On design of a route-optimised and seamless HCoP-B scheme for nested mobile networks

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Abstract: In this paper, we first apply the hierarchical concept to the care-of prefix (CoP) scheme as HCoP and enhance HCoP with a novel binding update tree (BUT) structure as HCoP-B for network mobility (NEMO) management of the nested mobile network. Second, we further extend HCoP-B to support the seamless handoff of the nested NEMO. As compared to schemes such as reverse routing header (RRH), route optimisation using tree information option (ROTIO) and HCoP with numerical performance evaluations, HCoP-B achieves the shortest handoff latency and significantly reduces the consumed network bandwidth of global binding update messages for route optimisations (RO) of all correspondent nodes (CN) after the nested mobile network hands over to a new AR. Besides, HCoP-B also achieves shorter playback disruption time and buffering time than ROTIO does, which is the only one scheme mentioned how to achieve seamless handoff for the NEMO in the literature, for ongoing real-time multimedia applications whenever the mobile subnet in the old nested mobile network hands over to a new one.

Keywords: care-of prefix; CoP; hierarchical CoP; HCoP-B; NEMO; binding update tree; BUT; seamless handoff; high performance networking.


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1 Introduction

The IETF network mobility (NEMO) working group extends MIPv6 (Johnson et al., 2003) as the NEMO basic support (NBS) protocol (Devarapalli and Wakikawa, 2005) to manage NEMO for mobile nodes (MN) in a single-layer mobile network. NBS achieves performance improvements over MIPv6 for NEMO in terms of reduced transmission powers, the number of handoffs, complexities, bandwidth
consumptions and location update delays (Perera et al., 2004). NBS creates a bi-directional tunnel between the mobile router (MR) and its home agent (MR-HA) to avoid ingress filtering. However, NBS suffers the pinball routing problem and non-optimal transmission paths (Thubert and Molteni, 2004) in the nested NEMO, which further introducing significant delays and packet overheads.

For completing route optimisation (RO) with researches which inherit the concept from MIPv6, each MN must send a binding update (BU) message to notify every connecting correspondent node (CN) to divert the transmission path to the NEMO directly. Consider ten MNs in the NEMO are connecting with a CN, these MNs must immediately send ten duplicate BUs to the same CN for RO after the NEMOs handoff, which significantly wastes wireless and Internet bandwidths. We call it the RO storm problem. In this paper, we focus on resolving pinball routing and RO storm problems for the nested NEMO by proposing a novel hierarchical care-of prefix (CoP) with the binding update tree (BUT) scheme, which is called HCoP-B in this paper.

On the other hand, there have been lots of researches working on how to support the seamless handoff for the ongoing real-time application of the MN with the technique of buffering, bicasting, and soft handover. Oppositely, rare works mentioned this issue for the nested NEMO which consists of several MNs and MRs moving together (Cho et al., 2006; Chowdhury et al., 2007; Han et al., 2006). Only route optimisation using tree information option (ROTIO) (Cho et al., 2006) describes its flow to redirect on-the-fly packets to the current location of the handoff mobile network for reducing packet losses. In this paper, we will extend HCoP-B to support the seamless handoff with shorter playback disruption time and smaller buffer spaces than ROTIO for ongoing real-time applications executed by MNs in the nested NEMO.

This paper is organised as follows. Section 2 summarises related works on mobility of the nested NEMO. Section 3 describes the HCoP-B scheme, associated algorithms and seamless mechanisms. Section 4 analyses performances of HCoP-B for RO and seamless handoff and presents numerical evaluation results of all these schemes. Section 5 concludes this paper.

2 Related works

Reverse routing header (RRH) (Thubert and Molteni, 2004) uses a type 4 routing header from the MN to record the home address (HoA) of each intermediate MR in the nested NEMO. As the packet arrives at the HA of the MNs serving MR, i.e., the closest MR, these routing information is stored in its binding cache for determining the optimal route of packets back to the MN in a type 2 routing header. In this way, RRH only needs to build a bi-directional tunnel between the MN’s serving MR and the MR-HA, which resolves the pinball routing problem. However, RRH introduces extra packet length and processing overhead for the routing header of each packet. The CN and MR-HA need spaces to record routing information for each MN.

ROTIO proposes a routing optimisation scheme with the extended tree information option (xTIO) (Thubert et al., 2006). Each MR in the nested NEMO sends a normal BU, which contains the HoA of the top-level mobile router (TLMR), to its home agent and a local BU, which contains routing information between the issuing MR and the TLMR, to the TLMR. ROTIO suffers only two levels of nested tunnels, i.e., one between the closest MR of the MN and the MRs HA and the other between the TLMR and the TLMRs HA, to send a packet from a CN to an MN in the nested NEMO. However, ROTIO suffers the non-optimal transmission path, increased packet overhead and TLMR/MR binding cache sizes. Further, ROTIO also describes its flow to redirect on-the-fly packets to the current location of the handoff mobile network for reducing packet losses.

