HCoP-B: A Hierarchical Care-of Prefix with BUT Scheme for Nested Mobile Networks

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Abstract—With current IETF Network Mobility (NEMO) Basic Support (NBS) to manage mobility of a mobile network which is moving as a whole, all communications to and from mobile network nodes inside the mobile network must go through multiple tunnels between upstream mobile routers and their home agents. This results in the non-optimized route and increased packet delay between communication peers. Hence, lots of network mobility schemes such as Reverse Routing Header (RRH), Mobile IPv6 route optimization for NEMO (MIRON) and Care-of Prefix (CoP) have been proposed to solve it. Whenever the whole mobile network or its mobile subnet change their points of network attachments, a huge amount of duplicate binding update messages are sent from the handoff mobile network to all connecting correspondent nodes on the Internet for establishing a direct and optimized packet route between them, which raises the corresponding consumed Internet and local wireless network bandwidth and in turn increases the packet transmission delay. However, traditional network mobility schemes cannot solve this serious binding update storm problem. In this paper, we apply the hierarchical concept to the CoP scheme as the Hierarchical CoP (HCoP) scheme and then enhance the HCoP with a novel Binding Update Tree structure as the HCoP-B for efficient NEMO mobility management of the nested mobile network. As compared to the traditional RRH, MIRON and HCoP with intensive performance analyses and simulations, HCoP-B achieves the shortest handoff latency, the lowest number of duplicate binding update messages conveyed over the Internet and the least amount of consumed Internet and local wireless network bandwidth for session initialization and route optimization of all connecting correspondent nodes at the expense of a small amount of extra binding caches in the binding update tree. We also discuss important issues about HCoP-B deployment, security and MAP location alternative. Consequently, HCoP-B achieves CN’s route optimization and resolves the associated binding update storm problem simultaneously for the nested mobile network.

Index Terms—Network Mobility, route optimization, binding update storm, binding update tree and HCoP-B

I. INTRODUCTION

NETWORK MOBILITY (NEMO) has been identified as an important concept of collective mobility of a set of mobile nodes as in the vehicular network [1]. The IETF Mobility EXTensions for IPv6 (MEXT) working group continues the work of its former, i.e., the NEMO one, and extends MIPv4 [2] as NEMOv4 [3] and MIPv6 [4] as the NEMO Basic Support (NBS) protocol [5] to manage network mobility for mobile network nodes (MNN) in a mobile network. The MIPv6 based NBS achieves performance improvements over MIPv6 for network mobility in terms of reduced transmission powers, the number of handoffs, complexities, bandwidth consumptions and location update delays [6]. 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 [7] in the nested, i.e., multi-layer, NEMO, which further introducing significant delays and packet overheads.

For researches which inherit the concept from MIPv6 to complete route optimization (RO) with the correspondent node (CN), each MNN must send a binding update (BU) message to notify every connecting CN to divert the transmission path directly to the current location of the NEMO after the NEMO’s handoff. Consider ten MNNs in the NEMO are connecting with a CN, e.g., a popular online video web site, these MNNs must immediately send ten duplicate BUs through MRs in the NEMO and routers on Internet to the same CN for RO, which will cause a burst of binding updates when the NEMO changes its point of network attachment and in turn waste wireless and Internet bandwidths [8]. When the mobile network is nested, the number of MNNs and connecting CNs can be huge, leading to severe network congestions and packet drops. It is called as the binding update storm problem [7], [9]. In this paper, we focus on resolving pinball routing and binding update storm problems altogether for the MIPv6-based 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.

This paper is organized as follows. Section 2 summarizes...
related works and their defects on mobility management of the nested NEMO. Section 3 describes the HCoP-B scheme and its associated algorithms to process the BUT such that the binding update storm problem can be resolved. Section 4 executes mathematical analyses for three representative NEMO schemes and the proposed HCoP-B on six performance metrics. Section 5 presents intensive simulation results of these metrics, which exhibits advantages of HCoP-B over these three traditional schemes. Section 6 discusses important issues about HCoP-B deployment, security and MAP location alternative. Finally, Section 7 concludes this paper.

II. RELATED WORKS

Besides the NBS protocol proposed by the NEMO working group, several NEMO schemes have been presented in the literature. They may differ from each other on their network topologies and approaches to acquire new CoAs, execute binding updates and generates different “optimal” routes between the CN and the MNN in the NEMO. There are three kinds of MNNs. The first one is the local fixed node (LFN) that is not mobile and does not have mobility support. The other two are mobile MNNs. A local mobile node (LMN) is typically a mobile node whose home network belongs to the mobile network. On the other hand, a visited mobile node (VMN) has a home network that does not belong to the mobile network [9]. According to differences on underlying network architectures, Lim [10] generally classified these NEMO schemes into three types: a) recursive approach; b) hierarchical approach; c) aggregation & surrogate (A&S) approach. The recursive approach requires sending the nested information of the nested NEMO on IPv6 routing header between network nodes like CNs, MRs and HAs, which have to cache and process this information [7], [11], [12]. The hierarchical approach is extended from the concept of HMIPv6 [13] to support micro-mobility by reducing the complexity on conveying control messages and thereby the length of the routing path [14]. The A&S approach updates routing information in the routing table of intermediate MRs inside the nested NEMO [15].

Reverse Routing Header (RRH) [7], which follows the recursive approach to avoid ingress filtering [16] in the MR, uses a type 4 routing header to record the care-of address (CoA) of each intermediate MR in the nested NEMO when the MNN first sends a packet to the CN. As the packet arrives at the HA of the MNN’s serving (closest) MR, these routing information is stored in the HA’s binding cache. Whenever the CN sends a packet destined to the MNN, this packet is routed to the HA of the MNN’s serving MR first and forwards to the MNN via an optimal route, according to CoAs of all intermediate MRs recorded in a type 2 routing header. In this way, RRH resolves the pinball routing problem. Moreover, as mentioned in Appendix A of [7], RRH can support route optimizations on the CN side in a way similar to that proposes for the HA side. 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 MNN. Similarly, ARO [11] explicitly describe address of Access Router (AR) in its control messages.

Hierarchical mobile network binding (HMNB) [17] adopts the hierarchical approach in the nested NEMO to propose the asymmetric tunneling and intra-domain communication mechanisms with its hierarchical local binding scheme and local binding cache management. However, HMNB suffers from its non-optimal routing path, extra binding cache consumption in each intermediate MR and asymmetric transmission delays for upward and downward transmissions. Oppositely, ROTIO [12], which combines concepts of both hierarchical and recursive approaches, proposes a routing optimization scheme with the extended tree information option (xTIO) [18]. However, ROTIO suffers two levels of nested tunnels as HMNB, i.e., one between the closest MR of the MNN and the MR’s HA and the other between the top-level mobile router (TLMR) and the TLMR’s HA, to send a packet from a CN to an MNN in the nested NEMO. Therefore, ROTIO also suffers from the non-optimal transmission path, increased routing-header packet overhead and extra TLMR/MR binding cache sizes.

Mobile IPv6 route optimization for NEMO (MIRON) [15], [19] follows the A&S approach to enable direct communication, i.e., route optimization, between the MNN and the CN. By using PANA and DHCPv6 functions in each MR to provide topologically meaningful IPv6 addresses to every child MR of the next lower layer and its VMN in the nested NEMO, every MR/VMN has an IPv6 address belonging to the foreign network that the TLMR is visiting. There are two types of operations in MIRON to enable RO for the CN. First, the MR performs the MIPv6 RO by sending the BU, which contains the address of the LFN as the HoA and the MR’s CoA as the CoA, to the CN on behalf of the LFN. Hence, packets sent by the CN follow a direct path to the MR and then to the LFN, according to the LFN’s address carried in the type 2 routing header of the packet. Second, MIRON allows the VMN to perform its own RO with the CN to avoid the MR-HA bidirectional tunnel. When a VMN attaches to a NEMO, MIRON uses the PANA protocol to authenticate and authorize this VMN and the DHCPv6 protocol to configure an IPv6 address for the VMN at its serving MR. The VMN then sends a BU message to its HA, performs return routability (RR) procedures with the CN for mitigating attacks, and conveys another BU to every CN to optimize the path between them. In this way, the pinball routing problem can be avoided by MIRON. However, MIRON lacks performance comparisons with other NEMO schemes, e.g., RRH, that support CN’s RO and improvements on its handoff latency, signaling overhead, etc.

Care-of Prefix (CoP) [20], which adopts the hierarchical and A&S approaches, proposes a routing mechanism using hierarchical mobile network prefix assignment and
hierarchical re-routing to optimize the routing and to reduce handoff signal overheads for a single-layer NEMO. It assumes each CN holds the address of a fixed aggregate router (AGR), which should be placed at the optimal location on the Internet, such that all packets destined for MNNs in the NEMO are carried via the AGR. The CoP handoff flow consists of three stages: 1) the prefix delegation stage for a new AR [20] or DHCPv6 server [21] to allocate the MR with a CoA which is topologically consistent with the hierarchical structure of the NEMO; 2) the binding update stage for the MR to send one BU containing the CoP and its local CoA to the AGR such that the AGR can maintain all the MNN-CoAs in a hierarchical manner; 3) the packet re-routing stage. Hence, the CN can send packets destined to an MNN via AGR directly. In essence, the AGR of CoP behaves as the MAP in HMIPv6. In this way, CoP resolves the pinball routing problem without suffering significant packet overheads of RRH. However, CoP introduces problems. First, CoP spends more time to delegate the care-of prefix for MRs of each layer, which in turn raises total handoff latency. Second, the AGR may not be placed at an optimal location for all CNs and the NEMO, which increases transmission delay, handoff latency and consumed bandwidth for BU messages. Unfortunately, AGR relocation procedure is also expensive.

Though RRH, MIRON and CoP could avoid the pinball routing problem with different ways, none of them further mentions how to cope with the binding update storm problem, which seriously degrades network performances due to the huge amount of duplicate BU messages simultaneously sent by MRs or MNNs in the nested NEMO to all connecting CNs for RO after the NEMO handoff. We will describe our HCoP-B, which is an integrated approach with both hierarchical and A&S concepts, to simultaneously achieve RO of all connecting CNs and resolve the binding update storm problem in Section 3.

