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Cellular universal IP for nested network mobility

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Abstract

In recent years, network mobility (NEMO) has been studied extensively due to its potential applications in military and public transportation. NEMO basic support protocol (NBSP), the current *de facto* NEMO standard based on mobile IPv6, can be readily deployed using the existing mobile IPv6 infrastructure. However, NBSP's root in mobile IPv6, such as the need of care-of address (CoA) and tunneling, results in substantial performance overhead, generally known as *route sub-optimality*, in nested NEMO environments. This paper tackles this problem by proposing a scheme based on cellular universal IP (CUIP) to eliminate the need for CoA and tunneling in supporting nested network mobility. Using quantitative analysis, we show that the proposed scheme outperforms the existing nested NEMO schemes by multiple folds in terms of bandwidth overhead. We also show how IP fragmentation negatively impacts route optimality, and that the proposed scheme is inherently superior to the existing schemes in this regard. More importantly, while the scalability of the existing schemes generally deteriorates with the network size, the complexity of our proposed scheme is independent of the network size and thus is far more scalable. Our results show that the proposed scheme is particularly suitable for nested NEMO networks formed by mobile routers with random and ad hoc movement patterns.

Keywords: Network mobility; IP mobility; Mobile network; Mobile router; Cellular universal IP; Universal addressing; IP fragmentation in mobile networks; Ad hoc mobile network; Scalability of network mobility; NEMO

1. Introduction

Network mobility (NEMO) has been an active research area in recent years because of its importance in military and vehicular applications [1,2]. NEMO basic support protocol (NBSP) [3] is the current *de facto* standard for NEMO which enables the local mobile nodes, visiting mobile nodes and local fixed nodes (they will be collectively referred to as *mobile network nodes* or MNNs hereinafter) within the coverage of a mobile router (MR) to move together as a mobile network. It also allows many of these mobile networks, possibly from different home networks of different prefixes, to join each other in an ad hoc manner and form a nested NEMO network.

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The tradeoff for NBSP is the route sub-optimality problem which substantially lowers the efficiency of packet delivery in terms of bandwidth and data latency [4]. The root cause of the route sub-optimality problem is the need to acquire a new care-of address (CoA) after one MR moves into the coverage of another, which in turn requires a bi-directional IP tunnel to be setup between the MR and its home agent (HA_{MR}). This route sub-optimality problem worsens as the number of nesting level grows, because each additional level of nesting adds an additional layer of bi-directional tunneling, which incurs 40-byte IPv6 header overhead to every packet traveling between the corresponding MR-HA_{MR} pair. For packets with small payload, such as the VoIP example given in [4], each layer of tunneling occupies 16 kbps of bandwidth per channel whereas the payload occupies only 8 kbps. In other words, in an N-level nested NEMO, there will be $N*200\%$ header overhead in each voice packet traveling through the already narrow wireless link between the top-level MR (also known as the root-MR) and the access router (AR) (see Fig. 1).

On the other hand, for packets with large payload the additional tunneling may cause unnecessary packet fragmentations because the additional header may increase the size of a packet beyond the network's maximum transmission unit (MTU) size, resulting in extra packet delay and bandwidth consumption. The fragmentation problem is especially significant for nested NEMO because when a packet gets fragmented at, say, the jth level of the hierarchy (with the root-MR being at level 1), the packet will be fragmented again and again with probability one from level $j-1$ all the way up to level 1. This fragmentation problem and its performance impact to nested NEMO will be further elaborated in Section 6.

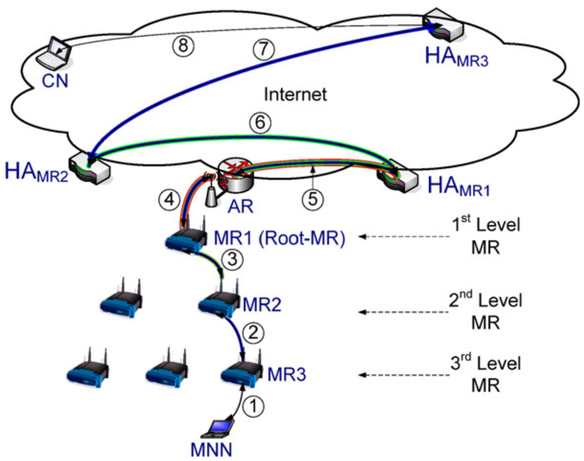

Fig. 1. Illustration of Route Sub-optimality.

