

Recommended Paper

PNEMO: A Network-Based Localized Mobility Management Protocol for Mobile Networks

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Abstract: Network mobility has attracted large attention to provide vehicles such as trains with Internet connectivity. NEMO Basic Support Protocol (NEMO-BS) supports network mobility. However, through our experiment using a train in service, NEMO-BS shows that the handover latency becomes very large if the signaling messages are lost due to instability of the wireless link during handover. There are several proposals such as N-PMIPv6 and N-NEMO to support network mobility based on network-based localized mobility management. However, these proposals have problems such as large tunneling overhead and transmission of the control messages for handover on the wireless link. This paper proposes PNEMO, a network-based localized mobility management protocol for mobile networks. In PNEMO, mobility management is basically handled in the wired network so that the signaling messages are not transmitted on the wireless link when handover occurs. This makes handover stable even if the wireless link is unstable during handover. PNEMO uses a single tunneling even if the mobile network is nested. PNEMO is implemented in Linux. The measured performance shows that the handover latency is almost constant even if the wireless link is unstable when handover occurs, and that the overhead of PNEMO is negligible in comparison with NEMO-BS.

Keywords: PMIPv6, NEMO, fast handover

1. Introduction

Network mobility has attracted large attention to provide vehicles such as trains, buses, and ships with Internet connectivity. If a passenger has a mobile device with a wireless LAN interface, the mobile device can be connected to the Internet. The IETF standardized NEMO Basic Support Protocol (NEMO-BS) [1] to support network mobility in the IPv6 Internet.

One of our projects aims at providing a high-speed train with broadband Internet connectivity. In this project, NEMO-BS is adopted as a network mobility protocol and a cross-layer collaboration mechanism [2] is employed for fast handover. This protocol is called *NEMO-FHO* (NEMO fast Handover). NEMO-FHO was implemented in Linux and evaluated by using a train in service in January and February, 2010 [3]. The speed of the train was approximately 130 km/h. As the communication medium between the mobile router on the train and the access routers on the ground, infrared communication devices were used [4]. The reason why the infrared communication devices were employed was to provide a train with over 1 Gbps bandwidth, which cannot be achieved by the current wireless LAN technologies. As a result, the communication disruption time due to handover was 124 msec in the best case but approximately 800 msec in the worst case. In the worst case, it can be assumed that some signaling

messages such as the RA (Router Advertisement) message and the BU (Binding Update) message are lost on the infrared link between the mobile router and the access router due to instability of the infrared link during handover. Loss of the signaling messages causes retransmission after timeout. This makes the handover latency larger.

On the other hand, the IETF standardized Proxy Mobile IPv6 (PMIPv6) [5]. It provides host mobility in an area called the PMIPv6 domain. PMIPv6 is a network-based localized mobility management protocol in which the location of the mobile node (MN) is managed by the network and the MN is not involved in the mobility signaling. Therefore, stable handover is expected because the signaling messages do not traverse the wireless link between the mobile node and the access router. However, PMIPv6 is a host mobility protocol and does not provide network mobility. There are several proposals based on PMIPv6 such as N-PMIPv6 [6] and N-NEMO [7] to support network mobility based on network-based localized mobility management. However, these proposals have problems such as large tunneling overhead and transmission of the control messages for handover on the wireless link.

This paper proposes *Proxy Network Mobility Protocol (PNEMO)* [8], a network mobility protocol based on network-based localized mobility management. Since the mobile router is not involved in handover signaling and the signaling messages are not transmitted on the wireless link, stable handover is expected even if the wireless link is unstable during handover.

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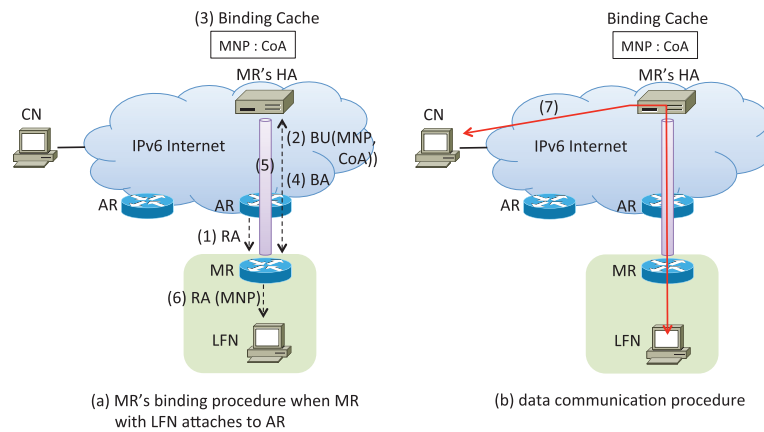


Fig. 1 Basic mechanism of NEMO-BS: MR with LFN.

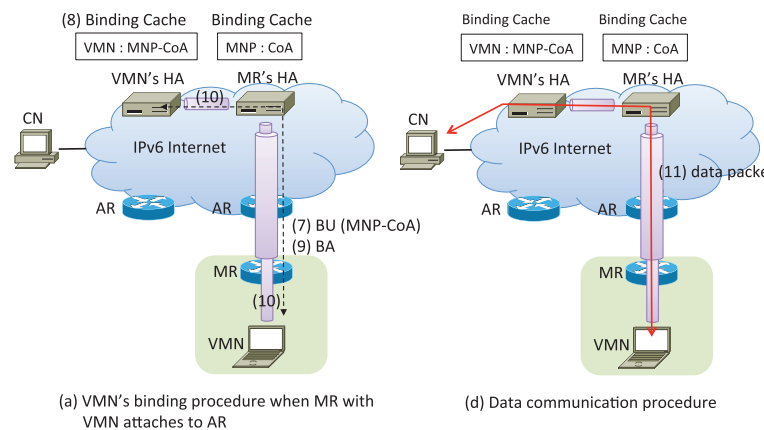


Fig. 2 Basic mechanism of NEMO-BS: MR with VMN.

PNEMO is implemented in Linux. The basic performance of PNEMO is also shown.

2. Basic Technologies: NEMO-BS and PMIPv6

This section explains two basic technologies: NEMO-BS and PMIPv6 on which PNEMO and related work are based.

2.1 NEMO-BS

NEMO-BS extends Mobile IPv6 [9] to support network mobility. Figures 1 and 2 show the basic mechanism of NEMO-BS. There are two types of mobile nodes: the *Local Fixed Node (LFN)* and the *Visited Mobile Node (VMN)*. The LFN is always connected to the same mobile network and does not have capability to move to another network. The VMN has capability to move to another network.

