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SIP-based MIP6-MANET: Design and implementation of mobile IPv6 and SIP-based mobile ad hoc networks*,†☆

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Abstract

In this paper, we designed and implemented an integrated wireless system, namely a SIP-based MIP6-MANET system. This SIP-based MIP6-MANET system is an integration and implementation of Mobile IPv6 and SIP-based mobile ad hoc networks (MANETs). To support mobile multimedia services, this work is the first result to combine session initiation protocol (SIP) into the integrated MIP6-MANET system. Our actual system implementation was built on the Linux OS (2.4.22 Kernel), the Orinoco IEEE 802.11b wireless card, and MIPL (mobile IPv6 for Linux), where the router advertisement and solicitation and binding update packets were adaptively modified and redefined to achieve the real implementation of the SIP-based MIP6-MANET integrated system. Our SIP-based MIP6-MANET system utilizes the IPv6 stateless address auto-configuration (SAA) mechanism to automatically get a care-of-address (CoA) without CoA address management from the IPv4-based DHCP server. The SIP-based MIP6-MANET system supports the IP mobility mechanism which maintains a session connection when a mobile host roams from one MANET subnet to another. The key contributions of the SIP-based MIP6-MANET system are stated as follows: (1) This system provides an efficient handoff mechanism to reduce the handoff time when a mobile node (MN) roams between different MANETs; (2) Our system can efficiently reduce the triangle routing delay when an MN roams to a foreign MANET; (3) It obviously improves the throughput and arrival rate between an MN and a corresponding node; (4) The response time of our system is decreased when an MN roams to a foreign MANET. Performance analysis also illustrated the performance, which showed that the integrated system is more efficient in terms of handoff probability, triangle routing delay, throughput, and response time than traditional MIPv4-based wireless infrastructure systems.

Keywords: Mobile Ad Hoc Network; Mobile IPv6; DSDV; SIP Protocol; Wireless Network

1. Introduction

Over the past few years, wireless communications and mobile computing have attracted much attention due to their portability. Wireless communication devices have become standard features in most portable computing devices, such as IEEE 802.11 WLAN cards, bluetooth, PHS/GPRS phone cards, and PDAs. In the near future, people will be able to carry computers while traveling and access interest information through a wireless Internet. Mobility has added a new and important dimension to the area of mobile computing and communications.

Recently, many important wireless communication techniques have successfully been investigated, such as IEEE 802.11x [1], Bluetooth [9], GSM/GPRS/3G/Beyond 3G/4G [6], Mobile IP [7,16,18], IPv6 [8,11], MANETs (mobile ad hoc networks) [10,12,13,17,19], WSNETs (wireless sensor networks) [8,9], and so on. A MANET [26] is a collection of mobile nodes (MNs) which can dynamically and quickly form a wireless network anytime and anywhere without the need of a preexisting wireless network infrastructure. A MANET system [26] has self-configuration and self-maintenance capabilities. One key difference of MANETs with infrastructure wireless networks is that MANETs allow the multi-hop routing protocol. This allows mobile hosts in MANETs to have longer transmission ranges than mobile hosts in a wireless LAN. In addition, Mobile IPv6 (MIPv6) [11] has recently been proposed as overcoming shortcomings of MIPv4 by offering a huge address space, route optimization, and a high-security mechanism. The advantage of using MIPv6 is described as

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follows. First, MIP6 supports the IP mobility mechanism which maintains a session connection between MNs. Compared to MIPv4, MIP6 utilizes the IPv6 stateless address auto-configuration (SAA) mechanism to automatically get a care-of-address (CoA) without CoA address management from an IPv4-based DHCP server. Furthermore, a direct notification mechanism, called binding update, is used in MIPv6 to route packets to the MN's new location. This work achieves route optimization. Efforts were made in this paper to build an integrated system for integrating Mobile IPv6 with MANET to produce a MIP6-MANET system.

To support multimedia communications, the session initiation protocol (SIP) [21] was considered for integration into our MIP6-MANET system. The SIP defined in IETF [21] has been proposed to be the core protocol for multimedia communications in the next generation of wired/wireless networks. The SIP is simpler than existing session initiation protocols, for instance the H.323 protocol. The SIP, like HTTP and SMTP, is a text-based protocol, which is very compatible with Internet-family protocols. The SIP is also an extensible protocol with highly scalability. The SIP is a transport protocol which can be implemented on small-sized mobile devices. It is very attractive to many developers of mobile applications. Consequently, a SIP-based MIP6-MANET system was developed and implemented in this work.

Existing integrated results have widely and recently been investigated [3,4,14,22,25,27,28]. Tseng et al. [25] gave integration and implementation experiences for the Mobile IP (IPv4) and mobile ad hoc networks. Salkintzis et al. [22] proposed WLAN-GPRS integration for next-generation mobile networks. Chakravorty et al. [3] proposed inter-network mobility with Mobile IPv6 and a GPRS-based network. Kim et al. [14] proposed a new mechanism for SIP with Mobile IPv6. Wu et al. [28] recently proposed a survey of Mobile IP in cellular and mobile ad-hoc networks. Chao et al. [4] proposed an architecture and communication protocol for IPv6 packet-based pico-cellular networks. Wu et al. [27] proposed an integrated cellular and ad hoc relaying system, the iCAR system [27].

In this paper, we have designed and implemented an integrated wireless system, namely a SIP-based MIP6-MANET system. This SIP-based MIP6-MANET system represents integration and implementation of Mobile IPv6 and SIP-based MANETs. To support multimedia communication, our work combines SIP messages into our integrated MIP6-MANET system. Our actual system implementation was built on the Linux OS (2.4.22 Kernel), an Orinoco IEEE 802.11b wireless card, and MIPL (Mobile IPv6 for Linux), where the router advertisement and solicitation and binding update packets were redefined to achieve implementation of the SIP-based MIP-MANET integrated system. Our SIP-based MIP6-MANET system utilizes the IPv6 SAA mechanism to automatically get a CoA without CoA address management from the IPv4-based DHCP server. The SIP-based MIP6-MANET system supports the IP mobility mechanism's ability to maintain a session connection when a mobile host roams from one MANET subnet to another. The key contributions of the SIP-based MIP6-MANET system are stated as follows. (1) This system provides an efficient handoff mechanism to reduce the cumulative handoff jitter when a mobile node (MN) roams between different MANETs. (2) Our system efficiently reduces the triangle routing latency when an MN roams to a foreign MANET. (3) It obviously improves the throughput and completion rate between an MN and a corresponding node. (4) The response time of our system decreases when an MN roams to a foreign MANET. Performance analysis also illustrated that the proposed mechanism is more efficient in terms of cumulative handoff jitter, triangle routing latency, completion rate, throughput, and response time than existing wireless LAN systems with MIPv4.

The paper is organized as follows. Section 2 reviews MANETs, Mobile IPv6, and the SIP. Section 3 introduces the SIP-based MIP6-MANET architecture. In Section 4, implementation of the SIP-based MIP6-MANET system is presented. Section 5 discusses the performance analysis. Section 6 discusses future work and conclusions.

2. Preliminary

This section separately reviews research results of MANETs, mobile IPv6, and the session initiation protocol (SIP). The motivation for designing the integrated system is described, and the important contributions of the SIP-based MIP6-MANET system are finally discussed.

2.1. Mobile ad hoc networks (MANETs)

The IETF working group (http://www.ietf.org/) for MANETs [26] has released many multi-hop routing protocols, which can be classified into proactive and reactive routing protocols. Proactive routing protocols evolved from distance-vector or linked-state routing protocols. Proactive routing protocols periodically exchange control messages with all neighboring nodes, and a global view of the network topology is maintained by each node. One well-known proactive routing protocol is the dynamic destination-sequenced distance-vector (DSDV) routing protocol [19]. In contrast, the reactive routing protocol searches for a route from a source to a destination in an on-demand manner. Existing reactive routing protocols include DSR [13], ZRP [10], CBR [12], and AODV [17]. Compared to on-demand routing protocols, the DSDV routing protocol has the following advantages.

- The DSDV routing protocol uses distance-vector technology to periodically update routing information in order to maintain a global view of the network topology. Therefore, data packets can immediately be sent out without routing delays.
- The DSDV routing protocol uses the sequence number which originates from the destination node to maintain an always-fresh routing table and uses the time-stamp method to delete broken-link entries in the routing table. Therefore, the packet does not cause loop problems between the source and destination because it checks the sequence number.

- The DSDV routing protocol requires a small amount of storage and a small amount of updated information.
- The DSDV routing protocol is easily implemented.

Because of these advantages, the DSDV routing protocol was used as the kernel routing protocol in our MANET system. Observe that the multi-hop routing capability of the MANET allows MNs to possibly extend the communication range, therefore the cumulative handoff jitter can be greatly reduced when the MN roams between different MANETs. Basically, the table-driven (proactive) routing protocol is suitable for the low-mobility environment. In addition, our integrated system can easily replace with the on-demand (reactive) routing protocol, such as AODV [17], for the high-mobility environment.