III. THE HCoP-B SCHEME AND THE BUT HANDLING ALGORITHMS

As mentioned in Section 2, the CoP approach only supports mobility management of the single-layer NEMO. In this section, for localizing handoff signaling and optimizing routing of the nested NEMO, we will propose the hierarchical CoP (HCoP) scheme by integrating the mobility anchor point (MAP) of the hierarchical approach, like HMIPv6, into the A&S CoP approach. In order to avoid problems resulted from the fixed AGR in CoP, the TLMR of the nested NEMO is proposed to be as an MAP in HCoP for the nested NEMO, which is called as the hierarchical registration approach in [8]. Examples of this approach include [14], [22]. The Map in HCoP extends the CoP care-of prefix allocation to the nested NEMO, maintains the binding cache for all MRs/MNNs and achieves optimal routing from the CN to the MNN in the nested NEMO via it. During the prefix delegation stage of HCoP after handoff, each MR and underlying LMNs/VMNs configure their new CoAs layer by layer in the nested NEMO. After that, they execute their local binding updates to the MAP, where maintains corresponding binding entries for them. Moreover, based on the route optimization procedure of CoP, every LMN/VMN in the nested NEMO with HCoP has to send a BU to every connecting CN to register its CoA as the CoA of the MAP. On the other hand, because the LFN has no mobility support, its serving MR has to send the BU to the CN on behalf of its LFN. The detailed time flow of HCoP handoff process will be illustrated in Section 4.1 for analyzing its performance. As a result, HCoP has two obvious problems. First is the significant handoff latency spent on sequentially delegating the care-of prefix into the nested NEMO, updating the local binding in the MAP and the binding in each connecting CN. The value of the handoff latency is getting higher as the layer of the nested NEMO grows. Second, HCoP still suffers from the binding update storm problem as MIRON, RRH and CoP do. For resolving these two problems of HCoP, we will propose the HCoP with a novel binding update tree (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 MNNs, HAs of MRs (MR-HAs) and HAs of VMNs (VMN-HAs) for the nested NEMO. HCoP-B mobility management processes are described in detail as follows. With this BUT structure and two handling algorithms, HCoP-B reduces the handoff latency and overcomes the binding update storm problem of HCoP simultaneously. At the end of this section, we will summarize all HCoP-B benefits on mobility managements of the nested NEMO.

A. HCoP-B Prefix Delegation

As soon as MR1, i.e., the MAP in Fig. 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 Hierarchical Mobile Router Advertisement (HMRA) [23] message into the nested NEMO. HMRA employs a field for age in the original Router Advertisement (RA) message so that each MR in the nested NEMO can distinguish the RA of the parent MR from that of the child MR and construct the correct parent-child relationship by using this age information. Based on the IPv6 stateless address autoconfiguration mechanism [24], MR1 can configure its new CoA as A::MR1_ID with the delegated care-of prefix (A::), e.g., EF80::, in the HMRA message and the MAC address (MR1_ID) of the egress network interface. The maximal lengths of the home prefix and care-of prefix of an MR are 64 bits because interface MAC addresses, which are based on EUI-64 identifiers, are typically 64-bits long [24]. This prefix delegation process shown as step 1 in Fig. 1 is repeated at each MR of every layer by assigning a subset of the care-of prefix to its child MRs, which is similar to the traditional IP subnetting process [25]. For example, MR1 continues advertising a longer care-of prefix (Aa::), which is formed by concatenating the
delegated care-of prefix (A::) of MR1 and a special bit pattern (a) allocated to MR2, in the HMRA message to its child MR2. Please refer to [26] for this kind of prefix delegation on NEMO. This care-of prefix delegation process introduces latency in the nested NEMO. With HCoP-B, each MR records the home prefix of its upper layer MR from the received HMRA message for building network topology of the NEMO at BUT at the binding update stage mentioned below.

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Fig. 1. HCoP-B local binding update process after prefix delegation

B. HCoP-B Binding Update

Building binding caches and NEMO topology in BUT

After the MR has configured its CoA, it sends only one local binding update (LBU), which maintains the binding relationship between the home prefix and the care-of prefix of this MR, to the MAP to update the binding cache for all LFNs and LMNs of the MR. This part of binding cache is called the local binding cache (LBC) in HCoP-B. For example, as denoted as step 2.1 in Fig. 1, after MR4 has configured its CoA (Aaa::MR4_ID) with the delegated CoP (Aaa::) and the MAC address (MR4_ID), it will send an LBU, which provides the home prefix of its parent MR, i.e., Prefix_MR2, to build the nested NEMO topology in BUT and the mapping between Prefix_MR4 and MR4_CoP (Aaa::) of MR4, for both local MNN1 and MNN2 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 (Aaa::VMN_ID) of the VMN, which is denoted as step 2.2 in Fig. 1. 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. Finally, the MAP will send a binding update to each MR-HA for building an entry in MR-HA’s binding cache with the mapping between Prefix_MR and its RCoA, i.e., A::MR1_ID, which is denoted as step 2.3 in Fig. 1. Similarly, the MAP also issues a BU to each VMN-HA for creating a binding between the VMN-HoA in VMN-HA’s cache, as shown at step 2.4. These aforementioned procedures are common to both HCoP and HCoP-B.

For the MAP to build the LBC/VBC and nested NEMO topology in BUT of HCoP-B, we modify the format of mobility option in the original BU message. According to the current list of IANA mobile IPv6 parameters [27], we define a new type 28 mobility option with two new flags, V and R, as shown in Fig. 2. If the R flag is set, three fields, i.e., MR-HP (MR’s home prefix)/VMN-HoA, MR-CoP (MR’s care-of prefix)/VMN-CoA and Parent MR-HP (Parent MR’s home prefix), are presented in this type 28 mobility option. Hence, the MR/VMN can simultaneously create its entry in the LBC/VBC and BUT of the MAP by sending an LBU with the R flag set in the type 28 mobility option. Otherwise, the MR/VMN can only create its entry for recording the CN’s address of a newly established session in the BUT of the MAP by sending an LBU without setting the R flag in the type 28 mobility option, as described in the following four-step operations. The V flag is used to differentiate values recorded in the MR-HP/VMN-HoA, MR-CoP/VMN-CoA fields. If it is set, the VMN sends its VMN-HoA and VMN-CoA in the LBU to the MAP to create an entry in the VBC; otherwise, the MR sends its MR-HP and corresponding MR-CoP for updating its binding in the LBC. Moreover, if the R flag is set, the MR/VMN sends the home prefix of its parent MR, i.e., Parent MR-HP, to the MAP for building correct NEMO topology. Other fields in the modified mobility option will be mentioned later.

Fig. 2. Format of the modified type 28 mobility option in HCoP-B.

When a new CN sends the first data packet of a newly established session to an MNN/VMN:

Fig. 3 is illustrated as an example to exhibit how HCoP-B processes BUT information.
Fig. 3. The BUT building and route optimization flows for the CN in HCoP-B

Step 1: Because CN1 does not know the current CoA of the local node MNN1 or the visited node VMN1 when the session starts, it issues the first data packet to the home address of MNN1 or VMN1. This packet is first intercepted by MR4-HA or VMN1-HA and tunneled to the MAP, i.e., MR1, according to the binding information in the binding cache of MR4-HA or VMN1-HA. Then the MAP decapsulates this packet and forwards it directly to MNN1 or VMN1 by replacing the destination IP address with the binding information recorded in the MAP’s LBC or VBC. When MNN1 or VMN1 receives this packet, it will record the address of CN1 in its binding update list (BUL) [4].

Step 2: With HCoP-B, MNN1 will transmit this address at the field of \textit{BU nodes} in the modified type 28 mobility option of the LBU without the R flag set to its serving MR4 for adding the counter value of CN1 by 1 in the BUL of MR4. This counter is used to record the total number of active connections from CN1 to all local MNNs of MR4.

Step 3: Whenever the MR adds a new CN with the counter value of 1 into its BUL, it will also send this CN address to the MAP (MR1) at the field of BU nodes in the modified type 28 mobility option of the LBU without the R flag set. Oppositely, if the counter value of the CN is greater than 1, which means this CN has ongoing connections with other MNNs of the MR, the MR will not send an LBU to the MAP for reducing wireless bandwidth consumption between them. However, VMN1 maintains its own BUL and issues an LBU to the MAP by itself.

Step 4: After the MAP receives the LBU from MR4 or VMN1, it will record the address of CN1 at corresponding BUL entries of MR4 or VMN1 in the BUT for this newly established session. Finally, the MAP will issue a GBU for MNN1 or VMN1 to CN1 for RO by creating an entry in the LBC or VBC of CN1.

After these four steps, the optimized path between CN1 and MNN1/VMN1 has been created. Hence, by referring to cache information in the LBC/VBC, CN1 can first encapsulate every subsequent packet with the MAP’s RCoA, i.e., A::MR1_ID in Fig. 3, as the new destination IP address and send it through a single tunnel to the MAP without passing through MR4-HA or VMN1-HA. Then the MAP decapsulates and forwards it directly to MNN1 or VMN1 as the first packet to avoid the pinball routing problem. Consequently, HCoP-B achieves route optimization from the CN to the MNN and VMN in the nested NEMO except the first packet.

\textbf{Maintenance of BUT information:}

Without increasing the signaling overhead to maintain the BUT of the MAP, HCoP-B could let MRs in the NEMO piggyback the type 28 mobility option with the R flag set on the original local binding refresh (LBR) message, which is periodically issued to the MAP, to refresh the VBC and LBC of the MAP. Moreover, if the MR is notified that the count value of a CN in its BUL is zero, which means there is no MNN under the MR having active connection with this CN, the MR will delete the record of this CN in its BUL and immediately issue an LBR with the zero lifetime to the MAP for deleting this CN from the MR’s entry in the BUT. Similarly, if the VMN stops its connection with a CN, it will delete this CN in its BUL and then request the MAP to delete the CN from the VMN’s entry with an LBR with the zero lifetime.

\textbf{C. HCoP-B Handoff Management}

With HCoP-B, there are two handoff types for a mobile subnet in the nested NEMO:

\textbf{Intra-MAP Handoff:}

Whenever a mobile subnet in the nested NEMO receives a layer 2 handoff trigger from a different MR under its current MAP, it is executing an intra-MAP handoff. After the leading MR of the subnet receives the HMRA message, it will only issue an LBU, which contains the home prefix of the new parent MR, to the MAP to modify the network topology of the NEMO in the BUT. 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 MR-CoPs or VMN-CoAs respectively.

\textbf{Inter-MAP Handoff:}

On the other hand, if a mobile subnet in the nested NEMO receives a layer 2 handoff trigger 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 performs the detachment and re-attachment phases to maintain correct information in both BUTs of the old and new MAPs.

\textit{(a) The detachment phase at the old MAP:}

As shown at step 1 in Fig. 4, the handoff leading MR (HLMR), i.e., MR2, of the mobile subnet will first issue an LBU with a new flag \textit{G} set in the BU header to notify the old
MAP of its leaving. The old MAP then replies an LBA which contains corresponding BUT information of the leaving mobile subnet to the MR2 in another new type 29 mobility option with four new flags \(t, \pi, m, i\) set in the LBA message, as shown at step 2 in Fig. 4. The format of the type 29 mobility option is shown in Fig. 5. This BUT information, which is illustrated inside the red box of Fig. 4, includes the hierarchical network topology of the leaving mobile subnet as well as information of all MR-HAs/VMN-HAs and connecting CNs.

For retrieving the hierarchical tree topology of the mobile subnet from the BUT of the old MAP, we modify the O-Tree algorithm [28] into the \(\text{GET\_BUT()}\) and \(\text{PUT\_BUT()}\) procedures in HCoP-B to support traversal of the BUT tree where each node can have any number of children nodes. The \(\text{GET\_BUT()}\) procedure uses the leading MR of the subnet as the tree root and two arrays \((T, \pi)\) for the MAP to traverse the tree topology of the mobile subnet in its BUT. The \(\text{GET\_BUT()}\) writes “1” into array \(T\) to indicate that the visited node, i.e., MR or VMN, has child nodes or “0” otherwise, which means the tree traversal process should backtrack to the parent node of the visited one. At the same time, the home prefix of the visited MR or the HoA of the visited VMN is recorded in array \(\pi\). The \(\text{RDN()}\) 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 \(M\) further records corresponding indexes in array \(I\) for all connecting CNs, the MR-HA and the VMN-HA of each visited node. Pseudo codes of the \(\text{GET\_BUT()}\) and \(\text{RDN()}\) are listed below. At the end of \(\text{GET\_BUT()}\), values of \(R\) and \(K\) are total numbers of MRs/VMNs and HAs/CNs in the mobile subnet respectively. Their values and contents of these four arrays are recorded in the type 29 mobility option of LBA and are sent to the HLMR of the mobile subnet, as described above. Table 1 lists results of \(\text{GET\_BUT(MR2)}\) when the mobile subnet with its leading MR2 in Fig. 4 leaving the old MAP.