Figure 1 shows the case that a mobile router (MR) with a LFN attaches to an access router (AR). When the MR attaches to the AR, the Router Advertisement (RA) messages is sent by the AR (Fig. 1-(1)). Upon receiving the RA message, the MR generates a care-of-address (CoA) and sends the Binding Update (BU) message containing the CoA and the mobile network prefix (MNP) to the home agent (HA) of the MR (Fig. 1-(2)). The MNP is the address prefix of the link with which the MR provides mobile nodes. Upon receiving the BU message, the HA creates the binding cache entry (BCE) such as MNP:CoA (Fig. 1-(3)). Next, the

HA returns the Binding Acknowledgement (BA) message to the MR (Fig. 1-(4)). As a result, a tunnel is established between the HA and MR (Fig. 1-(5)). Next, the MR sends the RA message containing the MNP to the LFN (Fig. 1-(6)). Upon receiving the RA, the LFN generates its IPv6 address. The data packet from the correspondent node (CN) to the LFN first reaches the HA. The HA forwards the packet to the MR by tunneling. The MR retrieves the original packet and forwards it to the LFN. The data packet from the LFN to the CN is also tunneled from the MR to the HA. The HA retrieves the original packet and forwards it to the CN (Fig. 1-(7)).

Figure 2 shows the case that a MR with a VMN is attached to an AR. The procedure of exchanging the BU/BA messages between the MR and the HA is the same as that in the case of LFN (Fig. 1-(1)–(6)). Upon receiving the RA message from the MR, the VMN generates a CoA and sends the BU message to the HA of the VMN (Fig. 2-(7)). Upon receiving the BU, the HA creates the BCE such as VMN:MNP-CoA (Fig. 2-(8)). VMN means the home address of the VMN and MNP-CoA means that the CoA is an address included in the range of MNP. Next, the HA returns the BA to the VMN (Fig. 2-(9)). As a result, a tunnel is established between the HA of the VMN and the VMN (Fig. 2-(10)). The data packet from the CN to the VMN first reaches the HA of the VMN. The HA of the VMN forwards the packet to the MNP-CoA by tunneling. Since the MNP-CoA is included in the range of the MNP, the packet reaches the HA of the MR. Next, the

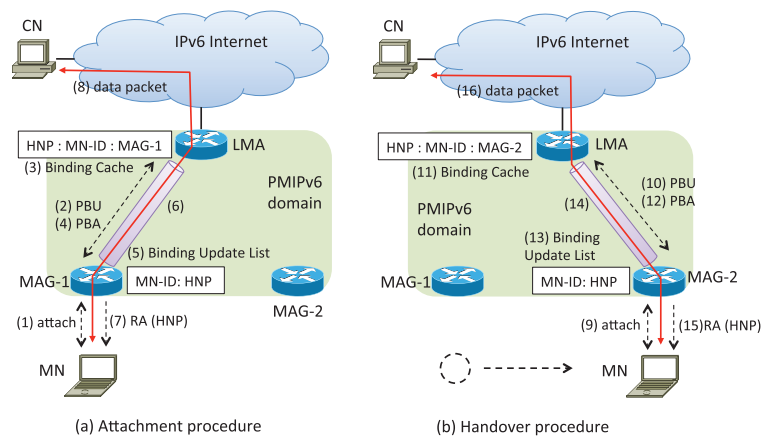


Fig. 3 Basic mechanism of PMIPv6.

HA of the MR forwards the packet to the MR by another tunneling. Upon receiving the packet with doubly tunneled packet, the MR removes the outer tunneling header and forwards the packet to the VMN. Upon receiving the packet, the VMN retrieves the original packet. The data packet from the VMN to the CN is first tunneled from the VMN to the HA of the VMN. This packet is also tunneled from the MR to the HA of the MR. Upon receiving the doubly tunneled packet, the HA of the MR removes the outer tunneling header and forwards the packet to the HA of the VMN. Upon receiving the packet, the HA of the VMN retrieves the original packet and forwards it to the CN (Fig. 1-(7)).

As described in Section 1, the handover time of NEMO-BS would be long if the signaling message such as the BU message is lost on the wireless link due to instability of the wireless link during handover.

2.2 PMIPv6

Figure 3 shows the basic mechanism of PMIPv6. It introduces the *Local Mobility Anchor (LMA)* as a local home agent. The LMA manages the current location of mobile nodes (MNs) in the PMIPv6 domain. The access router is called the *Mobile Access Gateway (MAG)*. When the MAG-1 detects attachment of a MN (Fig. 3-(1)), it registers the identifier of the MN (MN-ID) with the LMA by the *Proxy Binding Update (PBU)* message (Fig. 3-(2)). Upon receiving the PBU message, the LMA assigns the MN the *home network prefix (HNP)* and creates the BCE of the MN such as HNP:MN-ID:MAG-1 (Fig. 3-(3)). The HNP is the prefix of an IPv6 address belonging to the address block the LMA has. Next, the LMA returns the *Proxy Binding Acknowledgement (PBA)* message containing the HNP to the MAG-1 (Fig. 3-(4)). The MAG-1 creates the *binding update list entry (BULE)* of the MN (Fig. 3-(5)). As a result, a tunnel is established between the MAG-1 and the LMA (Fig. 3-(6)). Next, the MAG-1 sends the RA message containing the HNP to the MN (Fig. 3-(7)). Thus, the MN is not involved in the signaling procedure in PMIPv6.

The data packet from the CN to the MN first reaches the LMA. The LMA tunnels it to the MAG-1. The MAG-1 retrieves the original packet and forwards it to the MN. The data packet from the MN to the CN is tunneled by the MAG-1 to the LMA. The LMA retrieves the original packet and forwards it to the CN. (Fig. 3-(8)).

When the MN moves from the MAG-1 to the MAG-2, the MAG-2 detects the attachment of the MN (Fig. 3-(9)) and sends the PBU message containing the MN-ID to the LMA (Fig. 3-(10)). Upon receiving the PBU message, the LMA assigns the MN the same HNP and updates the BCE (Fig. 3-(11)). Next, the LMA returns the PBA message to the MAG-2 (Fig. 3-(12)). Upon receiving the PBA message, the MAG-2 creates the BULE (Fig. 3-(13)). As a result, a tunnel is established between the MAG-2 and the LMA (Fig. 3-(14)). Next, the MAG-2 sends the RA message containing the HNP (Fig. 3-(15)). Since the HNP remains unchanged after the handover, the MN is unaware of the handover.

As described in Section 1, the handover time of PMIPv6 is not affected by instability of wireless link during handover because the signaling messages are not transmitted on the wireless link. However, PMIPv6 does not support network mobility.

3. Related Work

This section surveys two proposals of network mobility protocols based on network-based localized mobility management.