CoP (Suzuki et al., 2005) proposes a routing mechanism using hierarchical mobile network prefix assignment and hierarchical re-routing to optimise the routing and to reduce handoff signal overheads. The CoP flow consists of three stages:

1. the prefix delegation
2. the BU
3. packet re-transmission.

CoP resolves the pinball routing problem without suffering significant packet overheads of RRH. As the NEMO is allocated a new CoP, only one BU is sent by the TLMR to the aggregate router (AGR) to modify its binding cache instead of multiple BUs sent by all MNs in the NEMO, which reduces handoff signal overheads. However, CoP introduces problems. First, CoP spends more time to delegate CoPs for MRs of each level, which in turn raises total handoff latency. Second, the AGR cannot be placed at an optimal location for all CNs, which increases transmission delay and consumed bandwidth.

None of RRH, ROTIO and CoP mentions how to cope with the RO storm problem, which seriously degrades network performances resulting from the huge amount of BU messages simultaneously sent by MNs in the NEMO to all connecting CNs for RO after the NEMO handoff. Though ROTIO has proposed its seamless mechanisms for the handoff of the NEMO, it introduces relatively longer playback disruption time and buffering time of the MN. We will describe our HCoP-B in Section 3.

3 The HCoP-B scheme and the BUT handling algorithms

We propose the hierarchical CoP (HCoP) scheme in this paper by integrating the concept of the mobility anchor point (MAP) from HMIPv6 (Soliman et al., 2005) into the CoP approach. The TLMR of the nested NEMO, i.e., the MAP, manages CoP allocation, maintains the binding cache for all MNs and achieves optimal routing from the CN to the MN in the nested NEMO via it. However, HCoP suffers from the RO storm problem as RRH and CoP do. Hence, we
propose the HCoP with a novel BUT scheme, i.e., HCoP-B, to build a BUT on the MAP to record the NEMO topology and information about all connecting CNs of MNs, MR-HAs and VMN-HAs for the nested NEMO. HCoP-B achieves the following advantages:

1. **It reduces the handoff latency by overlapping the duration to perform the prefix delegation and local binding update (LBU) to the MAP, and global binding update (GBU) from the MAP to HAs and CNs for RO.**

2. **It reduces bandwidth of GBU messages for RO from MNs to all connecting CNs with our BUT handling algorithms.**

3. **It resolves the RO storm problem existed in RRH, ROTIO and HCoP.**

4. **It supports seamless handoff for the nested NEMO.**

### 3.1 HCoP-B prefix delegation

As soon as MR1, i.e., the MAP in Figure 1, receives new wireless beacon signals from an access router (AR), it sends a router solicitation (RS) message to the AR for requesting the AR to advertise the HMRA (Cho and Paik, 2004) message into the nested NEMO. With the allocated CoP (A::) in the HMRA message and the MAC address (MR1_ID) of the egress network interface, MR1 can configure its new CoA as A::MR1_ID. This prefix delegation process is repeated at each MR of every level, which introduces latency in the nested NEMO. With HCoP-B, each MR records the home prefix of its upper level MR from the received HMRA message for building network topology of the NEMO at BUT at the BU stage.

### 3.2 HCoP-B BU

#### 3.2.1 Building binding caches and NEMO topology in BUT

After the MR has configured its CoA, it sends only one LBU, which maintains the many-to-many mapping between the home prefix and the CoP of this MR, to the MAP to update the binding cache for all local fixed nodes (LFN) and local mobile nodes (LMN) of the MR. This part of binding cache is called the local binding cache (LBC) in HCoP-B. For example, after MR4 configures its CoA (Aa::MR4_ID) with the allocated CoP (Aa::), it will send an LBU, which maintains the mapping between Prefix_MR4 and MR4_CoP (Aa::) of MR4, for both MN1 and MN2 to MR1. Oppositely, the VMN has to send its own LBU to the MAP to build the visitor binding cache (VBC), which maintains an one-to-one mapping between the HoA and CoA (Aa::VMN_ID) of the VMN. HCoP-B gives the VBC with a higher precedence over the LBC for searching the correct CoA of the VMN when it leaves its home network. The VBC and LBC will also be built at MR-HAs, VMN-HAs and all CNs after RO by the GBU messages. For the MAP to build the LBC/VBC and nested NEMO topology in BUT, we modify the format of mobility option in the original BU message. We define a new type 16 and three new flags, V, U and R, for this modified message. If the V flag is set, the VMN sends its VMN-HoA and VMN-CoA in LBU to the MAP to create an entry in VBC; otherwise, the MR sends its home prefix (MR-HP) and corresponding CoP (MR-CoP) for updating its binding in LBC. Moreover, if the U flag is set, the MR sends the home prefix of its upper MR (Upper MR-HP) to the MAP for building correct NEMO topology.