Fig. 1 illustrates another problem of route sub-optimality, namely, excessive route segments or pinball routing effect, in a three-level nested NEMO. Suppose MR1, MR2 and MR3 from different home networks represented by home agents HA_{MR1}, HA_{MR2} and HA_{MR3}, respectively, join each other in an ad hoc manner and form the nested NEMO as shown. Assume an MNN under the coverage of MR3 (i.e., the MNN belongs to MR3's mobile network) is involved in an ongoing session with a correspondent node (CN) located outside the nested NEMO. Let us also assume that the binding update at the home agent has been completed, and now the MNN simply sends an uplink data packet to the CN. The packet must then traverse the following path before reaching the CN.

1. MNN → MR3: The MNN sends the packet to MR3 in the normal way with the CN as the destination and the MNN itself as the source in the IPv6 header.
2. MR3 → MR2: MR3 encapsulates the packet with its HA (HA_{MR3}) as the destination and its CoA as the source in the outer IPv6 header.
3. MR2 → MR1: MR2 repeats step (2) and encapsulates the packet with HA_{MR2} as the destination and its CoA as the source in yet another outer IPv6 header.
4. MR1 → AR: MR1 repeats the step similar to (3), and then forwards the packet to the fixed AR (or the gateway). Note that the original piece of data is now encapsulated by four layers of IPv6 headers (including the IPv6 header originated from the MNN). The outermost layer now contains the HA_{MR1} as the destination and MR1's own CoA as the source.
5. AR → HA_{MR1}: After receiving the packet from MR1, the AR simply forwards it to HA_{MR1} according to the destination address in the outermost IPv6 header.
6. HA_{MR1} → HA_{MR2}: HA_{MR1} decapsulates the outermost IPv6 header. The second layer of IPv6 header now becomes the outermost one. The destination address of this layer is HA_{MR2} and, therefore, HA_{MR1} forwards it to HA_{MR2}.
7. HA_{MR2} → HA_{MR3}: Similar to step (6), HA_{MR2} decapsulates the outermost IPv6 header from the receiving packet. The third layer of IPv6

header now becomes the outermost header. The destination address of this layer is HA_{MR3} and, therefore, HA_{MR2} forwards it to HA_{MR3}.

8. $HA_{MR3} \rightarrow CN$: HA_{MR3} decapsulates the outermost IPv6 header from the received packet. The packet finally turns back to its "original shape" as it was sent out from the MNN. Thus, the destination address is now the CN's address, and HA_{MR3} forwards the packet accordingly.

As bi-directional tunneling is used in NBSP, the downlink packets sent from the CN to the MNN must traverse the same path in reverse order. That is, the opposite of the above eight route segments must be followed. Also, Fig. 1 only considers three levels of nested NEMO on the MNN side. In general, $2(N + M) + 2$ route segments will be traversed by a packet in a nested NEMO of N layers for the MNN side and a nested NEMO of M layers for the CN side.

Ng et al. [4] showed that additional problems, such as susceptibility to link failure and instability of network connection, are also indirect consequences of route sub-optimality. In this paper, we propose a new scheme for nested NEMO that is based on cellular universal IP (CUIP) [5]. We show that CUIP's unique universal addressing feature allows the proposed scheme to outperform other approaches by reducing the overall sub-optimality substantially.

Note that the term "route sub-optimality" is a general terminology used in the literature. In practice, excessive routing (i.e., pinball effect) is only part of the "sub-optimality". Later on, we will quantitatively analyze route sub-optimality in terms of bandwidth overhead and also the impact of packet fragmentation.

Finally, to focus our discussions on network mobility, we will only consider MR level mobility in this paper. That is, through prefix aggregation at the MRs [3], all the MNNs underneath a particular MR are assumed to be assigned with the network prefix of the MR and are moving together with the MR as a mobile network. We will show in Section 7 that MNN level mobility can also be supported by the proposed scheme if the MNNs are also CUIP-enabled.

2. Related work

In recent years, numerous solutions have been proposed to tackle route sub-optimality in NEMO networks. Many of them only focus on solid NEMO structure (i.e., non-nested NEMO). Examples of these schemes include the optimized route cache management protocol (ORC) [6] and the Global HA to HA protocol [7]. This section, however, deals with schemes specifically for enhancing the nested NEMO scenario.

2.1. HMIP based route optimization method (HMIP-RO)

HMIP-RO [8] is largely based on the original hierarchical mobile IP (HMIP) [9] scheme designed to enable micro-mobility of mobile hosts[1] (MHs). HMIP-RO employs a mobility anchor point (MAP) introduced in [9] to handle the MR mobility inside the nested NEMO. That is, as long as the MRs are moving within the MAP controlling domain, the HA_{MR}'s would not be aware of the movements. Hence, the handoff/roaming signaling overhead beyond the MAP can be significantly reduced. Also, the MAP is capable of encapsulating/decapsulating multiple levels of the IP tunnels formed within the nested NEMO. This enables the MAP to send and receive packets directly to and from the corresponding HA_{MR}. The pinball routing effect can therefore be reduced.

