, was recently investigated in [6]. In the MIPv6 protocol, an MH is identified by its home address. When an MH leaves its home domain, the MH is associated with a different access point by a new care-of address (CoA). The MH registers its

new CoA to its home agent (HA). The HA sends packets through a tunnel to the MH by its CoA, before executing the binding update operation to the CN. After completing the binding update operation to the CN, all packets from the CN are then directly delivered to the MH. Therefore, the MIPv6 protocol suffers a long delay latency and high packet losses during the handoff.

Following the MIPv6 protocol, Chao *et al.* [3] recently proposed a micro-mobility mechanism in integrated ad hoc and cellular IPv6 networks to provide a smooth handoff under high-speed movement. This protocol utilizes *dynamic access routers* to pre-execute the sub-binding operation to the CN for an MH. A multicast operation is used to send the same packets to many access points to satisfy the purpose of a smooth handoff with high-speed motion. However, this protocol produces many duplicate packets in the network and so greatly wastes network resources. Unfortunately, the binding update time is still the same as with the MIPv6 protocol. To actually improve the binding update time, a Hierarchical Mobile IPv6 (HMIPv6) [17] was developed by adding a new Mobility Anchor Point (MAP) in foreign domains. Each MH has two sub-CoAs, a regional CoA and an on-link CoA, which constitute the CoA.

The regional CoA is used from the CN to the MAP, and the on-link CoA is used from the MAP to the MN. When an MH is under the same MAP, then a local binding update is only performed from the MH to the MAP to reduce the binding update time. The message flow diagram of the HMIPv6 protocol is given Fig. 2(a), when an MH changes its previous MAP to a new MAP. In this figure, the main time cost of layer-3 handoff latency in HMIPv6 is performing DAD procedures for the newly generated LCoA and RCoA [18]. After finishing the DAD procedures for the LCoA and RCoA, the MH then performs a binding update using the newly generated LCoA and RCoA to the HA and CN, respectively. Figure 3(d) shows that the average handoff latency of the HMIPv6 protocol is 1400 ms. Although HMIPv6 reduces the binding update time, it still needs to execute DAD for the new RCoA when an MH changes to a new MAP domain.

Lai *et al.* [10] recently proposed a Stealth-time HMIPv6 (SHMIPv6) protocol to further improve the handoff latency, compared to HMIPv6 if the DAD is the main cost of handoff latency. This approach reduces the DAD delay time using the pre-handoff notification scheme and reduces the packet loss rate using the buffer technique. Figure 2(c) is the message flow diagram of the SHMIPv6 protocol. The main idea is to use a buffer technique in the previous MAP (pMAP) to buffer the data packets from the CN. When an MH moves to a new MAP, these buffered data packets will be forwarded to the MH from pMAP through the new MAP. The main idea of the SHMIPv6 protocol is to begin the binding update operation to the CN during data forwarding. Overall, the SHMIPv6 protocol reduces the DAD time for LCoA, but SHMIPv6 still does not significantly reduce the DAD time for the RCoA. Lee *et al.* [11] more recently proposed a new protocol, called the HMIPv6+, by integrating IAPP [16] and an access router to reduce the handoff latency. This approach uses IAPP multicast messages to notify the access router (AR) of a new domain to send packets to a new access point. This *rendezvous time*, the time to find a new AR, is

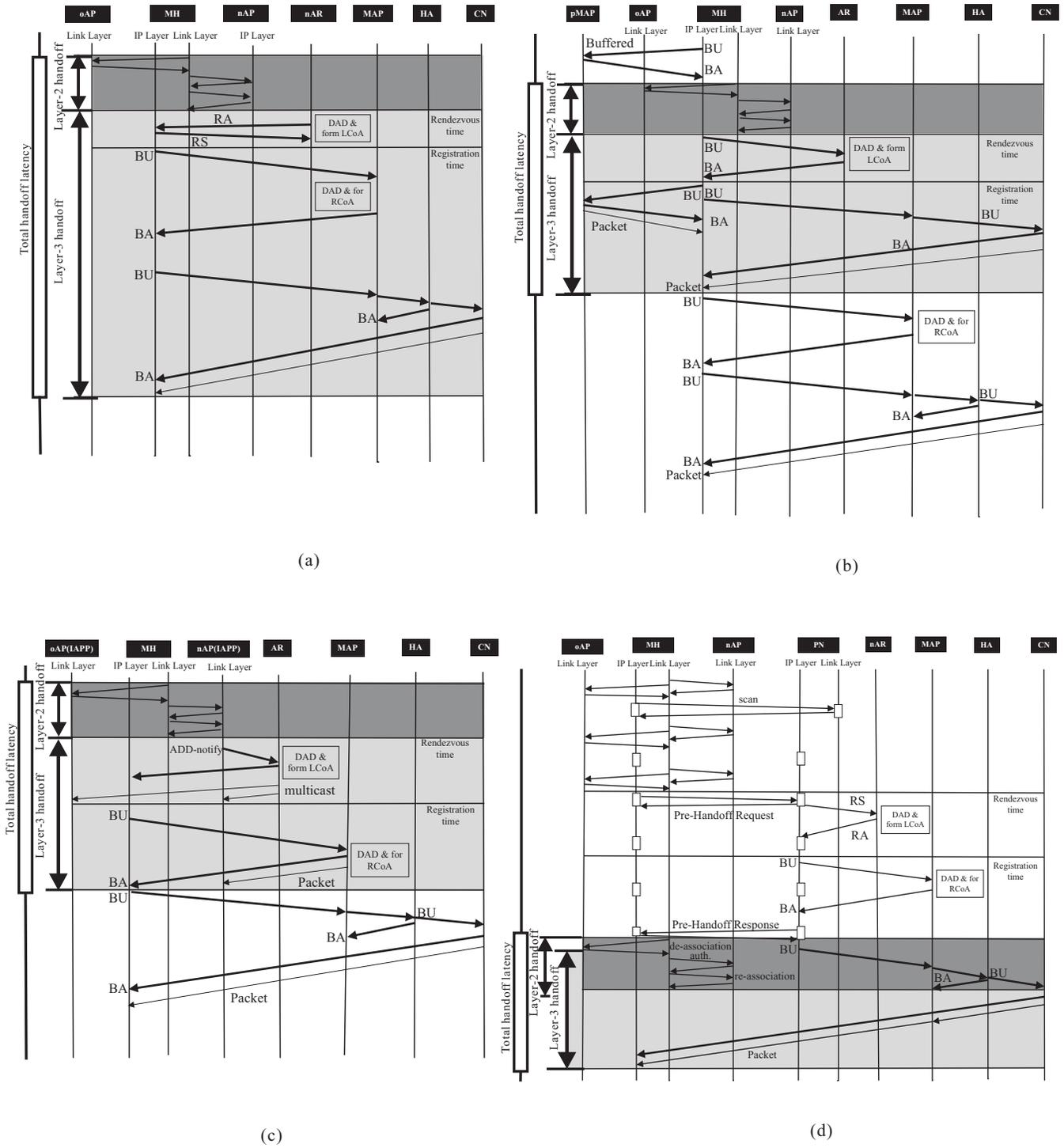


Fig. 2. Handoff procedures of (a) the HMIPv6, (b) SHMIPv6, (c) HMIPv6+, and (d) PHMIPv6 protocols.

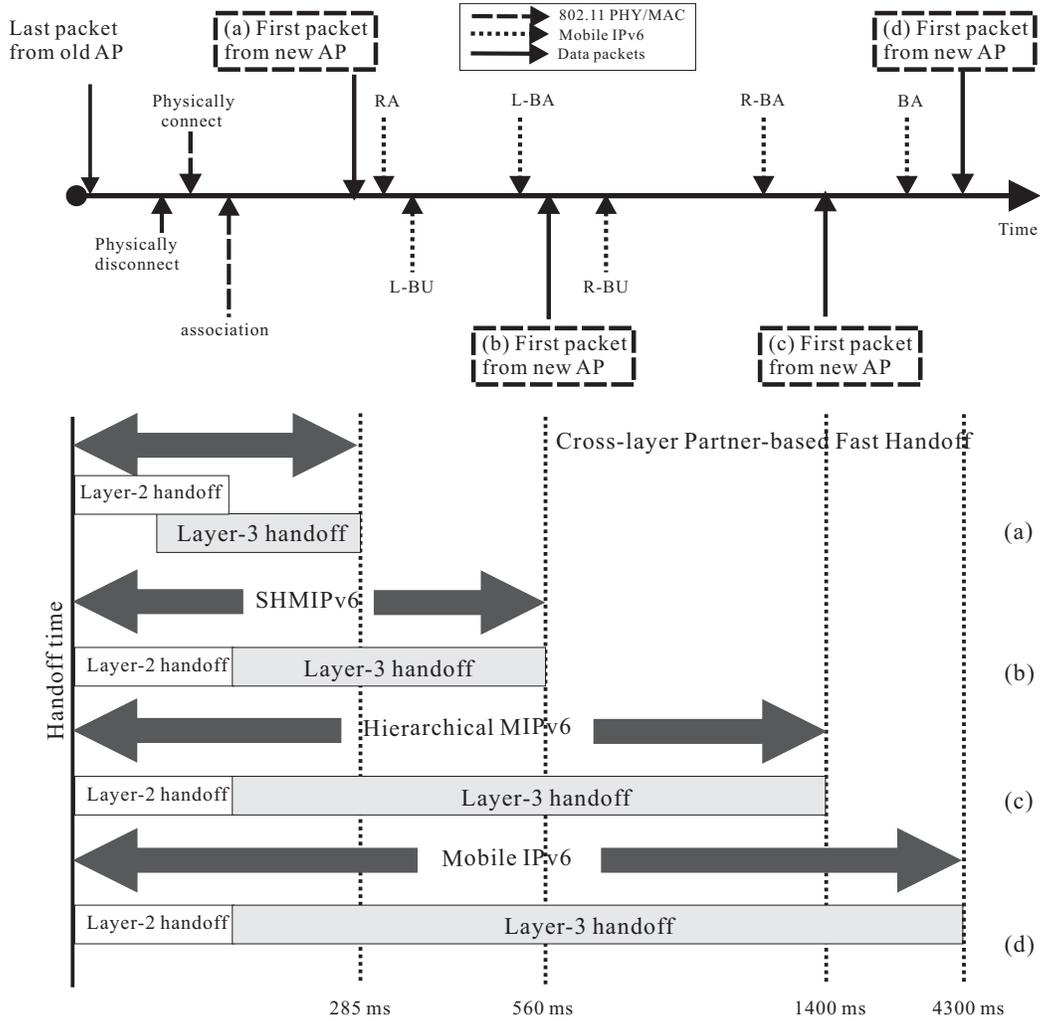


Fig. 3. Comparison of handoff delay times.

reduced by the IAPP notification as shown in Fig. 2(c). However, this protocol, which works well under all ARs, must support the IAPP function. For the fairness, this work does not compare HMIPv6+ with our new approach.