#### 3.2.2 Processing the BUT information:

Figure 1 is illustrated as an example to exhibit how HCoP-B processes BUT information. When MN1 or VMN1 receives the first packet sent from CN1 (step 1), it will record the address of CN1 in its binding update list (BUL) (Johnson et al., 2003). With our proposed HCoP-B, MN1 will transmit this address on the modified mobility option of the LBU with the R flag set to its serving MR4 for adding CN1 with the counter value of one into the BUL of MR4 (step 2). This counter is used to record the total number of active connections from CN1 to MNs of MR4. Whenever the MR adds a new CN into its BUL, it will send this CN address to the MAP (MR1) on the modified mobility option of the LBU with the R flag set. Oppositely, if the counter value of a CN is greater than 1, which means this CN has ongoing connections with other MNs of the MR, the MR will not send an LBU to the MAP for reducing wireless bandwidth consumption between them. However, VMN1 itself issues an LBU to the MAP (step 3). After the MAP receives the LBU from MR4 or VMN1, it will record the address of CN1 at BUT entries of MR4 or VMN1 in the NEMO topology. Finally, the MAP will issue a GBU for MN1 or VMN1 to CN1 to create an entry in the LBC or VBC of CN1 (step 4). With cache information in the LBC and VBC, CN1 can first send packets through a single tunnel to the MAP and then the MAP forwards packets to MN1 or VMN1 without suffering the pinball routing problem. Consequently, HCoP-B achieves RO of CN for the nested NEMO.
3.3 HCoP-B handoff management

With HCoP-B, there are two handoff types for a NEMO subnet:

- **Intra-MAP Handoff**: Whenever a mobile subnet in the nested NEMO receives more than one HMRA messages from different MRs of the same MAP, it is executing an intra-MAP handoff. The leading MR of the subnet will issue an LBU, which contains the home prefix of the new upper MR, to the MAP to modify the network topology of the NEMO. After completing the prefix delegation in the subnet, all underlying MRs or VMNs will issue LBUs to the MAP to update contents of the LBC or VBC with the newly allocated CoPs or CoAs respectively.

- **Inter-MAP Handoff**: On the other hand, if a mobile subnet in the nested NEMO receives another HMRA message from an MR of a new NEMO, it is leaving the old MAP and executing an inter-MAP handoff to the new MAP. HCoP-B handles BUTs of the old and new MAPs in the detachment and re-attachment phases:

### 3.3.1 The detachment phase at the old MAP

As shown at step 1 in Figure 2, the leading MR (MR2) of the mobile subnet will first issue an LBU with a new flag G set in the BU header to notify the old MAP of its leaving. The old MAP then replies an LBA which contains BUT information for the leaving mobile subnet to the MR2 in a new mobility option (type = 24), which is shown at step 2 in Figure 2. Four new flags $t$, $π$, $m$ and $i$ are proposed in the LBA message. This information, which is illustrated inside the red box of Figure 2, includes the hierarchical network topology of the leaving mobile subnet as well as HAs and connecting CNs of all MRs and VMNs.

**Figure 2** The detachment phase of HCoP-B inter-MAP handoff with MR2 as its leading MR (see online version for colours)

For retrieving the hierarchical tree topology of the mobile subnet from the BUT of the old MAP, HCoP-B modifies the O-Tree algorithm (Keeler and Westbrook, 1995) into the `GET_BUT()` and `PUT_BUT()` procedures in this paper. The `GET_BUT()` procedure uses the leading MR of the subnet as the tree root and two arrays ($T$, $Π$) for the MAP to traverse the tree topology of the mobile subnet. The `GET_BUT()` writes ‘1’ into array $T$ to indicate that the visited node has child nodes or ‘0’ otherwise, which means the tree traversal process should backtrack to the parent node. At the same time, the home prefix for the visited MR or the HoA for the visited VMN is recorded in array $Π$. The `RDN()` procedure is for each visited node to remove duplicate connecting CNs, MR-HAs and VMN-HAs in the whole mobile subnet. Array $I$ maintains the list of non-duplicate CNs, MR-HAs and VMN-HAs. Two-dimensional array $M$ records corresponding indexes in array $I$ for all connecting CNs, the MR-HA or the VMN-HA of each visited node. Table 1 lists results of `GET_BUT()` when the mobile subnet with its leading MR2 in Figure 2 leaving the old MAP.