2.2. IPv6 reverse routing header (IPv6-RRH)

The basic idea of IPv6-RRH [10] is to perform loose source routing for the nested NEMO. The scheme first determines the number of upper-level MRs along the path with the tree discovery algorithm [11]. The CoAs of all the MRs along the path will then be included in the "slots" of the reverse routing header (RRH) of the uplink (i.e., initiated from the MNN) packets. When the corresponding HA_{MR} receives the packets containing the reverse routing header, it analyzes the routing information provided, and then deduces the topology of the nested NEMO. In the downlink direction, after receiving or intercepting packets from the CN, the HA_{MR} constructs the most efficient multi-hop routing header for the packets addressed to the MNN based on the previously deduced topology. With

[1] The terms mobile host (MH) and mobile network node (MNN) all refer to the mobile terminals such as laptops or mobile phones. They appear with different labels here to reflect the different terminologies usually associated with their corresponding architectures – MH for traditional fixed line mobility networks and MNN for NEMO.

IPv6-RRH, only one layer of bi-directional tunnel is needed between the root-MR and the HA_{MR}.

3. Two-tier addressing vs. universal addressing

NBSP, HMIP-RO, IPv6-RRH and virtually all existing NEMO solutions are based on the *two-tier* addressing model used by Mobile IPv6 [12]. Generally speaking, under such an addressing model, while away from the home network (or home NEMO network in our context), an MH (or MR/MNN in our context) is identified by its home address, but is addressed by the CoA obtained from the foreign network (or foreign NEMO network in our context) it is visiting. The two-tier addressing model allows an MH to be reached globally. The major drawback of it is the requirement of the CoA acquisition in the foreign network to maintain the connectivity to the global network. In addition to the excessive handoff delay involved in acquiring the CoA [13,14], IP tunneling between the home and the foreign networks is also an inevitable consequence of adapting to the CoA concept. Hence, from the illustration given in Fig. 1, it can be concluded that the two-tier addressing model is the major cause of the route sub-optimality problem in the nested NEMO environment.

Another major class of two-tier addressing schemes is often known as identifier/locator split. A representative example of this class of schemes is the host identity protocol (HIP) [15]. In HIP, a host identity (HI) layer is inserted between the IP and TCP layers, so that the change of IP address (i.e., the locator) is fully transparent to the upper layers. In other words, the upper layers always see the HI as the permanent identifier of the device and are transparent to the device's mobility. In addition, the HI is supposed to be a public crypto key of the device, and both the MH and the CN must be authenticated before a direct connection between them can be made. Since CoA is not necessary, the need of IP tunneling is eliminated. However, aside from the excessive handoff delay caused by the acquisition of a new IP address through DHCP and two roundtrips of handshaking, HIP will inevitably face the phenomenon known as "binding storm" [10] when HIP is deployed in the NEMO environment. The reason is the following. In HIP, one HI can only serve as the identification of one device. As a result, unlike prefix aggregation [3], an MR being identified by its HI cannot serve as an "aggregated address" for the MNNs under its coverage. Each MNN must then initiate its own HIP exchange mechanism with its CN independently whenever the MR changes its location. When the number of MNNs is considerably large, a "HIP exchange storm", effectively identical to binding storm, will result.

In order to avoid the route sub-optimality and binding storm problems, the *universal* addressing model, which is the model used in [5] to represent a scheme that identifies and addresses an MH with the same IP address globally, should be considered. However, the universal addressing model is generally considered to be associated with the following problems.

1. The model is generally thought as not scalable because every router along the path from the CN toward an MH must contain the "full" route entry of the MH and must perform "flat routing" (i.e., routing based on the full route entry) globally along the entire path. Note that it is impossible to construct a hierarchical prefix routing (or route aggregation) structure for the mobile hosts because the traditional concept of prefix is simply not applicable to IP mobility. In other words, if universal addressing is to be deployed for global mobility, flat routing is needed globally, which could cause a significant scalability concern to the global core network.
2. In the traditional IP architecture, ingress filtering of source IP address [16] is normally considered a standard way to defend the networks from attacks initiated by bogus IP addresses. With universal addressing, packets from a visiting MH will be filtered out because they contain a different prefix in the source address than the visiting network.