3.1 N-PMIPv6

N-PMIPv6 [6] extends PMIPv6 to support network mobility. Figure 4 shows the basic mechanism of N-PMIPv6. N-PMIPv6 introduces the *moving MAG (mMAG)* in addition to the LMA and the MAG (fixed MAG). The mobile node connected to a mobile network is called the *Mobile Network Node (MNN)*. When a mMAG with a MNN attaches to the fixed MAG-1, the fixed MAG-1 sends the PBU message containing the mMAG-ID to the LMA (Fig. 4-(1)). Upon receiving the PBU, the LMA assigns the mMAG the HNP-1 and creates the BCE (Fig. 4-(2)). Next, the LMA returns the PBA to the fixed MAG-1 (Fig. 4-(3)). Upon receiving the PBA, the fixed MAG-1 sends the RA message containing the HNP-1 to the mMAG. (Fig. 4-(4)). Upon receiving the RA message, the mMAG sends the PBU message containing the MNN-ID to the LMA (Fig. 4-(5)). Upon receiving the PBU message, the LMA assigns the MNN the HNP-2 and creates the BCE (Fig. 4-(6)). N-PMIPv6 adds a new field, the *M flag*, to the BCE. The M flag of MNN's BCE is set to indicate that the MNN is connected to a mobile network. Next, the LMA returns the PBA to the mMAG (Fig. 4-(7)). Upon receiving the PBA, the

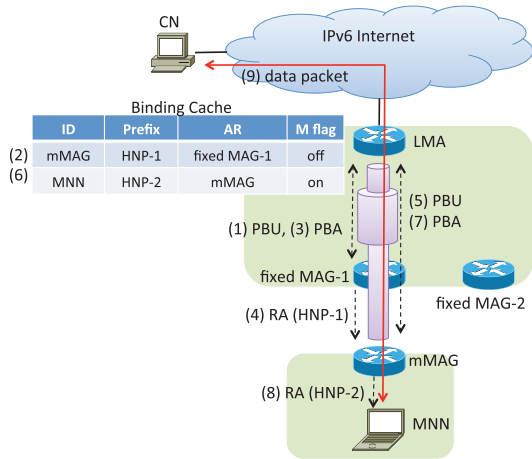


Fig. 4 Basic mechanism of N-PMIPv6.

mMAG sends the RA message containing HNP-2 to the MNN (Fig. 4-(8)).

The data packet destined to the MNN first reaches the LMA. The LMA finds MNN’s BCE. Since the M flag is on in MNN’s BCE, the LMA searches for mMAG’s BCE. Next, the LMA encapsulates the packet for tunneling to the mMAG and encapsulates it again for tunneling to the fixed MAG. The LMA forwards the packet to the fixed MAG. The fixed MAG removes the outer tunneling header and forwards it to the mMAG. The mMAG retrieves the original packet and forwards it to the MNN (Fig. 4-(9)).

When the mMAG moves to the fixed MAG-2, the same procedures as Fig. 4-(1)–(4) are executed. In this procedure, the AR field of the mMAG’s BCE is updated from fixed MAG-1 to fixed MAG-2. Other fields of mMAG’s BCE and MNN’s BCE remain unchanged. Thus, in N-PMIPv6, the signaling messages are not sent on the wireless link when a handover occurs.

However, as described above, N-PMIPv6 has large tunneling overhead because it uses multiple encapsulations. The deeper the nested level of the mobile networks becomes, the larger the tunneling overhead becomes. In addition, local communication has very large tunneling overhead because the communication path goes through the LMA. Local communication means the communication between two MNNs that are connected to different two mobile networks under the same MAG.

3.2 Network Mobility Support in PMIPv6 Network

Network Mobility Support in PMIPv6 Network (N-NEMO) [7] improves N-PMIPv6 to reduce tunneling overhead. **Figure 5** shows the basic mechanism of N-NEMO. It is composed of the LMA, the MAG, the MR, and the MNN. There are two types of MNNs: the LFN and the VMN as defined in NEMO-BS. As shown in Fig. 5, N-NEMO splits the tunnel to the MNN into two parts at the MAG to reduce tunneling overhead. N-NEMO defines two new signaling messages: the *Localized Proxy Binding Update (LPBU) message* and the *Localized Proxy Binding Acknowledgment (LPBA) message*. They are exchanged between the MR and the MAG to register the MNN with the MAG.

When a MR with a MNN attaches to the MAG-1, the MAG-1 sends the PBU message to the LMA (Fig. 5-(1)). Upon receiving

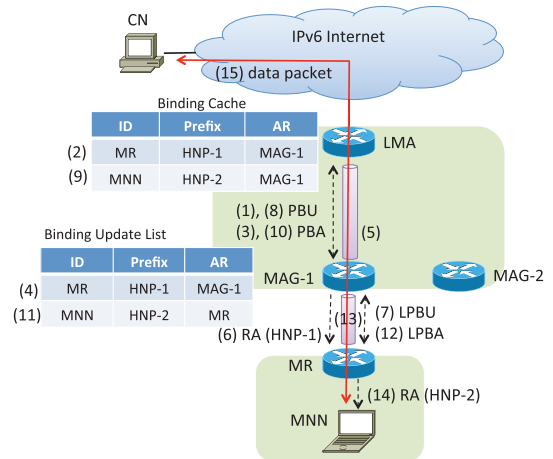


Fig. 5 Basic mechanism of N-NEMO.

ing the PBU message, the LMA assigns the MR the HNP-1 and creates the BCE entry (Fig. 5-(2)). Next, the LMA returns the PBA message to the MAG-1 (Fig. 5-(3)). Upon receiving the PBA message, the MAG-1 creates the BULE (Fig. 5-(4)). As a result, a tunnel is established between the MAG-1 and the LMA (Fig. 5-(5)). Next, the MAG-1 sends the RA message containing HNP-1 to the MR (Fig. 5-(6)). Since the MR knows that MNN is connected to it, it sends the LPBU message containing the MNN-ID to the MAG-1 (Fig. 5-(7)). Upon receiving the LPBU message, the MAG-1 sends another PBU message to the LMA (Fig. 5-(8)). Upon receiving the PBU message, the LMA assigns the MNN the HNP-2 and creates the BCE (Fig. 5-(9)). Next, the LMA returns the PBA message (Fig. 5-(10)). Upon receiving the PBA message, the MAG-1 creates the BULE (Fig. 5-(11)) and returns the LPBA message to the MR. (Fig. 5-(12)). As a result, a tunnel is established between the MR and the MAG-1 (Fig. 5-(13)). Next, the MR sends the RA message containing HNP-2 to the MNN (Fig. 5-(14)).

The data packet destined to the MNN first reaches the LMA. The LMA finds MNN’s BCE. The LMA tunnels the data packet to the MAG-1. Upon receiving the tunneled data packet, the MAG-1 retrieves the original packet. The MAG-1 finds MNN’s BULE. It encapsulate the packet and forwards it to the MR. Upon receiving the tunneled packet, the MR retrieves the original packet and forwards it to the MNN.

When the MR moves to the MAG-2, the same procedures (Fig. 5-(1)–(14)) are executed. Thus, in N-NEMO, the signaling messages are sent on the wireless link when a handover occurs although the tunneling overhead is reduced by avoiding multiple tunneling if the mobile network is not nested. However, if the mobile network is nested, N-NEMO also uses multiple tunneling. Thus, similar to N-PMIPv6, the deeper the nested level of the mobile network becomes, the larger the tunneling overhead becomes. N-NEMO has tunneling overhead in local communication because the communication path goes through the MAG.

As a summary of the survey of the related work, N-PMIPv6 avoids the transmission of the signaling messages on the wireless link when the MR executes handover. However, it has large tunneling overhead. N-NEMO reduces tunneling overhead by splitting the tunnel but the signaling messages are sent on the wireless

link when the MR executes handover. Both N-PMIPv6 and N-NEMO use multiple tunneling if the mobile network is nested. They have large overhead in local communication.