Efforts are made in this work to reduce the DAD time for the LCoA and RCoA and the packet loss rate. A cross-layer partner-based fast handoff mechanism based on HMIPv6, called the PHMIPv6 protocol, is investigated in this paper. A cooperative node, called a partner node (PN), is adopted in the PHMIPv6 protocol. Figure 2(d) gives the message flow datagram of the PHMIPv6 protocol. Our approach reduces the DAD time with the assistance of the PN. The main idea is to use a PN to perform the DAD procedure before the MH switches to a new MAP. The MH finds the new AP based on the layer-2 information from the layer-2 handoff procedure, and the MN dispatches a PN to perform the pre-handoff operation. When the PN completes the pre-handoff operation and acquires a new CoA for the MH, then, the MH may continue to ask the PN to perform the binding update operation for the MH. When the MH really hands off to a new AP and MAP, then the MH can immediately receive the data packets from the CN with

very low handoff latency. Figure 3 shows the total handoff latency of PHMIPv6, SHMIPv6, HMIPv6, and MIPv6 protocols. Figures 3(a-d) illustrate that the average handoff latencies of the PHMIPv6, SHMIPv6, HMIPv6, and MIPv6 protocols are 285, 560, 1400, and 4300 ms, respectively. Therefore, our PHMIPv6 protocol has the lowest handoff latency.

### III. PRELIMINARIES

This section first describes the system architecture of the PHMIPv6 protocol. Our PHMIPv6 protocol is a cross-layer, layer-2 + layer-3, approach. The main idea of layer-2 and layer-3 approaches are then introduced, and the ideas and advantages of the cross-layer design are finally presented.

#### A. System architecture

Figure 4 shows the system architecture of our work. Our work is based on the HMIPv6 protocol [17]. In this work, a cooperative node, called a PN, is adopted by our scheme, which is denoted the Partner-based HMIPv6 (or PHMIPv6) protocol. Our PHMIPv6 protocol utilizes PN to improve the handoff latency during the handoff process. In the following, we formally introduce the PN.

**Definition 1: Partner Node (PN):** Given an MN, a neighboring node of the MN is denoted the PN, where the MN and PN are located in different MAP domains. The PN can directly connect with an IP network through an AP (access point) and can directly communicate with the MN using an ad hoc network. The main task of the PN is to perform the pre-handoff procedure for the MN before the MN reaches a new MAP domain.

Figure 4 illustrates the PHMIPv6 system architecture which is based on the HMIPv6 system architecture [17]. For instance as shown in Figure 4, PHMIPv6 protocol divides the network into two IPv6 subnet domains;  $3ffe:3600:2000:2100::/64$  and  $3ffe:3600:2000:2000::/64$ . The MH sends data packets from the AP and previous access router (pAR) to the corresponding node (CN) through the previous MAP (pMAP). That is, the CN sends data packets to the RCoA of the MH, and the MAP then forwards the packets to the LCoA of the MH. When the MH moves into a new MAP (nMAP) domain, the MH performs the registration procedure to its nMAP. Macro-mobility occurs if the MH switches from a pMAP to a nMAP domain. Then, the MH must acquire a new unique CoA to register the CoA to a new access router (nAR) and nMAP. Observe that in our PHMIPv6 protocol, the MH performs the registration procedure with the assistance of the PN, if the PN exists during macro-mobility.

Figure 5 gives the protocol stack of PHMIPv6. The bottom layer of the PHMIPv6 protocol stack is the embedded mobile device (NIC). The second layer is the Wi-Fi card driver to control the operation of the Wi-Fi card, and the higher layer is layer-2 and layer-3 mobility management. In our PHMIPv6 protocol, the MH and PN both modify layer-2 and layer-3 mobility management parts. This work aims to discuss layer-2 and layer-3, and the upper layer is not changed. This work also does not modify any

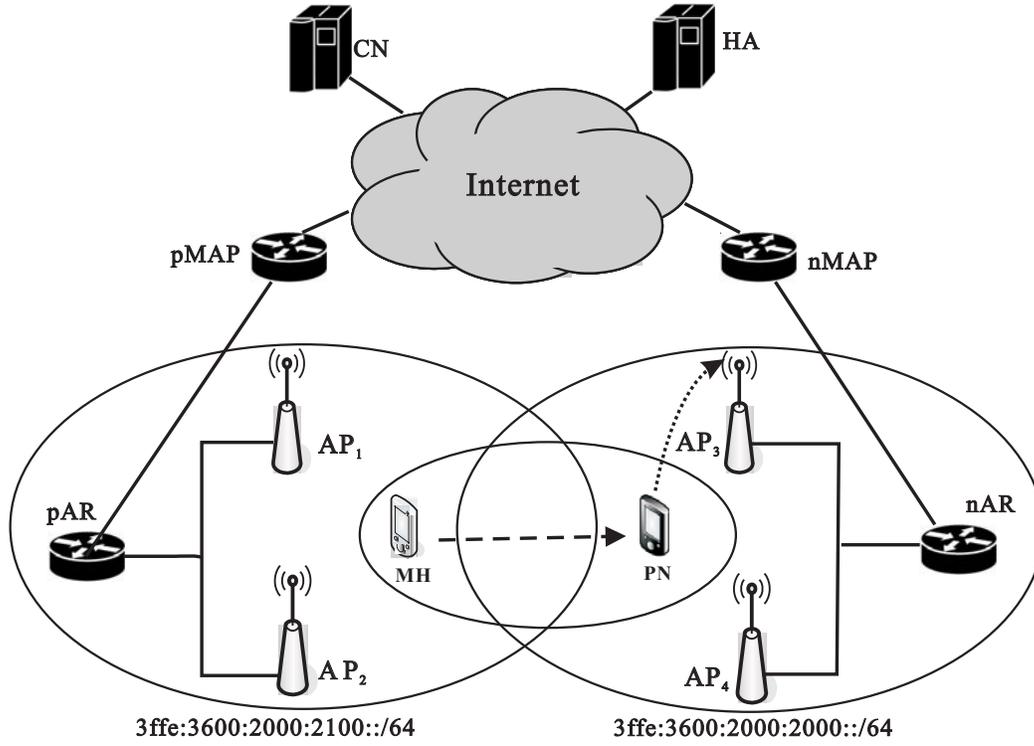


Fig. 4. System architecture of the PHMIPv6 protocol.

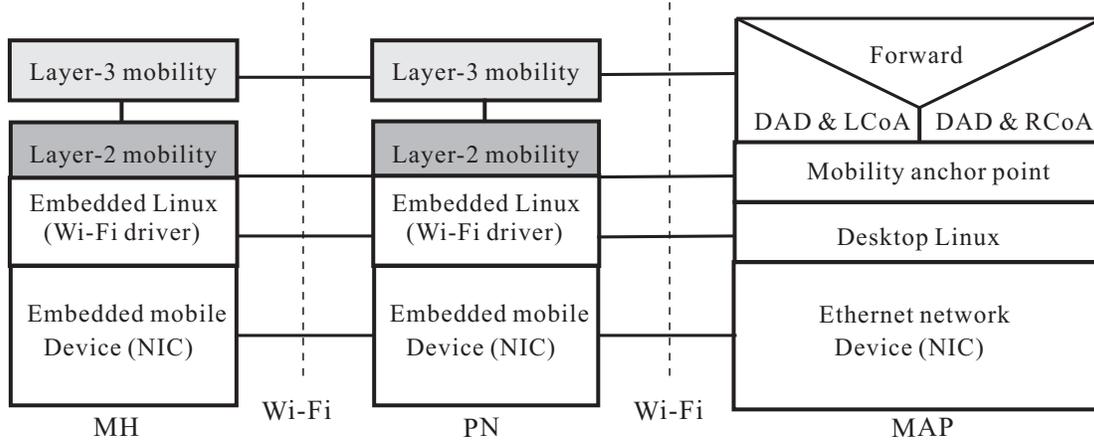


Fig. 5. Protocol stack of the PHMIPv6.

network entities of the HMIPv6 protocol, therefore the protocol stack of the MAP is the same as the original MAP defined in the HMIPv6 protocol. The layer-2 handoff procedure of the PHMIPv6 protocol adopts a DeuceScan scheme [4] which aims to improve the accuracy of choosing a new AP depending on the quality of the surrounding APs. The layer-3 handoff procedure of the PHMIPv6 protocol uses a PN in the nMAP domain to assist the MH in pre-performing the handoff procedure.

### B. Cross-layer fast handoff approach

Our cross-layer fast handoff approach is a layer-2/3 approach. Therefore, we explain the main ideas in our layer-2 and layer-3 methods, and then present the main idea of cross-layer design for our fast handoff

approach.

The layer-2 handoff process in IEEE 802.11-based networks includes *scanning*, *authorization*, and *re-association* phases, as shown in Fig. 6. Because the probe delay occupies most of the handoff delay time, efforts have focused mainly on reducing the probe delay to develop faster handoff schemes [4][19].

Recently, Chen *et al.* [4] presented a new fast layer-2 handoff scheme, called the DeuceScan scheme, to further reduce the probe delay for 802.11-based WLANs. A spatiotemporal approach is developed in this work to utilize a spatiotemporal graph to provide spatiotemporal information for making accurate handoff decisions by correctly searching for the next AP. The DeuceScan scheme is a pre-scan approach which efficiently reduces the MAC layer handoff latency. Two factors of stable signal strength and variation in the variable signal strength (signal variation) are both used in our developed DeuceScan scheme. The DeuceScan scheme [4] is used to act as our layer-2 method. The deuce procedure uses the signal strength denoted  $D_s(\alpha, \beta)$ , where  $\alpha$  is the extra number of partial scans for APs and  $\beta$  is the number of scan cycles. The important idea of the DeuceScan scheme is the deuce process. The first important property of the deuce process is the partial pre-scanning operation. Observe that one additional partial pre-scan operation can be performed in the same time period of one full pre-scan operation. Given  $\alpha + 3$  APs,  $AP_{i_1}$ ,  $AP_{i_2}$ ,  $AP_{i_3}, \dots$ , and  $AP_{i_{\alpha+3}}$ , the main operation of the deuce process is to maintain the same results of  $RSS_{t_i}^{AP_{i_1}} > RSS_{t_i}^{AP_{i_2}} > RSS_{t_i}^{AP_{i_3}} > \dots > RSS_{t_i}^{AP_{i_{\alpha+3}}}$  for  $\beta$  consecutive times, where  $\alpha + 3 <$  the total number of channels. If we can maintain the same results of  $RSS_{t_i}^{AP_{i_1}} > RSS_{t_i}^{AP_{i_2}} > RSS_{t_i}^{AP_{i_3}} > \dots > RSS_{t_i}^{AP_{i_{\alpha+3}}}$  for  $\beta$  consecutive times, then it can be guaranteed that the result is accurate and correct. In addition, it is possible to perform one more partial pre-scanning operation within the time period of a full pre-scanning operation. With the same time period as the layer-2 scanning operation, the more-accurate information of new MAP is obtained using the DeuceScan scheme [4]. The detailed operation is described in [4].

The key function of the PN is to reduce the handoff delay time. The existing HMIPv6 protocol [17] still suffers from a long DAD latency. To improve the handoff latency, efforts made in this work to reduce the DAD latency with the assistance of the PN. The key idea of reducing the handoff latency using the PN is introduced as follows. First, the PN is a MN in a nMAP domain, in which the MH will possibly enter. The main task of the PN is to perform the pre-handoff procedure to obtain a new unique CoA in the nMAP domain. Observe that the MH is in the pMAP domain and the PN is in the nMAP domain, while the MH and PN communicate with each other in ad hoc communication [19]. It is important that the DAD time for the LCoA and RCoA be reduced with the assistance of the PN. This is because the pre-handoff procedure can be initiated and performed by the PN when the MH has still not switched to the nMAP domain. But when the MH has really switched to the nMAP domain, the PN can immediately deliver the LCoA and RCoA to the MH, while the LCoA and RCoA are already checked by performing the DAD operation. This significantly reduces the handoff latency.