The first problem has been solved by CUIP [5], which introduces an efficient and scalable way of deploying universal addressing. In this paper, we extend the scheme to the nested NEMO environment and prove that the new scheme can eliminate the route sub-optimality problem regardless of the number of nesting levels. In CUIP, an alternative security scheme is proposed to replace ingress filtering, which could potentially be applied to NEMO networks as well. The full investigation of its applicability, however, is left as a future work.

4. Overview of cellular universal IP (CUIP)

CUIP [5] is an IP mobility scheme that effectively eliminates the major source of handoff delay in IP mobility, namely CoA acquisition, and therefore removes the need for IP tunneling, even under global mobility. The major characteristics of CUIP are summarized as follows.

1. All MHs are addressed universally. That is, no matter where an MH is located, it will always be addressed and identified by the same IPv6 address globally.
2. With respect to a particular MH, all foreign wireless access networks are viewed as partitions of the same hierarchy rooted at the top-level router (TLR) of the home network the MH belongs to. According to [17], the tier-1 routers are all interconnected in a mesh manner, therefore a direct Layer-3 connection between any two TLRs (presumably tier-1 routers of the domains) can be assumed. As a result, a global hierarchy is formed and an inter-domain handoff can now be treated as a handoff within the same hierarchy. Fig. 2 illustrates this "self-centralized" global hierarchy concept. The MH A is being handed off from its home domain to a foreign domain. In CUIP, the foreign domain is logically viewed as a partition of the global hierarchy rooted by A's home TLR. In other words, this inter-domain handoff is now viewed as occurring within the same logical hierarchy, which can be handled by CUIP without the need for CoA or tunneling at all. On the other hand, with respect to the MH B, the global hierarchy will be different (i.e., it will be rooted by B's home TLR). Furthermore, it is important to note that, even for inter-domain handoff, the signaling and routing between the two involved wireless access networks are done through the direct Layer-3 connection. The core network, as well as the legacy CN, are completely unaware of the handoff and therefore are not necessary to support CUIP.
3. In a hierarchical network structure, all roaming/handoff scenarios must consist of exactly one cross-over router (COR) between the previous route and the new route, where the COR is defined as the router at the forking point of the two routes with respect to the MH. If the COR is on the home route, it is a *home COR*. Otherwise, it is a *new COR* (see Fig. 3). After roaming/handoff, only the routers on the new route and the previous route, up to the COR of this roaming/handoff (home or new), need to be updated by CUIP. The roaming/handoff is therefore transparent to the rest of the network beyond the COR, including the Internet and the CN.
4. In [5], a *home route* concept is introduced. The home route of an MH is defined to be the entire route, extending from the TLR all the way down to a wireless access router (WAR), assigned to the MH during subscription to mobile service. Based on the home route, a globally unique address, called *universal address* in [5], is derived. The routing along the home route is hierarchically prefix based and is considered to be optimal. When an MH is away from its home route, it is said to be on a foreign route, which is defined as the part of the route in the hierarchy that deviates from the home route. The routing on the foreign route is flat based (i.e., full address routing) and is therefore considered to be inefficient. However, this inefficiency can be minimized by assigning the home route to each MH

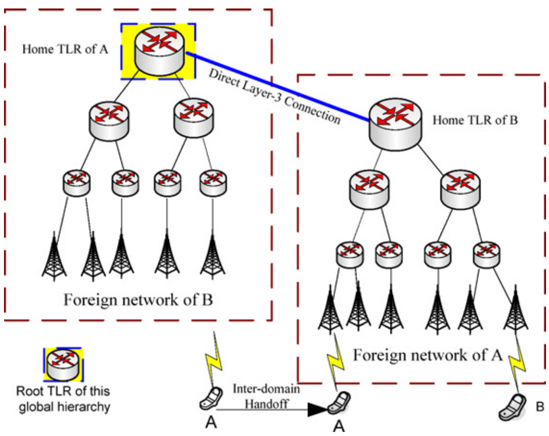

Fig. 2. The self-centralized global hierarchy formed between the home and the foreign domains of A.