4. Design and Implementation of PNEMO

4.1 Overview of PNEMO

PNEMO employs network-based localized mobility management to avoid signaling message loss on wireless link during handover. The components of PNEMO are similar to PMIPv6 and NEMO-BS as described in Section 4.2. PNEMO also employs the home network prefix and the mobile network prefix defined in PMIPv6 and NEMO-BS. PNEMO employs only a single tunneling between the LMA and the MAG to avoid multiple tunneling if a mobile network is nested. To achieve this, PNEMO introduces the NEMO State Table (NST) in the MR as described in Section 4.3. In network-based localized mobility management, the MAG can obtain only the identity of the MR or the VMN that attaches to the MAG, i.e., the MAG cannot obtain the information of the VMN or the nested mobile network under the MR when the MR executes handover. To solve this, PNEMO extends the binding cache entry (BCE) in the LMA and the binding update list entry (BULE) in the MAG so that the LMA and MAG can manage the VMN or the nested mobile network as described in Section 4.3. To register the information of the VMN or the nested mobile network with the BCE and the BULE, PNEMO defines four control messages as described in Section 4.4.

4.2 Components and Prefixes in PNEMO

Similar to PMIPv6, PNEMO is effective in a domain called *the PNEMO domain*. The PNEMO domain is composed of the LMAs, the MAGs, the MRs, and the MNs. In case that the mobile network is nested, the MR in the lower level mobile network is called *the subMR*. The MN is categorized into the LFN (Local Fixed Node) and the VMN (Visited Mobile Node) as defined in NEMO-BS. PNEMO uses tunneling only between the LMA and the MAG even if the mobile network is nested. The LMA assigns the MR the HNP and the MNP. The HNP is used as the prefix of MR's IPv6 address while the MNP is used as the address prefix of the link to which the LFN is connected. The MR announces the MNP to the LFN by the RA message. The LFN generates its IPv6 address based on the MNP. Since the LMA assigns the MR the same HNP and MNP when the MR moves to another MAG, the IPv6 addresses of the MR and the LFN remain unchanged after MR's handover. The LMA assigns the VMN the HNP, which is used as the prefix of VMN's IPv6 address. Since the LMA assigns the VMN the same HNP when the VMN moves to another MR or MAG, VMN's IPv6 address remains unchanged after VMN's handover.

Figure 6 shows an example of a PNEMO domain composed of a LMA, two MAGs, and two mobile networks. The top level mobile network is composed of a MR (MR1), a LFN (LFN1), and a VMN (VMN1). The nested mobile network is composed of a subMR (MR2), a LFN (LFN2), and a VMN (VMN2). In addition, a VMN (VMN3) is directly connected to a MAG (MAG2). The MR1 is assigned MR1-HNP and MR1-MNP, and announces MR1-MNP to the LFN1 by the RA message while the

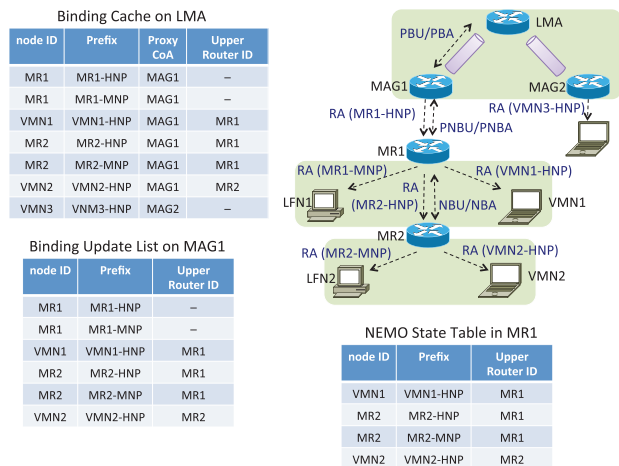


Fig. 6 PNEMO components and prefixes.

VMN1 is assigned VMN1-HNP. The MR2 is assigned MR2-HNP and MR2-MNP, and announces MR2-MNP to the LFN2 by the RA message while the VMN2 is assigned VMN2-HNP. The VMN3 is assigned VMN3-HNP.

4.3 Tables in LMA, MAG, and MR

PNEMO extends the BC (binding cache) in the LMA and the BUL (binding update list) in the MAG to manage MRs, subMRs, and VMNs. The BC in the LMA is composed of the BCEs (binding cache entries), each of which manages a MR, a subMR, or a VMN in the PNEMO domain. The BCE is composed of the node identifier (ID) field, the prefix field, the proxy CoA field, and the upper router ID field. The node ID field contains the identifier of the MR, the subMR, or the VMN. The prefix field contains the HNP or the MNP assigned to the MR, the subMR, or the VMN. The proxy CoA field contains the address of the MAG under which the MR, the subMR, or the VMN is connected. The upper router ID field contains the identifier of the upper level router to which the subMR or the VMN is connected. As shown in Fig. 6, the BC in the LMA is composed of entries of all nodes except for the LFN1 and the LFN2 in the PNEMO domain.

The BUL in the MAG is composed of the BULEs (binding update list entries), each of which manages the MR, the subMR, or the VMN under the MAG. The BULE is composed of the node ID field and the upper router ID field. The node ID field contains the ID of the MR, the subMR, or the VMN under the MAG. The upper router ID field contains the identifier of the upper level router to which the node of this entry is connected. As shown in Fig. 6, the BUL in the MAG1 is composed of entries of the MR1, the VMN1, the MR2, and the VMN2.

PNEMO introduces *the NEMO State Table (NST)* in the MR. The NST is composed of the NSTEs (NEMO state table entries), each of which manages the subMR or the VMN under the MR. The NSTE is composed of the node ID field and the upper router ID field. The node ID field contains the ID of the subMR or the VMN under the MR. The upper router ID field contains the identifier of the upper level router to which the node of this entry is connected. As shown in Fig. 6, the NST in the MR1 is composed of entries of the VMN1, the MR2, and the VMN2.

4.4 Control Messages

PNEMO introduces four signaling messages: the *Nested Binding Update (NBU) message*, the *Nested Binding Acknowledgment (NBA) message*, the *Proxy Nested Binding Update (PNBU) message*, and the *Proxy Nested Binding Acknowledgment (PNBA) message*. The NBU message and the NBA message are exchanged between the subMR and the upper level MR (or the subMR) to inform the upper level MR of the information of the lower level subMR and the VMN connected to the lower level subMR. When the MR (or the subMR) receives the NBU message from the lower level subMR, the MR creates the NSTEs of the lower level subMR and the VMNs included in the NBU message. In Fig. 6, for example, the MR2 sends the NBU message to MR1 to register the MR2 and the VMN2 with the NST in the MR1.