<table>
<thead>
<tr>
<th>$T$</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Π$</td>
<td>Prefix_MR2</td>
<td>Prefix_MR4</td>
<td>VMN1-HoA</td>
<td>Prefix_MR5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M[Prefix_{MR2}]$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$M[Prefix_{MR4}]$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$M[VMN1-HoA]$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$M[Prefix_{MR5}]$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$I$</td>
<td>MR2-HA</td>
<td>CN1</td>
<td>CN2</td>
<td>CN3</td>
<td>CN4</td>
<td>CN5</td>
</tr>
</tbody>
</table>

### 3.3.2 The re-attachment phase at the new MAP

As shown in Figure 3, when the mobile subnet with MR2 as its leading MR re-attaches into the new NEMO with MRa as its new MAP and receives a new CoP, HCoP-B overlaps the following two steps to resolve the RO-storm problem with HCoP-B.

**Step 1.1** MR2 sends BUT information of its mobile subnet, which is copied from the LBA message replied by the old MAP as described above, in the LBU with the mobility option (type = 24) to the new MAP MRa. As soon as MRa receives this information, it copies data into arrays $T$, $Π$, $M$ and $I$ and then performs the `PUT_BUT(MR2)` procedure to restore BUT information of the MR2 mobile subnet to the BUT of the new NEMO. Operations are repeated until all elements in array $T$ have been examined to completely rebuild the tree of the subnet in the BUT of the new MAP. Results are shown in Table 2.

**Step 1.2** At the end of `PUT_BUT()`, the new MAP collects non-duplicate BU information in the mobile subnet for all MR-HAs and active CNs. Then, the new MAP can issue only one GBU, which contains all Prefix_MRs and VMN-HoAs of this
node from array H. Hence, each CN, MR-HA or VMN-HA can simultaneously update all entries of these Prefix_MRs in its LBC and VMN-HoAs in its VBC with the mapping of Prefix_MR/VMN-HoA to the new MAPs RCoA or to the VMN-HA.

Step 2.1 MR2 continues advertising the HMRA message to delegate the CoP into the mobile subnet such that all underlying MRs and MNs can allocate new CoA addresses from the CoP in the HMRA message for later communication.

Step 2.2 After each MR/VMN acquires a new CoA, it issues an LBU to the new MAP to update its LBC/VBC with the mapping of the Prefix_MR/VMN-HoA to the new MR-CoP/VMN-CoA.

Figure 3 The re-attachment phase of HCoP-B inter-MAP handoff with MR2 as its leading MR (see online version for colours)

Table 2 Results of PUT_BUT(MR2) for Figure 3

<table>
<thead>
<tr>
<th>I</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR2-HA</td>
<td>Prefix_MR2</td>
</tr>
<tr>
<td>CN1</td>
<td>Prefix_MR4, VMN1-HoA, Prefix_MR5</td>
</tr>
<tr>
<td>CN2</td>
<td>Prefix_MR4, Prefix_MR5</td>
</tr>
<tr>
<td>CN3</td>
<td>Prefix_MR4, VMN1-HoA, Prefix_MR5</td>
</tr>
<tr>
<td>CN4</td>
<td>Prefix_MR4, Prefix_MR5</td>
</tr>
<tr>
<td>CN5</td>
<td>Prefix_MR4, VMN1-HoA, Prefix_MR5</td>
</tr>
<tr>
<td>MR4-HA</td>
<td>Prefix_MR4</td>
</tr>
<tr>
<td>VMN1-HA</td>
<td>VMN1-HoA</td>
</tr>
<tr>
<td>MR5-HA</td>
<td>Prefix_MR5</td>
</tr>
<tr>
<td>BUL[Prefix_MR2]</td>
<td>MR2-HA</td>
</tr>
<tr>
<td>BUL[Prefix_MR4]</td>
<td>CN1, CN2, CN3, CN4, CN5, MR4-HA</td>
</tr>
<tr>
<td>BUL[VMN1-HoA]</td>
<td>CN1, CN3, CN5, VMN1-HA</td>
</tr>
<tr>
<td>BUL[Prefix_MR5]</td>
<td>CN1, CN2, CN3, CN4, CN5, MR5-HA</td>
</tr>
</tbody>
</table>

3.3.3 Media re-transmission after RO with HCoP-B

As soon as the CN has updated its VBC and LBC for RO as above, HCoP-B only needs to build a tunnel to the MAP on the path from the CN to the MN, which solves the pinball routing problem.