2.2. Mobile IPv6

The mobile IPv6 is defined by IETF (http://www.ietf.org/) and supports the IP mobility management mechanism. The address spaces and main operation of Mobile IPv6 are described. The address auto-configuration schemes of Mobile IPv6 can be divided into stateful and stateless auto-configurations [15,24,26]. The stateful auto-configuration scheme requires the exchange of additional information such that an MN obtains a new IPv6 address by the DHCP server. The stateless auto-configuration scheme can obtain a new IPv6 address by combining the subnet prefix address and its MAC address [24]. The advantage of the stateless auto-configuration scheme is that it generates a new IPv6 address without the need for an external DHCP server. The Ethernet interface identifier (EII) is based on the EUI-64 identifier [15,24] derived from 48-bit IEEE 802 MAC address. Therefore, in our implementation, MNs can obtain the subnet prefix through the router advertisement, and then combine the EUI-64 identifier to generate a new IPv6 address.

In the Mobile IPv6 architecture, there are three main elements; the MN, home agent (HA), and correspondent node (CN), but the foreign agent (FA) does not exist in the Mobile IPv6 architecture. In Mobile IPv6, the role and function of FA are replaced by IPv6 routers. When the MN enters a foreign subnet, the MN gets a CoA [5,7] by either the stateful or stateless auto-configuration scheme. All new control messages used in Mobile IPv6 are defined as the IPv6 destination option extension header [8,20,23]. These options used in IPv6 carry additional information which are examined only by the destination node. Three new control messages are defined in mobile IPv6 system as follows.

- Binding update: this message is used by an MN to inform an HA or other CNs about the new CoA of an MN.
- Binding acknowledgment: this message is used by the HA or a CN to inform the system that the HA or CN has successfully received the binding update message.
- Binding request: the binding request message is used by any node to request an MN to send a binding update message with the current CoA.

Compared to Mobile IPv4, Mobile IPv6 provides a more-efficient handoff mechanism by eliminating the triangle routing problem. As expected, therefore, using Mobile IPv6 can reduce the response time when an MN has roamed owing to elimination of the triangle routing problem with Mobile IPv6.

2.3. Session initiation protocol (SIP)

To support the multimedia communication in our MIP6-MANET system, the session initiation protocol (SIP) [21] was integrated into our system. The SIP [21] as defined by IETF [21] will possibly serve as the core protocol for multimedia communications for the next generation of wired/wireless networks. SIP protocol is an agile, general-purpose tool for creating, modifying, and terminating sessions that works independently of underlying transport protocols and without dependency on the type of session that is being established. When a user establishes a session, audio and video streams can setup on two different specialized network applications. Recently, SIP protocol has been implemented by a number of vendors, especially for VoIP applications. Therefore, this work supports the VoIP capability over SIP-based MIP6-MANET systems. The basic components of the SIP [14] are briefly reviewed as follows.

- Proxy: a proxy server receives a request and then forwards it towards the current location of the callee, either directly to the callee or to another server that might be better located to inform the callee.
- Redirect server: a redirect server receives a request and informs the caller about the next (hop) server. The caller then contacts the next (hop) server directly.
- User agent: a user agent is a logical entity in the terminal equipment that can act as both a user agent client and a user agent server.
- Registrar: a registrar is a server that accepts REGISTER requests and places the domain information it receives in a registrar server database.

Example of basic SIP architecture is given in Fig. 1. In the SIP, a user is identified in the form of ‘user@domain’. This address can be resolved by a SIP proxy which is responsible for the user’s domain. To identify the actual location of the user in terms of an IP address, the user needs to register an IP address to registrar server, where registrar server is responsible for keeping the domain of the user agent. When inviting a user, the caller sends an invitation to the SIP proxy which is responsible for the user’s domain, to check in the registrar’s database about the location of the user and the forward the invitation to the callee. The callee can either accept or reject the invitation. The session initiation is then finalized by having the caller acknowledge reception of the callee’s answer. This SIP-based MIP6-MANET system is an integration and implementation of Mobile IPv6 and SIP-based MANETs. A higher completion rate and higher throughput of an MN in our SIP-based MIP6-MANET system were obtained as expected, compared to a wireless LAN system with MIPv4, due to the multi-hop routing

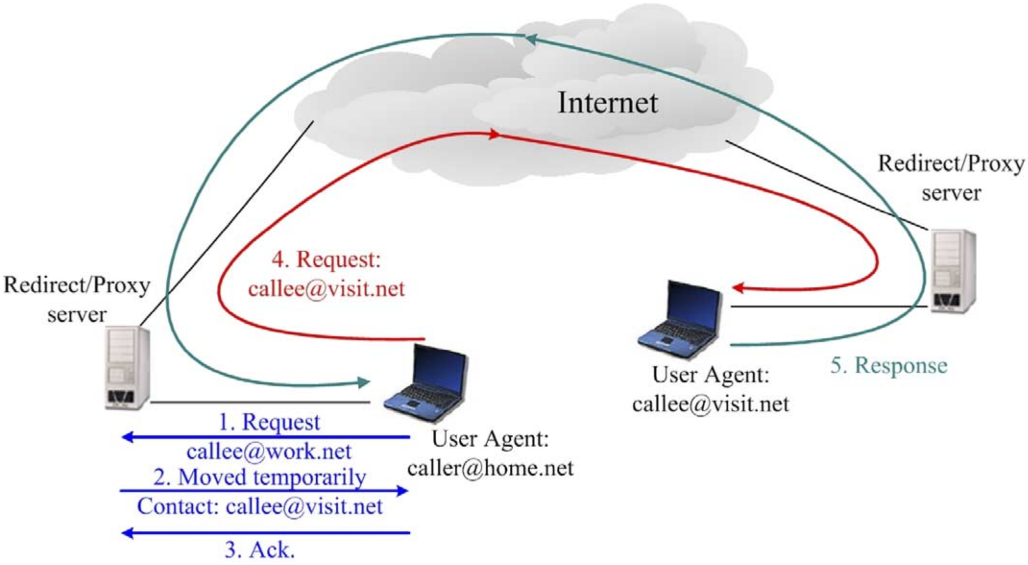


Fig. 1. Basic SIP architecture.

capabilities of MANETs and elimination of the triangle routing problem by Mobile IPv6. Efforts were made in this work to develop an integrated SIP-based MIP6-MANET system with the goal of low cumulative handoff jitter, low triangle routing latency, a high completion rate, high throughput, and a low response time.

3. The SIP-based MIP6-MANET architecture

This section presents the integrated system architecture and then defines modified packets used in our SIP-based MIP6-MANET system.

3.1. The SIP-based MIP6-MANET architecture

In the following, we present our SIP-based MIP6-MANET architecture Fig. 2. The SIP-based MIP6-MANET architecture consists of three kinds of MANETs for an MN; a home MANET, a foreign MANET, and a corresponding MANET. In our architecture, each subnet is a MANET with multi-hop routing capability and multi-hop communication coverage. All subnets, or MANETs, are connected together by a native IPv6 backbone network [2]. Observe that our integrated system may co-exist in dual IP4/IPv6 backbone network if 6 to 4 tunnel mechanism, IPv4/IPv6 gateway, and IPv6 tunnel broker are ready and provided. The MN's home agent is within the home MANET. The MN may roam from a home MANET into a foreign MANET, or roam from a foreign MANET back home or into another foreign MANET. A corresponding node (CN) located in a corresponding MANET attempts to communicate with an MN, where the MN is now at a home or in a foreign MANET. Observe that the corresponding MANET is also the home or a foreign MANET. In our implementation, MIPL (Mobile IPv6 for Linux) was adopted for our integrated system to provide the mobility management capability between different MANETs. In our implementation, all routers have two NICs (network interface cards): one is a standard Ethernet card (Eth0 was logically used in this work) for connecting to the IPv6 Internet and the other one is a Wi–Fi wireless LAN card (Eth1 was used) for connecting to a MANET. But the MN and RN (relaying node) each has only one Wi–Fi wireless LAN card for sending/receiving/forwarding control and data messages, where the RN is used to forward messages. For example as shown in Fig. 3, the IPv6 address space of the home, foreign, and corresponding MANETs are assumed to 3FFF::/16, 3FFE::/16 and 3EEE::/16, respectively. To support the SIP capability, the SIP domain names of the home, foreign, and corresponding MANETs are assumed to be '@home.com.tw', '@visit.com.tw', and '@wmn.com.tw', respectively. In the SIP, a user is identified through a SIP URI in the form of 'user@domain'. Therefore, the SIP domain names of the MN, RN, and CN are 'MN@home.com.tw', 'RN@visit.com.tw' and 'CN@wmn.com.tw', respectively. The detailed operation of a SIP-based MIP6-MANET system is discussed in Section 4.