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**Pseudo codes of the \(\text{GET\_BUT()}\) algorithm are listed below:**

```plaintext
root = the leading MR of the mobile subnet;
R = 1; // R is the counter value for the number of MR/VMN in the mobile subnet

invoke \(\text{GET\_BUT(root)}\);
record the prefix of \(\text{root}\) in array \(\pi\);

GET\_BUT(node) { 
  invoke \(\text{RDN(node)}\) to remove duplicate nodes;
  flag = 0;
  Repeat {
    if \(\text{node}\) has unvisited child nodes then {
      child = one of the unvisited child nodes;
      add the prefix of \(\text{child}\) into array \(\pi\);
      record the value of \(I\) into array \(T\);
      \(R = R + 1\); // increase the counter value by 1
      invoke \(\text{GET\_BUT(child)}\);
    }
    else { // \(\text{node}\) has no unvisited child nodes
      record the value of \(0\) in array \(T\);
      flag = 1;
    }
  } until \(\text{flag} = 1\); // repeat the loop until all child nodes are visited
```

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\[//\text{end of GET\_BUT()}
\]

\[
\text{RDN(node) \{ //Remove Duplicate Node (CN/MR-HA/VMN-HA) \}
\]

\[
\text{static int } K \text{; \//variable } K \text{ records the end of array } I
\]

\[
B = BUL[node]; \text{ //array } B \text{ copies the connecting } CN/MR-HA/VMN-HA \text{ of node from the BUL}
\]

\[
\text{set each element } i \text{ of array } M[node, i] \text{ as } 0; \text{ //initialize array } M
\]

\[
\text{for each unvisited CN/MR-HA/VMN-HA in array } B \text{ \{}
\]

\[
\text{if (array } I \text{ is not empty) then } \{}
\]

\[
\text{if (CN/MR-HA/VMN-HA is found in array } I \text{ at index } i) \text{ then}
\]

\[
M[node, i] = 1; \text{ //for the HA or connecting CN of node found in array } I, \text{ record } I \text{ at array } M[node, i]
\]

\[
\text{else } \{} \text{ //CN/MR-HA/VMN-HA is a new element if it cannot be found in array } I
\]

\[
K = K + 1; \text{ //advance the end of array } I
\]

\[
I[K] = CN/MR-HA/VMN-HA; \text{ //append this CN/MR-HA/VMN-HA to the end of array } I
\]

\[
M[node, K] = 1; \text{ //for the new HA or connecting CN of node, record the last index } K \text{ of array } I \text{ to array } M
\]

\[\}} \text{ //end of RDN()}
\]

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### Table 1.

| \(T\) | \(|\Pi|\) | \(M[\text{Prefix}_MR2]\) | \(M[\text{Prefix}_MR4]\) | \(M[\text{VMN1-HoA}]\) | \(M[\text{Prefix}_MR5]\) | \(I\) |
|---|---|---|---|---|---|---|
| 1 | 0 0 0 0 0 0 0 0 | 0 1 1 1 1 1 0 0 | 0 1 1 1 1 0 1 0 | 0 1 1 1 1 0 0 1 | 0 1 1 1 1 0 1 0 | MR2-HA CN1 CN2 CN3 CN4 CN5 MR4-HA VMN1-HA MR5-HA |

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(b) The re-attachment phase at the new MAP:

As shown in Fig. 6, when the mobile subnet with MR2 as its HLMR re-attaches into the new NEMO with MRa as its new MAP and receives a new CoP \(Ba::\), HCoP-B overlaps the following two steps to achieve CN’s RO and resolve the binding update storm problem simultaneously.

Step 1.1: MR2 sends BUT information of its mobile subnet, which is retrieved from the LBA message replied by the old MAP in the detachment phase as described above, in a new LBU message with the type 29 mobility option to the new MAP MRa. As soon as MRa receives this LBU, it copies data from the LBU into arrays \(T, |\Pi|, M, I\) respectively and then performs the PUT\_BUT(MR2) procedure to restore corresponding BUT information of the mobile subnet with MR2 as its HLMR to the BUT of the new NEMO. PUT\_BUT() pops out the first element in array \(|\Pi|\), which is \(\text{Prefix}_MR2\), and sets \(\text{Prefix}_MR2\) as the child node of MRa, who advertises the HMRA message to the current node MR2. The RESTORE() procedure is invoked to restore CNs/MR-HAs/VMN-HAs, which is from array I, of the current node \(\text{Prefix}_MR2\) into the array BUL, depending on values of the current node in array \(M\). RESTORE() can also collect non-duplicate \(\text{Prefix}_MR/VMN\)-HoA information in array H for all elements, i.e., CNs/HAs, in array I. Then PUT\_BUT() rebuilds the tree topology of the mobile subnet with MR2 as the tree root. If the value of next element in array \(T\) is equal to 1, the current node is pushed into a stack and next element in array \(|\Pi|\) is set as the new current node to restore its information in array BUL and H. Otherwise, the current node is set as the node popped from the stack, which means that the current node has no more child nodes to visit and its parent node would be the next node to continue the tree traversal of the mobile subnet. Operations are repeated until all elements in array \(T\) have been examined to completely rebuild the subnet tree in the BUT of the new MAP. Results of PUT\_BUT(MR2) are listed in Table 2.

Step 1.2: At the end of PUT\_BUT(MR2), the new MAP collects non-duplicate binding update information in the mobile subnet for all MR-HAs/VMN-HAs and active CNs. Then, for executing the route optimization and global binding update to each CN, MR-HA and VMN-HA in array I, the
Step 2.2: After each MR/VMN acquires a new CoA, it will
Step 2.1: At the same time of Steps 1.1 and 1.2, MR2 continues
advertising the HMRA message to delegate the CoP into the
VMN-HA. As shown in Fig. 6, the new MAP with HCoP-B
will issue a GBU message to CN1 to update entries of
Prefix_MR4 and Prefix_MR5 in CN1’s LBC and that of
VMN1-HoA in its VBC, instead of three GBU messages
sent by RRH, MIRON and HCoP.
Step 2.1: At the same time of Steps 1.1 and 1.2, MR2 continues
advertising the HMRA message to delegate the CoP into the
mobile subnet such that all underlying MRs and MNNs can
acquire their 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 will
issue an LBU with a type 28 mobility option 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
respectively.

<table>
<thead>
<tr>
<th>Table 2. Results of PUT_BUT(MR2) for Fig. 6.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H [MR2-HA]</td>
</tr>
<tr>
<td>H [CN1]</td>
</tr>
<tr>
<td>H [CN2]</td>
</tr>
<tr>
<td>H [CN4]</td>
</tr>
<tr>
<td>H [MR4-HA]</td>
</tr>
<tr>
<td>H [VMN1-HA]</td>
</tr>
<tr>
<td>H [MR5-HA]</td>
</tr>
<tr>
<td>BUL[Prefix_MR2]</td>
</tr>
<tr>
<td>BUL[Prefix_MR4]</td>
</tr>
<tr>
<td>BUL[VMN1-HoA]</td>
</tr>
<tr>
<td>BUL[Prefix_MR5]</td>
</tr>
</tbody>
</table>

Pseudo codes of the PUT_BUT() algorithm are listed below:

```plaintext
PUT_BUT() {
    node = the first element of array T;
    set node as the leading MR of the mobile subnet and attach node to
the upper MR in the new NEMO;
    invoke RESTORE(node); //restore information of node into
the BUL of the new NEMO and array H

    Repeat {
        if (the value of next element in array T is 1) then {
            //next element is the child of node
            push node into stack; //for later backtracking
            node = next element of array T; //get the child node of node
            invoke RESTORE(node); //restore information of current node;
        } else //the value of next element in array T is 0, which means that
            node has no more child nodes
        node = the node popped from stack; //backtrack to the parent
            node
    } until (every element in array T is visited);
}; //end of PUT_BUT()
```

(c) Media transmission after route optimization with HCoP-B
As soon as the CN has updated its VBC and LBC for RO as
described above, it only needs to build a tunnel to transmit all
encapsulated packets to the MAP. Then the MAP decapsulates
these packets and forwards them directly to the MNN. In this
way, HCoP-B avoids the pinball routing problem.

D. HCoP-B Benefits on Mobility Managements of Nested
NEMO

From descriptions about HCoP-B prefix delegation, binding
update and handoff management processes above, we can
conclude the following advantages of HCoP-B:

1) It achieves an optimal route from the CN to the MNN
through the MAP in the nested NEMO without suffering
the pinball routing problem.

2) It reduces the handoff latency of a moving mobile subnet
by overlapping two parts of mobility management
processes: the first part is the process to perform the prefix
delegation inside the mobile subnet and the LBU messages
to the MAP and the second one is that to issue the GBU
messages from the MAP to MR-HAs/VMN-HAs and CNs,
which are located on the Internet, for RO. This handoff
latency reduction is much more significant as the layer of
the nested NEMO grows.

3) It also reduces the number of GBU messages and corresponding
consumed Internet and local wireless
bandwidth for RO from MNMs to all connecting CNs with
our BUT structure and handling algorithms at the cost of a
little higher extra binding caches, which exhibits the
performance tradeoff between the extra binding cache
consumption and the other five metrics of HCoP-B.
However, from simulation results in Section 5, we can
observe that performance improvements of the other five
metrics are worthy to consume a little more extra binding
caches in HCoP-B. This means HCoP-B resolves the
binding update storm problem existed in RRH, MIRON,
HCoP and other NEMO schemes in the literature.

4) It supports mobility management for all kinds of mobile
nodes, i.e., LFN, LMN and VMN in the nested NEMO.
IV. PERFORMANCE ANALYSIS

In this section, we will mathematically evaluate five performance metrics for handling CN’s RO at the handoff of the mobile subnet and another one for session initialization in a nested NEMO, which is assumed as an L-layer full N-ary tree, with MIRON, RRH, HCoP and HCoP-B schemes. We assume all MNNs are VMNs to simplify the analysis here. These six performance metrics are:

1. The handoff delay.
2. The number of GBUs for RO of CNs when handoff.
3. The consumed Internet bandwidth of GBUs for RO of CNs when handoff.
4. The extra binding cache sizes when handoff.
5. The local wireless bandwidth consumption inside the NEMO when handoff.
6. The local wireless bandwidth consumption inside the NEMO for session initialization.

Notations and their values used in this analysis are listed in Table 3.