3.4 HCoP-B seamless handoff

In this paper, depending on which destination the mobile subnet re-attaches to after handoff, we classify the seamless handoff of the nested NEMO into two cases.

3.4.1 The mobile subnet connects to a new AR and becomes a new NEMO by itself

As shown in Figure 4, the seamless handoff flow of HCoP-B for case 1 is described as follows:

1 When the mobile subnet with MR2 as its HLMR leaves its current NEMO with MR1 as the old MAP and re-attaches to AR2 directly, this mobile subnet itself becomes a new NEMO under AR2 and the HLMR, i.e., MR2, behaves as a new MAP. According to operations of the detachment phase described above, the new MAP, i.e., MR2, owns its BUT information which has been retrieved from MR1.

2 For this case, MR2 does not need to perform Step 1.1 of the re-attachment phase. It only has to issue modified GBU messages to all connecting CNs of MNs as Step 1.2. At the same time, MR2 further issues a handoff BU (Cho et al., 2006) which has the same format of the modified GBU message, to the old MAP MR1.

3 As soon as MR1 receives the handoff BU, it will immediately update corresponding entries of in its LBC and VBC with mappings of all Prefix_MRs/VMN-HoAs in the new NEMO to the RCoA of the new MAP MR2.

4 Whenever MR1 receives packets destined to an MN of the new NEMO, it will redirect them to MR2 through a tunnel between MR1 and MR2, according to the route specified by the mapping of its LBC/VBC. This packet redirection process is repeated until the CN is notified by the GBU issued from MR2 in Step 1.2. After that, the CN will route successive packets directly to MR2.

5 MR2 first decapsulates redirected packets from MR1 and then forwards them to the destination MN in the new NEMO by querying its LBC/VBC. In this way, packet losses of the MN during the handoff can be reduced by this kind of packet forwarding mechanisms in HCoP-B, without soft handover or bicasting techniques.
3.4.2 The mobile subnet connects to an MR and becomes a new subnet in a new NEMO:

As shown in Figure 5, the seamless handoff flow of HCoP-B for case 2 is similar to that of case 1. When the mobile subnet with MR2 as its HLMR leaves MR1 and re-attaches to MRa, i.e., the new MAP in the new NEMO, this mobile subnet joins this new NEMO. Compared to the flow of case 1, MR2 has to execute all detachment operations of Step 1.1 with MR1 and re-attachment ones of Step 1.2 with MRa to re-build corresponding information of this handoff mobile subnet in the BUT of MRa. After that, MRa has to issue the handoff BU to MR1 for packet redirection with Steps 3, 4 and 5 as in case 1.

Advantages of HCoP-B seamless handoff are listed below:

1. It conveys the handoff BU message from the new MAP to the old one only through the new and old ARs. Oppositely, the handoff BU of ROTIO suffers a much longer path, which traverses the HLMR, the new TLMR (MAP), the new AR, the new TLMR-HA, the old TLMR-HA, the old AR, the old TLMR, and the previous parent MR (PPMR) of the HLMR for case 2. Moreover, redirected packets will follow the reverse path of the handoff BU to the new NEMO, which means HCoP-B also achieves a much shorter route and transmission delay than ROTIO does for them. In this paper, we define the playback disruption time for the real-time multimedia application executed by the MN as the duration from the time when the handoff starts to the time when the first redirected packet is received by the deepest MN in the nested NEMO. Consequently, HCoP-B provides much smaller playback disruption time than ROTIO.

2. We have shown how HCoP-B supports shorter handoff latency than ROTIO, RRH and HCoP above. It means the MN with HCoP-B will receive successive packets, which adopts the direct path from the CN to the new MAP, earlier than the other three NEMO schemes. If redirected packets from the old NEMO arrive at the new NEMO later than successive ones via the direct path from the CN, all successive packets received before the last redirected packet must be buffered in the MN to reorder their sequences for correct playback. We define the duration to buffer these out-of order packets at the deepest MN as the buffering time in this paper.

4 Performance evaluations

In the following, we will analyse handoff latencies of ROTIO, RRH, HCoP and HCoP-B and playback disruption times and buffering times of ROTIO and HCoP-B. The handoff latency of each scheme is defined as the time to complete its handoff flow and resume packet transmissions to the deepest MN in the nested NEMO. Notations and their values used are listed in Table 3. We assume the topology of the nested NEMO is an L-level complete binary tree, as shown in Figure 6. Hop counts from the serving AR of the nested NEMO to the HA, $H_{i}^{AR}$, and to the active CN of the $i$th MR, $MR_{i}^{AR}$, at the $i$th layer are denoted as $H_{i}^{AR}$ and $H_{i}^{CN}$.
respectively. Their values are assumed to be uniformly distributed among one to 30 internet hops. Connecting CNs of MNs under any MR in the nested NEMO is uniformly selected from a set of ten CNs.