3.2. The modified messages

Before introducing our SIP-based MIP6-MANET system, some ICMPv6 and mobile IPv6 packets are modified and re-defined. Before defining the DSDV routing, router advertisement, and binding update messages, we first define the IPv6 header which is used for all modified messages. The detail packet format of IPv6_Header is shown in Fig. 4. IPv6_Header (next header, source address, destination address), where the next header type can be TCP, UTP, ICMPv6 format, a routing header, a fragment header, a hop-by-hop option header, or a destination option header [11]; source address indicates the IPv6 address for the source node; and destination address indicates the IPv6 address for the destination node. To easily define the DSDV routing, router advertisement, and binding update messages, we use a plus symbol '+' to express different payloads carried by the IPv6 header packet. For instance, IPv6_Header (TCP, 3fff::1/16, 3fff::2/16)+payload indicates that source node, 3fff::1, sends a TCP payload to destination

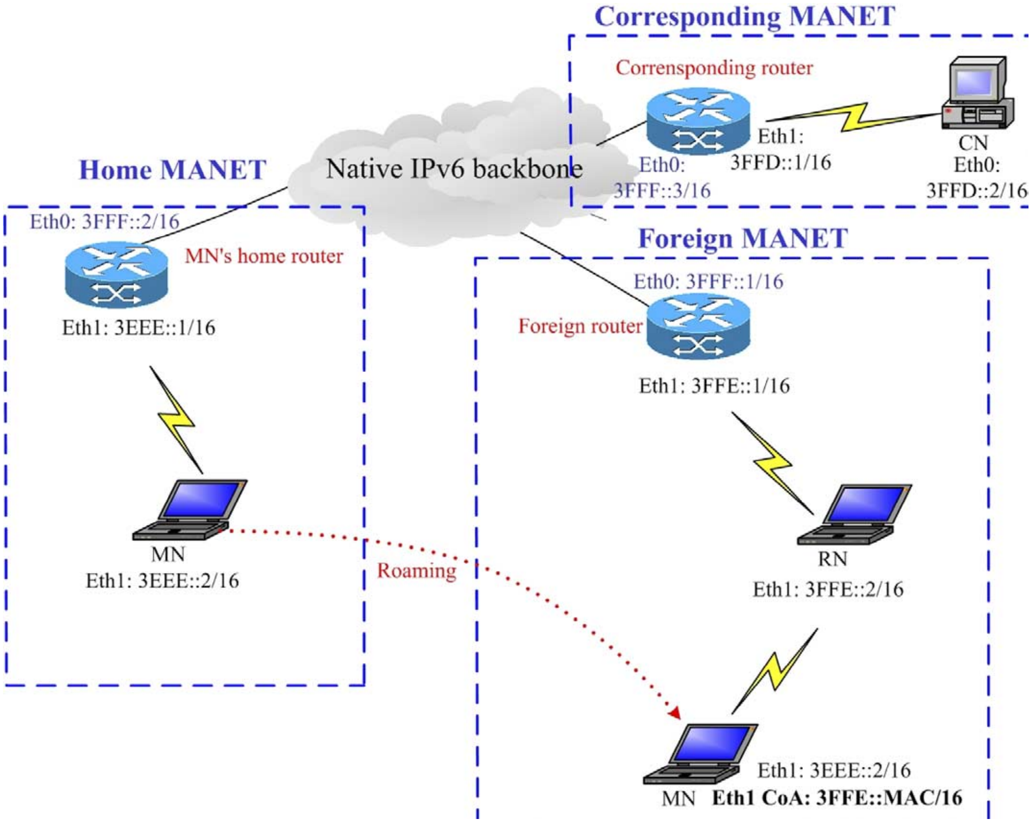


Fig. 2. Our MIP6-MANET system architecture.

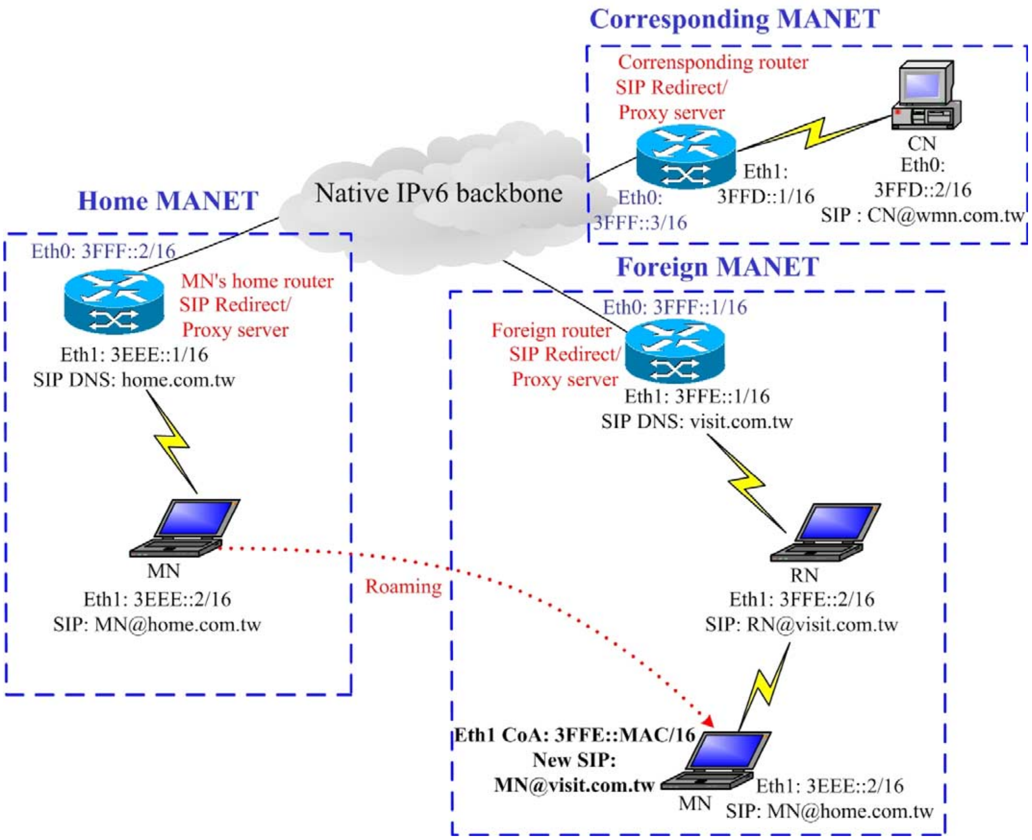


Fig. 3. Our SIP-based MIP6-MANET system architecture.

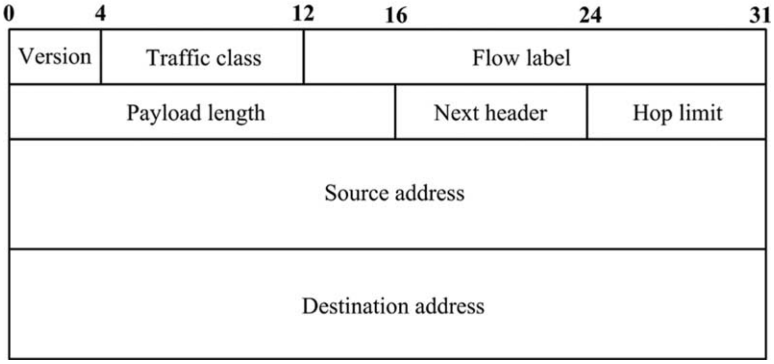


Fig. 4. The IPv6 header.

node 3fff::2. In the following, the DSDV routing, router advertisement, and binding update messages are, respectively, defined by IPv6_Header+ICMP6_Routing_Message, IPv6_Header+Modify_RA, and IPv6_Header+Modify_BU.

3.2.1. DSDV routing message

To perform the DSDV routing protocol, each MN periodically broadcasts DSDV routing messages to maintain a global view of the MANET topology. The ICMPv6 message is defined to exchange DSDV routing information among MNs. As mentioned before, each router (HA and VR) has two network interface cards. Within the MANET, the DSDV routing protocol is used to gather the routing information and the Mobile IPv6 protocol is used among MANETs. In a MANET, each MN uses the modified ICMPv6 message, IPv6_Header+ICMP6_Routing_Message, to exchange DSDV routing information. The detailed format of modified ICMPv6 message for DSDV routing is given in Fig. 5. The modified ICMPv6 message is IPv6_Header+ICMP6_Routing_Message, where ICMP6_Routing_Message is defined; ICMP6_Routing_Message (type, DSDV routing information), where type is a new defined type, numbered 145, the other numbers of the ICMP message refer to the RFC-2463 Internet Control Message Protocol (ICMPv6) [5] for Internet Protocol Version 6 (IPv6) Specification [11]; DSDV routing information maintains information on the next-hop address toward the destination node. For example as shown in Fig. 2, assume that an MN and RN are in a foreign MANET, an RN periodically broadcasts IPv6_Header (ICMPv6 header, 0::0, FF02::2)+ ICMP6_Routing_Message (145, 3FFF::/16 gw 3FFE::1), where 3FFF::/16 gw 3FFE::1 denotes that the next forwarding node is 3FFE::1 and the final destination node is 3FFF::/16. In this example, IPv6_Header+ICMP6_Routing_Message will be sent to 3FFF::1/16, 3FFF::2/16, and 3FFF::3/16. Observe that IPv6_Header (ICMPv6 header, 0::0, FF02::2) uses the loopback address '0::0' and multicast address 'FF02::2' to perform the multicast operation for IPv6_Header+ICMP6_Routing_Message. As shown in Fig. 3, the home, foreign, and corresponding routers, (HR, VR, CR) serve as the SIP proxy servers within the home, foreign, and corresponding MANETs, respectively. To help the MN maintain the correct subnet prefix and SIP domain name, the advertisement message and binding update message are thus modified. We adopted the IPv6 raw socket to implement and modify the mobile IPv6 packet, and the SIP message was added to the advertisement message and binding update message below.