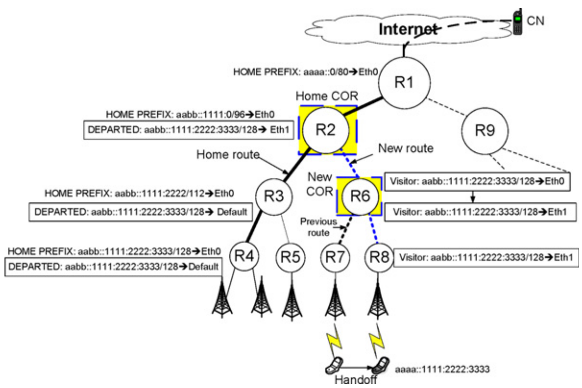

Fig. 3. Network architecture of CUIP.

intelligently so that the home route of an MH will be the route under which the MH is most frequently used. For example, a home route may be assigned to an MH based on the user's home/office location or the user's recent mobility pattern. Thus, when an MH is at or nearby its home route, the majority of the route will be along the home route, and therefore majority of the routing will be efficient. As illustrated in Fig. 3, the routing of the routers above the home COR (R2) is prefix based (optimal routing) and for the routers below the home COR is flat based (inefficient routing).

5. In [5], a hybrid prefix/flat routing table structure tailored for mobility, called *mobility routing table* (MRT), is introduced. The main idea of the MRT is to use prefix routing whenever possible, and use flat routing otherwise. The basic operation of the MRT is the following. First, packets for an MH are always routed to and along its home route, and then the prefix of the MH is located. If the MH is on the home route with respect to this router (e.g., R1 in Fig. 3), the query is completed and the packet is forwarded to the returned interface. Otherwise (e.g., R2, R3 and R4 because the MH is away from home w.r.t. these three routers), MRT looks for the MH's full address inside the *prefixed section* (a section containing only the full addresses of this same prefix). Thus, the "full address" lookup of an MH is scalable because only the entries of this prefix are queried. This routing table lookup can be considered as "partial prefix lookup". Second, along the new route (e.g., R6 and R8), the query would quickly fail for all the prefix entries because the router is not on the MH's home route. The query will then look up the MH's full address in the *visitor section* (a section containing only the visiting MHs' full addresses). This lookup is also scalable because the full addresses inside the prefixed sections are all skipped. In short, MRT combines the efficiency of prefix-routing and the flexibility of flat-routing to provide highly scalable universal addressing for global mobility.

In [5], two signaling schemes, namely cellular universal handoff update (CUHU) and cellular universal roaming update (CURU), are introduced to handle handoff and roaming, respectively. In this paper, the differentiation of handoff and roaming is not important, hence it is sufficient to highlight the following common key points of these two schemes.

1. The signaling schemes only need to update the new and previous paths up to the COR of the handoff.
2. At the COR, the CUIP specific option header will be removed so that the outgoing packets will be seen as normal IPv6 packets beyond the COR. This ensures the complete compatibility with legacy IPv6 devices on the Internet.

Fig. 3 briefly illustrates the routing operation in CUIP, in which the full entries inserted by the CUIP signaling are indicated by the rectangular boxes. Assuming the home route of the MH of IP address aaaa::1111:2222:3333 is the thicken black line shown on the left of the figure (R1–R2–R3–R4). Therefore, the routers along this path contain the home prefix of this MH. After a sequence of handoffs, the MH is now attached to R8. After the route update is completed, all routers along the new route (R2–R6–R8) and the routers on the home route below R2 (e.g., R3 and R4) will be updated by the CUIP signaling. With respect to routers on the home route above R2 (e.g., R1), however, the MH is still "at home" and the routing is still prefix based. Therefore, when packets are sent toward the MH from anywhere globally, they will be routed to the home COR (R2), from there they will be routed along the new route to the MH.

Finally, CUIP's inherent hierarchical network structure allows CUIP to architecturally fit into nested NEMO networks because nested NEMO is also hierarchical [18] by definition. In addition, as discussed in Section 1, the route sub-optimality is the indirect consequence of adapting to the CoA. By contrast, CUIP's universal addressing scheme completely eliminates the need of CoA even for global mobility. This further suggests CUIP to be a good enabler of nested NEMO.

5. CUIP for nested NEMO

In the CUIP-enabled nested NEMO network (referred to as CUIP–NEMO hereinafter), we assume that all the MRs support CUIP both as a router and as an MH. An MR behaves as a CUIP router when it receives CUIP signaling from the downlink (i.e., from some MRs underneath itself). On the other hand, an MR behaves as a CUIP host when it is initiating the CUIP roaming/handoff signaling mechanism by itself. The MNNs, however, are not required to support CUIP unless they will move away from their designated MR's coverage to become a visiting mobile node (VMN) of another MR. Again, we assume that all the MNNs move together with its designated MR and we will discuss the case of VMNs as a scenario by itself. Furthermore, to simplify our discussions, we assume that when an MR moves, all the lower-level MRs will move together, or they will lose connectivity. Finally, each MR is assigned a globally unique IPv6 prefix (referred to as universal prefix hereinafter) by an operator when the MR is first assigned to a nested NEMO as its home network. Consequently, this universal prefix also reflects the home route of the MR.