Table 3  Notations and their descriptions

<table>
<thead>
<tr>
<th>Notations</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>The number of levels of the nested NEMO</td>
</tr>
<tr>
<td>MR&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The ith MR at the ith layer of the nested NEMO</td>
</tr>
<tr>
<td>CN&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The set of connecting CNs under the ith MR at the ith layer of the nested NEMO</td>
</tr>
<tr>
<td>N&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The number of MRs and VMNs which have active connections with CN&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td>H&lt;sub&gt;D&lt;/sub&gt;</td>
<td>Distance in hop count from the source node S to the destination one D in the nested NEMO</td>
</tr>
<tr>
<td>t&lt;sub&gt;bc&lt;/sub&gt;</td>
<td>The processing time, which value is 1 ms, for the node to update the LBC/VBC when receiving the BU.</td>
</tr>
<tr>
<td>t&lt;sub&gt;cc&lt;/sub&gt;</td>
<td>The processing time, which value is 1 ms, for the MR to configure its new CoA when receiving the CoP from the MAP.</td>
</tr>
<tr>
<td>t&lt;sub&gt;a&lt;/sub&gt;</td>
<td>The propagation delay, which value is 2 ms/hop, between any two adjacent nodes in the nested NEMO.</td>
</tr>
<tr>
<td>t&lt;sub&gt;p&lt;/sub&gt;</td>
<td>The propagation delay, which value is 10 ms/hop, between any two adjacent nodes in the internet.</td>
</tr>
<tr>
<td>t&lt;sub&gt;RS&lt;/sub&gt;, t&lt;sub&gt;RA&lt;/sub&gt;</td>
<td>The propagation delay, which value is 2 ms/hop, to transmit the RS, RA, HMRA or RA-TIO message between two adjacent MRs in the nested NEMO.</td>
</tr>
</tbody>
</table>

4.1 Route optimisation using tree information option

As shown in Figure 7, when the mobile subnet of the nested NEMO with ROTIO executes its handoff, the HLMR, i.e., MR<sup>out</sup> in its intermediate MR list, which needs the time of t<sub>RS</sub> + t<sub>RA</sub> + t<sub>cc</sub>. After that, MR<sup>out</sup> sends the router advertisement message with extended tree information option (RA-xTIO) downward to each MR<sub>i</sub> at layer l under the HLMR such that each MR<sub>i</sub> can record the routing path from the new TLMR, i.e., MR<sup>out</sup> in its intermediate MR list, which consists of MR<sup>in</sup>, MR<sup>out</sup>, AR1, AR2, MR<sup>out</sup> and MR<sup>in</sup>, is equal to t<sub>a</sub> × (l<sub>PPMR</sub> + l + 3) + t<sub>out</sub> × H<sub>AR1</sub> + H<sub>AR2</sub>. On the other hand, after each MR<sub>i</sub> receives the RA-xTIO message, it then sends an LBU with its routing information to MR<sup>out</sup> and a GBU to its HA, i.e., HA<sub>out</sub>, for routing all successive packets to the MN in the new NEMO via the new TLMR-HA, i.e., HA<sub>out</sub> and AR2, instead of via oHA<sub>out</sub> and AR1 before the handoff. In ROTIO, the time for each HA<sub>out</sub> to receive the GBU message from its MR is t<sub>a</sub> × (l + 1) + t<sub>out</sub> × H<sub>AR1</sub> + t<sub>bc</sub>. After that, the MN will receive successive packets through the new path, i.e., HA<sub>out</sub> → AR1 → AR2 → MR<sup>out</sup> → MR<sup>in</sup> → MN, with the time of t<sub>out</sub> × (H<sub>AR2</sub> + H<sub>AR1</sub> + H<sub>AR2</sub>) + t<sub>a</sub> × (l + 2). Consequently, the handoff latency and maximal playback disruption time for ROTIO case 2 are formulated as equations (1) and (2), respectively. Further, the MN has to buffer all successive packets received before the last redirected packet such that the buffering time of ROTIO case 2 is formulated as equation (3).