3.2.2. New router advertisement message

This modified message adds a 'D' flag into a reserved field. The 'D' flag being ON indicates that the router advertisement message contains the subnet prefix and SIP domain name. The 'D' flag being OFF expresses that the general router advertisement message is currently being used. The detailed packet format of the router advertisement message is given in Fig. 6. In our implementation, the inet6_option_space( ) socket API is used to calculate the extra packet length, and the inet6_option_space( ) API is used to insert the additional SIP information into the extension header that connects with the IPv6 packet. The modified router advertisement message is IPv6_Header+Modify_RA, and Modify_RA is defined; Modify_RA (D flag field, subnet prefix of option field, SIP domain name of option field), where D flag field can be ON or OFF; the subnet prefix of the option field is the information of the subnet prefix; and the SIP domain name of the option field is information on the SIP domain name. For example as shown in Fig. 3, RN periodically broadcasts a modified router

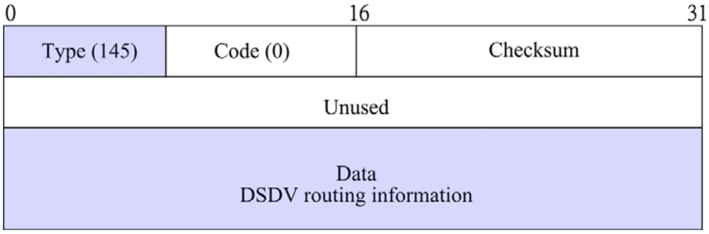


Fig. 5. Modified ICMPv6 message for DSDV routing.

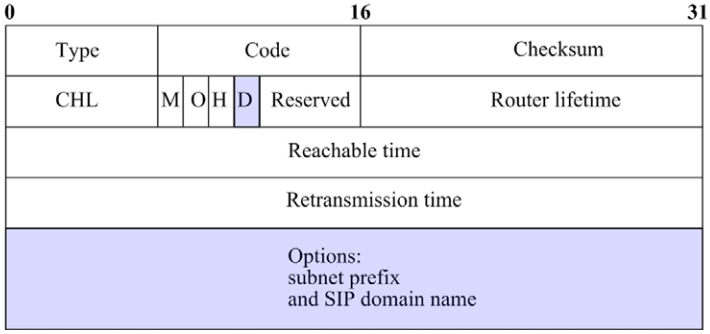


Fig. 6. Modified router advertisement message.

advertisement message IPv6_Header (ICMPv6 header, 0::0, FF02::2) + Modify_RA (ON, 3FFE::/16, visit.com.tw), where Modify_RA contains the IPv6 subnet prefix, 3FFE::/16, and the SIP domain information, visit.com.tw, of the foreign MANET for the current MN.

3.2.3. New binding update message

Since, the message is a new one, the number of the new option type is 10 to indicate that the modified binding updated message contains the new SIP domain name. The packet adds a field to store the SIP domain name and home address for an MN. The HA can use the modified binding update message to maintain the current location and related information of the MN. Observe that the source address field in the IPv6 header becomes the CoA of the MN and the destination field is the IPv6 address of the HA. The detailed binding update message is illustrated in Fig. 7. We also used the inet6_option_space( ) and inet6_option_space( ) socket API for implementation. The modified binding updated message is IPv6_Header + Modify_BU, and Modify_BU is defined; Modify_BU (option type, home address of MN, new SIP domain name), where a new option type is provided, set to 10, to indicate that the binding message additionally contains the SIP domain name; the home address of the MN is information on the home IPv6 address of the MN; and the new SIP domain name is information on the new SIP domain name of the foreign subnet. For example as shown in Fig. 3, when the MN roams from a home MANET to a foreign MANET, the MN gets a CoA and a new SIP domain name. After that, the MN sends the modified binding update message, IPv6_Header (mobility header, 3FFE::MAC/16, 3FFF::2/16) + Modify_BU (10, 3EEE::2/16, MN@visit.com.tw), to the HA. This binding update message is sent from 3FFE::MAC/16 (MN's CoA) to 3FFF::2/16 (HA) with the current MN's home address 3EEE::2/16 and the new SIP domain name MN@visit.com.tw.

4. The SIP-based MIP6-MANET system

This section presents the detailed implementation of the SIP-based MIP-6 MANET system. The first part discusses implementation of the native IPv6 DS DV routing protocol within a MANET. The second part describes implementation of mobility management when an MN roams from a home MANET to a foreign MANET or from a foreign MANET back to the original home MANET through the native IPv6 backbone network [2]. To easily explain the operation of the SIP-based MIP6-MANET system, let $X \xrightarrow{\text{forward}} Y$ indicate that mobile node X forwards a data message to mobile node Y, and $X \xrightarrow{\text{multicast}} Y$ imply that X multicasts a data message to Y within a one-hop transmission range. In addition, let $X \overset{\text{action}}{\Rightarrow} Y$ denote that X executes a communication action to Y, where X and Y are MNs or routers, and communication action = {packet, binding, multihop, tunnel}. Usually, $X \overset{\text{action}}{\Rightarrow} Y$ is

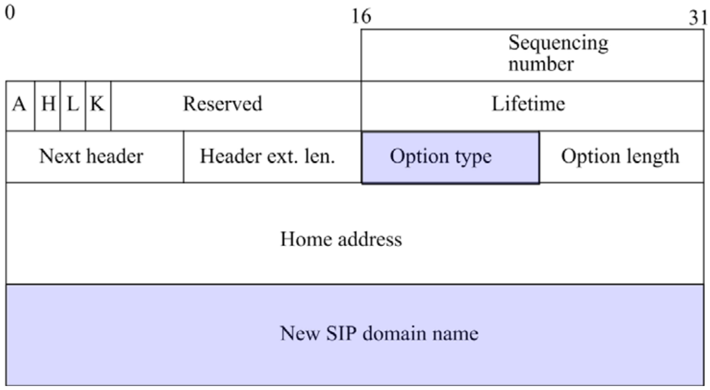


Fig. 7. Modified binding update message.

achieved by one or more $X \xrightarrow{\text{forward}} Y$ and $X \xrightarrow{\text{multicast}} Y$ steps. For example:

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

$X \xrightarrow{\text{forward}} Y$ indicates that X sends a binding message to Y.

$X \overset{\text{multihop}}{\Rightarrow} Y$ indicates that a data packet is sent from X to Y through the multi-hop routing.

$X \overset{\text{forward}}{\Rightarrow} Y$ indicates that X establishes a tunnel from X to Y.

4.1. The Native IPv6 DSDV routing protocol (MN $\overset{packet}{\Rightarrow}$ CN without Mobility)

For a home, foreign, or corresponding MANET, a native IPv6 DSDV routing protocol is implemented within the MANET. A message flowchart of the native IPv6 DSDV routing protocol is given in Fig. 8 for MN $\overset{\text{packet}}{\Rightarrow}$ CN. The general operation is given below. An example can be seen in Fig. 2.

S1: MN, RN $\overset{\text{multicast}}{\Rightarrow}$ all neighboring nodes: The RN, MN, and all MANET nodes periodically multicast IPv6_Header + ICMP6_Routing_Message to all neighboring nodes to maintain all routing paths for the MANET topology.

For instance as shown in Fig. 8, the MN periodically multicasts an IPv6_Header (ICMPv6 header, 0::0, FF02::2) + ICMP6_Routing_Message (145, 3FFF::/16 gw 3FFE::2/16) message, and the RN periodically multicasts an IPv6_Header (ICMPv6 header, 0::0, FF02::2) + ICMP6_Routing_Message (145, 3FFF::/16 gw 3FFE::1/16) message once every 3 s.

S2: MN $\overset{\text{packet}}{\Rightarrow}$ CN: a data packet is initially sent by the MN to the CN.

For instance, the MN sends a TCP packet, IPv6_Header (TCP, 3EEE::2/16, 3FFD::2/16) + payload, to the CN.

S3: MN $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ … $\xrightarrow{\text{forward}}$ FR (foreign router) $\xrightarrow{\text{forward}}$ … $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ …RN $\xrightarrow{\text{forward}}$ CN: Every MN and RN open a 'forward flag' in the Linux environment. The DSDV-IPv6 version routing protocol is designed and implemented within a MANET, and all MANETs are connected through the native IPv6 backbone [2].

For example as shown in Fig. 8, RN, FR, and CR receive the packet IPv6_Header (TCP, 3EEE::2/16, 3FFD::2/16) + payload which was sent from the MN. From the third field of IPv6_Header, this packet will eventually be sent to CN by MN $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ FR $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ CN.