<table>
<thead>
<tr>
<th>Notations</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>The number of layers in the nested NEMO</td>
</tr>
<tr>
<td>$MR_i$</td>
<td>The $i$th MR at the $i$th layer of the nested NEMO</td>
</tr>
<tr>
<td>$CN_i$</td>
<td>The set of connecting CNs under the $i$th MR at the $i$th layer of the nested NEMO</td>
</tr>
<tr>
<td>$N_i$</td>
<td>The number of MRs and VMNs which have active connections with $CN_i$</td>
</tr>
<tr>
<td>$D^{S}$</td>
<td>Distance in hop count from the source node $S$ to the destination one $D$</td>
</tr>
<tr>
<td>$t_{bc}$</td>
<td>The processing time, which value is 1ms, for the node to update its binding cache.</td>
</tr>
<tr>
<td>$t_{ce}$</td>
<td>The processing time, which value is 1ms, for the MR to configure its new CoA when receiving the CoP from the MAP.</td>
</tr>
<tr>
<td>$t_{in}$</td>
<td>The propagation delay, which value is 2ms/hop, between any two adjacent nodes in the nested NEMO.</td>
</tr>
<tr>
<td>$t_{out}$</td>
<td>The propagation delay, which value is 10ms/hop, between any two adjacent nodes in Internet.</td>
</tr>
<tr>
<td>$t_{RS}$, $t_{RA}$</td>
<td>The propagation delay, which value is 2ms/hop, to transmit the RS, RA, HMRA, RA-TIO, DHCP request or DHCP reply message between two adjacent MRs in the nested NEMO.</td>
</tr>
<tr>
<td>$t_{DHCP}$, $t_{RR}$</td>
<td>The propagation delay, which value is 2ms/hop, to transmit the RA, HMRA, RA-TIO, DHCP request or DHCP reply message between two adjacent MRs in the nested NEMO.</td>
</tr>
<tr>
<td>$t_{DRreq}$, $t_{DHCP}$</td>
<td>The propagation delay, which value is 2ms/hop, to transmit the RA, HMRA, RA-TIO, DHCP request or DHCP reply message between two adjacent MRs in the nested NEMO.</td>
</tr>
</tbody>
</table>

A. The handoff latency

The handoff latency of each scheme is defined as the time to complete its handoff flow for route optimization of all connecting CNs and then resume packet transmissions to the deepest MNN in the nested NEMO. Please note that the MNN with RRH issues its first packet, which works as GBU messages sent by the MNN with MIRON, to connecting CNs when the mobile subnet executes both intra-MAP and inter-MAP handoffs. On the other hand, HCoP and HCoP-B only send GBUs to connecting CNs for the inter-MAP handoff.

- **RRH:**
  For providing a fair comparison to RRH, HCoP and HCoP-B on the handoff latency, we omit the authentication- and security-related PANA and RR operations of MIRON as shown in Fig. 7-1. When the mobile subnet of the nested NEMO with MIRON executes its handoff, the HLMR, i.e., $MR_{\text{outer}}$, issues the DHCP request (Dreq) message first to its parent MR (PMR) in the new nested NEMO for requesting its new MR-CoA that is returned in the DHCP reply (Drep) message, which spends the time of ($t_{DRreq} + t_{DHCP} + t_{ce}$). After that, each $MR_i$, including the HLMR and all MRs under the HLMR, can immediately follow the same DHCP operation to configure their topologically meaningful CoAs from its parent MR with the time ($t_{DRep} + t_{ce}$) × $(l - l_{HLMR} + 1)$ as soon as the parent MR receives its CoA. Each $MR_i$, including the HLMR and all MRs under the HLMR, and its MNNs will send GBUs and receive corresponding GBAs to update binding caches of its $HA_i$ and all connecting CNs respectively with the maximal time of $2 \times [t_{in} \times (l + 2) + t_{out} + H^{SR}] + t_{bc}$, where $D \in \{ \text{all } HA_i \text{ and } CN_i \}$. Hence, the MNN will receive resumed packets directly from CNs after GBAs. Consequently, the maximal MIRON handoff latency for the MNN in the mobile subnet to receive resumed packets through the new AR is formulated as (1), no matter what kind of handoff is executed.

\[
t_{HLMR} = (t_{DRreq} + t_{DHCP} + t_{ce}) + (t_{DRep} + t_{ce}) \times (l - l_{HLMR} + 1) + t_{bc} + (2 \times l + 4) \times t_{in} + 2 \times t_{out} \times H^{SR}
\]  

(1)

![Handoff Flow](image)
from the HLMR. After that, each MNN under MR\textsubscript{i} sends its first packet, containing a type 4 routing header for recording all intermediate MR-CoAs in the nested NEMO, to each connecting CN for optimizing the reverse route from the CN back to this MNN. The total time for this RO procedure is the sum of the RA-TIO distribution time, i.e., \(t_{\text{RA-TIO}} \times (l - l_{\text{HLMR}} + 1)\), and the time for all MNNs in the mobile subnet to exchange their first packets with all connecting CNs for route optimization, which is formulated as \(t_{\text{RA-TIO}} \times (l - l_{\text{HLMR}} + 1)\) + \(2 \times t_{bc} + (4 \times l + 6) \times t_{in} + 2 \times t_{out} \times H_{D}^{AR}\). Consequently, the RRH handoff latency for the MNN to receive resumed packets through the new NEMO is formulated as (2) for both intra-MAP and inter-MAP handoffs.

\[
\begin{align*}
& (t_{RS} + t_{RA} + t_{cc} + (l - l_{\text{HLMR}} + 1)) + \\
& (2 \times l + 4) \times t_{in} + 2 \times t_{out} \times H_{D}^{AR} + t_{bc}
\end{align*}
\]

**HCoP:**

As shown in Fig. 7-3, when the mobile subnet of the nested NEMO with HCoP executes its inter-MAP handoff, MR\textsubscript{in} first acquire its new MR-CoA with the time of \(t_{\text{HMRRA}} \times (l - l_{\text{HLMR}} + 1)\). Then it issues the HMRRA message to every underlying MR\textsubscript{i} and MNNs for configuring their new CoAs layer by layer with the time of \(t_{\text{HMRRA}} \times (l - l_{\text{HLMR}} + 1)\). After that, MR\textsubscript{i} and its MNNs execute their local binding updates to the MAP, i.e., MR\textsubscript{o}, and receive LBAs from the MAP with the time of \(t_{\text{LBRA}} \times (l - l_{\text{HLMR}} + 1)\). At this time, MR\textsubscript{i} and its MNNs send GBUs to the HA of MR\textsubscript{i} and all connecting CNs of MNNs respectively for route optimization, and wait for corresponding GBAs with the maximal time of \(t_{\text{HMRRA}} \times (l - l_{\text{HLMR}} + 1)\). The inter-MAP handoff latency for the mobile subnet in the nested NEMO with HCoP to complete its handoff is the sum of the time for delegating the HLMR’s prefix, that for delegating prefixes within the nested NEMO and updating local bindings in the MAP and that for MRs and MNNs to update global bindings in HAs and CNs, which is formulated as (3).

\[
\begin{align*}
& t_{RS} + t_{\text{HMRRA}} + t_{cc} + (l - l_{\text{HLMR}} + 1) + \\
& 2 \times t_{bc} + (4 \times l + 6) \times t_{in} + 2 \times t_{out} \times H_{D}^{AR}\n\end{align*}
\]

**HCoP-B:**

The inter-MAP handoff flow of HCoP-B is shown in Fig. 7-4. Whenever the HLMR, i.e., MR\textsubscript{in} at the \(l_{\text{HLMR}}\) layer in the old nested NEMO, of the mobile subnet with HCoP-B receives a new layer 2 trigger, it starts the handoff detachment phase by first sending an LBU to the old MAP, i.e., MR\textsubscript{o}, and waiting the corresponding LBA where contains the BUT information of the mobile subnet. This phase needs a round-trip time between the HLMR and the old MAP, which is equal to \(2 \times t_{in} \times l_{\text{HLMR}}\). As soon as the detachment phase of HCoP-B is completed, MR\textsubscript{in} with HCoP-B, like with HCoP, executes its prefix delegation with the time of \(t_{\text{RS}} + t_{\text{HMRRA}} + t_{cc}\). With operations described in Section 3, at the same time when the HLMR, i.e., MR\textsubscript{in} at the \(l_{\text{HLMR}}\) layer in the new NEMO, delegates prefix into the mobile subnet for all underlying MRs/MNNs to execute their local bindings with the new MAP, i.e., MR\textsubscript{o}, MR\textsubscript{in} will transfer the BUT information of this mobile subnet within the LBU.
message to \(MR^i_{\text{HLMR}}\) for executing operations of the HCoP-B re-attachment phase, which needs the time of \(t_{\text{in}} \times l_{\text{HLMR}} + t_{\text{bc}}\). After that, \(MR^i_{\text{HLMR}}\) immediately issues GBU-s to HAs of all MRs in the mobile subnet for updating binding information and to connecting CNs of all MNNs for optimizing the media route to MNNs with the maximal time of \((t_{\text{in}} + t_{\text{out}} \times H_D^i) + 2 > t_{\text{bc}} + 2 > t_{\text{in}} \times (l + 1),\) where \(D \in \{\text{all } H^j_k \text{ and } CN^j_1\}\). It is obvious that HCoP-B overlaps the prefix delegation and local binding update operations inside the NEMO with the global binding update one on Internet, which significantly reduces total handoff latency for the mobile subnet in the nested NEMO, which is formulated in (5). On the other hand, the intra-MAP handoff latency of HCoP-B is equal to that of HCoP:

\[
(2 \times j_{\text{HLMR}} + l_{\text{HLMR}} + l + 3) \times t_{\text{in}} + 2 \times t_{\text{out}} \times H_D^R
\]

(5)

**B. The number of global BU for RO of CNs when handoff**

In this subsection, we will compare the number of issued GBU-s from the handoff mobile subnet to all connecting CNs for RO with all these schemes. The more the GBU message issue, the more bandwidth and processing capabilities on the Internet and the mobile network consume. Because this paper focuses on solving the binding update storm problem, we ignore GBU messages sent to MR-HAs here.

- **MIRON, RRH and HCoP**

As shown in Figs 7-1, 7-2 and 7-3 for MIRON, RRH, HCoP respectively, it is MNNs, instead of MRs, to issues the first packet containing the type 4 routing header or GBU messages to connecting CNs. For the nested NEMO with an L-layer full N-ary tree topology, the number of MRs, which are located at the \(j\)th layer of the nested NEMO, under the mobile subnet with the HLMR, i.e., \(MR^i_{\text{HLMR}}\) at the \(l_{\text{HLMR}}\) layer, is equal to \(N^{-j}_{\text{HLMR}}\). Therefore, the number of GBU messages sent to connecting CNs is equal to total numbers of GBU messages issued by all MNNs of each MR \(i\) at layer \(j\) in the mobile subnet for \(j \geq l_{\text{HLMR}}\), which is equal to \(\sum_{j=l_{\text{HLMR}}}^{N^{-j}_{\text{HLMR}}} \sum_{i=1}^{N_{\text{MNN}}(j_{\text{MNN}})} |CN^j_{i_{\text{MNN}}}|\), where \(|CN^j_{i_{\text{MNN}}}|\) is the number of connecting CNs for each \(MNN^j_{i_{\text{MNN}}}\). Please note that HCoP inherits the concept of the hierarchical mobility management and does not need to issue GBU messages to CNs when the mobile subnet executes the intra-MAP handoff. Oppositely, MIRON and RRH have to send GBU messages for both intra- and inter-MAP handoffs.