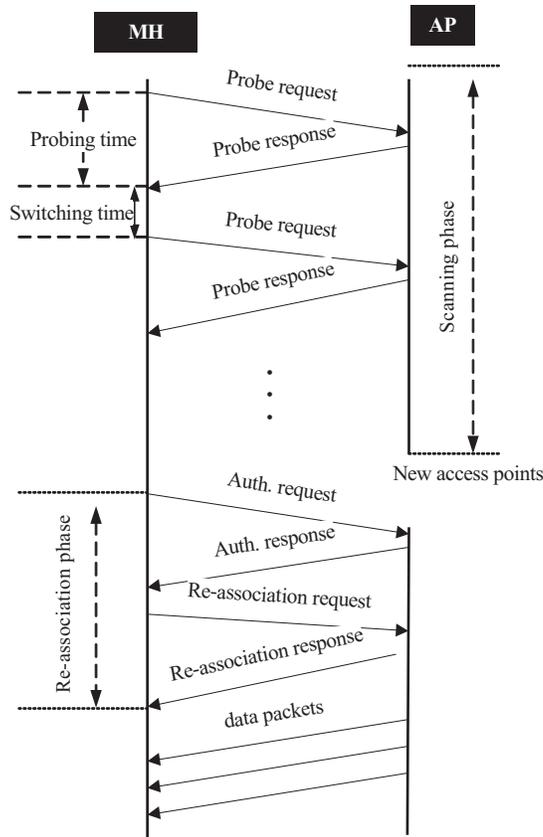


Fig. 6. Layer-2 handoff.

One important contribution of this work is the cross-layer design for the fast handoff scheme. Our cross-layer design is a merging of adjacent layers (layer-2 and layer-3) to improve the handoff latency. Figure 7 shows our cross-layer model. From layer-2, the DeuceScan scheme [4] is used in the MH to accurately predict the next AP and search for the existence of a PN in the nMAP domain before the MH begins the handoff procedure. The result from the DeuceScan scheme [4] is very important for the MH to make the decision when the MH initiates a request to a PN in the nMAP domain to perform the pre-handoff procedure. Usually, when the MH intends to switch to a nMAP domain, then the MH can acquire the new and unique CoA from the PN, and then the MH performs the normal layer-2 handoff operation and asks the PN to perform the location update operation to the HLR by the PN. Observe that the handoff time in layer-2 and the location update time in layer-3 overlap. This is the key value of our cross-layer design. The next section describes the detailed operations of our PHMIPv6 protocol.

#### IV. PARTNER-BASED HMIPv6 (PHMIPv6) PROTOCOL

This section presents our partner-based fast handoff mechanism based on the HMIPv6 (PHMIPv6) protocol. The PHMIPv6 protocol is a cross-layer design which merges adjacent layers, layer-2 and layer-3. The PHMIPv6 protocol is divided into two cases: successful and unsuccessful cases. Both cases assume

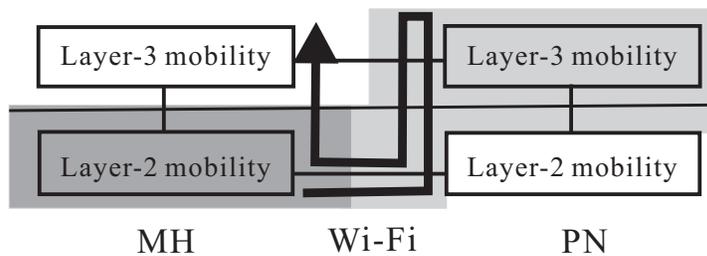


Fig. 7. Cross-layer model.

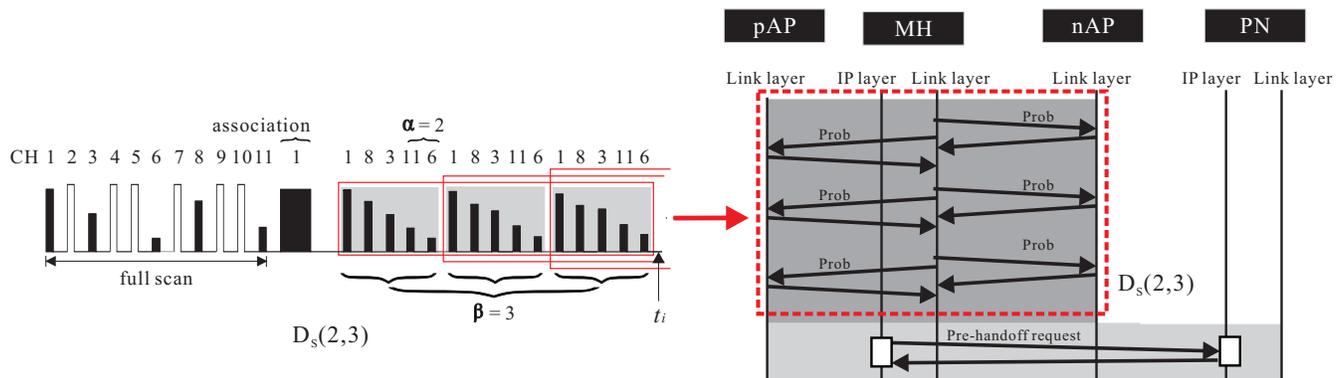


Fig. 8. Cross-layer idea.

that the PN exists in the nMAP domain and the MH can connect to the PN by ad hoc communication. If no PN exists in the nMAP domain, then the MH performs the original HMIPv6 handoff protocol. Observe that the MH is still in the pMAP domain. The successful case is that the MH finds a PN in the nMAP domain, and then the MH switches to the same nMAP domain. The unsuccessful case is that the MH finds a PN in the nMAP domain, but the MH switches to a different nMAP domain.

The basic operation of the PHMIPv6 protocol is that the MH finds a cooperative PN in an nMAP domain, and the MH ask the PN to perform a pre-handoff operation by sending a pre-handoff request from the MH to the PN. Many PNs exist in different MAP domains, and the MH needs to find a suitable PN with layer-2 assistance. To explain the operation of the PHMIPv6 protocol, let  $X \xrightarrow{forward} Y$  indicate that  $X$  forwards a data message to  $Y$  and  $X \xrightarrow{broadcast} Y$  imply that  $X$  broadcasts the message to  $Y$  within a one-hop transmission range. In addition, let  $X \xrightarrow{action} Y$  denote that  $X$  executes a *communication action* to  $Y$ , where  $X$  and  $Y$  may be the MH, PN, or routers, and *communication action* =  $\{packet, binding, LCoA, RCoA\}$ . Usually,  $X \xrightarrow{action} Y$  is achieved by one or many  $X \xrightarrow{forward} Y$  and  $X \xrightarrow{multicast} Y$  operations. For example,

$X \xrightarrow{packet} Y$  indicates that  $X$  sends the control or data packet to  $Y$ , where  $X$  and  $Y$  might or might not be one-hop neighboring nodes.

$X \xrightarrow{binding} Y$  indicates that  $X$  sends a binding update request to  $Y$ .

$X \xrightarrow{LCoA} Y$  indicates that a new LCoA is generated and has performed the DAD operation from  $X$  to  $Y$  through a binding message.

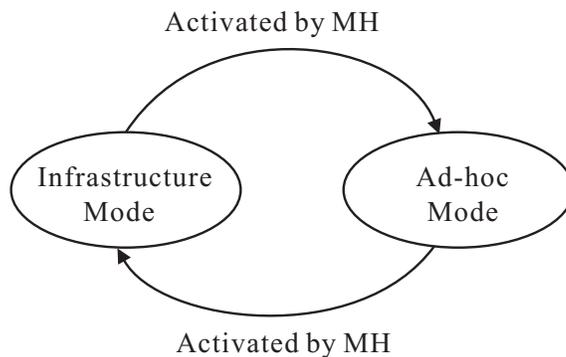


Fig. 9. Finite state machine (FSM) of the PHMIPv6 protocol.

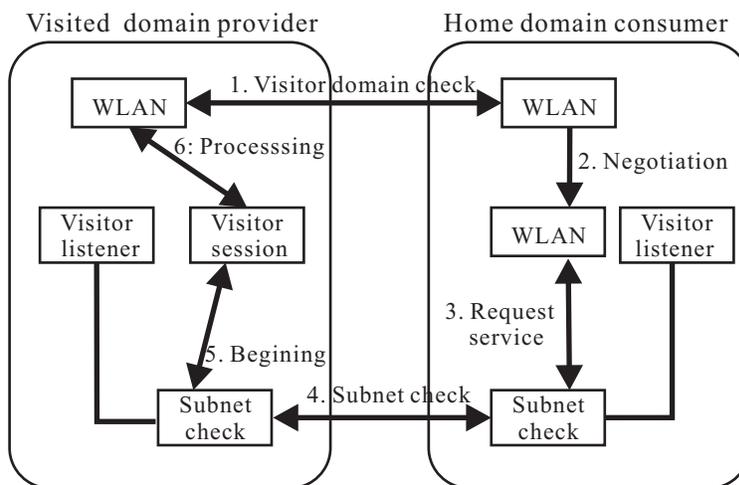


Fig. 10. State diagram of the PHMIPv6 protocol.

$X \xrightarrow{RCoA} Y$  indicates that a new RCoA is generated and has performed the DAD operation from  $X$  to  $Y$  through a binding message.

The detailed operations of successful and unsuccessful cases are respectively present in sections 4.1 and 4.2.

#### A. Successful case

The successful case occurs when an MH switches to an nMAP domain, while a PN in the nMAP domain has already performed the pre-handoff procedure. In this work, we only discuss the case of an MH switching to different MAP domains. The case of handoff over different APs in the same pMAP domain is simple and can be successfully worked out by a similar operation.

By performing a layer-2 deuce procedure  $D_s(\alpha, \beta)$  [4], the MH can accurately predict the next new AP in a different MAP domain when the MH is still in the pMAP domain. At the same time, the MH also tries to discover a PN in the nMAP domain. When the deuce procedure  $D_s(\alpha, \beta)$  provides a stable and correct new AP for the MH, then, the MH initializes a pre-handoff procedure by sending a pre-handoff request from the MH to the PN to obtain a unique CoA. Observe that an MH must turn the transmission

mode into an infrastructure mode or ad-hoc mode, as shown in Fig. 9. The MH communicates with the AP if the MH is in the infrastructure mode, and it communicates with a PN if it is in the ad-hoc mode. A simple synchronization scheme is needed herein to achieve the same mode within a fixed time interval. A PN must turn into the ad hoc mode in the same time interval, called the ad-hoc time interval. During the ad-hoc time interval, the MH performs the layer-2 scanning channel process by sending out scanning request messages from the MH to discover the existence of PNs. When a PN can receive the scanning request message, it replies to the scanning response message with new subnet information. When the MH receives the scanning response message form the PN, the subnet information and MAC address of the PN are added to the partner-aware table, as illustrated in Fig. 10. The detailed message flow of the successful case is given Fig. 12. An example of a successful case is given in Fig. 11. The detailed operations are described as follows.