The PNBU message and the PBNA message are exchanged between the MR and the MAG to inform the MAG of the information of the MR, the subMRs and the VMNs under the MR. When the MAG receives the PNBU message from the MR, the MAG creates BULEs of the MR, the subMRs, and the VMNs included in the PNBU message. In Fig. 6, for example, the MR1 sends the PNBU message to the MAG1 to register the MR1, the VMN1, the MR2, and the VMN2 with the BUL in the MAG1.

Similar to PMIPv6, it is assumed that the MAG can detect attachment and detachment of the MR or the VMN. In addition, the MAG can detect the identifier of the attached or detached node. The MAG exchanges the PBU message and the PBA message with the LMA on behalf of the MR or the VMN. When the MAG detects attachment of the MR, the MAG sends the PBU message including the information of the nodes registered with the BUL to the LMA. Upon receiving the PBU message, the LMA creates the BCEs of the nodes included in the PBU message, assigns the HNP and/or the NMP, and returns the PBA to the MAG. Upon receiving the PBA message, the MAG creates the BULE of the MR and establishes a tunnel to the LMA. For data packet forwarding, the MAG also configures the routing information to the nodes registered with the BUL.

4.5 Registration Procedures

There are three cases in attachment of the VMN or the MR as follows:

- case-1: the VMN (or the MR) attaches to the MAG.
- case-2: the VMN (or the MR) attaches to the MR.
- case-3: the VMN (or the MR) attaches to the subMR.

Since the registration procedures of the VMN and those of the MR are the same, only the registration procedures of the VMN are described below. The difference between VMN’s attachment and MR’s attachment is that the HNP is assigned in case of VMN’s attachment while the HNP and the MNP are assigned in case of MR’s attachment.

4.5.1 Case-1: VMN’s Attachment to MAG

In this case, the VMN attaches to the MAG. Suppose that the VMN3 attaches to the MAG2 in Fig. 6. Figure 7 shows the registration procedure. In this figure, the fields written in red indicate the fields created by the registration procedure. The signaling sequence of this case is the same as that of PMIPv6.

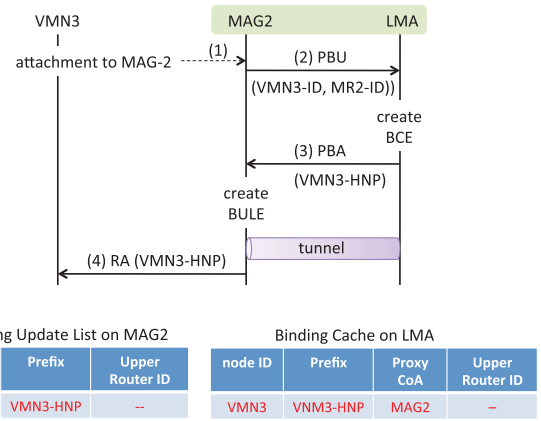


Fig. 7 Registration procedure (case-1).

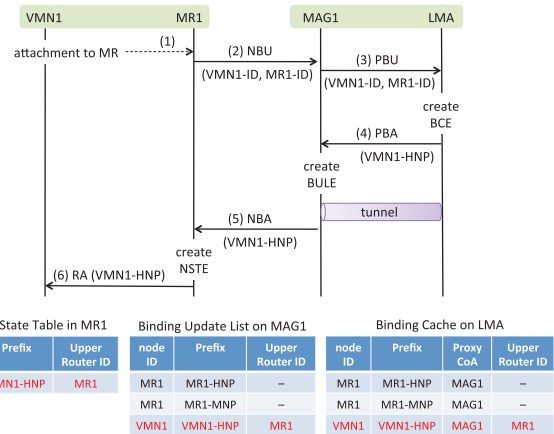


Fig. 8 Registration procedure (case-2).

When the MAG2 detects attachment of the VMN3 (Fig. 7-(1)), the MAG2 obtains VMN3-ID and sends the PBU message containing VMN3-ID and MAG2-ID to the LMA (Fig. 7-(2)). Upon receiving the PBU message, the LMA assigns the VMN3 VMN3-HNP. The LMA creates VMN3’s BCE and registers VMN3-HNP with the BCE. Next, the LMA returns the PBA message containing VMN3-HNP to the MAG2 (Fig. 7-(3)). Upon receiving the PBA message, the MAG2 creates VMN3’s BULE and registers VMN3-HNP with the BULE. At this point, the tunnel between the LMA and the MAG2 is established. Next, the MAG2 sends the RA message to inform the VMN3 of VMN3-HNP (Fig. 7-(4)).

The data communication procedure is omitted because it is the same as that of PMIPv6.

4.5.2 Case-2: VMN’s Attachment to the MR

In this case, the VMN attaches to the MR. Suppose that the VMN1 attaches to the MR1 in Fig. 6. Figure 8 shows the registration procedure. In this figure, the fields written in red indicate the fields created by the registration procedure. This procedure uses the NBU message and the NBA message defined in PNEMO to inform the MAG1 and the LMA of the information of the VMN1. When the MR1 detects attachment of the VMN1 (Fig. 8-(1)), the MR1 obtains VMN1-ID. Next, the MR1 generates the NBU message containing VMN1-ID and MR1-ID. the MR1 sends the NBU message to the MAG1 (Fig. 8-(2)). Upon receiving the NBU message, the MAG1 generates the PBU message containing VMN1-ID and MR1-ID. Next, the MAG1 sends the PBU message to the

LMA (Fig. 8-(3)). Upon receiving the PBU, the LMA assigns the VMN1 the VMN1-HNP and creates VMN1's BCE. VMN1-HNP and MR1-ID are registered with the BCE. Next, the LMA returns the PBA message containing the VMN1-HNP to the MAG1 (Fig. 8-(4)). At this point, the tunnel between the LMA and the MAG1 is established. Upon receiving the PBA message, the MAG1 creates VMN1's BULE and registers VMN1-HNP and MR1-ID with the BULE. Next, the MAG1 configures the routing information to the VMN1 and returns the NBA message containing VMN1-HNP to the MR1 (Fig. 8-(5)). Upon receiving the NBA message, the MR1 creates VMN1's BSTE and registers VMN1-HNP and MR1-ID with the NSTE. Finally, the MR1 sends the RA message to inform the VMN1 of VMN1-HNP (Fig. 8-(6)).

In data communication, a packet destined to the VMN1 first reaches the LMA. The LMA searches for the BC and finds VMN1's BCE. The LMA tunnels the packet to the MAG1 because the Proxy CoA field of VMN1's BCE indicates MAG1. Upon receiving the tunneled packet, the MAG1 retrieves the original packet. Next, the MAG1 searches for the BUL and finds VMN1's BULE. The MAG1 forwards the packet to the MR1 because the Upper Router ID of VMN1's BULE indicates the MR1. Upon receiving the packet, the MR1 forwards it to VMN1.