- **HCoP-B**

As shown in Fig. 7-4, the MAP with HCoP-B collects CN information in the BUT to generate only one GBU message, which records information of all MRs and MNNs, for each connecting CN in the mobile subnet, no matter how many MNNs under any MR in the mobile subnet have active connections with the CN. Hence, the number of GBU messages sent to all connecting CNs for RO with HCoP-B is equal to the number of elements in the union set of connecting CNs, i.e., \(CN^j_{i_{\text{MNN}}}\), under \(MR^i_{\text{HLMR}}\) in the mobile subnet with the HLMR, i.e., \(MR^i_{\text{HLMR}}\) at the \(l_{\text{HLMR}}\) layer, which is denoted as \(\bigcup_{i_{\text{MNN}} \in CN^j_{i_{\text{MNN}}} \forall i_{\text{MNN}}, j_{\text{HLMR}} \leq j \leq L, 1 \leq i_{\text{MNN}} \leq N^{-j}_{\text{HLMR}}}\).

**C. Internet bandwidth consumption of global BU for RO of CNs when handoff**

We define the Internet bandwidth consumed by these GBU messages as the total lengths of them which are leaving the NEMO through the egress interface of the TLMR/MAP. Depending on the information conveyed in the GBU message for RO of CNs, MIRON, RRH, HCoP and HCoP-B have different GBU message lengths. Please note that both MIRON and RRH issue GBU messages and consume corresponding Internet bandwidth even when the mobile subnet executes the intra-MAP handoff.

- **RRH**

The MNN under MR at layer \(j\) has to issue its first packet with the length of \((142 + 16 \times j), i.e., 2 \times IPv6 \text{ header} + \text{routing header} + \text{BU header} + \text{mobility option (TIO)} = 2 \times 40 + [8 + 16 \times (j + 1)] + 6 + 32, \) bytes to record 16-byte care-of addresses of total \((j+1)\) intermediate MRs, including the TLMR and itself, in the type 4 routing header. Hence, the consumed Internet bandwidth of RRH for the handoff mobile subnet with \(MR^i_{\text{HLMR}}\) as its HLMR in the L-layer full N-ary nested NEMO is

\[
\sum_{j=l_{\text{HLMR}}}^{N^{-j}_{\text{HLMR}}} \sum_{i=1}^{N_{\text{MNN}}(j_{\text{MNN}})} |CN^j_{i_{\text{MNN}}}| \times (142 + 16 \times j).
\]

- **MIRON and HCoP**

GBU message lengths of MIRON and HCoP are 88, i.e., IPv6 Header + Home Address Option (HAO) + BU header + CoA Option = 40 + 24 + 6 + 18, bytes such that the consumed Internet bandwidth of GBU messages is equal to...
\[ \sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{l=2}^{N^{l}_{/\text{subnet}}} \left[ \sum_{i=1}^{N^{i}_{/\text{MN}}} \left( |CN^{i}_{/j}| \times 88 \right) \right] \text{ for the HCoP inter-MAP handoff and both MIRON intra- and inter-MAP handoffs.} \]

- **HCoP-B**
  
  HCoP-B sends only one modified GBU message to a connecting CN as described in Section 3. This GBU message records address information of length \((122 + 16 \times N)\), i.e., IPv6 Header + HA0 + BU header + type 28 Mobility Option = 40 + 24 + 6 + 4 + 16 \times 3 + 16 \times N, bytes for the number of \(N\) MRs and VMNs which are collected in array \(H\) of PUT\_BUF() and carried in the type 28 mobility option at the field of “BU nodes” for CN \(j\). The consumed Internet bandwidth for GBU messages with HCoP-B is \(\sum_{j=1}^{N^{j}_{/\text{hsubnet}}} (122 + 16 \times N)\), where \(\bigcup\{CN\}_{\text{HCoP-B}}\) denotes the union set of all connecting CNs in the mobile subnet with HCoP-B, as shown in Section 4.2.

- **D. Extra binding cache sizes of the nested NEMO when handoff**
  
  Here we analyze extra binding cache sizes used for the mobile subnet of the nested NEMO with both schemes.

- **MIRON**
  
  To enable every CoA, which is allocated by DHCPv6, to be globally reachable in MIRON, every MR in the nested NEMO has to keep track of addresses of all nodes, i.e., home addresses of underlying MNNs and MRs, requesting their IPv6 addresses, i.e., CoAs, using DHCPv6 and then insert host routes in its routing table that allow it to route packets destined to those addresses [19]. Hence, extra binding caches of MIRON are the sum of address lengths of all underlying MRs and MNNs in the mobile subnet, which is listed in (6).

\[
\sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{l=1}^{N^{l}_{/\text{subnet}}} \sum_{i=1}^{N^{i}_{/\text{MN}}} \left( |MR^{i}_{/\text{HoA}} + MR^{i}_{/\text{CoP}} + (MNN^{i}_{/j}_{/\text{HoA}} + MNN^{i}_{/j}_{/\text{CoA}}) \right) \left( \left( \sum_{k=1}^{32 + \sum_{j=1}^{N^{j}_{/\text{MN}}} |MNN^{j}_{/\text{MN}}|} 32 \right) \right) \]

\[= \sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{i=1}^{N^{i}_{/\text{MN}}} \left( 32 + \sum_{j=1}^{N^{j}_{/\text{MN}}} |MNN^{j}_{/\text{MN}}|} \right) \]

\[= 32 \times \left( N^{j}_{/\text{hsubnet}} + 1 \right) - N^{j}_{/\text{subnet}} + \sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{i=1}^{N^{i}_{/\text{MN}}} |MNN^{j}_{/\text{MN}}|} \]

- **RRH**
  
  Though RRH does not apply the hierarchical mobility management at the TLMR, each CN of the mobile subnet has to store its own part of current routing information, which is carried by the type 4 routing header in the first packet from \(MNN^{i}_{/j}\) of each MR \(i\) at layer \(j\) in the mobile subnet after handoff, for \(MNN^{i}_{/j}\) in its binding caches. Each binding cache entry of the CN contains an index for \(MNN^{i}_{/j}_{/\text{HoA}}\) and associated routing information, consisting of the first hop to \(MR^{i}_{/\text{CoA}}\) and a type 2 routing header indicating the routing path, i.e., \(MR^{i}_{/\text{CoA}} \rightarrow \ldots \rightarrow MR^{j}_{/\text{CoA}} \rightarrow MNN^{j}_{/\text{CoA}}\), from the TLMR to \(MNN^{j}_{/\text{CoA}}\). After summation up all these routing information distributed among \(CN^{j}_{/i}\) of \(MNN^{i}_{/j}\) under \(MR^{i}_{/\text{CoA}}\), the extra binding caches for the mobile subnet with RRH is formulated in (7), where \(\{MNN^{j}_{/i}\}\) denote the set of all MNNs of MR \(i\) at layer \(j\).

\[
\sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{i=1}^{N^{i}_{/\text{MN}}} \sum_{j=1}^{N^{j}_{/\text{MN}}} \left( MNN^{j}_{/i}_{/\text{HoA}} + \sum_{k=1}^{32 + \sum_{j=1}^{N^{j}_{/\text{MN}}} |MNN^{j}_{/\text{MN}}|} \times |CN^{j}_{/i}| \right) \]

\[= \sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{i=1}^{N^{i}_{/\text{MN}}} \sum_{j=1}^{N^{j}_{/\text{MN}}} \left( 32 + \sum_{k=1}^{\sum_{j=1}^{N^{j}_{/\text{MN}}} |MNN^{j}_{/\text{MN}}|} \right) \times |CN^{j}_{/i}| \]

\[= 16 \times \sum_{j=1}^{N^{j}_{/\text{hsubnet}}} \sum_{i=1}^{N^{i}_{/\text{MN}}} \sum_{j=1}^{N^{j}_{/\text{MN}}} \left( j + 3 \right) \times |CN^{j}_{/i}| \]

- **HCoP**
  
  HCoP only records the mapping of the home prefix of each MR \(i\) at layer \(j\), i.e., \(MR^{i}_{/\text{CoA}}\), to its allocated CoP, i.e., \(MR^{i}_{/\text{CoP}}\), in LBC and that of the HoA of \(MNN^{i}_{/j}\) under each MR \(i\) at layer \(j\), i.e., \(MNN^{i}_{/j}_{/\text{HoA}}\), to its allocated MNN-CoA, i.e., \(MNN^{i}_{/j}_{/\text{CoA}}\), in VBC at the MAP. Extra binding caches of HCoP are also formulated by (6), except \(MR^{i}_{/\text{HoA}}\) is replaced by \(MR^{i}_{/\text{CoP}}\).

- **HCoP-B**
  
  Besides LBC and VBC caches as HCoP, HCoP-B needs extra binding caches, which are listed in (8), to record information of the mobile subnet in the BUT at MAP. As shown in Fig. 3, the BUT contains two parts of information. The first part consists of the home prefix, i.e., \(MR^{i}_{/\text{CoP}}\), and the HA’s address, i.e., \(MR^{i}_{/\text{HoA}}\), of each MR \(i\) at layer \(j\). The second one comprises the home address, i.e., \(MNN^{j}_{/i}_{/\text{HoA}}\), the HA’s address, i.e., \(MNN^{j}_{/i}_{/\text{CoA}}\), and all connecting CNs, i.e., \(CN^{j}_{/i}\), of each \(MNN^{j}_{/i}\) under this MR. Total extra binding cache sizes of HCoP-B are the sum of values calculated by (6) and (8).
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As described in Section 3.2, whenever an MNN/VMN in the nested NEMO starts a session with a new CN, the serving MR or the VMN itself will execute the four-step HCoP-B binding update process to send an LBU, which includes the address of this CN at the field of “BU nodes” in the modified type 28 mobility option without the R flag set, to the MAP to create a corresponding BUT entry. The length of this LBU message is 66, i.e., IPv6 Header + BU header + type 28 Mobility Option without the R flag set = 40 + 6 + (4 + 16), bytes. Consequently, the total local wireless bandwidth consumption for initializing all sessions between each MNN and its connecting CN through all ingress interfaces of the MAP is equal to
\[
\sum_{j=1}^{L \text{HLMR}} \sum_{i=1}^{N^{j-\text{HLMR}}} \sum_{l=1}^{|\text{MNN}^{j}_{i}/l|} |CN^{j}_{i,l}| \times 66.
\]
Please note that CN addresses of the newly established sessions could be piggybacked in the modified type 28 mobility option of the LBR messages, which are periodically issued to the MAP, as described in Section 3.2. Consequently, the consumed local wireless bandwidth of HCoP-B for simultaneously maintaining all session informations in BUT and binding ones in LBC/VBC can be further reduced during the sessions.

V. Simulation Results

Based on mesh topologies in [29], [30], we assume a mesh network, which consists of 15×15 ARs as shown in Fig. 8, is used as the backbone network in our Java-coded simulation program. In the beginning of this program, the number of the nested NEMO, which is an L-layer full binary tree, under each AR is defined as the density D of the nested NEMO in this paper. Each MR in the nested NEMO owns three active MNNs, which are all VMNs, during the simulation. The CN and MR-HA are assumed to be directly connected to an AR and uniformly distributed in the backbone. CNs with whom MNMs establish a session are uniformly selected from a set of fifteen CNs.