4.2 Reverse routing header

When the nested NEMO with RRH executes its handoff, the TLMR, i.e., MR<sup>out</sup>, first performs prefix delegation to acquire its new MR-CoA with the time of t<sub>RS</sub> + t<sub>RA</sub> + t<sub>cc</sub>. After that, the TLMR issues the RA-TIO message into the nested NEMO level by level such that every underlying MR can configure its new MR-CoA and execute GBU through the new AR to its HA. If RO is required for RRH, each MR must send a GBU, containing a type 4 routing header, to each active CN for optimising the packet route from the CN to the MN. The total time, t<sub>RS</sub> + t<sub>RA</sub> + t<sub>CC</sub> such that the time spent for prefix delegation in the nested NEMO and that for all MRs to send GBUs to their connecting CNs.

\[
(t_{RS} + t_{RA} + t_{cc}) + t_{AR-RATIO} \times (1 - l_{HLMR}) + t_{bc}
\]

\[
(t_{RS} + t_{RA} + t_{cc}) + t_{in} \times (H_{AR2} + H_{AR1} + H_{AR2}) + t_{bc}
\]

\[
(t_{in} \times (H_{AR2} + H_{AR1} + H_{AR2}) + t_{bc}) + 2 \times t_{SR}
\]
When the nested NEMO with HCoP executes its handoff, the MAP first performs prefix delegation to acquire its new MR-CoA with the time of \( t_{iRM} + t_{HMRA} + t_{cc} \). The MAP then issues the HMRA message to every underlying MR for configuring its new MR-CoA one level by one level with the time of \( (t_{HMRA} + t_{cc}) \times l \). Then the MR executes LBU to the MAP and receives the LBA from the MAP with the time of \( 2 \times t_{in} \times (l+2) + H_{CN}^{AR2} + t_{bc} \). The handoff latency for the nested NEMO with HCoP is the sum of the time for delegating MAPs prefix, that for delegating prefixes within the nested NEMO, that for updating local bindings, and that for MRs and MNs to update global bindings in CNs. It is formulated as equation (5).

\[
t_{RS} + t_{iRM} \times (2 \times l + 6) + 2 \times t_{bc} + 2 \times t_{out} \times H_{CN}^{AR2} + (t_{HMRA} + t_{cc}) \times (l+1)
\]

### 4.4 HCoP-B

As shown in Figure 8, after the detachment, prefix delegation and LBU processes of the HLMR, which is denoted as \( MR_{HLMR}^{NEMO} \) at the \( l_{HLMR} \) layer in the old nested NEMO and \( MR_{HLMR}^{NEMO} \) at the \( l_{HLMR} \) layer in the new NEMO, of the mobile subnet with HCoP-B, \( MR_{0}^{NEMO} \) sends GBU messages to all connecting CNs and a handoff BU to \( oMR_{1} \) at the same time when \( MR_{HLMR}^{NEMO} \) delegates the CoP of the new NEMO into the mobile subnet for all underlying MRs/MNs to execute their local bindings with \( MR_{1} \). The CN routes all packets to the MN via the old path, i.e., \( CN \rightarrow AR_{1} \rightarrow oMR_{0} \rightarrow MR_{HL}^{NEMO} \rightarrow MN \), until it receives the GBU message from \( MR_{0}^{NEMO} \). Then all successive packets will follow the new route, i.e., \( CN \rightarrow AR_{2} \rightarrow MR_{0}^{NEMO} \rightarrow MR_{HL}^{NEMO} \rightarrow MN \), to the MN with the delay of \( t_{out} \times H_{AR2}^{CN} + t_{in} \times (l+2) \). The HCoP-B handoff latency is expressed as equation (6). As soon as \( oMR_{0} \) receives the handoff BU, it will redirect all following packets first to \( MR_{1} \) and then to the MN via AR1 and AR2. The delay of the first redirected packet issued from the CN to arrive at the MN in the new NEMO for HCoP-B case 2 is expressed as \( 2 \times t_{out} \times H_{AR2}^{CN} + t_{in} \times (l+5) \). Consequently, the maximal playback disruption time and buffering time of HCoP-B case 2 are formulated as equations (7) and (8) respectively.

\[
(t_{RS} + t_{HMRA} + t_{cc}) + 2 \times t_{bc} + (2 \times t_{in} + t_{out} + H_{CN}^{AR2}) + (t_{HMRA} + t_{cc}) + 2 \times t_{bc} + (2 \times t_{in} + t_{out} + H_{AR1}^{CN} + H_{AR1}^{AR2} + H_{AR2}^{CN})
\]

### 5 Experimental results

We will compare numerical results of handoff delays, consumed network bandwidth, playback disruption times and buffering times of GBUs with ROTIO, RRH, HCoP and HCoP-B schemes in this section. As shown in Figure 9, handoff latencies of ROTIO, HCoP, RRH and HCoP-B are grown as the level \( L \) of the nested NEMO raises, according to equations above. Because ROTIO still suffers the triangle route problem between the TLMR and its HA, it introduces the largest handoff latencies for the MN to receive packets from the CN after the NEMO handoff. As compared to HCoP, which cannot issue the GBU message to the CN for
RO until the prefix delegation and LBU stages have been finished, RRH can immediately execute operations for RO of the CN as soon as the MR receives the RA-TIO message and thereby has smaller handoff latencies than HCoP. However, with information recorded in the BUT of the MAP, HCoP-B overlaps executions of the prefix delegation and LBU stages inside the nested NEMO and the GBU stage for HAs and CNs outside, which achieve the smallest handoff latencies.