- Step 1:  $MH \xrightarrow{\text{broadcast}} PN$ : If the MH moves to a boundary location of a serving AP, and the MH uses the Network Time protocol (NTP) [14] between different APs for the purpose of synchronization. The PN periodically broadcasts IPv6\_Header (ICMPv6 header, 0::0, FF02::2) + Modify\_RA (ON, 3FFE::/16, @visit.com.tw)+ subnet prefix of the serving access router (AR). When the MH receives the IPv6\_Header + Modify\_RA packet from the MN, the information of new subnet, SSID of the access point, and signal strength of the PN are kept in the MH. Observe that, if no PN is found by the MH, it performs the original HMIPv6 handoff procedure and skips all remaining steps.
- Step 2:  $PN \xrightarrow{\text{broadcast}} MH$ : It is possible that many PNs reply with response messages to the MH, thus the MH confirms the response message and selects the best PN. After the MH determines a PN for the new MAP domain, it stores the messages in a partner-aware table. The best PN for the MH is identified before the layer-2 handoff procedure of the MH. An instance is shown in Fig. 11(a).
- Step 3:  $MH \xrightarrow{\text{update}} SAT$  (*subnet-aware table*): The MH changes into the ad hoc mode, and sends out partner-aware information request messages. After the PN receives the request message, it replies with a partner-aware response message to the MH. The response message includes information of the SSID of the AP, the MAC address and subnet prefix of the PN, and the nMAP address. Then the MH updates all new information of its own partner-aware table.
- Step 4: After performing step 3, if the MH still has not found a suitable PN for the nMAP domain, steps 1-3 are again performed.
- Step 5:  $DS \xrightarrow{\text{notify}} MH$ : By performing the deuce procedure  $D_s(\alpha, \beta)$ , the MH can determine the next new AP in the same or different MAP domain when the MH is still in the pMAP domain. If the AP is in the same pMAP domain, the MH performs the layer-2 handoff and directly connects to the new AP. In addition, if the MH is in the pMAP domain and the PN is in the nMAP domain,

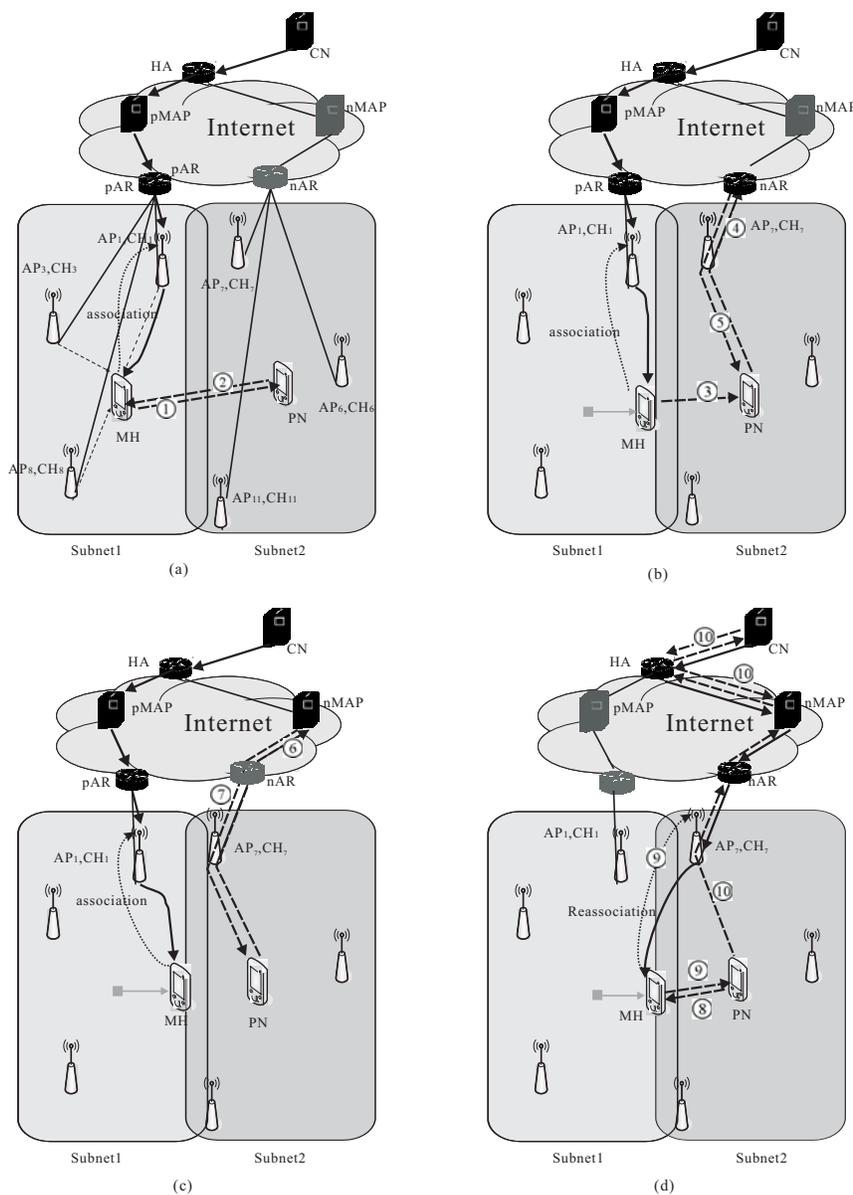


Fig. 11. The scenario of a successful case of the PHMIPv6 protocol.

then the MH begins the pre-handoff procedure.

Step 6:  $MH \xrightarrow{prehandoff} PN$ : The MH sends out a pre-handoff request message to the PN in the ad hoc mode to perform the pre-handoff procedure. The MH changes into the ad hoc mode again to receive the pre-handoff response message.

Step 7:  $PN \xrightarrow{LCoA} nAR$  (or  $MH \xrightarrow{multihop} PN \xrightarrow{LCoA} nAR$ ): After the PN receives the pre-handoff request message, it sends out a router solicitation message to the nAR for the MH. The AR sends the router advertisement message to the PN to generate a new LCoA. A DAD operation performed for the LCoA is illustrated in Fig. 11(b).

Step 8:  $PN \xrightarrow{RCoA} nMAP$  (or  $MH \xrightarrow{multihop} PN \xrightarrow{RCoA} nMAP$ ): After the PN acquires a new LCoA for the MH, it begins to acquire its RCoA for the MH. The PN sends out a binding update message to

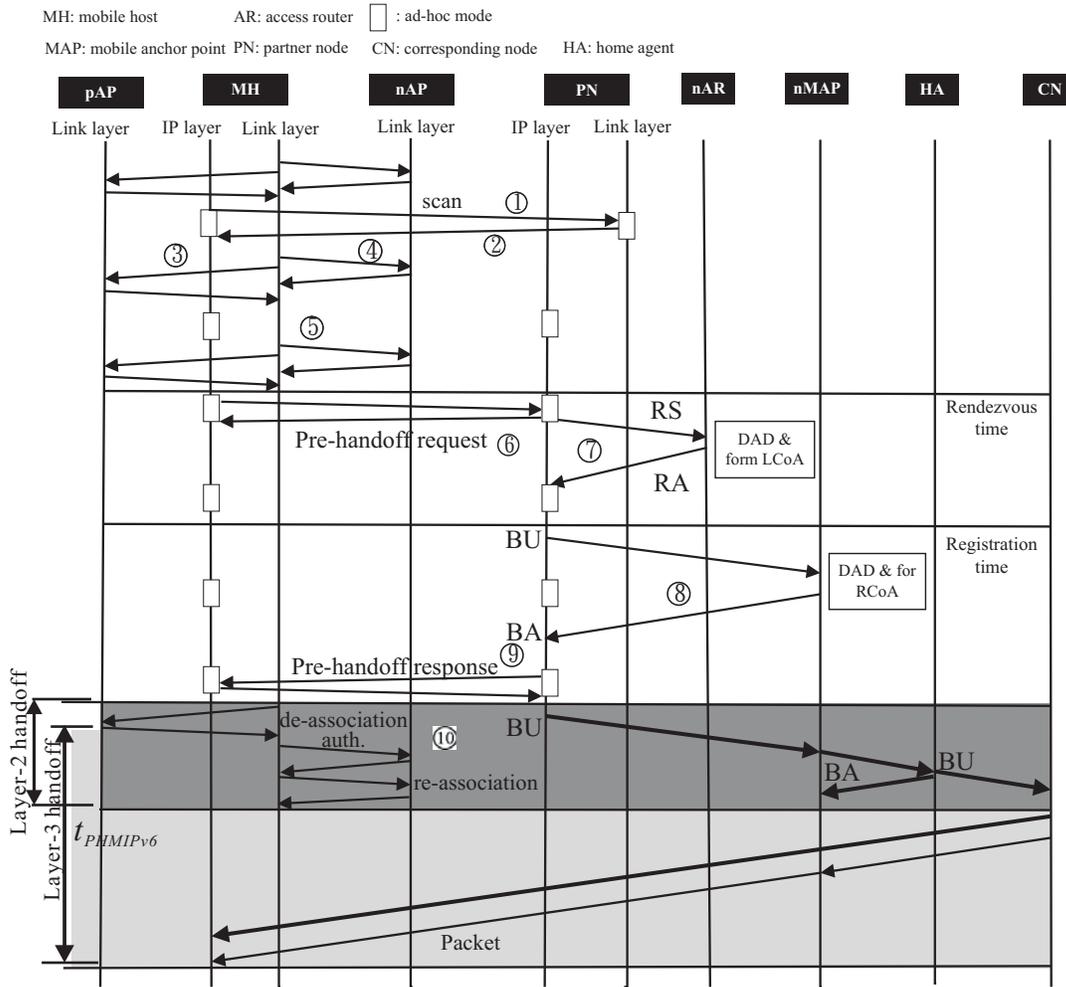


Fig. 12. A successful case of message flow with the PHMIPv6 protocol.

the nMAP. The nMAP generates a new RCoA and performs the DAD procedure for the RCoA. The nMAP then returns the binding ack. message back to the MH to obtain the new RCoA as shown in Fig. 11(c).

Step 9:  $PN \xrightarrow{response} MH$  and  $MH \xrightarrow{handoff} nAP$ : The PN replies with a pre-handoff response message, and the MH confirms the message. The MH begins to perform the layer-2 handoff, and asks the PN to use the new LCoA and RCoA of the MH to send out a location update message to the CN.

Step 10:  $PN \xrightarrow{binding} nMAP$  and  $CN \xrightarrow{packets} MH$ : After the PN sends the location update message to the HA and CN for the MH, then, the CN sends data packets to the new LCoA and RCoA of the MH. The detailed operation is given in Fig. 11(d). The total handoff time,  $t_{PHMIPv6}$ , of the handoff procedure is illustrated in Fig. 12. Figure 12 shows the detailed message flow of the PHMIPv6 protocol.