4.5.3 Case-3: VMN's Attach to subMR

In this case, the VMN attaches to the subMR of the nested mobile network. Suppose that the VMN2 attaches to the MR2 in Fig. 6. **Figure 9** shows the registration procedure. In this figure, the fields written in red indicate the fields created by the registration procedure. In this procedure, the MR2 (subMR) sends the NBU message to inform the MR1 of the information of the VMN2. When the MR2 detects attachment of the VMN2 (Fig. 9-(1)), the MR2 obtains VMN2-ID and generates the NBU message containing VMN2-ID and MR2-ID. Next, the MR2 sends the NBU message to the MR1 (Fig. 9-(2)). Upon receiving the NBU message, the MR1 sends the PNBU message containing MR1-ID, MR2-ID, and VMN2-ID to the MAG1 (Fig. 9-(3)). Upon receiving the PNBU message, the MAG1 generates the PBU message containing MR1-ID, MR2-ID, and VMN2-ID. The MAG1 sends the PBU message to the LMA (Fig. 9-(4)). Upon receiving the PBU message, the LMA assigns the VMN2 VMN2-HNP and creates VMN2's BCE. MR2-ID and VMN2-HNP are registered with the BCE. Next, the LMA returns the PBA message containing the VMN2-HNP to the MAG1 (Fig. 9-(5)). Upon receiving the PBA message, the MAG1 generates VMN2's BULE and registers VMN2-HNP with the BULE. Next, the MAG1 configures the routing information to the VMN2 and returns the PNBA message containing VMN2-HNP to the MR1 (Fig. 9-(6)). Upon receiving the NPBA message, the MR1 generates VMN2's NSTE and registers VMN2-HNP with the NSTE. Next, the MR1 configures the routing information to the VMN2 and returns the NBA message containing VMN2-HNP to the MR2 (Fig. 9-(7)). Upon receiving the NBA message, the MR2 generates VMN2's NSTE and registers VMN2-HNP with the NSTE. Finally, the MR2 sends the RA message to inform the VMN2 of VMN2-HNP (Fig. 9-(8)).

In data communication, a packet destined to VMN2 first reaches the LMA. The LMA searches for the BC and finds VMN2's BCE. The LMA tunnels the packet to the MAG1 be-

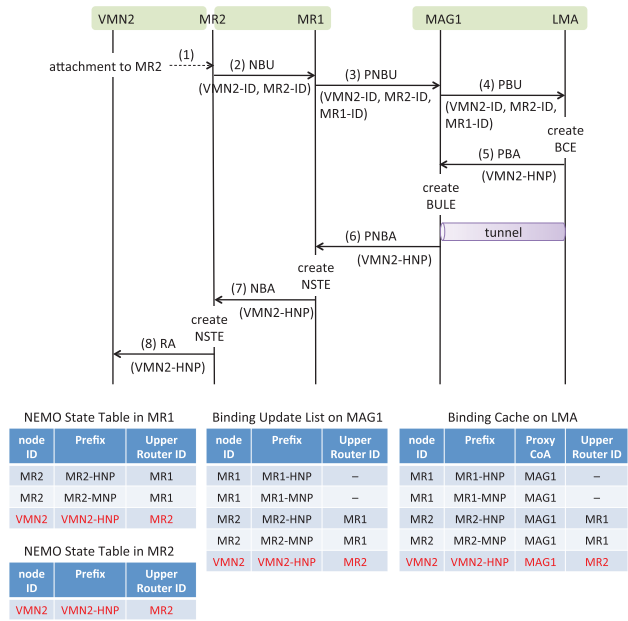


Fig. 9 Registration procedure (case-3).

cause the Proxy CoA field of VMN2's BCE indicates the MAG1. Upon receiving the tunneled packet, the MAG1 retrieves the original packet. Next, the MAG1 searches for BUL and finds VMN2's BULE. The MAG1 forwards the packet to the MR1 because the Upper Router ID field of VMN2's BULE indicates the MR1. Upon receiving the packet, the MR1 searches for the NST and finds VMN2's NSTE. Next, the MR1 forwards the packet to the MR2 because the Upper Router ID field of VMN2's NSTE indicates the MR2. Upon receiving the packet, the MR2 forwards it to the VMN2.

4.6 Handover Procedures

There are a lot of handover cases in terms of whether the mobile network is nested or not, whether the mobile node is the LFN or the VMN, and whether the VMN moves alone or the VMN moves with the MR. This paper describes the following typical three cases.

- case-1: the VMN moves from the pMAG (previous MAG) to the nMAG (new MAG).
- case-2: the MR with the LFN moves from the pMAG to the nMAG.
- case-3: the MR with the VMN moves from the pMAG to the nMAG.

4.6.1 Case-1: VMN's Handover between MAGs

This handover procedure is the same as that of PMIPv6. **Figure 10** shows the handover procedure. In this figure, the fields written in red indicate the fields modified by the handover procedure. First, the pMAG detects detachment of the VMN (Fig. 10-(1)). The nMAG detects attachment of the VMN and obtains VMN-ID (Fig. 10-(2)). Next, the nMAG sends the PBU message containing VMN-ID and the nMAG-ID to the LMA (Fig. 10-(3)). Upon receiving the PBU message, the LMA updates the Proxy CoA field of VMN's BCE. Next, the LMA returns the PBA message containing VMN-HNP. (Fig. 10-(4)). Upon receiving the PBA

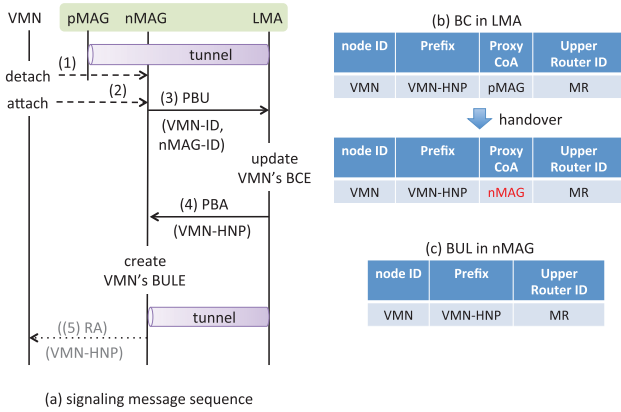


Fig. 10 Handover procedure (case-1).

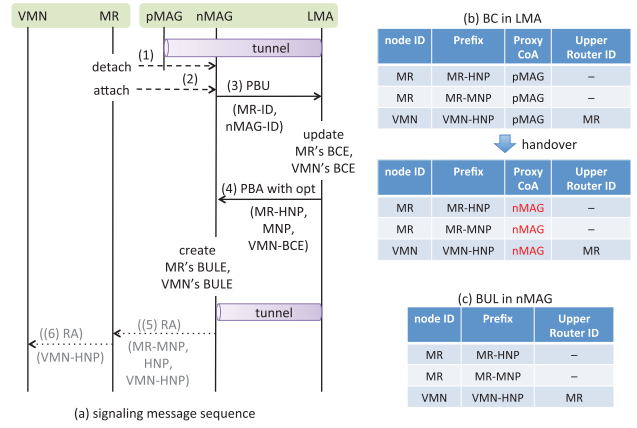


Fig. 12 Handover procedure (case-3).