In the following subsections, we will show how CUIP–NEMO handles the common communication scenarios involving nested NEMO. Note that the functionality of the top level router (TLR) used in CUIP is replaced by the access router (AR) in order to better match the terminology used in the NEMO literature.

5.1. Scenario #1: Communications within the same nested NEMO and all MRs are along their corresponding home route

Fig. 4 shows the simplest communication scenario – both the MNN and the CN are within the same nested NEMO and are on their corresponding home routes. In this case, the packets initiated from the CN will be forwarded, according to normal routing mechanism, toward the home route of the MNN formed by MR1–MR2–MR3. Once the packets reach the home route of the MNN (i.e., reaching MR1 in this case), they will be routed to the MNN accordingly through prefix based routing. That is, the packets will be forwarded along CN → MR5 → MR4 → MR1 → MR2 → MR3 → MNN. Note that packets from MR5 will not be routed to MR6 because MR6 is not the upper-level MR of MR5. While the nested NEMO is formed, a tree structure is defined among all the MRs (the way to define this tree structure, however, is outside the scope of this paper). That is, MR4 will be configured to be the upper level MR of MR5. Uplink packets routed through MR5 will then always be directed to MR4, but not MR6. On the other hand, the CN is also on its home route, packets from the MNN therefore will also be directed to it with a similar routing mechanism in the reverse direction.

5.2. Scenario#2: Communications across different mobile networks

Fig. 5 depicts a scenario in which MR2 changes its network location (through roaming/handoff) from its home NEMO to a foreign NEMO. Recalling that when an MR changes its network location, all the MRs and MNNs logically underneath its coverage move along with it. For example, in Fig. 5, all the entities below MR2's coverage, including MR3 and the MNNs underneath MR3, move along with MR2. We will now see how MR2 and MR3 deal with the mobility with CUIP-NEMO.

In CUIP–NEMO, all the MRs underneath a moving MR are unaware of the movement. In our example, the prefix entry of MR3 (i.e., aaaa::1111:5555:6666:0/112) inside MR2 remains

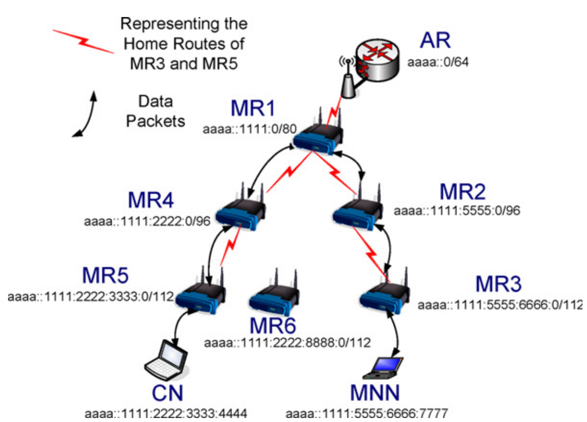

Fig. 4. Communications within the same nested NEMO.

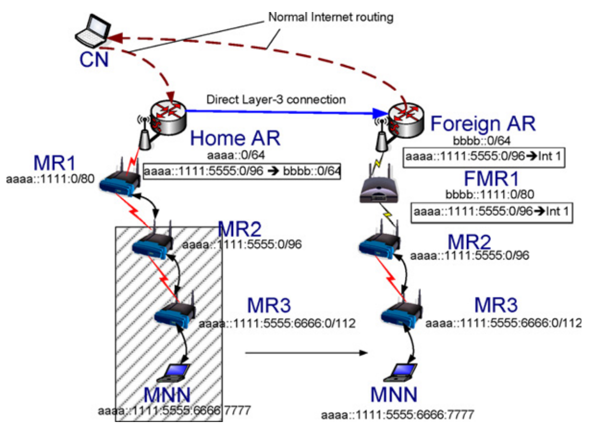

Fig. 5. Roaming/handoff across two nested NEMOs.

unchanged after the movement of MR2. Therefore, nothing needs to be changed at MR3 and the MRs below it. (Note that the prefixes after the slash (e.g., /80) used in the examples throughout this paper are arbitrarily chosen for illustration purpose. They may not reflect the real prefixes allocation in the real life deployments.)