As soon as an MNN/VMN in the nested NEMO establishes a session with a new CN, it has to issue a GBU, which contains its current CoA, through the TLMR/MAP to this CN for RO. Session initialization operations of MIRON, RRH and HCoP are similar to their handoff ones as illustrated in Figs 7-1, 7-2 and 7-3, respectively. Hence, total local wireless bandwidth consumptions of RRH, MIRON and HCoP for initializing all sessions between each MNN and its connecting CN through their current CoA, through the TLMR/MAP to this CN for RO. Please note that analyses here only consider the extra signaling overheads needed for session initialization. Oppositely, irrelevant signaling costs, which are not directly consumed by the session initialization operation such as those for delegating prefixes in the NEMO, updating bindings on MR-HAs or VMN-HAs, etc., are not included. In the following, we will analyze local wireless bandwidth consumptions of these four schemes for session initialization. These results also apply to these four schemes for notifying their CNs of terminations of all route-optimized sessions.

- MIRON, RRH and HCoP

As soon as an MNN/VMN in the nested NEMO establishes a session with a new CN, it has to issue a GBU, which contains its current CoA, through the TLMR/MAP to this CN for RO. Session initialization operations of MIRON, RRH and HCoP are similar to their handoff ones as illustrated in Figs 7-1, 7-2 and 7-3, respectively. Hence, total local wireless bandwidth consumptions of RRH, MIRON and HCoP for initializing all sessions between each MNN and its connecting CN through their current CoA, through the TLMR/MAP to this CN for RO. Please note that analyses here only consider the extra signaling overheads needed for session initialization. Oppositely, irrelevant signaling costs, which are not directly consumed by the session initialization operation such as those for delegating prefixes in the NEMO, updating bindings on MR-HAs or VMN-HAs, etc., are not included. In the following, we will analyze local wireless bandwidth consumptions of these four schemes for session initialization. These results also apply to these four schemes for notifying their CNs of terminations of all route-optimized sessions.

- HCoP-B
After initialization of the simulation program, we perform three steps for the handoff of a mobile subnet in the nested NEMO.

1) For choosing a mobile subnet in the old NEMO to execute its handoff, the MR at the lower layer with a larger $l$ value, e.g., the passenger in the bus, should have a higher handoff probability than that at the higher layer, e.g., the bus, to leave the nested NEMO, according to the observation from the real life. Thus, the handoff probability, i.e., $P_l$, of the mobile subnet with the HLMR at the $l$th layer in the old nested NEMO is calculated by this equation:

$$P_l = \frac{(l+1)}{L} \times P, \text{ if } 0 \leq l < (L-1) \text{ or } P_l = P, \text{ if } l \geq (L-1),$$

$P$ is given as the handoff probability of the nested NEMO in this simulation program. At each time unit, the simulation program first generates a random number which is uniformly distributed between 0 and 1. It then executes the process of choosing the handoff mobile subnet from the NEMO’s TLMR/MAP and advances downward to the next lower level in the old NEMO until the handoff probability $P_l$ of the mobile subnet with its HLMR at layer $l$ is larger than the generated random number.

2) After a candidate mobile subnet has been chosen to perform its handoff, we have to decide its handoff type as the intra-MAP handoff or the inter-MAP one. We assume the probability of executing the inter-MAP handoff is defined as $P_l \times \gamma$, where $\gamma$ is the percentage of the inter-MAP handoff. Further, the mobile subnet, which executes the inter-MAP handoff, will follow the 2-D random-walk model for square cells [31] to hand over to a new nested NEMO of the neighboring AR in one of eight possible directions with equal probabilities of $P_l \times \gamma / 8$ at each time unit after the last handoff is completed. Furthermore, if the mobile subnet moves out of the boundary of the mesh backbone during the simulation, this mobile subnet is considered as “dead” and its performance data is excluded from calculations of final simulation results.

3) Finally, we have to decide the destination for the handoff mobile subnet in the chosen direction. Because the possible destination of the handoff mobile subnet may be any MR in the new NEMO, we will conduct our simulations with two criteria, i.e., the width-first and depth-first ones, for the mobile subnet to re-attach to an MR, which has not own two child MRs, at the highest and lowest layers in the new NEMO. In this way, we can observe the upper and lower bounds of all performance metrics and in turn calculate their average values to exhibit much more general performance behaviors of these NEMO schemes. However, if there is no NEMO attached to the destination AR of the mobile subnet, the handoff mobile subnet will directly attach to this AR and then become a new NEMO by itself under this AR.

In the following, we will first compare simulation results of five performance metrics for handling the handoff of the mobile subnet with MIRON, RRH, HCoP and HCoP-B by varying the number of level ($L$) of the nested NEMO and the proportion of the inter-MAP handoff ($\gamma$). Each figure comprises two parts of results with the depth-first and width-first criteria. For example, curves of RRH with the depth-first and width-first criteria are denoted as RRH-D and RRH-W respectively. We further compare their results on local wireless bandwidth consumptions for session initialization. Simulations are executed ten times with durations of one hundred time units to calculate average values of these six performance metrics.

A. The handoff latency

As shown in Fig. 9, we vary values of $L$ but remain those of $P$, $D$ and $\gamma$ unchanged to observe handoff latencies of MIRON, RRH, HCoP and HCoP-B. No matter which criterion (depth-first or width-first) is used, handoff latencies are increased as the initial layer $L$ of the nested NEMO raises, which is conformed to analyses in Section 4.1. Among these four NEMO schemes, because MIRON and RRH have to issue GBU messages or first packets to CNs for RO after their prefix delegation stages for both intra- and inter-MAP handoffs, both of them have larger handoff latencies than HCoP and HCoP-B, which only send GBU messages for inter-MAP handoffs due to their hierarchical mobility management. However, with information recorded in the BUT of the MAP, HCoP-B overlaps executions of the prefix delegation and local binding update stages inside the nested NEMO and the global binding update stage for HAs and CNs outside such that it achieves the smallest handoff latencies. Please note that handoff latencies of
these NEMO schemes with the depth-first criterion are higher than those with the width-first one, as shown in Fig. 9. Because the handoff mobile subnet with the depth-first criterion re-attaches to the MR at the deepest layer in the new NEMO, we can observe that handoff latencies with the depth-first criterion grow faster than those with the width-first one as \( L \) increases, which differentiates handoff latencies of these four NEMO schemes.

![Handoff Latencies vs. L for MIRON, RRH, HCoP and HCoP-B](image)

**Fig. 9. Handoff latencies vs. \( L \) for MIRON, RRH, HCoP and HCoP-B**

For comparing overall handoff latencies of MIRON, RRH, HCoP and HCoP-B, we first calculate average handoff latencies of these four schemes under all values of \( L \) in Fig. 9 and then divide average handoff latencies of MIRON, RRH and HCoP over that of HCoP-B to exhibit their normalized handoff latencies over HCoP-B with both depth-first and width-first criteria. We finally acquire the overall normalized handoff latencies of MIRON, RRH and HCoP over that of HCoP-B by averaging normalized values of these three schemes with the depth-first and width-first criteria. These results are shown in Table 4. Among these four NEMO schemes, MIRON spends the longest overall latency, which is 101.13% longer than that of HCoP-B. Overall handoff latencies of HCoP-B are 96.89% and 27.43% longer than that of HCoP-B respectively.

**Table 4. Comparison of normalized handoff latencies of these four NEMO schemes**

<table>
<thead>
<tr>
<th></th>
<th>MIRON</th>
<th>RRH</th>
<th>HCoP</th>
<th>HCoP-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth-First</td>
<td>215.16%</td>
<td>209.33%</td>
<td>141.84%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Width-First</td>
<td>187.09%</td>
<td>184.46%</td>
<td>113.03%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Overall</td>
<td>201.13%</td>
<td>196.89%</td>
<td>127.43%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

As shown in Fig. 10, if we vary the value of the proportion of inter-MAP handoff (\( \gamma \)) from 0 to 1 but with \( L \) fixed as 4, handoff latencies of both non-hierarchical MIRON and RRH schemes with depth- and width-first criteria remain almost constant, because they perform the same global binding update process for all intra- and inter-MAP handoffs. On the other hand, those of both hierarchical HCoP and HCoP-B grow proportionally to the value of \( \gamma \). As all handoffs of the mobile subnet are the inter-MAP one, i.e., \( \gamma = 1 \), handoff latencies of HCoP with the two criteria raise fast to reach values higher than those of MIRON and RRH, because HCoP cannot issue GBU messages until it completes its local binding update process, which is conformed to the analysis in Section 4.1. However, handoff latencies of HCoP-B grow slower than those of HCoP. Even when \( \gamma = 1 \), it achieves smaller latencies than MIRON and RRH.

**Fig. 10. Handoff latencies vs. \( \gamma \) for MIRON, RRH, HCoP and HCoP-B**

**B. The number of GBUs for RO of CNs when handoff**

As shown in Fig. 11 when \( P \) is fixed at 50%, numbers of GBU messages to connecting CNs for RO with MIRON, RRH and HCoP are raised rapidly as the initial layer \( L \) of the nested NEMO grows, but those of HCoP-B remain below the number of possible CNs as \( L \) raises. As described in Section 4.2, MNMs of MIRON and RRH have to issue GBU messages or first packets for both intra- and inter-MAP handoffs such that both of them send the largest number of GBU messages, which are almost twice of those sent by HCoP for the inter-MAP handoff only. However, our HCoP-B proposes the BUT on the MAP of the NEMO and associated GET_BUT() and PUT_BUT() algorithms to collects non-duplicate binding update information such that it can significantly reduce the number of GBU messages sent to all CNs for RO. Moreover, with the width-first criterion, the mobile subnet prefers to re-attach to the highest possible layer of the new NEMO, instead of to the lowest one with the depth-first criterion. Hence, all schemes have higher numbers of GBU messages with the depth-first criterion. Thus, the relationship for the number of issued GBU messages among these four schemes is: \( \text{RRH} \equiv \text{MIRON} > \text{HCoP} >> \text{HCoP-B} \).

As shown in Fig. 12, if we also vary the value of the proportion of inter-MAP handoff (\( \gamma \)) from 0 to 1 but with \( L \)
fixed as 4, we can observe number of GBU messages of both MIRON and RRH almost remain at high constant values. However, HCoP grows fast enough to catch up with MIRON and RRH when $\gamma = 1$. Oppositely, HCoP-B only has to issue a modified GBU message to each connecting CN, no matter how many MRs and MNNs exist in the nested NEMO and what proportion of the inter-MAP handoff is. This means HCoP-B actually solves the binding update storm problem.

C. Consumed Internet bandwidth of GBUs for RO of CNs when handoff

As shown in Fig. 13, consumed Internet bandwidth of GBU messages for MIRON, HCoP and RRH raise as the initial layer $L$ of the nested NEMO increases. Referring to analyses in Section 4.3, the length of GBU message sent by $l_{iMR}$ of RRH for both intra- and inter-MAP handoffs is proportional to the $l$ value such that RRH consumes much more bandwidth than the other three schemes do, no matter which criterion is adopted. Though the length of the MIRON GBU message is equal to that of HCoP, the number of MIRON GBU message issued for the mobile subnet is about twice of HCoP, as shown in Section 5.2, such that MIRON nearly consumes twice of the Internet bandwidth of HCoP as $L$ varies. However, HCoP-B raises its value slowly as $L$ increases and consumes the least amount of Internet bandwidth among these four schemes due to its modified GBU message format and the BUT mechanisms to reduce duplicate GBU messages for all connecting CNs.