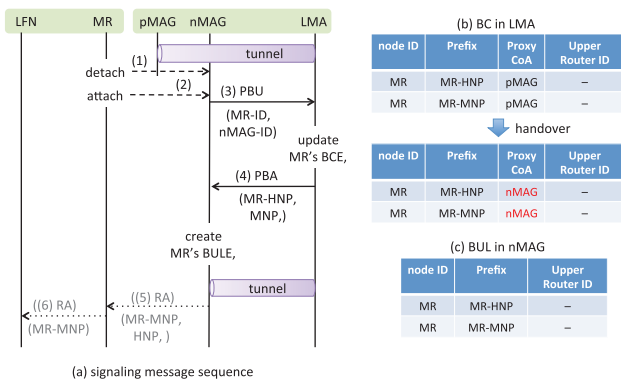


Fig. 11 Handover procedure (case-2).

message, nMAG creates VMN’s BULE. At this point, the tunnel between nMAG and the LMA is established. Next, the nMAG sends the RA message containing VMN-HNP to the VMN (Fig. 10-(5)). Note that the transmission of the RA message is not mandatory for the VMN because the HNP remains unchanged after the handover.

4.6.2 Case-2: Handover of MR with LFN between MAGs

Figure 11 shows the handover procedure of the case-2. In this figure, the fields written in red indicate the fields modified by the handover procedure. First, the pMAG detects detachment of the MR (Fig. 11-(1)). The nMAG detects attachment of the MR and obtains MR-ID (Fig. 11-(2)). Next, the nMAG sends the PBU message containing MR-ID to the LMA (Fig. 11-(3)). Upon receiving the PBU message, the LMA updates the Proxy CoA field of MR’s BCE and generates the PBA message containing MR-HNP and MR-MNP. Next, the LMA returns the PBA message to the nMAG (Fig. 11-(4)). Upon receiving the PBA message, the nMAG creates MR’s BULE and configures the routing information to the MR. At this point, the tunnel between the nMAG and the LMA is established. Next, the nMAG sends the RA message containing MR-HNP and MR-MNP (Fig. 11-(5)). Upon receiving the RA message, the MR sends the RA message containing MR-MNP to the LFN (Fig. 11-(6)). Note that the transmission of the RA messages in the steps 5 and 6 is not mandatory for the MR and the LFN because the MR-HNP and MR-MNP remain unchanged.

4.6.3 Case-3: Handover of MR with VMN between MAGs

Figure 12 shows the handover procedure. In this figure, the fields written in red indicate the fields modified by the handover procedure. First, pMAG detects detachment of the MR (Fig. 12-

(1)). The nMAG detects attachment of the MR and obtains MR-ID (Fig. 12-(2)). Next, the nMAG sends the PBU message containing MR-ID and nMAG-ID to the LMA (Fig. 12-(3)). Upon receiving the PBU message, the LMA updates the Proxy CoA field of MR’s BCE from pMAG-ID to nMAG-ID. The LMA searches for a BCE whose upper router ID field indicates MR-ID. As a result, VMN’s BCE is found. The LMA updates the Proxy CoA field of VMS’s BCE from pMAG-ID to nMAG-ID. Next, the LMA returns the PBA message containing the VMN’s BCE to the nMAG in addition to MR-HNP and MR-MNP (Fig. 12-(4)). Upon receiving the PBA message, the nMAG creates the BULEs of the MR and the VMN, and configures the routing information to the MR. At this point, the tunnel between the nMAG and the LMA is established. Next, the nMAG sends the RA message containing MR-HNP, MR-MNP, and VMN-HNP to the MR (Fig. 12-(5)). Upon receiving the RA message, the MR also sends the RA message containing VMN-HNP to the VMN (Fig. 12-(6)). Note that the transmission of two RA messages in steps 5 and 6 is not mandatory because MR-HNP and MR-MNP, and VMN-HNP remain unchanged.

4.7 Implementation

Our laboratory has an implementation of PMIPv6 on Linux. PNEMO was implemented based on this PMIPv6 implementation on Linux 2.6.29.5. The daemon program mip6d was modified as shown in Fig. 13.

5. Evaluation of PNEMO

5.1 Evaluation Environment

The performance of PNEMO was measured in a test network composed of one LMA, two MAGs, one MR, one subMR, one VMN or LFN, and one CN. The configuration of the test network and the specification of the machines are shown in Fig. 14. All the links are 100 Mbps Ethernet. The RTT between two adjacent nodes is less than 1 msec. This test network is used in the following subsections.

The Wireless Environment Emulator (WEE) was used to emulate the wireless link of the test network. The WEE was developed in our laboratory. It is software running on a PC with multiple network interfaces and emulates the behavior of a wireless link such as delay, jitter, bandwidth, and packet loss rate based on

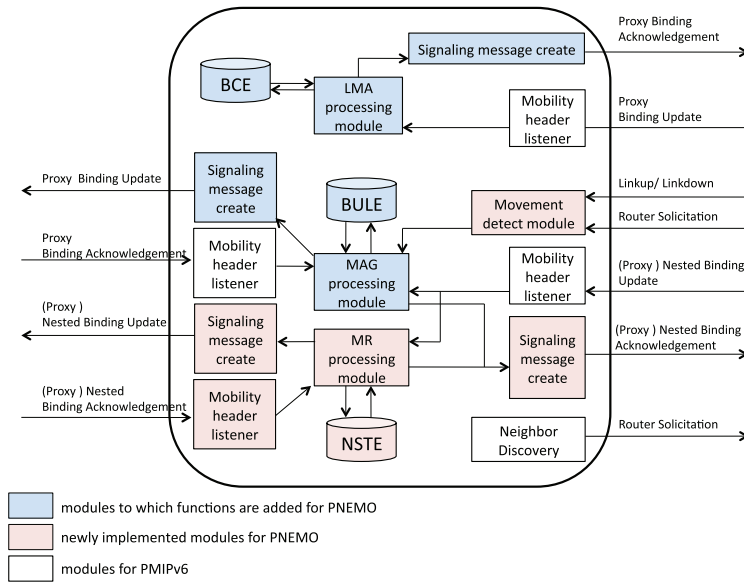


Fig. 13 Module diagram of PNEMO implementation.

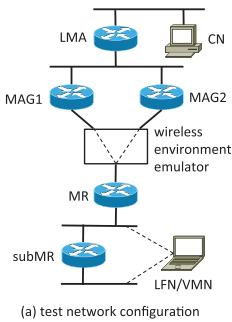


Fig. 14 Test network.

(b) machine specification

node	CPU	memory	OS
LMA	Celeron 1.86 GHz	2 GB	Linux 2.6.29.5
MAG1	Celeron 1.86 GHz	2 GB	Linux 2.6.29.5
MAG2	Celeron 1.86 GHz	2 GB	Linux 2.6.29.5
MR	Celeron 1.86 GHz	2 GB	Linux 2.6.29.5
subMR	Celeron 1.86 GHz	2 GB	Linux 2.6.29.5
LFN/VMN	Celeron 1.86 GHz	2 GB	Linux 2.6.24.16
CN	Core2 1.86 GHz	2 GB	Linux 2.6.24.16

Table 1 Registration time and handover time.

	case-1	case-2	case-3
registration time	2.50 msec	3.26 msec	4.19 msec
handover time	2.44 msec	2.56 msec	2.80 msec

Table 2 Processing time of PNEMO and PMIPv6.