MR2, however, is the one that initiates the movement. Therefore, it will behave as a CUIP-based host during roaming/handoff. After roaming/handoff, MR2 initiates the CUIP signaling procedures with its universal prefix to update the upper-level MRs in the hierarchy up to the COR. Note that the scenario depicted in Fig. 5 is an inter-domain mobility scenario. According to the original CUIP, the home AR will serve as the COR for this roaming/handoff. As a result, packets addressed to an MNN underneath MR3 will first be routed to its home AR, and its home AR will direct them to the appropriate foreign AR through the direct Layer-3 connection between them (i.e., no tunneling is needed), and from there the packets will be forwarded to MR3 accordingly. Note that the interface "Int 1" used in the routing (i.e., entries inside the rectangular boxes) is only a general interface for illustration purpose. In practice, this interface may be an interface specific to the wireless technology being used (e.g., MAC address for 802.11).

5.3. Scenario #3: Communications in a nested NEMO with MRs from different mobile networks

Fig. 6 shows a nested NEMO with the MRs all belonging to different home networks. Let us assume MR1, MR2, MR3 and MR4 all belong to different nested NEMO networks represented by their corresponding home ARs, namely AR1, AR2, AR3 and AR4, respectively, and hence they are all prefixed according to these ARs. These MRs then formed the nested NEMO shown in Fig. 6 in an ad hoc manner. Assuming the routing tables inside all the routers (fixed or mobile) have already been updated through the CURU/CUHU signaling. The downlink packets to the MNN are fist routed to AR4, which is the home AR of MR4, and AR4 will then redirect them to AR1 directly, shortcutting AR2 and AR3. The uplink packets are routed directly toward the CN from AR1. It is important to note that, although Fig. 6 is effectively identical to the nested NEMO shown in Fig. 1, the pinball routing and tunneling overheads have been eliminated.

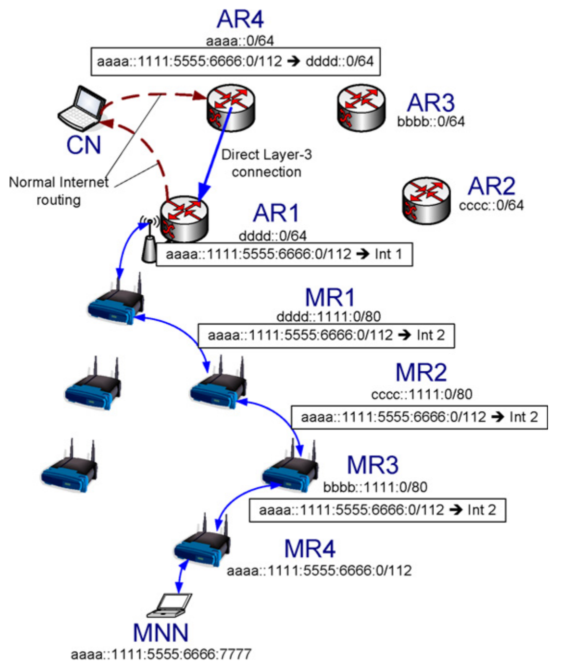

Fig. 6. Communications through MRs from different networks.

5.4. Scenario #4: Communications of a visiting mobile node

CUIP–NEMO is fully capable of supporting mobility at the host level, as long as the MNN is CUIP-enabled. Recall that a CUIP–NEMO enabled MR can act as a host as well as a router. Therefore, when a CUIP-enabled MNN underneath an MR sends a CUIP signaling messages to the MR, the MR will simply consider itself as a router and configure the MRT accordingly. Let us consider the scenario of a VMN shown in Fig. 7 Suppose an MNN is moving from its home nested NEMO network (Home NEMO), represented by the Home AR, to a foreign nested NEMO network (Foreign NEMO) represented by the Foreign AR, so that it is now seen as a VMN at the Foreign NEMO. Since the MNN supports CUIP, as soon as it detects from, say, Layer-2 signaling, that it has moved to a Foreign NEMO, it will initiate the CURU/CUHU mechanism to update the mobility routing tables with the its universal address along the new route in the Foreign NEMO. The Foreign NEMO, with CUIP–NEMO support assumed, will then follow the CURU/CUHU mechanism described in [5] to notify the Home AR with the whereabouts of the MNN. After the CURU/CUHU mechanism is completed, all the packets addressed to the MNN

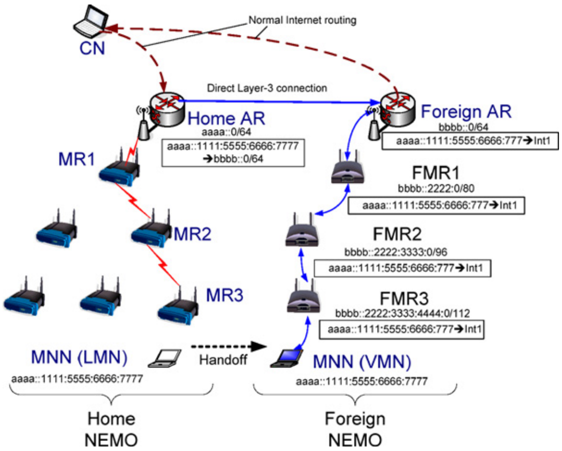

Fig. 7. Support of visiting mobile node in CUIP–NEMO.