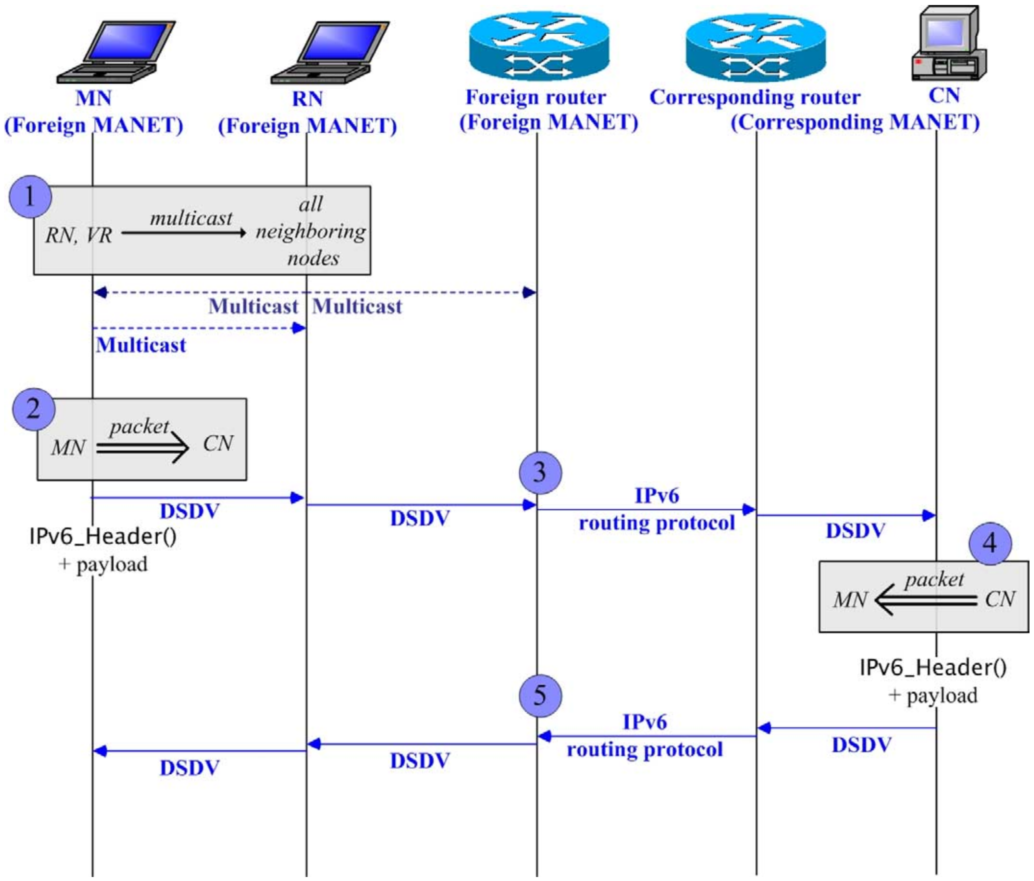


Fig. 8. Flowchart of the native IPv6 DSDV routing protocol.

S4: CN $\overset{\text{packet}}{\Rightarrow}$ MN: after the CN receives the packet from the MN, the CN sends an ACK. message to the MN.

For instance as shown in Fig. 8, the CN replies with a TCP ACK. packet IPv6_Header (TCP, 3FFD::2/16, 3EEE::2/16)+ACK. message to the MN.

S5: CN $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ … $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ … $\xrightarrow{\text{forward}}$ FR $\xrightarrow{\text{forward}}$ …RN $\xrightarrow{\text{forward}}$ MN: the reverse path of S3 is used to send the ACK. packet from the CN to the MN.

For instance as shown in Fig. 2, an ACK. packet, IPv6_Header (TCP, 3FFD::2/16, 3EEE::2/16)+ACK, is sent from the CN to the MN through CN $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ FR $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ MN.

4.2. MN roams between different MANETs (MN $\xrightarrow{\text{packet}}$ CN with mobility)

In this subsection, we introduce the roaming operation of the SIP-based MIP6-MANET system, show the general case, and give an example from Fig. 3 environment. Two cases are discussed for MN $\overset{\text{packet}}{\Rightarrow}$ CN, but the MN is roaming between different MANETs.

C1: The MN is roaming from a home MANET to a foreign MANET. The message flowchart is given in Fig. 9, where the home MANET is 3EEE::/16 and the foreign MANET is 3FFE::/16.

C2: The MN is roaming from a foreign MANET back to the home MANET. The message flowchart is given in Fig. 10, where the home MANET is 3EEE::/16 and the foreign MANET is 3FFE::/16.

The detailed operation of mobility management is illustrated as follows.

S1: RN in MANET $\xrightarrow{\text{multicast}}$ MN: All nodes, i.e. RNs, in a MANET periodically multicast the Modify_RA message. When the MN enters this MANET and receives the Modify_RA message, then the IPv6 SAA mechanism is used to generate a CoA and a new SIP address.

In case C1, as illustrated in Fig. 9, the RN periodically multicasts an IPv6_Header (ICMPv6 header, 0::0, FF02::2)+Modify_RA (ON, 3FFE::/16, @visit.com.tw) message. When the MN receives the IPv6_Header+Modify_RA packet, a new CoA, 3FFE:MAC/16, and a new SIP address, MM@visit.com.tw, are generated. In case C2, as illustrated in Fig. 10, the HR periodically multicasts an IPv6_Header (ICMPv6 header, 0::0, FF02::2)+Modify_RA (ON, 3EEE::/16, @home.com.tw) message. When the MN receives the IPv6_Header+Modify_RA packet, a home address, 3EEE:2/16, and a new SIP address, MM@home.com.tw, are generated.

S2: MN $\overset{\text{binding}}{\Rightarrow}$ HA: after the MN receives the Modify_RA message, the MN sends a Modify_BU message to the HA.

In case C1, as illustrated in Fig. 9, the MN sends an IPv6_Header (mobility header, 3FFE::EUI-64/16, 3FFF::2/16)+Modify_BU (option type 10, 3EEE::2, MN@visit.com.tw) message to the HR by MN $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ FR $\xrightarrow{\text{forward}}$ HR. Thus, the HA changes the binding table and the HR establishes a tunnel path between it and the FR. In case C2, as illustrated in Fig. 10, the MN sends an IPv6_Header (mobility header, 3EEE::2/16, 3EEE::1/16)+Modify_BU (option type 10, 3EEE::2, MN@home.com.tw) message to the HR and observes that the routing path is MN $\xrightarrow{\text{forward}}$ HR. Thus, the HA changes the binding table, and the HR removes the tunnel path between it and the FR.

S3: CN $\overset{\text{packet}}{\Rightarrow}$ MN (or CN $\overset{\text{multihop}}{\Rightarrow}$ HR $\overset{\text{tunnel}}{\Rightarrow}$ FR $\overset{\text{multihop}}{\Rightarrow}$ MN): A CN sends a packet to the MN. This packet is first sent to the HR and then to the MN through a tunnel.

In case C1, as illustrated in Fig. 9, the CN sends the TCP packet IPv6_Header (TCP, 3FFD::2/16, 3EEE::2/16)+payload to the MN by transmission path CN $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ HR $\overset{\text{tunnel}}{\Rightarrow}$ FR $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ MN. In case C2, as illustrated in Fig. 10, the CN sends TCP packet IPv6_Header (TCP, 3FFD::2/16, 3EEE::2/16)+payload to the MN by transmission path CN $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ HR $\xrightarrow{\text{forward}}$ MN.

S4: MN $\overset{\text{binding}}{\Rightarrow}$ CN(or MN $\overset{\text{multihop}}{\Rightarrow}$ HR or FR $\overset{\text{multihop}}{\Rightarrow}$ CR $\overset{\text{multihop}}{\Rightarrow}$ CN): After the MN receives the first packet from the CN, then the MN sends the Modify_BU message to the CN to notify it of the current location of the MN.

In case C1, as illustrated in Fig. 9, the MN, in a foreign MANET, sends an IPv6_Header (mobility header, 3FFE::EUI-64/16, 3FFD::2/16)+Modify_BU (10, 3EEE::2/16, MN@visit.com.tw) message to the CN by MN $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ VR $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ CN. In case C2, as illustrated in Fig. 10, the MN, in its home MANET, maintains the correct connection between the MN and CN after roaming. A connection is already established between the MN and CN before roaming; when the MN enters a new MANET, the MN sends an IPv6_Header (mobility header, 3EEE::2/16, 3FFD::2/16)+Modify_BU (option type 10, 3EEE::2, MN@home.com.tw) message to the CN by MN $\xrightarrow{\text{forward}}$ HR $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ CN. After the CN receives the Modify_BU message, the CN checks the second parameter of the IPv6_Header message and the second parameter of the MN's Modify_BU message to determine that the MN has returned to its home network.

S5: CN $\overset{\text{packet}}{\Rightarrow}$ MN (or CN $\overset{\text{multihop}}{\Rightarrow}$ VR $\overset{\text{multihop}}{\Rightarrow}$ MN): after the CN receives the binding packet from the MN, the CN can use the MN's current CoA to directly sends a packet to the MN.