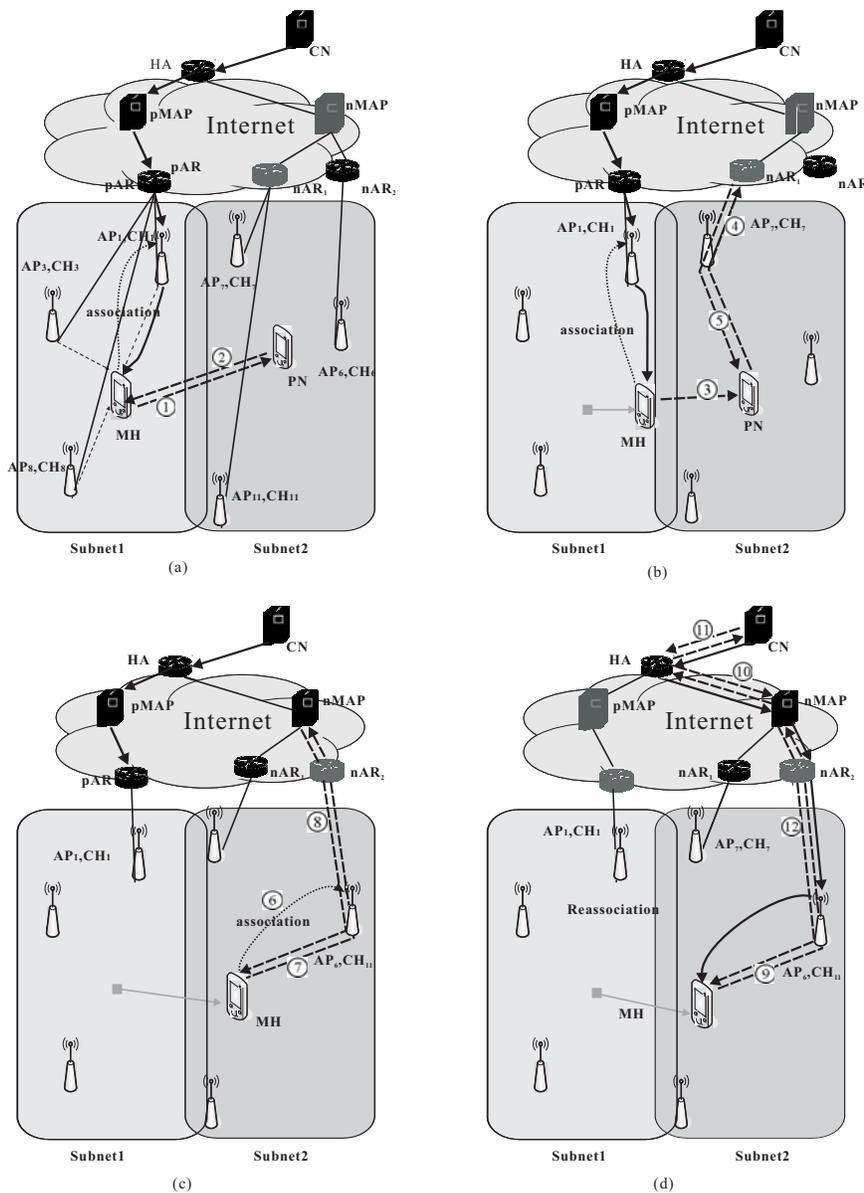


Fig. 13. Scenario of an unsuccessful case with the PHMIPv6 protocol.

### B. Unsuccessful case

This section describes an unsuccessful case when the MH moves to  $\bar{n}$ MAP domain, where the PN is in the pMAP domain and  $\bar{n}$ MAP  $\neq$  nMAP. In fact, the PN has already performed the pre-handoff procedure to obtain the new LCoA and RCoA. But if the MH moves to the  $\bar{n}$ MAP domain, where  $\bar{n}$ MAP  $\neq$  nMAP, it means that the new RCoA in the PN is useless. Therefore, the MH needs to obtain the new RCoA in the  $\bar{n}$ MAP domain.

In the unsuccessful case, steps 1~9 are the same as in the successful case, as described in Section IV.A; if an unsuccessful case occurs, new steps 10'-12' are given as follows.

Step 10':  $MH \xrightarrow{\text{handoff}} nAP$ : The LCoA is obtained from step 7, but the RCoA from step 8 is incorrect, so the MH then performs the layer-2 handoff to the nAP in the  $\bar{n}$ MAP domain.

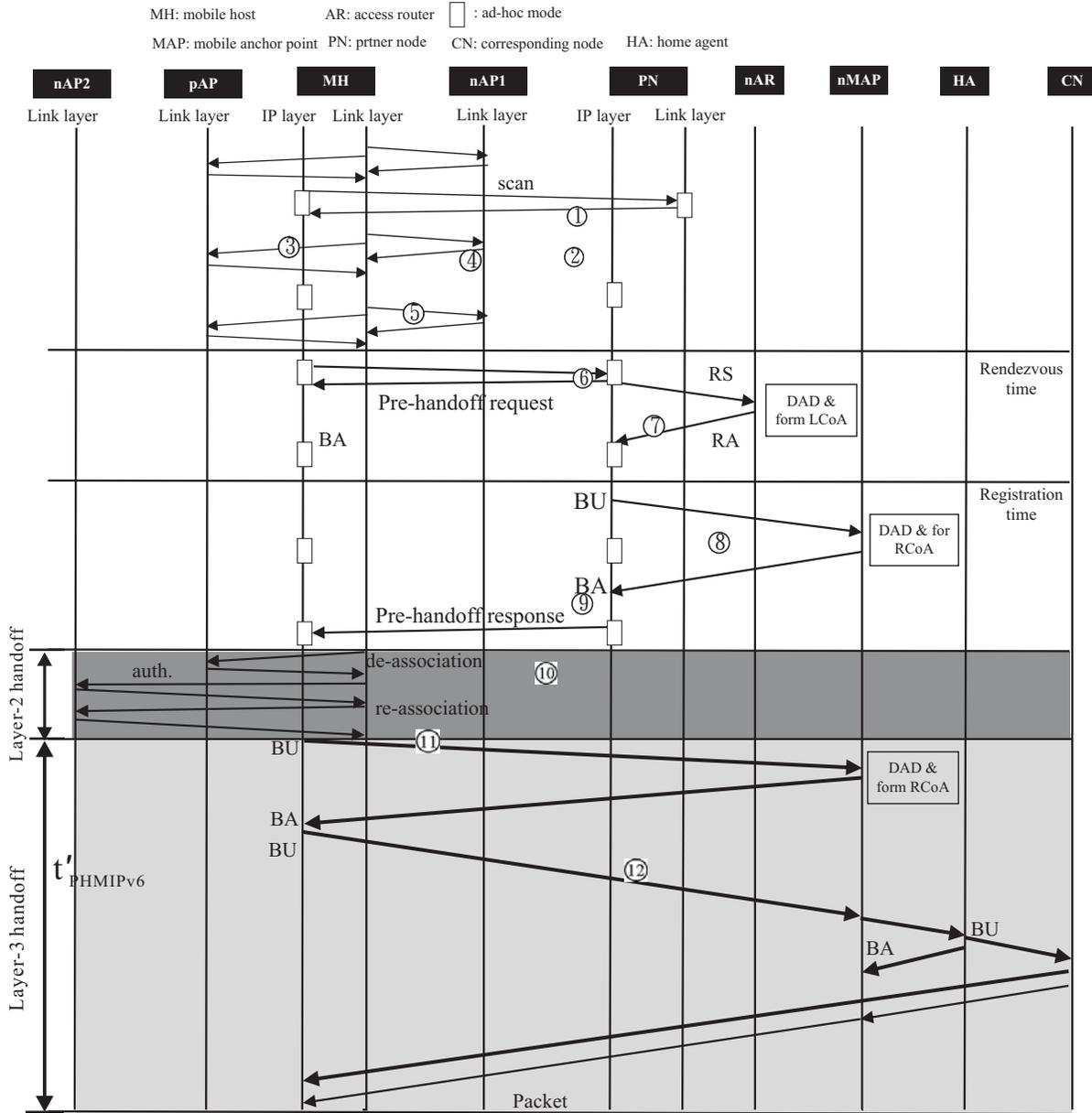


Fig. 14. An unsuccessful case of message flow with the PHMIPv6 protocol.

Step 11':  $MH \xrightarrow{RCoA} nMAP$  (or  $MH \xrightarrow{multihop} PN \xrightarrow{RCoA} nMAP$ ): Since the MH already has the new LCoA, the MH then directly acquires a new RCoA. For instance as shown in Fig. 13(c), the nMAP generates a new RCoA through a DAD procedure.

Step 12':  $MH \xrightarrow{binding} nMAP$  and  $CN \xrightarrow{packets} MH$ : The MH sends the binding update message to the HA and CN through the nMAP. An example is given in Fig. 13(d). After receiving the message, the CN then sends the data packets to the new LCoA and RCoA of the MH. The total handoff time of an unsuccessful case, denoted as  $t_{U-PHMIPv6}$ , is shown in Fig. 14. Figure 14 gives the detailed message flow of an unsuccessful case with the PHMIPv6 protocol.

## V. PERFORMANCE ANALYSIS

The handoff latency of the PHMIPv6, HMIPv6 [17], and SHMIPv6 [10] protocols are analyzed. The simulation results are then analyzed.

### A. Mathematical analysis

In our mathematical analysis, we used the same definitions from [3][10], the network parameters are given in Table 1.

Table 1. Network parameters

$BW_w$	Bandwidth of the wired backbones
$BW_{wl}$	Bandwidth of the wireless link
$L_w$	Latency of the wired link
$L_{wl}$	Latency of the wireless link
$S_{ctr}$	Average size of the control message
$n$	Number of hops between the MH and the router
$t_{D\_internet}$	Average delay of a packet traveling in the Internet
$t_{D\_DAD}$	Average delay of the DAD time

Let  $t_{PN}$  be the time it takes the PN to perform the pre-handoff procedure;  $t_{PN} = t_{PN\_discovery} + t_{rendezvous} + t_{DAD\_LCoA} + t_{DAD\_RCoA} + t_{binding\_CN}$ , where  $t_{PN\_discovery}$  is the time it takes an MH to find the PN which belongs to the nMAP domain;  $t_{rendezvous}$  is the time it takes the MH to find an nAR and receive the router advertisement message from nAR;  $t_{DAD\_LCoA}$  is the time it takes a PN to perform the DAD operation of LCoA;  $t_{DAD\_RCoA}$  is the time it takes a PN to perform the DAD operation of RCoA; and  $t_{binding\_CN}$  is the time it takes a PN to send a binding update message to the HA, or CN if the MH notifies the PN of the handoff.

Let  $S_{ctr}$  be the average size of the control messages,  $BW_w$  be the bandwidth of wired backbones,  $BW_{wl}$  be the bandwidth of the wireless link,  $\beta$  be the value from layer-2 deuce procedure  $D_s(\alpha, \beta)$ ,  $t_{D\_DAD}$  be the average delay of the DAD time, and  $t_{D\_internet}$  be the average delay of a packet traveling in the Internet. First,  $t_{PN\_discovery}$  is

$$\begin{aligned}
 t_{PN\_discovery} &= \frac{n}{\beta}(t_{subnet\_inf}) \\
 &= \frac{n}{\beta}\left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) \quad , \text{ where } n = \beta, 2\beta, \dots
 \end{aligned} \tag{1}$$

Then,  $t_{rendezvous} = t_{solicitation} + t_{advertisement}$ , where  $t_{solicitation}$  is the time it takes the PN to send the

router solicitation message through the AP, to which the PN belongs, for the MH, and  $t_{advertisement}$  is the time it takes the nAR to send the router advertisement message through the AP, to which the PN belongs, for the MH. Thus,

$$t_{solicitation} = \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet}, \quad (2)$$

$$t_{advertisement} = \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet}. \quad (3)$$

Then,  $t_{DAD\_LCoA} = t_{binding\_ack} + t_{D\_DAD}$ , where  $t_{binding\_ack}$  is the time it takes the PN to send notify-binding acknowledge message to the MH, and  $t_{binding\_ack}$  is

$$t_{binding\_ack} = \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet}. \quad (4)$$

Then,  $t_{DAD\_RCoA} = t_{binding\_MAP} + t_{binding\_ack} + t_{D\_DAD}$ , where  $t_{binding\_MAP}$  is the time it takes the PN to send the binding update message through the nAP to the nMAP,  $t_{ack\_MAP}$  is the time it takes the MAP to send the binding acknowledge message through the nAR to the nAP. Thus,

$$t_{binding\_MAP} = \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \quad (5)$$

Finally,  $t_{binding\_CN} = 2 \left[ \left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \right]$ .