Figure 9  Handoff latencies of ROTIO, RRH, HCoP and HCoP-B for RO of CN (see online version for colours)

Depending on the information conveyed in the GBU message of ROTIO, RRH, HCoP and HCoP-B for RO of CNs, GBU messages of these four schemes have different packet lengths. For RRH, the MR at level $l$ issues the GBU message of length $(142 + 16 \times l)$ bytes, i.e., $2 \times$ IPv6 header + routing header + BU header + mobility option (TIO) = $2 \times 40 + [8 + 16 \times (l + 1)] + 6 + 32$, to record 16-byte home addresses of total $(l+1)$ MRs in the type 4 routing header. The consumed bandwidth of GBU messages with RRH in the nested NEMO is the sum of total GBU messages which are raised as L. GBU message lengths of ROTIO and HCoP are 144, i.e., $3 \times$ IPv6 Header + BU Header + CoA Option = $3 \times 40 + 6 + 18$, and 88, i.e., IPv6 Header + HAO + BU + CoA Option = $40 + 24 + 6 + 18$, bytes respectively such that consumed GBU bandwidths of these two schemes are both raised as L. However, HCoP-B sends only one modified GBU message, where records address information of length $(122 + 16 \times N_j)$, i.e., IPv6 Header + HAO + BU + type 16 mobility option = $40 + 24 + 6 + 4 + 16 \times 3 + 16 \times N_j$, for the number of $N_j$ MRs and VMNs which are collected in the array H of PUT_BUT(), to CN $j$ as described in Section 3. As shown in Figure 10, HCoP-B consumes the least amount of GBU bandwidth than HCoP, ROTIO and RRH in the nested NEMO as the level L increases.

Figure 10  GBU bandwidth consumptions of ROTIO, RRH, HCoP and HCoP-B for RO of CN (see online version for colours)

Based on analytical results formulated by equations (2) and (7), playback disruption times of ROTIO and HCoP-B are relative to values of $I_{HLMR}/I_{PPMR}$ and $J_{HLMR}/J_{PPMR}$ respectively. As the initial layer L of the nested NEMO in this simulation raises, their values and corresponding disruption times grow accordingly, which is shown in Figure 11. Further, because ROTIO has to issue the handoff BU from the HLMR to the PPMR in the old NEMO via the old TLMR-HA for redirecting all on-the-fly packets to the new NEMO, this redirection flow suffers three times of transmissions between nodes in internet, i.e., the old TLMR-HA ($oHA_0$), the old AR (AR1) and the new AR (AR2), and the round-trip path between the PPMR and AR1. Oppositely, by using the BUT information, the new MAP in HCoP-B can send the handoff BU to the old MAP for packet redirection only through the round-trip Internet path between AR1 and AR2. Consequently, HCoP-B achieves much shorter
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redirection path and thereby smaller playback disruption time for the real-time multimedia application than ROTIO, as shown in Figure 11.

Moreover, due to the extra round-trip path between the PPMR and the old TLMR for packet redirection, the MN with ROTIO has to spend more time to wait for the last redirected packet and buffer more successive packets received from the new path than that of HCoP-B, which can be observed from equations (3) and (8). As shown in Figure 12, HCoP-B provides shorter buffering times than ROTIO does, no matter what value of the initial layer (L) of the nested NEMO is.

Figure 12 Buffering time of ROTIO and HCoP-B (see online version for colours)

6 Conclusions

We have proposed the HCoP-B mobility management scheme for the nested NEMO with the novel BUT architecture and associated algorithms in this paper. Our HCoP-B scheme achieves the shortest handoff latency and the least amount of network bandwidth to connecting CNs for RO after the nested NEMO hands over to a new AR. With this mobility management scheme and the BUT architecture, the RO storm problem of the nested NEMO is solved. Furthermore, with the proposed packet redirection mechanisms between the old and new MAPs in this paper, HCoP-B also provides shorter playback disruption time and buffering time than ROTIO for the seamless handoff when the mobile subnet in the old nested NEMO hands over to a new one.

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References