In case C1, as illustrated in Fig. 9, the CN uses the MN's CoA as its destination node and directly sends IPv6_Header (TCP, 3FFD::2/16, 3FFE::EUI-64/16)+payload to the MN by CN $\xrightarrow{\text{forward}}$ CR $\xrightarrow{\text{forward}}$ VR $\xrightarrow{\text{forward}}$ RN $\xrightarrow{\text{forward}}$ MN. In case C2, as illustrated in Fig. 10, the CN sends TCP packet IPv6_Header

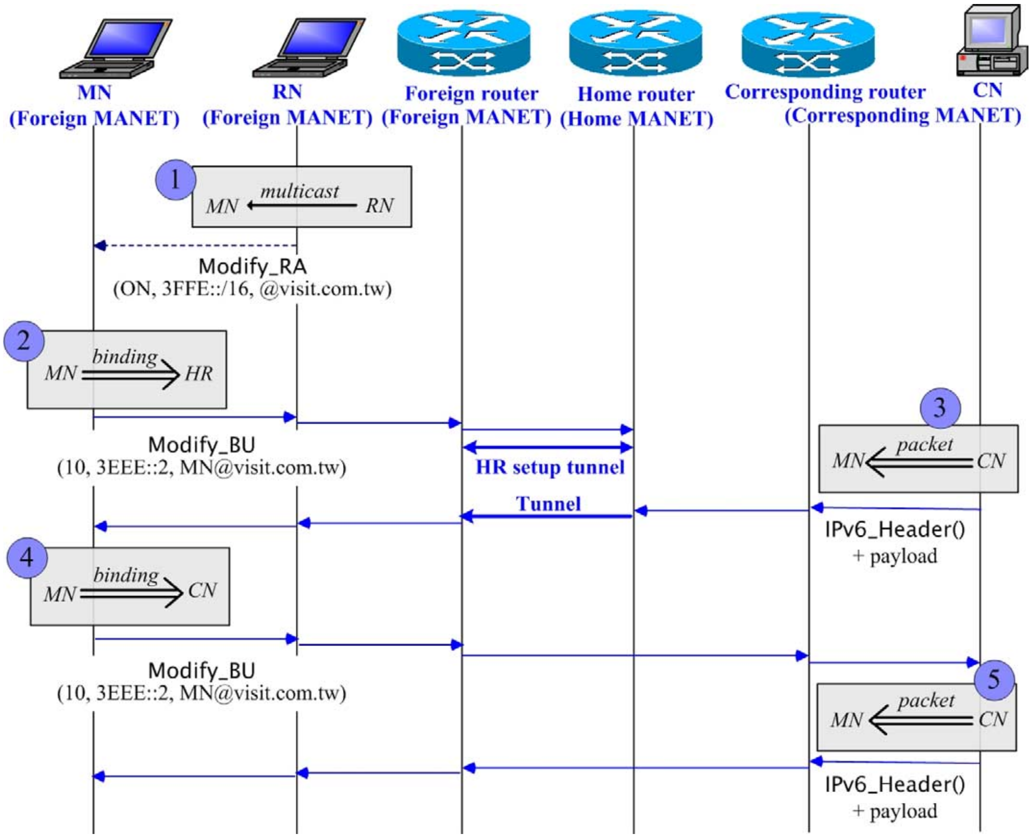


Fig. 9. Flowchart when an MN is roaming from a home MANET to a foreign MANET.

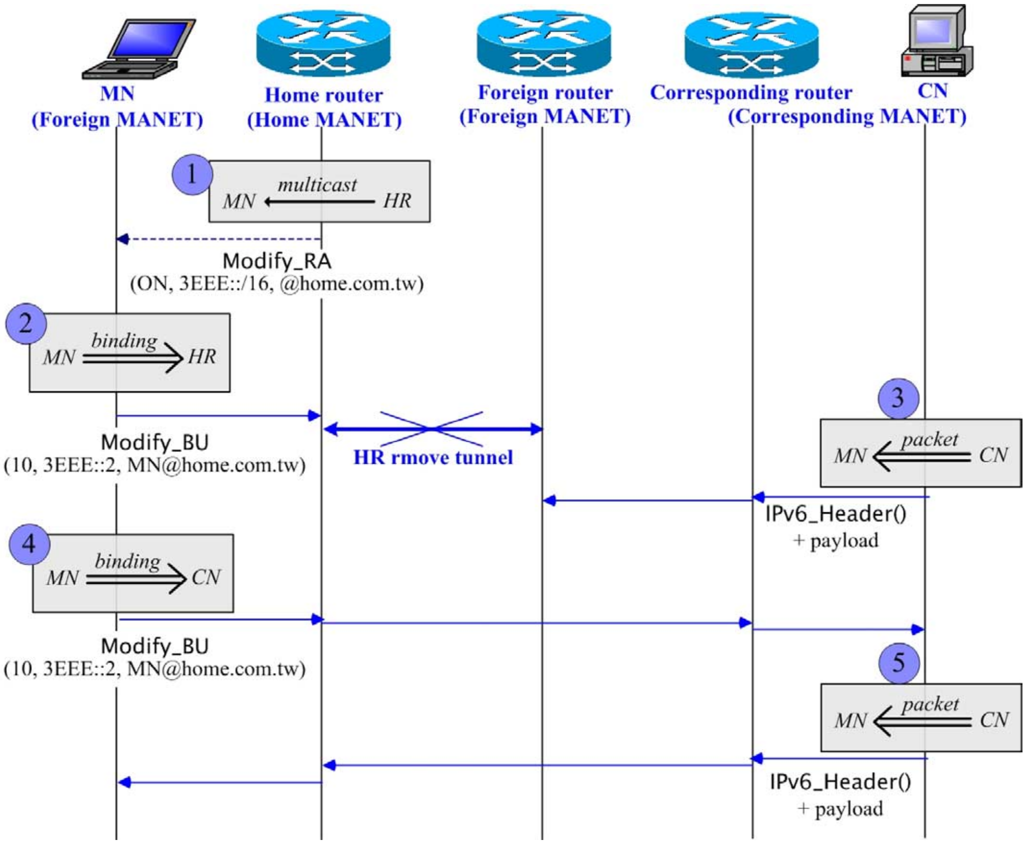
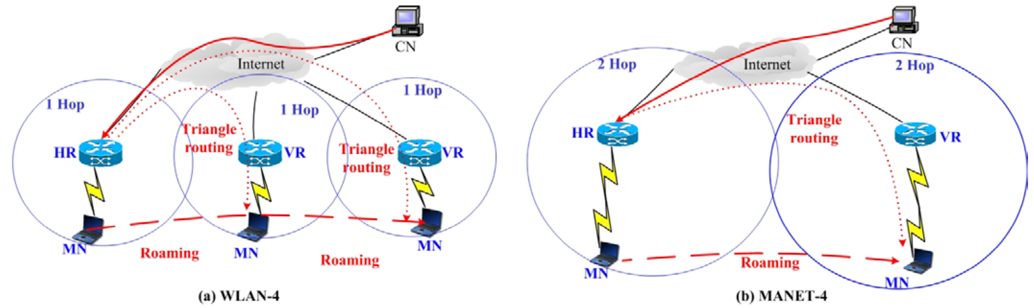
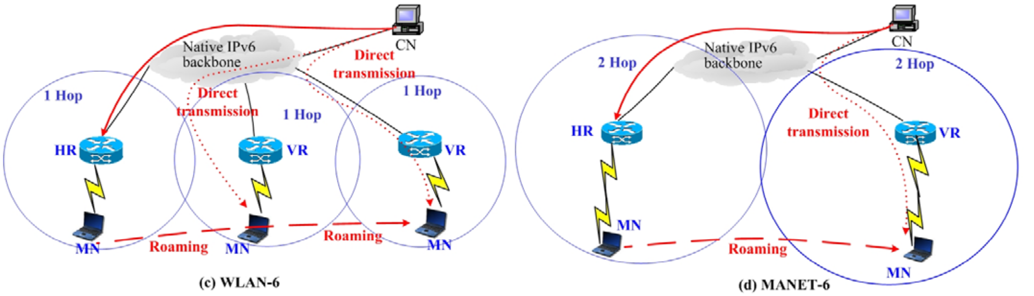


Fig. 10. Flowchart of an MN roaming from a foreign MANET back to its home MANET.



(a) WLAN-4 (b) MANET-4



(c) WLAN-6 (d) MANET-6

Fig. 11. Four wireless network models.

(TCP, 3FFD::2/16, 3EEE::2/16)+payload to the MN by transmission path $\text{CN} \xrightarrow{\text{forward}} \text{CR} \xrightarrow{\text{forward}} \text{HR} \xrightarrow{\text{forward}} \text{MN}$. The triangle routing problem is eliminated between MANETs due to the use of Mobile IPv6 mechanism.

5. Performance analysis

To make a fair comparison, we actually had to implement four kinds of wireless network models to evaluate the system performance of the SIP-based MIP6-MANET system. A sniffer was developed to acquire the performance analysis data from these four wireless network models. As shown in Fig. 11, the four wireless network models are defined as follows.