Therefore,

$$\begin{aligned} t_{PN} &= t_{PN\_discovery} + t_{rendezvous} + t_{DAD\_LCoA} + t_{DAD\_RCoA} + t_{binding\_CN}. \\ &= \frac{n}{\beta} \left(\frac{S_{ctr}}{BW_w} + L_w\right) + 4 \left[ \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \right] \\ &\quad + 4 \left[ \left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \right] + 2t_{D\_DAD}. \end{aligned} \quad (6)$$

From [17], we can derive  $t_{HMIPv6}$  as follows:

$$\begin{aligned} t_{HMIPv6} &= t_{layer\_2} + t_{rendezvous} + t_{DAD\_LCoA} + t_{DAD\_RCoA} + t_{binding\_CN} \\ &= t_{layer\_2} + 6 \left[ \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \right] \\ &\quad + 2 \left[ \left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \right] + 2t_{D\_DAD}, \end{aligned} \quad (7)$$

where  $t_{layer\_2}$  is the layer-2 handoff delay time. Similarly,  $t_{SHMIPv6}$  [10] is derived below:

$$\begin{aligned} t_{SHMIPv6} &= t_{layer\_2} + t_{rendezvous} + t_{DAD\_LCoA} + \min(t_{pmap}, t_{bu\_HA}) \\ &= t_{layer\_2} + 4 \left[ \left(\frac{S_{ctr}}{BW_{wl}} + L_{wl}\right) + n\left(\frac{S_{ctr}}{BW_w} + L_w\right) + t_{D\_internet} \right] \\ &\quad + \min(t_{pmap}, t_{HA}) + t_{D\_DAD}. \end{aligned} \quad (8)$$

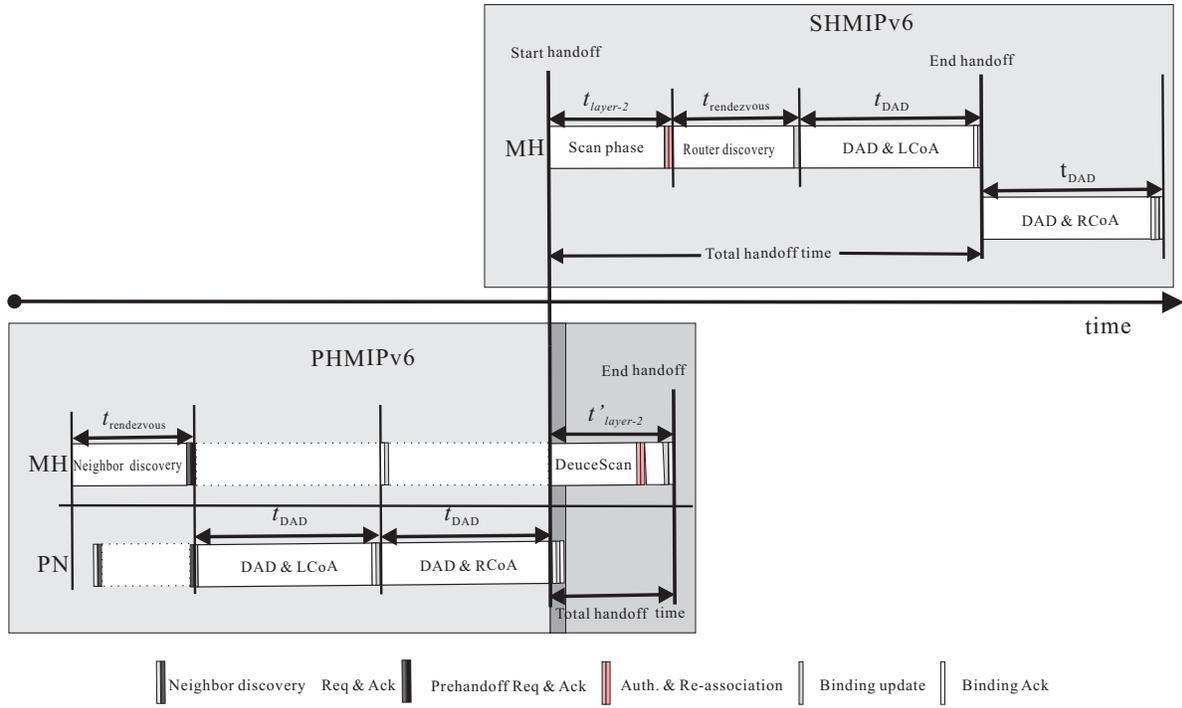


Fig. 15. Delay times of the SHMIPv6 and PHMIPv6 protocols.

For the successful case, the handoff latency of PHMIPv6 can be represented by

$$\begin{aligned}
 t_{PHMIPv6} &= t'_{layer-2} + t_{layer-3} - t_{overlap} \\
 &= t'_{layer-2} + t_{binding\_MAP} + t_{binding\_CN} - t_{binding\_MAP} \\
 &= t'_{layer-2} + 2 \left[ \left( \frac{S_{ctr}}{BW_{wl}} + L_{wl} \right) + n \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right]
 \end{aligned} \tag{9}$$

where  $t'_{layer-2}$  is the layer-2 handoff delay time in our PHMIPv6 protocol. Let  $t_{\Delta_1}$  be the time difference between  $t_{SHMIPv6}$  and  $t_{HMIPv6}$ :

$$\begin{aligned}
 t_{\Delta_1} &= t_{HMIPv6} - t_{SHMIPv6} \\
 &= t_{binding\_CN} + t_{DAD\_RCoA} - \min(t_{pmap}, t_{HA}) \\
 &\leq t_{binding\_CN} + t_{DAD\_RCoA} \\
 &= 2 \left[ \left( \frac{S_{ctr}}{BW_{wl}} + L_{wl} \right) + n \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + 2 \left[ \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] \\
 &\quad + t_{D\_DAD}.
 \end{aligned} \tag{10}$$

Let  $t_{\Delta_2}$  be the time difference between  $t_{HMIPv6}$  and  $t_{PHMIPv6}$ :

$$\begin{aligned}
t_{\Delta_2} &= t_{HMIPv6} - t_{PHMIPv6} \\
&= (t_{layer.2} - t'_{layer.2}) + t_{DAD.LCoA} + t_{DAD.RCoA} \\
&= (t_{layer.2} - t'_{layer.2}) + 4 \left[ \left( \frac{S_{ctr}}{BW_{wl}} + L_{wl} \right) + n \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] \\
&\quad + 2 \left[ \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + 2t_{D\_DAD}.
\end{aligned} \tag{11}$$

It can be seen that  $t_{\Delta_2} - t_{\Delta_1} = 2 \left[ \left( \frac{S_{ctr}}{BW_{wl}} + L_{wl} \right) + n \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + (t_{layer.2} - t'_{layer.2}) + 2t_{D\_DAD} > 0$ . This verifies that the handoff latency of the successful case of our PHMIPv6 is better than that of HMIPv6 and SHMIPv6. An example is given in Fig. 15.

For the unsuccessful case, let  $t_{U\_PHMIPv6}$  be the handoff latency of the unsuccessful case of PHMIPv6. Thus,

$$\begin{aligned}
t_{U\_PHMIPv6} &= t'_{layer.2} + t_{layer.3} \\
&= t'_{layer.2} + t_{DAD.RCoA} + t_{binding.CN} \\
&= t'_{layer.2} + 2 \left[ \left( \frac{S_{ctr}}{BW_{wl}} + L_{wl} \right) + n \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] \\
&\quad + 2 \left[ \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + t_{D\_DAD}.
\end{aligned} \tag{12}$$

Let  $t_{\Delta_3}$  be the time difference between  $t_{HMIPv6}$  and  $t_{U\_PHMIPv6}$ :

$$\begin{aligned}
t_{\Delta_3} &= t_{HMIPv6} - t_{U\_PHMIPv6} \\
&= (t_{layer.2} - t'_{layer.2}) + t_{DAD.LCoA} \\
&= (t_{layer.2} - t'_{layer.2}) + 2 \left[ \left( \frac{S_{ctr}}{BW_{wl}} + L_{wl} \right) + n \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] \\
&\quad + 2 \left[ \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + t_{D\_DAD}.
\end{aligned} \tag{13}$$

It can be seen that  $t_{\Delta_3} - t_{\Delta_1} = \left[ \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + (t_{layer.2} - t'_{layer.2})$ .

If  $t'_{layer.2} < \left[ \left( \frac{S_{ctr}}{BW_w} + L_w \right) + t_{D\_internet} \right] + t_{layer.2}$ , then  $t_{\Delta_3} - t_{\Delta_1} > 0$ . This verifies that the handoff latency of the unsuccessful case of our PHMIPv6 is still better than that of HMIPv6 and SHMIPv6. An example is given in Fig. 15.

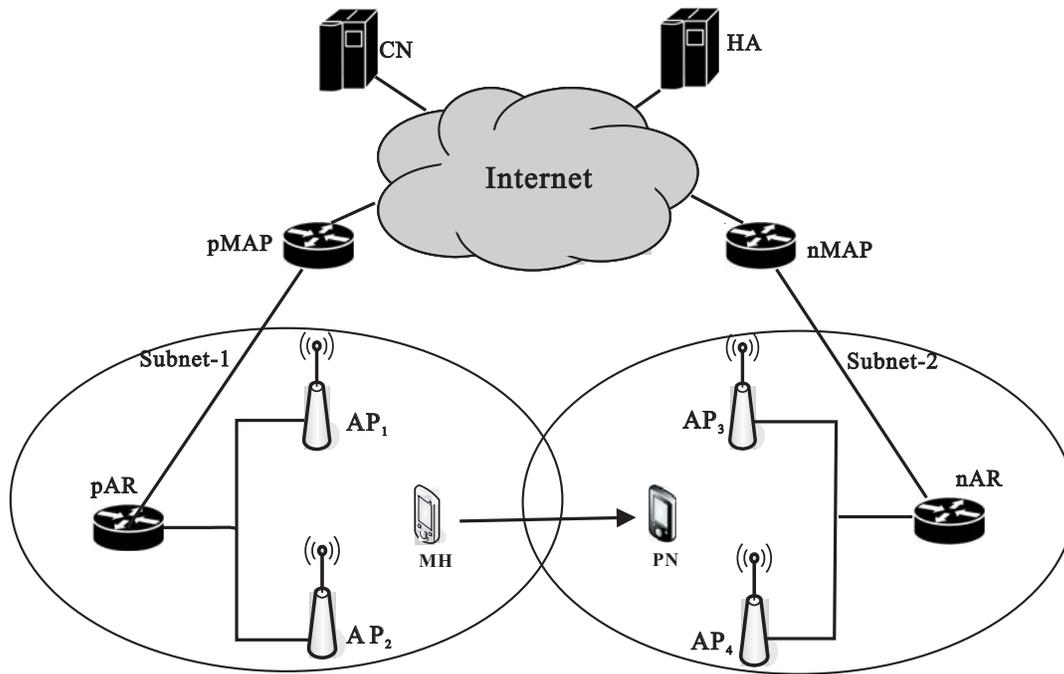


Fig. 16. Handoff testbed.