In Fig. 14, as the value of the proportion of inter-MAP handoff ($\gamma$) from 0 to 1, we can observe that both non-hierarchical MIRON and RRH schemes do not have obvious variations on their consumed Internet bandwidth, but hierarchical HCoP and HCoP-B raise their values accordingly. HCoP grows with a higher rate to catch up with MIRON when $\gamma = 1$. Oppositely, by introducing much less GBU messages and consumed Internet bandwidth than MIRON, RRH and HCoP do, HCoP-B actually resolves the binding update storm problem, no matter how many MRs and MNNs exist in the...
nested NEMO and what proportion of the inter-MAP handoff is.

\[ L = 4, D = 1.5, P = 50\% \]

\[ 5000 \quad 10000 \quad 15000 \quad 20000 \quad 25000 \quad 30000 \quad 35000 \]

\[ 0 \quad 0.25 \quad 0.5 \quad 0.75 \quad 1 \]

Proportion of Inter-MAP Handoff (\( \gamma \))

**Fig. 14.** The consumed Internet bandwidth of GBUs vs. \( \gamma \) for MIRON, RRH, HCoP and HCoP-B

D. The extra binding cache sizes when handoff

In this section, we will compare average extra binding cache sizes needed by these four NEMO schemes when the mobile subnet re-attaches to the new NEMO. When we fix D, P and \( \gamma \) as 1.5, 50% and 50% respectively, extra binding cache sizes of MIRON, RRH, HCoP and HCoP-B when the mobile subnet re-attaches to the new NEMO grow larger as L, which is shown in Fig. 15. It is obvious that the hierarchical HCoP needs the least amount of extra binding caches for its LBC and VBC among these four NEMO schemes, which are about one half of the extra binding caches of the non-hierarchical MIRON. Because HCoP-B needs extra binding caches to record all connecting CNs, which is proportional to the number of possible CNs, and the network topology in the BUT, it thereby consumes a few more binding caches than MIRON and HCoP do with both depth- and width-first criteria. However, because RRH has to record routing paths from the TLMR to all intermediate MRs in the mobile subnet at connecting CNs of all MNNs, it will need much more binding caches, which is proportional to the product of the number of MNNs and that of their intermediate MRs in the mobile subnet as described in Section 4.4, than HCoP-B does as L grows larger. On the other hand, because the handoff mobile subnet with the depth-first criterion generally comprises more MRs than that with the width-first one, extra binding caches of these four NEMO schemes with the depth-first criterion are higher than those with the width-first one as shown in Fig. 15.

Normalized extra binding caches needed by MIRON, RRH and HCoP over that of HCoP-B are listed in Table 7. It is obvious that our HCoP-B needs more extra binding cache than MIRON and HCoP with the depth-first and width-first criteria, which results in the overall performance of HCoP-B is about 30.85% that of RRH. As mentioned in Section 3, this is a tradeoff between the extra binding cache and the other four performance metrics. Finally, as the value of the proportion of inter-MAP handoff (\( \gamma \)) from 0 to 1 in Fig. 16, we can observe that both hierarchical HCoP and HCoP-B raise their values accordingly. Though HCoP-B grows with a higher rate than HCoP, its extra binding cache sizes is below one half of that of RRH when \( \gamma = 1 \).

\[ L = 4, D = 1.5, P = 50\% \]

\[ 0 \quad 2000 \quad 4000 \quad 6000 \quad 8000 \quad 10000 \quad 12000 \quad 14000 \quad 16000 \]

\[ 0 \quad 0.25 \quad 0.5 \quad 0.75 \quad 1 \]

Proportion of Inter-MAP Handoff (\( \gamma \))

**Fig. 15.** The extra binding cache sizes of GBUs vs. L for MIRON, RRH, HCoP and HCoP-B

**TABLE 7.** COMPARISON OF NORMALIZED EXTRA BINDING CACHES OF THESE FOUR NEMO SCHEMES

<table>
<thead>
<tr>
<th></th>
<th>MIRON</th>
<th>RRH</th>
<th>HCoP</th>
<th>HCoP-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth-First</td>
<td>25.97%</td>
<td>353.26%</td>
<td>12.98%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Width-First</td>
<td>38.89%</td>
<td>295.00%</td>
<td>19.20%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Overall</td>
<td>32.43%</td>
<td>324.13%</td>
<td>16.09%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

**Fig. 16.** The extra binding cache sizes of GBUs vs. \( \gamma \) for MIRON, RRH, HCoP and HCoP-B

E. The local wireless bandwidth consumption inside the NEMO when handoff

In this section, we will compare local wireless bandwidth consumptions inside the NEMO for the handoff of the mobile subnet with these four NEMO schemes. As mentioned in
Section 4.5, different NEMO schemes consume different total local wireless bandwidth inside the NEMO. First, MNNs of the mobile subnet have to send GBU messages to all CNs for the intra- and inter-MAP handoffs of both non-hierarchical MIRON and RRH and for the inter-MAP handoff of the hierarchical HCoP. Hence, these three schemes need the same amount of local wireless bandwidth inside the NEMO as their consumed Internet bandwidth as shown in Section 5.3. On the other hand, HCoP and HCoP-B require different local wireless bandwidth for executing their local mobility management processes inside the NEMO. With these two schemes, all VMNs and MRs in the handoff mobile subnet have to issue LBU messages to the MAP for building binding entries in the VBC and LBC. Besides this local bandwidth consumption, HCoP-B further consumes wireless bandwidth inside the NEMO for the handoff mobile subnet to convey its corresponding BUT information from/to the old/new MAP in the LBA/LBU messages when it first detaches from the old NEMO and then re-attaches to the new one respectively.

As shown in Fig. 17, total local wireless bandwidth consumptions of these four NEMO schemes raise as L grows, especially with the depth-first criterion which creates larger handoff mobile subnets than the width-first one. First, we will compare both non-hierarchical MIRON and RRH. RRH needs more total local wireless bandwidth than MIRON does because it consumes much more local wireless bandwidth for conveying its GBU messages, which was shown in Section 5.3. Moreover, though HCoP-B needs more local wireless bandwidth for its local mobility management than HCoP, it requires the lowest amount of total local wireless bandwidth among these four schemes, which is because it does not consume any local wireless bandwidth inside the NEMO to transmit the great amount of GBU messages.

As shown in Fig. 18, the proportion of inter-MAP handoff (γ) from 0 to 1, both non-hierarchical MIRON and RRH almost have constant local wireless bandwidth consumptions, but hierarchical HCoP and HCoP-B accordingly raise their values with different rates. HCoP grows with a higher rate than HCoP-B does. Finally, Table 8 lists normalized local wireless bandwidth consumptions of MIRON, RRH and HCoP over that of HCoP-B with the depth-first and width-first criteria respectively, and in turn overall performances of these schemes. The local wireless bandwidth consumption of our HCoP-B is only equal to 9.43%, 4.87% and 19.75% of those of MIRON, RRH and HCoP respectively, which is a significant performance improvement for the binding update storm problem in the nested NEMO.

**F. Local wireless bandwidth consumption inside the NEMO for session initialization**

In this section, we will compare local wireless bandwidth consumptions inside the NEMO for establishing all new sessions between MNNs and CNs with these four NEMO schemes. After initialization of the simulation program, every session has been established between an MNN and a corresponding CN. Therefore, local wireless bandwidth consumptions for session initialization, i.e., the aggregate local wireless bandwidth consumed on all ingress interfaces of the TLMR/MAP to execute the signaling flow for RO of all newly established sessions as mentioned in Section 4.6, with these four NEMO schemes can be calculated. According to analyses in Section 4.6, total local wireless bandwidth consumptions of RRH, MIRON and HCoP for initializing all sessions between each MNN and its connecting CN are equal to their Internet bandwidth consumptions of GBUs for CN’s RO. Oppositely, that of HCoP-B is equal to total length of all LBUs which are issued by all MRs/VMNs to the MAP to create corresponding BUL entries for recording CN addresses of all sessions.

As shown in Fig. 19, total local wireless bandwidth consumptions...
consumptions of these four NEMO schemes for session initialization raise as L grows. First, because the length of GBU message sent by $MR_i$ or its VMN with RRH is proportional to the $l$ value, RRH consumes much more local wireless bandwidth for session initialization than the other three schemes do. Second, as a result of the same GBU lengths, MIRON nearly consumes the same local wireless bandwidth for session initialization as HCoP does when L varies. Moreover, HCoP-B requires the lowest amount of total local wireless bandwidth for session initialization among all schemes, due to its shortest LBU message where includes the new type 28 mobility option.

After calculating the normalized consumed local wireless bandwidth of MIRON, RRH and HCoP over the proposed HCoP-B for session initialization, as listed in Table 9, HCoP-B exhibits significant performance improvements over the other three traditional NEMO schemes. As compared to these three schemes, the overall performance of HCoP-B on the consumed local wireless bandwidth for session initialization is almost 35.15% of that of RRH, 74.55% of that of MIRON and 75% of that of HCoP.

Table 10 summaries normalized overall performances on six metrics for NEMO, RRH, HCoP and HCoP-B.

A. Alternative of the MAP location:

In HCoP-B, we have proposed to let the TLMR acting as a MAP for locally managing the LBC/VBC and BUT of the nested NEMO to limit the amount of signaling outside the local NEMO domain, which is different to the approach taken by traditional hierarchical mobility management schemes like HMIPv6 to configure the MAP on a fixed router in the network infrastructure. Besides those first five performance metrics that have been analyzed and simulated for the mobile subnet handoff as described above, we needs further investigations on the HCoP-B handoff efficiency when the nested NEMO moves as a whole, which is frequent on the vehicular network. In the following, we will compare signaling overheads, i.e., the HCoP-B Internet and local wireless bandwidth consumptions of the TLMR as defined in Section 4.3 and 4.5 respectively, of these two alternatives on choosing the MAP’s location with two handoff scenarios. As shown in Fig. 20 when the MAP is located in the infrastructure backbone, as the TLMR changes its point of attachment from AR1 to AR2 or from AR1 to AR3, the NEMO performs the intra-MAP or inter-MAP handoff respectively. Oppositely, the NEMO executes the same HCoP-B handoff operations for these two scenarios, as shown in Fig. 21 when the MAP is located at the TLMR.

When the MAP is located in the infrastructure backbone:
- Handoff scenario 1 (Intra-MAP handoff):
After the NEMO has finished its prefix delegation process, each MR/VMN will issue an LBU to MAP1 via the TLMR for building its binding cache entry in the LBC/VBC, as mentioned in Section 3.2. Hence, the local wireless bandwidth consumption and Internet bandwidth consumption at the TLMR of this HCoP-B alternative are equal to its extra binding cache sizes of the whole NEMO at the MAP, which is calculated by (6) with \( l_{\text{HLMR}} = 0 \).