(1) Mobile IPv4-based WLAN System (WLAN-4): This wireless system is connected by many distinct WLANs through a native IPv4 backbone network, for which Mobile IPv4 was adopted as the mobility management scheme.
(2) Mobile IPv4-based MANET System (MANET-4): this wireless system is connected by many distinct MANETs through a native IPv4 backbone network, for which Mobile IPv4 was adopted as the mobility management scheme.
(3) Mobile IPv6-based WLAN System (WLAN-6): this wireless system is connected by many distinct WLANs through a native IPv6 backbone network [2], for which Mobile IPv6 was adopted as the mobility management scheme.
(4) Mobile IPv6-based MANET System (MANET-6): This wireless system is connected by many distinct MANETs through a native IPv6 backbone network [2], for which Mobile IPv6 was adopted as the mobility management scheme.

To easily express these four wireless network systems which we used in our implementation, we also used MANET-4 (2 hop) and MANET-6 (2 hop) to denote whether the transmission range of our MANET-4 and MANET-6 is a two-hop one, because our actual implementation only considered two-hop routing results in a MANET. As illustrated in Fig. 11(a) and (c), the WLAN-4 and WLAN-6 systems each has three WLANs. Under such a scenario, the moving pattern for an MN is to roam from the leftmost WLAN to the rightmost WLAN. At least three handoff procedures occur the roaming operation. As shown in Fig. 11(b) and (d), the MANET-4 (2 hop) and MANET-6 (2 hop) systems each has two MANETs. The MN uses the same moving pattern, but the MN roams from the left MANET to the right MANET. For the same distance moved, only one handoff procedure occurred during the roaming operation. In our implementation, the home WLAN or MANET router and the foreign WLAN or MANET router can be access points. The home WLAN or MANET router and the foreign WLAN or MANET router are connected by the native IPv4/IPv6 backbone network [8][11]. Each one has an IEEE Wi–Fi wireless card (Lucent Orinoco IEEE 802.11b wireless card); MIPL (Mobile IPv6 for Linux) was used to build our WLAN-6 (2 hop) MANET-6 (2 hop) systems; and each MN is running the Linux 2.4.20 kernel.

A sniffer was developed to acquire and maintain all data of the cumulative handoff jitter, triangle routing latency, response

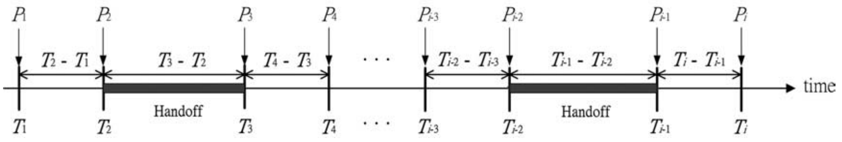


Fig. 12. Example of *handoff jitter*.

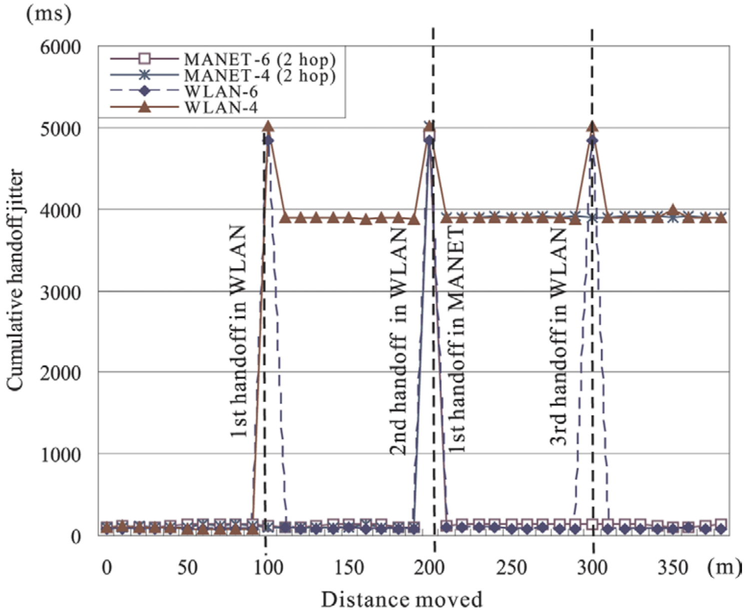


Fig. 13. Performance of cumulative handoff jitter vs. distance moved.

time, completion rate, and throughput, between a CN and the mobile MN. The performance metrics for this work are defined here.

- Cumulative Handoff Jitter (CHJ): consider three consecutive packets, P_{i-2}, $P_{i\text{-}1}$, and P_i, received by an MN in our proposed system, let T_{i-2}, $T_{i\text{-}1}$, and T_i denote the receiving times for packets P_{i-2}, $P_{i\text{-}1}$, and P_i, respectively, *handoff jitter* is defined as $\mathrm{HJ}_{j-2} = (T_i - T_{i-1}) - (T_{i-1} - T_{i-2}) = T_i - 2T_{i-1} + T_{i-2}$. The *cumulative handoff jitter* is denoted as $\mathrm{CHJ}_j = i = 3^{j-1} \sum \mathrm{HJ}_i$, where $\mathrm{HJ}_3 = T_3 - 2T_2 + T_1$.
- Triangle Routing Latency (TRL): the triangle routing delay is the extra delay time caused by triangle routing when the MN is handoff between MANETs.
- Response Time (RT): the response time is the time interval between two consecutive packets, P_i and P_{i+1}, received by an MN.
- Throughput (TH): the throughput is total number of data packets which can transmitted between a pair of a CN and MN per unit time.
- Completion Rate (CR): the completion rate is the received percentage for all packets received by an MN.

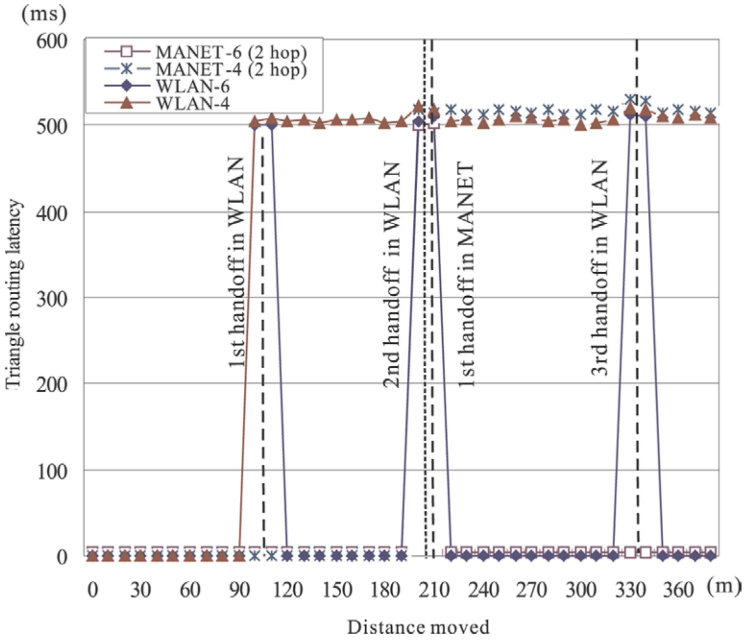


Fig. 14. Performance of triangle routing latency vs. distance moved.

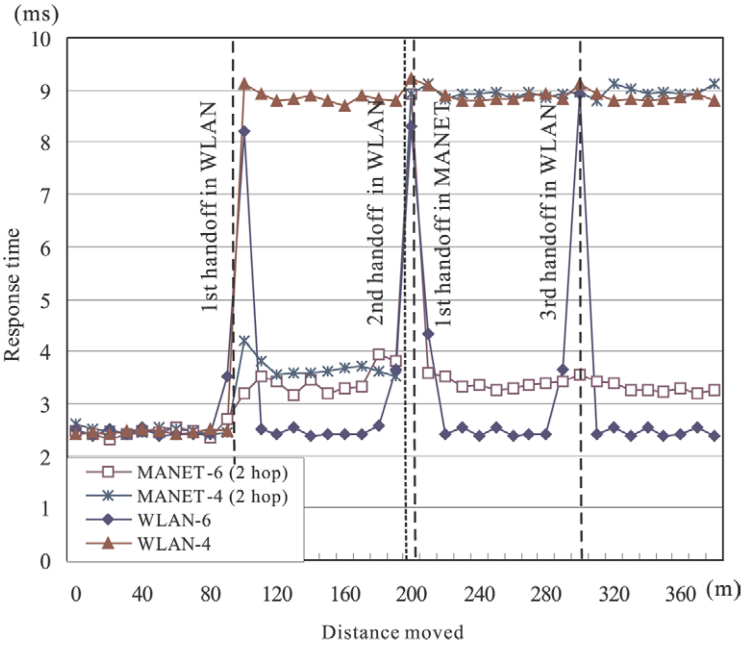


Fig. 15. Performance of *response time* vs. *distance moved*.

Examples of HJ and CHJ_j are given in Fig. 12. In the following, we illustrate the performance of the cumulative handoff jitter, triangle routing latency, response time, throughput, and completion rate.