### B. Simulation results

Our paper presents a new PHMIPv6 protocol. To evaluate our PHMIPv6 protocol, the Mobile IPv6 (MIPv6) [6], Hierarchical Mobile IPv6 (HMIPv6) [17], and Stealth-time Hierarchical Mobile IPv6 (SHMIPv6) [10], protocols are implemented in our IEEE 802.11-based handoff testbed system.

Our IEEE 802.11-based handoff testbed system uses the HMIPL (Hierarchical Mobile IPv6 for Linux) to build the testbed environment, and each MAP runs a Linux 2.4.20 kernel. The MH and PN are implemented using an Ipaq HP 5550/5450 Pocket PC with embedded Linux 2.4.20 and an Atheros PCI wireless card. We modified the open source driver, madwifi [9], to implement the layer-2 DeuceScan procedure [4]. In addition, a sniffer program was developed to estimate the handoff delay times for all implemented protocols. Figure 16 shows our testbed system.

In our simulation, PHMIPv6- $x$ -hop and U-PHMIPv6- $x$ -hop were used to denote the PHMIPv6 (successful case) and U-PHMIPv6 (unsuccessful case) protocols with  $x$  hops for finding a cooperative PN. The performance metrics observed are as follows.

- The *handoff latency (HL)* is the delay time in which a mobile host disconnects the previous AP (pAP) and re-connects to a new AP (nAP) and receives a data packet from corresponding node through the nAP. The handoff latency is defined as the time interval from when the last packet was received from the pAP to when a new packet is received from the nAP.
- The *packet loss (PL)* is the number of packets lost during the time a mobile host connects to nAP to receive new packets from the corresponding node.

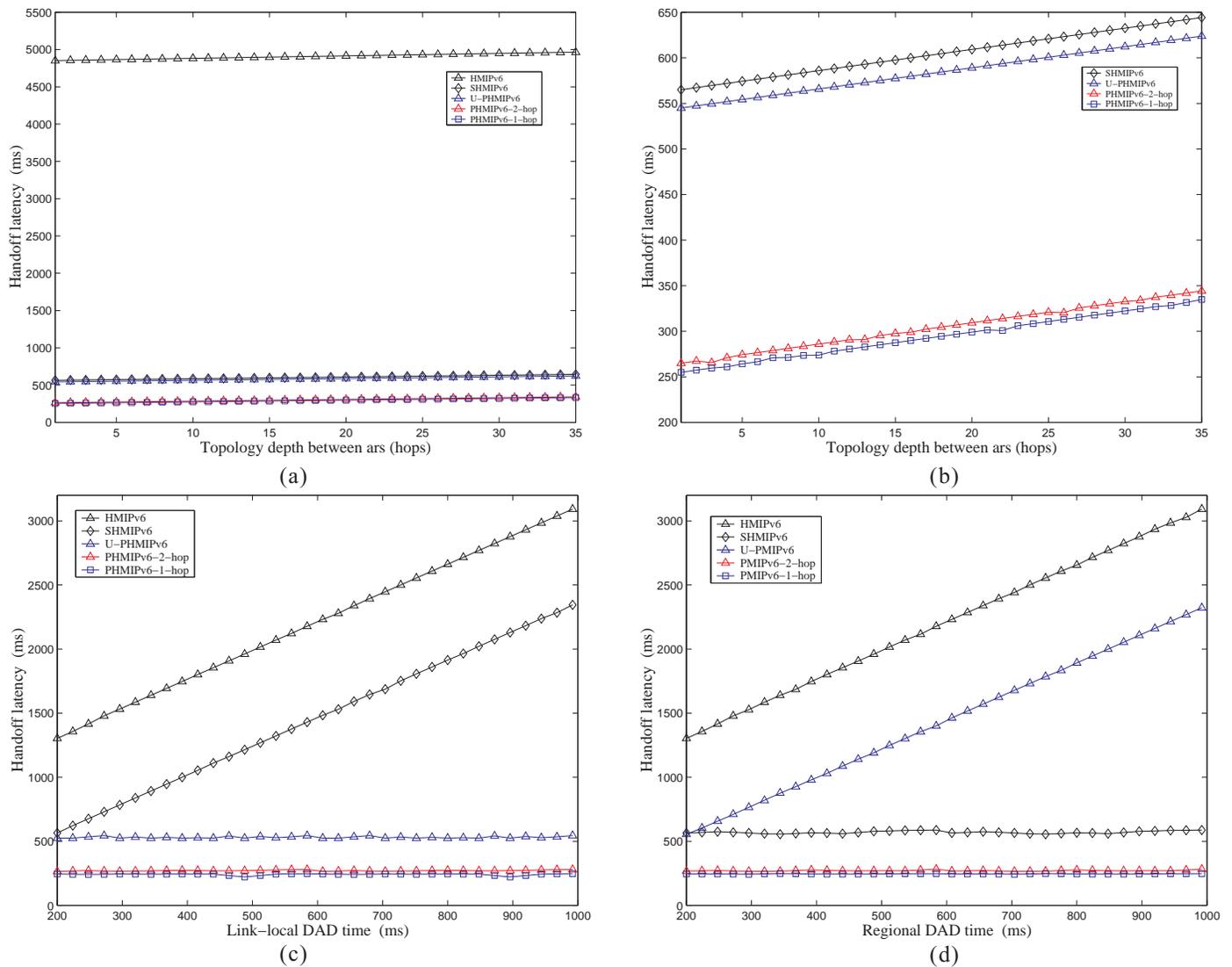


Fig. 17. (a)(b) Handoff latency vs distance between ARs (hops), (c) handoff latency vs. link-local DAD time, (d) handoff latency vs. regional DAD time.

- The *handoff jitter* ( $HJ$ ) is the jitter that is counted during the handoff time. Assuming that three consecutively received packets,  $P_{i-2}$ ,  $P_{i-1}$ , and  $P_i$ , are received by a mobile host, let  $T_{i-2}$ ,  $T_{i-1}$ , and  $T_i$  denotes the times to receive packets  $P_{i-2}$ ,  $P_{i-1}$ , and  $P_i$ , then the handoff jitter is defined as 
$$HJ_{j-2} = (T_i - T_{i-1}) - (T_{i-1} - T_{i-2}) = T_i - 2T_{i-1} + T_{i-2}.$$

1) *Handoff latency*: Figure 17 illustrates the micro-mobility handoff (vertical handoff) latency vs. distance between ARs (hops) for the MIPv6, PHMIP, SHMIPv6, and HMIPv6, and our PHMIPv6 protocols. The time latency is the time from the pAR to nAR. The typical wireless-link delay between the MH and nAR is between 10 and 50 ms. Figure 17 (a) illustrates the fact that the MIPv6 protocol has highest latency compared to all existing protocols. Figure 17 (b) drops the MIPv6 protocol and only compares the other protocols. As shown in Fig. 17(b), the curves of PHMIPv6-1-hop and PHMIPv6-2-hop (250 ~ 350 ms) are lower than those of U-PHMIPv6 (545 ~ 610 ms) and SHMIPv6 (570 ~ 650 ms). The average

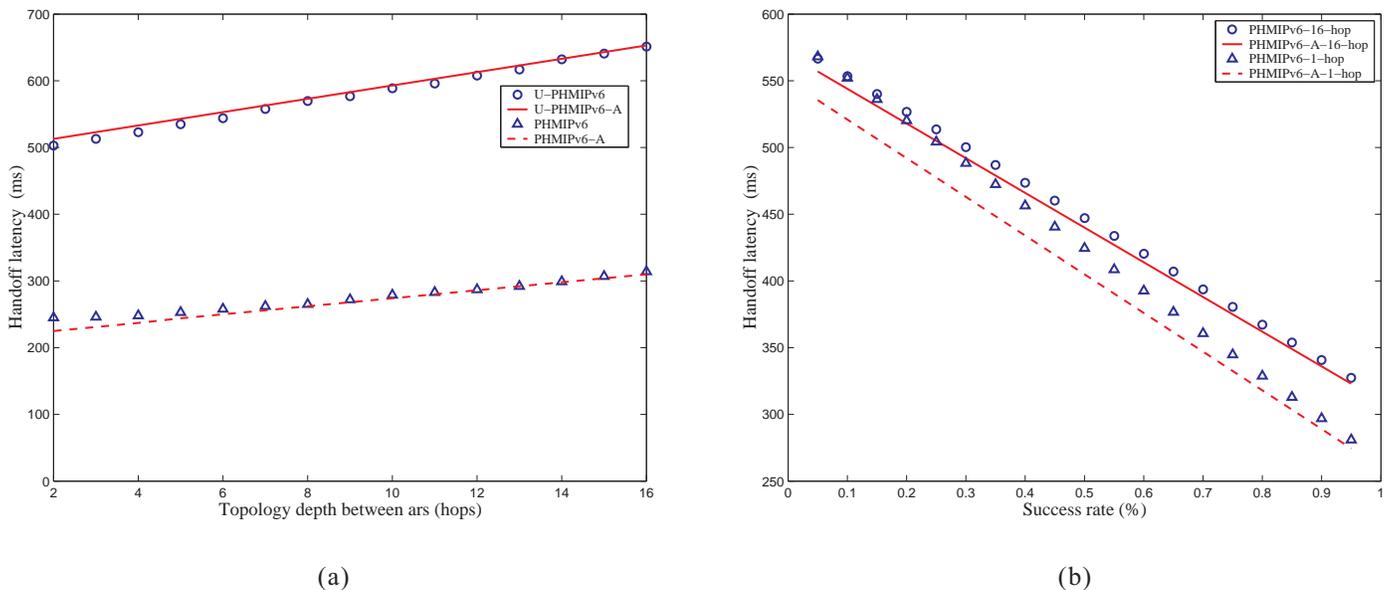


Fig. 18. (a) Handoff latency vs. distance between ARs and (b) handoff latency vs. success rate (%).

HL values were in the following order: PHMIPv6-1-hop < PHMIPv6-2-hop < U-PHMIPv6 < SHMIPv6 from the perspective of distance between ARs. This verifies that the performance of U-PHMIPv6 was close to that of SHMIPv6, and our PHMIPv6 protocol had better handoff latency than the other protocols. This is because the overlapping result for our cross-layer partner-based design significantly reduces the handoff latency. The required DAD time of our PHMIPv6 protocol decreased by 200 ms, or about 40% of the HMIPv6 protocol.

Figure 17(c) illustrates the HL of the MH under various link-local DAD times. In general, the HL increases as the link-local DAD time increases. However, we observed that the HL of SHMIPv6 and HMIPv6 increased as the link-local DAD time increased. But, for PHMIPv6 and U-PHMIPv6, the higher link-local DAD time was, the HL did not increase, because the link-local DAD procedure had been pre-performed by the PN. The curves of PHMIPv6-1-hop and PHMIPv6-2-hop (250 ~ 350 ms) were lower than those of SHMIPv6 (570 ~ 2200 ms) and U-PHMIPv6 (545 ~ 610 ms). The average HL values were in the following order: PHMIPv6-1-hop < PHMIPv6-2-hop < U-PHMIPv6 < SHMIPv6 under various link-local DAD times.