	PNEMO	PMIPv6
Registration time	2.50 msec	2.19 msec
Handover time	2.44 msec	2.00 msec

Table 3 Processing time of PNEMO, NEMO-BS, and NEMO-FHO.

	PNEMO	NEMO-BS	NEMO-FHO
Registration time	2.83 msec	2605.25 msec	2.90 msec
Handover time	2.56 msec	1839.69 msec	2.59 msec

probability functions. It can also emulate handover according to the script. The values in Sections 5.2 and 5.3 were measured 10 times and the average was calculated.

5.2 Basic Performance

The registration time is the total of the processing time on each node from the time at which the attachment event is detected by the MAG or the MR to the time at which the RA message is transmitted by the MAG or the MR. The handover time is the total of the processing time on each node from the time at which the attachment event is detected by the nMAG to the time at which the nMAG receives the PBA message. Table 1 shows the registration time in each case described in Section 4.5 and the handover time in each case described in Section 4.6. Note that the registration time and the handover time do not include the communication delay. In an actual environment, the RTT between the MAG and the LMA and the RTT between the MAG and the VMN or the MR must be added. The sum of these RTTs would be less than 10 msec.

The registration time of case-2 is longer than that of case-1 and the registration time of case-3 is longer than that of case-2 because the number of message exchanges increases as the nested level becomes deeper.

5.3 Comparison with Related Work

Similar to PMIPv6, PNEMO supports host mobility. Table 2 shows the comparison of the registration time and the handover time of PNEMO and PMIPv6. The values of PMIPv6 were also measured in the test network. The values of PNEMO correspond to the values of the case-1 described in Section 5.2. Both procedures of PNEMO take approximately 0.4 msec longer than those of PMIPv6 because the functions for network mobility are also executed in PNEMO.

Similar to NEMO-BS and NEMO-FHO, PNEMO supports network mobility. Table 3 shows the comparison of the registration time and the handover time of PNEMO, NEMO-BS, and NEMO-FHO. The registration time is the time when a MR with a VMN attaches to a MAG. The handover time is the time when a MR with a VMN executes a handover between two MAGs. The performance of NEMO-BS and NEMO-FHO was measured in the test network. The registration time of PNEMO was also measured in the test network. The handover time of PNEMO corresponds to the value in the case-2 described in Section 5.2. Both procedures of NEMO-BS take time in order of second because it executes DAD (Duplicate Address Detection). Both procedures of NEMO-FHO take time in order of msec because NEMO-FHO eliminates DAD. Both procedures of PNEMO are a little bit faster

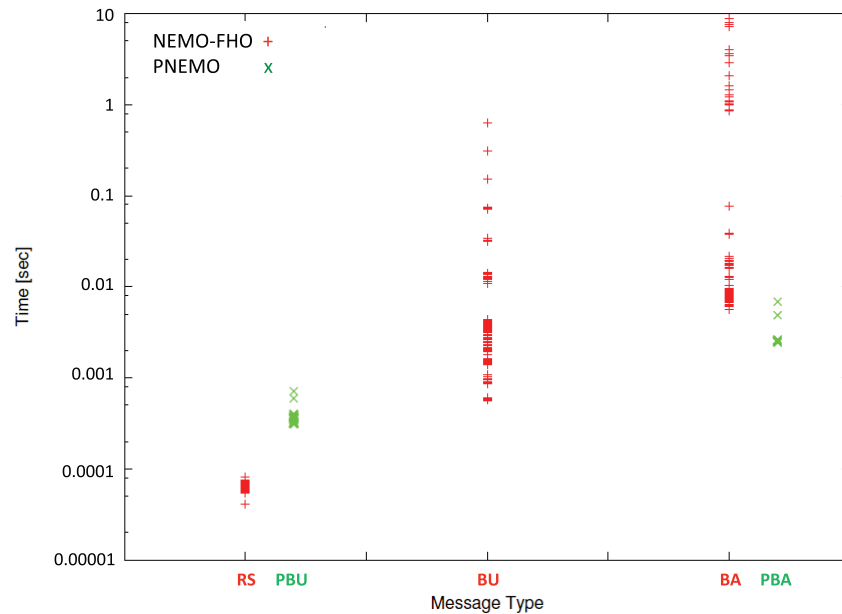


Fig. 15 Handover time of PNEMO and NEMO-BS (frame loss rate = 10%).

than NEMO-FHO because the MR is not involved in the signaling procedure in PNEMO.

5.4 Handover Time over Unstable Wireless Link

The handover time over a wireless link with 10% frame loss rate was measured 100 times for PNEMO and NEMO-FHO, respectively. In our experiments such as described in Ref. [3], instability of the infrared link during handover was observed. It was measured by the ping command at a 1-msec interval. However, it was impossible to formulate the loss pattern because it looked random. The frame loss rate was more than 10% at least. Therefore, 10% is used as the frame loss rate to make NEMO-FHO advantageous. Note that the frame loss rate does not affect the performance of PNEMO.

Figure 15 plots all values. The x-axis is the received signaling message type in PNEMO and NEMO-FHO, respectively. The y-axis is the time at which a signaling message was received. The time 0 is the time at which attachment of the MR is detected.

In case of NEMO-FHO, the times of RS reception, BU transmission, and BA reception by the access router are plotted. The completion of handover is defined as the time at which the BA is received. As Fig. 15 shows, the shortest handover time is in order of msec but the longest one is in order of second.

In case of PNEMO, the times of PBU transmission and PBA reception by the MAG are plotted. The completion of handover is defined as the time at which the PBA is received. As Fig. 15 shows, all measurement values are in order of msec. Thus, PNEMO can achieve stable handover even if the wireless link is unstable during the handover procedure.

6. Summary

This paper proposed PNEMO (Proxy Network Mobility Protocol), a network mobility protocol based on network-based localized mobility management. PNEMO uses tunneling only between the LMA and the MAG even if the mobile network is nested

to reduce tunneling overhead. Upon handover, since the signaling messages are exchanged between the MAG and the LMA, i.e., they are not transmitted on the wireless link, it makes handover stable even if the wireless link is unstable during handover. PNEMO was implemented on Linux. The measurement results show that the registration processing time is 2.5–4.2 msec and the handover processing time is 2.4–2.8 msec. The handover time over unstable wireless link is in msec order. If we have a chance, we would like to have experiments using a car or a train to make it sure that PNEMO achieves stable handover even if the wireless link is unstable during handover.

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Editor's Recommendation

The authors proposed a mobile network protocol based on network-based local mobility management, which protocol sup-

press the tunneling header overhead. In addition, it implements the proposed protocol, and the performance evaluation by comparison with existing protocols, have shown its effectiveness. The protocol design has been thoroughly tested, and have been for standardization activities, their usefulness is very high. Thus, this paper deserves recommendation from the SIGDPS committee.

(Chairman of SIGDPS Michiaki Katsumoto)



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