5.1. Performance of cumulative handoff jitter (CHJ) vs. distance moved

Fig. 13 shows the actual results of cumulative handoff jitter (CHJ) vs. distance moved for the four wireless network models. With the same moving pattern and distance, two handoff operations occurred in the WLAN-4 and WLAN-6 models, but only one handoff operation occurred in the MANET-4 and MANET-6 models. The value of $\mathrm{CHJ}_j = i = 3^{j-1} \sum \mathrm{HJ}_i$ was calculated for WLAN-4, WLAN-6, MANET-4, and MANET-6 models. As illustrated in Fig. 13, the high value of CHJ_j implies that a handoff occurred. For the WLAN-4 and WLAN-6 models, the high value of CHJ_j occurred when the distance moved was 100, 200, or 300 m. But for MANET-4 and MANET-6, only one high value of CHJ_j was obtained when the distance moved was 200 m. This indicates that a low handoff probability was obtained by the MANET-4 and MANET-6 systems due to their multi-hop routing capability. The first handoff occurred for WLAN-4 and WLAN-6 at about 100 m. After that, the CHJ_j was

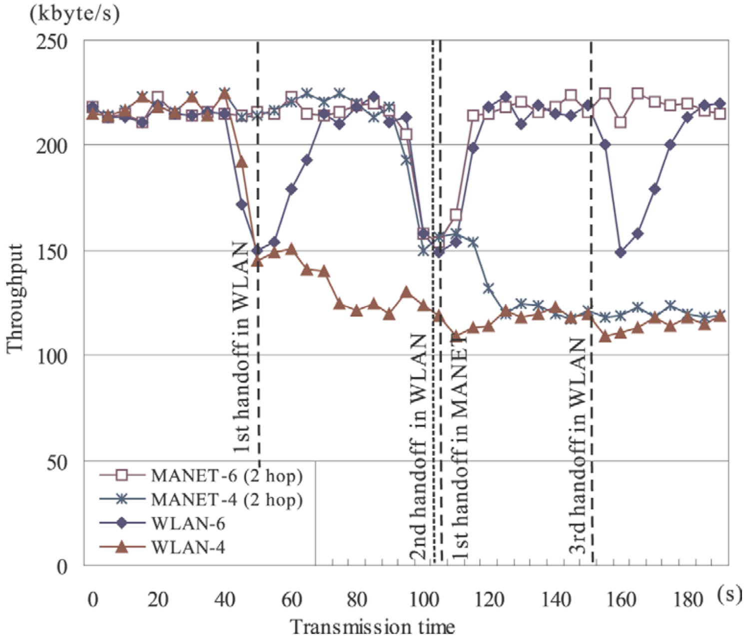


Fig. 16. Performance of *throughput* vs. *transmission time*.

4000 ms for WLAN-4 due to the triangle routing problem when using IPv4, but the CHJ$_j$ was approximately zero for WLAN-6 because no triangle routing problem occurs when using IPv6. Not until the distance moved was 200 m, did the first handoff for MANET-4 and MANET-6 occur and the second handoff for WLAN-4 and WLAN-6 happen. After that, the CHJ$_j$ was still 4000 ms for MANET-4 due to the triangle routing problem when using IPv4, but the HJ was about zero for MANET-6 because no triangle routing problem occurs when using IPv6. As a short summary, it can be seen that a low handoff probability was obtained for MANET-4 and MANET-6, as compared to WLAN-4 and WLAN-6.

5.2. Performance of triangle routing latency (TRL) vs. distance moved

With the same moving pattern and distance, Fig. 14 illustrates the triangle routing latency (TRL) vs. distance moved for the four models. The triangle routing latencies for the four wireless network models are given in Fig. 14, which shows there were two handoffs each for WLAN-4 and WLAN-6, and one handoff each for MANET-4 and MANET-6. When an MN roams to a foreign network (WLAN or MANET), WLAN-4 and MANET-4 suffer the triangle routing problem. The triangle routing latency was high when a handoff occurred, especially for the WLAN-4 and MANET-4 models. This is because the tunnel still existed between the MN and HA.

5.3. Performance of response time (RT) vs. distance moved

With the same moving pattern and distance, Fig. 15 illustrates the actual results of response time (RT) vs. distance moved. The response time was calculated by the time interval between two consecutive packets, P_i and P_{i+1}, received by an MN. The performance of response time is shown in Fig. 15. Before the first handoff, the response time of the Fig. 15 environment was about 2.5 ms. After the first handoff, the response time became 9 ms for the WLAN-4 system, but that of WLAN-6 was 2.5 ms due elimination of the triangle routing problem when using mobile IPv6. Fig. 15 shows that the average triangle routing latency of MANET-6 was 50% that of MANET-4 after the first handoff operation. Similarly, the average triangle routing latency of WLAN-6 was 30% that of WLAN-4 after the first handoff operation. In addition, the response time of WLAN-6 was better than that of MANET-6 due to its single-hop routing, but the handoff probability of WLAN-6 was higher than that of MANET-6.

5.4. Performance of throughput (TH) vs. transmission time

With the same moving pattern and distance, Fig. 16 illustrates the actual results of throughput (TH) vs. transmission time. The throughput was calculated by the number of data packets received by an MN per second, which was obtained by our sniffer. The throughput for WLAN-4, WLAN-6, MANET-4, and MANET-6 was the same as before the first handoff. At 50 s, the throughput of MANET-4 and MANET-6 was 210 kbyte/s, but the throughput of WLAN-4 and WLAN-6 was 150 kbyte/s. By eliminating the triangle routing, the throughput of MANET-6 and MANET-4 was about 210 and 110 kbyte/s after the first handoff of MANET-6 and MANET-4.

5.5. Performance of complete rate (CR) vs. transmission time

With the same moving pattern and distance, Fig. 17 illustrates the actual results of the completion rate (CR) vs. transmission time. The completion rate was calculated by determining the received packet percentage by an MN when a CN sent a 30-Mbyte data packet to the MN. The performance of the completion rate is given in Fig. 17. Before the first handoff

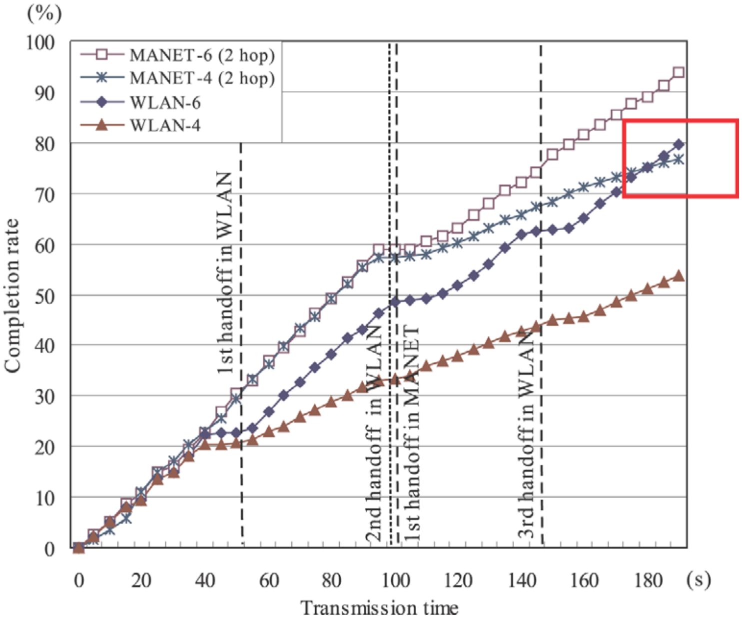


Fig. 17. Performance of *completion rate* vs. *transmission time*.

when the transmission time was 55 s, the completion rate for all four wireless network models were equal. After 55 s, MANET-6 and MANET-4 had better performance for the completion rate, since no handoff occurred. The first handoff for MANET-6 and MANET-4 and the second handoff for WLAN-4 and WLAN-6 occurred at 100 s. After that, the performance of the completion rate of MANET-6 was better than that of MANET-4 owing to eliminate the triangle routing latency for MANET-6. For the same reason, the performance of completion rate of WLAN-6 was better than that of WLAN-4. However, the performance of completion rate of WLAN-6 was better than that of MANET-4 because WLAN-6 had a better response time than MANET-4. However, this is because our wireless model only allows the two-hop routing mechanism. Therefore, WLAN-6 would not necessarily have better performance for the completion rate if MANET-4 had more multi-hop routing results.

Therefore, our SIP-based MIP6-MANET system provides the real data and experiences to illustrate the performance achievements of the high completion rate due to its low cumulative handoff jitter and low triangle routing latency.

6. Conclusions

In this paper, we have designed and implemented an integrated wireless system, namely a SIP-based MIP6-MANET system. This SIP-based MIP6-MANET system is an integration and implementation of Mobile IPv6 and SIP-based Mobile Ad Hoc Networks (MANETs). To support the multimedia communication, our work combined session initiation protocol (SIP) messages into our integrated MIP6-MANET system. Performance analysis illustrated the performance, which showed that the proposed mechanisms is more efficient in terms of handoff probability, triangle routing delay, throughput, and response time than existing wireless LAN systems with MIPv4. Our future work is to further integrate the GPRS network into our SIP-based MIP6-MANET system to create a SIP-based MIP6-MANET/GPRS system and to offer VoIP capability with our integrated system.

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