Figure 17(d) illustrates the HL of the MH under various regional DAD times. In general, the HL increased as the regional DAD time increased. For each case, the higher the regional DAD time was, the higher the HL was. We observed that the U-HMIPv6 and HMIPv6 increased as the regional DAD time increased. Because U-PHMIPv6 did not improve the regional DAD procedure, for PHMIPv6 and SHMIPv6, the higher the regional DAD time was, the HL did not increase, because the regional DAD time procedure had been performed by the PN and SHMIPv6 used the buffer technology. The curves of PHMIPv6-1-hop and PHMIPv6-2-hop (250 ~ 350 ms) were lower than those of U-PHMIPv6 (560 ~ 2200

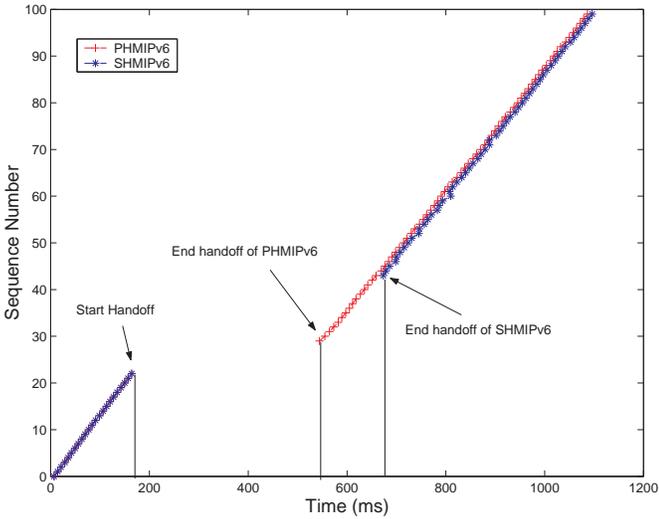
ms) and SHMIPv6 (555 ~ 630 ms). The average HL values were in the following order: PHMIPv6-1-hop < PHMIPv6-2-hop < SHMIPv6 < U-PHMIPv6 under various regional DAD times.

Figure 18(a) displays the mathematical analysis for our PHMIPv6 scheme. In general, the HL increased as the distance between the ARs (hops) increased. For each case, the higher the distance between the ARs (hops) was, the higher the HL was. We observed that the PHMIPv6 increased as the distance between the ARs increased which was nearly equal to PHMIPv6-A. The U-PHMIPv6 was also similar to U-HMIPv6-A. It was nearly the same as our implementation in low hop counts as illustrated by the the curves of PHMIPv6 and PHMIPv6-A from 250 to 340 ms and the curves of U-PHMIPv6 and U-PHMIPv6-A from 560 to 650 ms.

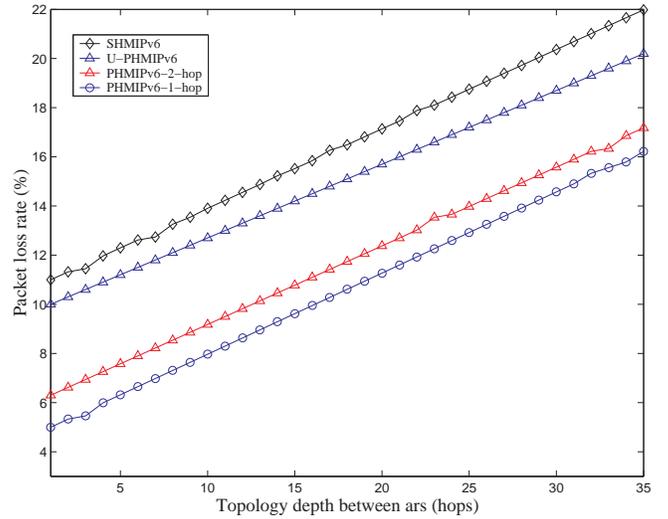
Figure 18(b) shows the use of mathematical analysis for our PHMIPv6 scheme under various success rates. In general, the success rate increased as the HL dropped. For each case, the higher the success rate was, the lower the HL was. We observed that the PHMIPv6-1-hop and PHMIPv6-1-hop-A drops were similar under a high success rate. And the drops in PHMIPv6-16-hop and PHMIPv6-16-hop-A were also similar under a higher success rate, because under a higher success rate, the MH can successfully switch to the nMAP domain in our PHMIPv6 scheme.

2) *Packet loss*: Figure 19 illustrates the micro-mobility packet (vertical handoff) loss vs. distance between ARs (hops) for the SHMIPv6, U-PHMIPv6, and PHMIPv6 protocols. The packet loss is measured by the hops from the pAR to the nAR. The typical wireless-link delay between the MH and nAR is between 10 and 50 ms. Figure 19(a) shows the simulation results of the PL vs. time. We observed that from the start handoff time to handoff time of SHMIPv6 and PHMIPv6, the PHMIPv6 scheme receives packets from the CN earlier than does the SHMIPv6 scheme. The curves of PHMIPv6 and SHMIPv6 start the handoff at a time of 180 ms. The PHMIPv6 receives the new packets at a time of 560 ms which was lower than the SHMIPv6 at a time of 720 ms.

Figure 19 (b) illustrates the PL of the MH under various distances between the ARs (hops). In general, the PL increased as the distance between the ARs (hops) increased. For each case, the higher the distance between the ARs (hops) was, the higher the PL was. We observed that PHMIPv6-1-hop, PHMIPv6-2-hop, U-PHMIPv6, and SHMIPv6 increased as the distance between the ARs (hops) increased. PHMIPv6-1-hop and PHMIPv6-2-hop increased similarly, because PHMIPv6-2-hop adds one hop to the discovery range. U-PHMIPv6 was lower than SHMIPv6, because the U-PHMIPv6 scheme uses a DeuceScan scheme to decrease the layer-2 handoff time. The curves of PHMIPv6-1-hop and PHMIPv6-2-hop (4 ~ 16%) were lower than those of SHMIPv6 (11 ~ 22 %) and U-PHMIPv6 (10 ~ 19%). The average PL values were in the following order: PHMIPv6-1-hop < PHMIPv6-2-hop < U-PHMIPv6 < SHMIPv6 under various distance between ARs (hops).

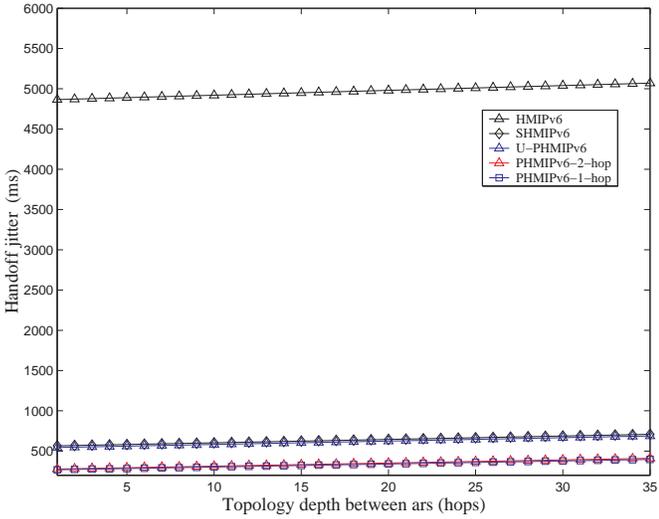


(a)

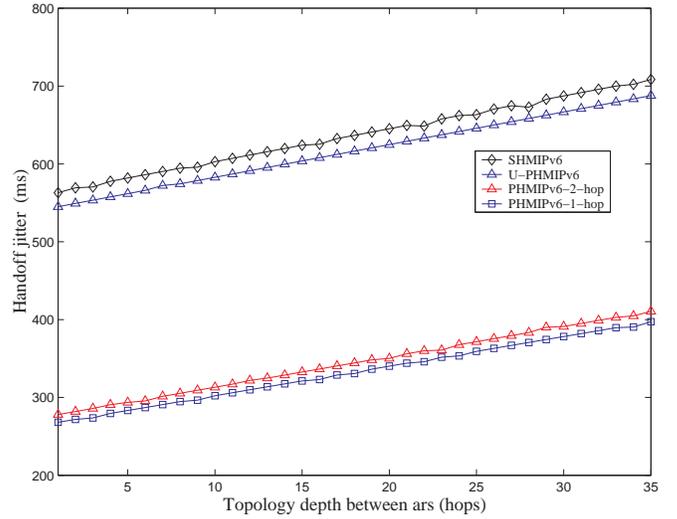


(b)

Fig. 19. (a) Sequence number vs. time and (b) handoff latency vs. the success rate (%).



(a)



(b)

Fig. 20. Handoff jitter vs. distance between ARs.

3) *Handoff jitter*: Figure 20 illustrates the micro-mobility handoff (vertical handoff) jitter vs. distance between ARs (hops) for the MIPv6, PHMIP, SHMIPv6, HMIPv6, and PHMIPv6 protocols. The handoff jitter was measured as the time from the pAR to the nAR. The typical wireless-link delay between the MH and nAR is between 10 and 50 ms.

Figure 20 (a) illustrates the fact that the MIPv6 protocol has highest jitter compared to all existing protocols. Therefore, Fig. 17(b) drops the MIPv6 protocol and only compares the other protocols. As shown in Fig. 20(a), the curves of PHMIPv6-1-hop and PHMIPv6-2-hop (245 ~ 340 ms) were lower than those of SHMIPv6 (560 ~ 645 ms) and U-PHMIPv6 (540 ~ 600 ms). The average HJ values were in the

following order: PHMIPv6-1-hop < PHMIPv6-2-hop < U\_PHMIPv6 < SHMIPv6 from the perspective of distances between the ARs.

This verifies that the performance of U\_PHMIPv6 is close that of SHMIPv6, and our PHMIPv6 protocol has better handoff jitter than the other protocols. This is because the overlapping result for our cross-layer partner-based design can significantly reduce the handoff jitter.

## VI. CONCLUSIONS

In this paper, we propose a cross-layer partner-based fast handoff mechanism based on HMIPv6, called the PHMIPv6 protocol. Our PHMIPv6 protocol is a cross-layer, layer-2 + layer-3, approach. A cooperative node, called a partner node, is adopted in the PHMIPv6 protocol. A new layer-2 trigger scheme used in the PHMIPv6 protocol accurately predicts the next AP (access point) and then invites a cooperative partner node in the area of the next AP. With the aid of the partner node, CoA can be pre-acquired and the DAD operation can be pre-executed by the partner node before the mobile node initializes the handoff request. The PHMIPv6 protocol significantly reduces the handoff delay time and packet losses. In the mathematical analysis, we verified that our PHMIPv6 protocol offers a better handoff latency than MIPv6, HMIPv6, and SHMIPv6. Finally, the experimental results also illustrated that the PHMIPv6 protocol actually achieves performance improvements in the handoff delay time, packet loss rate, and handoff delay jitter.

## VII. ACKNOWLEDGMENTS

A preliminary version of this paper was presented in *IEEE Vehicular Technology Conference 2007 Fall*, Maryland, USA, in October 2007. This research was supported by the National Science Council of the R.O.C. under grants NSC-95-2219-E-305-001, NSC-96-2219-E-305-001 and NSC-97-2219-E-305-001.

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