- **Handoff scenario 2 (Inter-MAP handoff):**
  Besides the same local wireless bandwidth consumption of the TLMR in the Intra-MAP handoff scenario, which is formulated by (6) with \( l_{\text{HLMR}} = 0 \), for updating LBC/VBC bindings in the new MAP, the TLMR of this HCoP-B alternative needs more Internet bandwidth to execute two extra steps, i.e., detachment and re-attachment ones, to retrieve the complete BUT information of the NEMO from the old MAP before handoff and then restore them to the new MAP after handoff, as described in Section 3.3. Thus, the Internet bandwidth consumption for the inter-MAP handoff of the whole NEMO with this HCoP-B alternative is formulated as (12) with \( l_{\text{HLMR}} = 0 \).

\[
\sum_{j \in \{\text{CN}\}_{\text{HCoP-B}}} (122 + 16 \times N_j) \text{ with } l_{\text{HLMR}} = 0,
\]

where \( \bigcup_{\text{CN}} \{\text{CN}\}_{\text{HCoP-B}} \) denotes the union set of all connecting CNs in the NEMO, as shown in Section 4.2. Moreover, the local wireless bandwidth consumption at the TLMR of this HCoP-B alternative is equal to that when the MAP is located in the infrastructure backbone.

For evaluating signaling overheads of these two HCoP-B alternatives from simulations when the nested NEMO moves as a whole, we will calculate the sum, which is called the total bandwidth consumption here, of the local wireless bandwidth consumption and the Internet one of each handoff scenario with these two HCoP-B alternatives. As shown in Fig. 22, we can observe several performance behaviors of these two HCoP-B alternatives. First, when the level (L) of the nested NEMO is small, total bandwidth consumptions of scenarios 1 and 2 when the MAP is located in the infrastructure are lower than those of both scenarios when the TLMR acts as the MAP. However, as L grows larger, total bandwidth consumptions of both scenarios when the TLMR acts as the MAP raise faster and finally exceed those of both scenarios when the TLMR acts as the MAP. As discussions above, local wireless bandwidth consumptions of both scenarios of these two HCoP-B alternatives are all formulated by (6) with \( l_{\text{HLMR}} = 0 \). Hence, total bandwidth consumptions of them differ from each other due to their different Internet bandwidth consumptions, which are formulated by (6) and (12) with \( l_{\text{HLMR}} = 0 \) for scenarios 1 and 2 respectively when the MAP is in the infrastructure and by

\[
\sum_{j \in \{\text{CN}\}_{\text{HCoP-B}}} (122 + 16 \times N_j) \text{ with } l_{\text{HLMR}} = 0
\]

for both scenarios when the TLMR acts as the MAP. Because the value of (12) is dominated by \( R \times K \), which is proportional to the product of total numbers of MNNs and all connecting CNs as described in Section 4.5, the total bandwidth consumption of scenario 2, i.e., the inter-MAP handoff, when the MAP is in the infrastructure will outnumber those, which are proportional to total numbers of MNNs that have ongoing connections with the CN, of both scenarios when the TLMR acts as the MAP as \( L > 3 \). Similarly, the value of (6) is proportional to total numbers of MNNs and MRs in the NEMO such that total bandwidth consumptions of scenario 1, i.e., the intra-MAP handoff, when the MAP is in the infrastructure are higher than those when the TLMR acts as the MAP as \( L > 4 \). In summary, the proposed HCoP-B alternative, which lets the TLMR act as the MAP, achieves advantages, such as no need to provide MAP functions on fixed routers in the infrastructure and the lower signaling bandwidth consumptions for a large NEMO to move as a whole, over the traditional alternative, which configures...
the MAP of HCoP in the infrastructure.

Fig. 22: Total bandwidth consumptions of two handoff scenarios when MAP is located at the TLMR or in the Infrastructure backbone

**B. Deployment Issues:**

IETF RFC 4889 [8] has classified the solution space of possible approaches that have been taken to solve the route optimization-related problems for NEMO. It also has analyzed the scope of the solutions, the benefits, and the impacts to the existing implementations and deployments. How to extending nodes with new functionalities has been identified as an important issue of NEMO route optimization in this RFC. In theory, the NEMO route optimization solution which requires the smaller number of nodes to be changed will be adopted more easily in the Internet. It may be difficult to introduce new functionalities in some nodes like LFNs and CNs, which could be any IPv6 node by definition. However, [8] points out the dilemma only those nodes that have been modified can enjoy the benefits of route optimization.

In the following, we will compare those four RO schemes analyzed in this paper with NBS to inspect which nodes of them should be modified. With MIRON, MRs, including the TLMR, and VMNs have to be modified to include the DHCP and PANA modules to perform the RO operation. All CNs and MR-HAs/VMN-HAs must record current CoAs of VMNs. For those LFNs that do not have any mobility capability, the MR performs all the RO and mobility tasks on their behalf. With RRH to support RO, all CNs and MR-HAs/VMN-HAs have to maintain the routing information about CoAs of all intermediate MRs in the nested NEMO for forwarding packets back to MNs when they receive the first packet from VMNs or LMNs, as mentioned in Section 2. Instead of generating an empty type 4 routing header in the first packet by VMNs or LMNs themselves, the serving MR of the LFN has to perform similar operations. As proposed in Section 3, both HCoP and HCoP-B let the TLMR act as the MAP to manage binding information sent by MRs and VMNs in the LBC and VBC after the AR delegates prefixes in HMRA messages into the nested NEMO. After session initialization operations, all CNs, which record the MAP’s RCoA, could first tunnel packets to the MAP and then the MAP forward these packets to current CoAs of their session peers. HCoP-B further argues its LFNs, LMNs, VMNs and MRs with capabilities to collect addresses of CNs for building the BUT structure in the TLMR. Hence, the TLMR can collect non-duplicate binding update information for all MR-HAs/VMN-HAs and active CNs such that HCoP-B can reduce significant signaling overheads for RO to solve the binding update storm problem when the NEMO changes its point of attachment. However, if the LFN cannot be upgraded with this function and there is no LMN under its serving MR communicating with the same CN of the LFN, all packets originated from the LFN’s CN must follow the non-optimized path, which is the same as that passed through by the first packet of each LMN/VMN session before RO, via the HA of the LFN’s serving MR and the MAP of the nested NEMO to it. Though HCoP-B upgrades all its nodes with different degrees of modifications as shown in Table 11, it achieves significant performance improvements on five metrics, as shown in Table 10, over the other three schemes with fewer modified nodes. Consequently, there are tradeoffs between benefits and deployment costs of these NEMO route optimization schemes.

**C. Security Issues:**

In the following, we discuss security issues of HCoP-B. There are previous works [32]-[34] considering security in network mobility. All of them assume the MNN can delegate its signaling right to the MR, as mentioned in [35], for updating location information with the CN on behalf of the MNN in a secure way. In [32], three MIPv6-based solutions are further proposed to use strong cryptography for creating the security association between the CN and the MR in non-nested NEMO. On the other hand, the Host Identity Protocol (HIP) [36], [37] is adopted in the latter two works [33], [34] to design secure network mobility infrastructures for the nested NEMO. With HIP, all MNNs and MRs are identified with their cryptographic host identifiers (HI). A new Host Identity Layer between the transport and IP layers maintains the mapping between the HI and corresponding IP address. Because the HI in HIP is a public-key, it can be used to verify signatures without access to certificates or a public-key infrastructure. Further, the
end-to-end transport layer connections are bound to HIs, instead of IP addresses which would change according to current locations of two communication ends. Hence, the proposed infrastructure in [33] supports IPSec, route and signaling optimization on nested mobile networks. However, it has the disadvantage of highly relying on the IPSec ESP transport format. Moreover, the HIP-NEMO solution, based on its micromobility topology management, signaling delegation and connection tracking mechanisms, enables secure and efficient network mobility management in the new HIP layer [34]. It builds a hierarchical topology of mobility enabled Local Rendezvous Servers (mLRVS) in the nested NEMO to collect information, i.e., the HI, the actual IP address of the MNN and the IP address assigned by the mLRVS to the MNN, about all nodes under them. Its operations are similar to those HCoP-B. Though HIP-NEMO has clear advantages, it suffers several drawbacks. First, the MNN has to be upgraded with new functions, which may cause the deployment issue as HCoP-B. Second, it cannot avoid the binding update storm problem for updating CNs of all MNNs when the whole mobile network changes its point of attachment. Third, it lacks detail operation flows and performance evaluations.

In our HCoP-B, the MAP, i.e., the TLMR of the nested NEMO, must send GBUs to all connecting CNs to update binding information for RO on behalf of all MNNs within the NEMO after handoff. In this case, the CN must verify the MAP is allowed to send the GBU on behalf of the MNN for security reasons. If the signaling delegation and HIP processes in [33] or [34] could be integrated into HCoP-B, the MNN in HCoP-B is able to delegate its signaling right to its serving MR and further to the MAP such that authentications between all CNs and the MAP could be achieved to resolve the binding update storm problem securely in HCoP-B. Detail operations need more investigations and performance evaluations in the future.

VII. CONCLUSIONS AND FUTURE WORKS

We have proposed the HCoP-B mobility management scheme with the novel BUT architecture and associated algorithms for the nested NEMO in this paper. As compared to three traditional NEMO schemes, i.e., MIRON, RRH and HCoP, that support route optimization for connecting CNs after the mobile subnet in the nested NEMO hands over to a new NEMO, our HCoP-B scheme achieves the shortest handoff latency, the smallest number of GBU messages and the least amounts of consumed Internet and local wireless bandwidth for RO at the cost of higher extra binding caches than MIRON and HCoP. It also consumes the least amount of local wireless bandwidth for session initialization. We further discuss important issues about HCoP-B deployment, security and MAP location alternative. Consequently, with the HCoP-B mobility management scheme and its BUT architecture, the binding update storm problem of the nested NEMO is efficiently solved. Our future works will first focus on how to integrate the HIP signaling delegation process with HCoP-B to achieve mutual trust between CNs and the MAP. Second, we will provide seamless handoff mechanisms in this HCoP-B scheme and compare its performance to those shown in the literature like [38], [39].

APPENDIX: ACRONYMS

Access Router (AR)  
Binding Update (BU)  
Binding Update Tree (BUT)  
Correspondent Node (CN)  
Care-of Prefix (CoP)  
Global Binding Update (GBU)  
Hierarchical CoP with BUT (HCoP-B)  
Handoff Leading MR (HLMR)  
Hierarchical Mobile Router Advertisement (HMRA)  
Home Address (HoA)  
Local Binding Cache (LBC)  
Local Binding Update (LBU)  
Mobility Anchor Point (MAP)  
IETF Mobility EXTensions for IPv6 (MEXT)  
Mobile Network Nodes (MNN)  
Mobile Router (MR)  
Mobile Router Home Agent (MR-HA)  
NETwork MObility (NEMO)  
Parent MR (PMR)  
Previous Parent MR (PPMR)  
Router Advertisement (RA)  
Router Advertisement message with extended Tree Information Option (RA-xTIO)  
Route Optimization (RO)  
Router Solicitation (RS)  
Top-Level Mobile Router (TLMR)  
Visitor Binding Cache (VBC)  
Visited Mobile Node (VMN)

REFERENCES


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