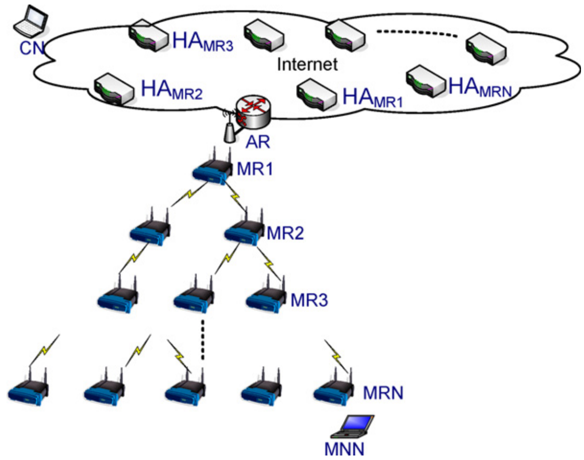

Fig. 8. A common nested NEMO architecture for performance analysis of different schemes.

will first be routed to the Home AR, and the Home AR will redirect them to the Foreign AR through the direct Layer-3 connection between the two ARs (again, no tunneling is needed), which will then forward the packets to the MNN according to the route entries configured by CURU/CUHU.

To conserve space, we will not discuss all possible nested NEMO scenarios here. The four scenarios above, however, have already covered the most fundamental ones, and other scenarios can be derived from them.

6. Quantitative analysis of nested NEMO schemes

We now quantitatively analyze the impact of tunneling overhead towards the scalability of nested NEMO. In a nested NEMO network, all the MRs are connected to its uplink and/or downlink counterparts wirelessly. Since these links are characterized by low bandwidth and high loss rate, the overall throughput can be very limited. This is especially significant at the link between the root-MR and the AR (referred to as the "bottleneck link" hereinafter), because every uplink and downlink packet of the nested NEMO network will pass through this link. As a result, the bandwidth overhead induced by each nested NEMO scheme over this bottleneck link can directly affect the scalability of each scheme.

It should be noted that all nested NEMO schemes share the same hierarchical architecture. This makes performance comparisons between the schemes relatively easy. Fig. 8 depicts such a general nested NEMO structured with a hierarchy of N levels of MRs. MR1 is considered to be the root-MR of the hierarchy and is connected to the AR wirelessly. Inside the core network, or the Internet, if HA functionality is needed, there can be N $\mathrm{HA_{MR}}$'s corresponding to the N MRs along the path leading to the MNN. The analysis will be based on communications between an MNN under the coverage of MRN and a CN in the core network. We will first evaluate the bandwidth overhead for different schemes without considering IP fragmentation. Then we will show how IP fragmentation negatively impacts the results obtained.

6.1. Bandwidth overhead at the bottleneck link (fragmentation ignored)

Within the context of nested NEMO, bandwidth overhead increases as the number of encapsulations increases. The bandwidth overhead at the bottleneck link, with IP fragmentation ignored, can be generally expressed in (1) for any particular nested NEMO scheme X

$$\Omega(X) = K_{\mathrm{B}} C(X), \tag{1}$$

where $\Omega(X)$ is the bandwidth overhead at the bottleneck link generated by encapsulations per uplink packet sent by one MNN when scheme X is used, K_{B} is the bandwidth occupied per layer of encapsulation, and $C(X)$ is the the number of IPv6 header encapsulations needed for the scheme X at the bottleneck link, including the "original" IPv6 header constructed by the MNN, to transmit the data from the MNN to the CN.

6.1.1. NEMO basic support protocol

In NBSP, one extra layer of encapsulation is added as the packet sent from the MNN travels one level up in the hierarchy until the packet leaves the nested NEMO network through the root-MR. Recalling that the original IPv6 header is also considered in $C(NBSP)$, the number of encapsulations at the bottleneck link for NBSP is $N+1$. Thus, (1) becomes

$$\Omega(NBSP) = K_B(N+1). \quad (2)$$

6.1.2. HMIP based route optimization method

According to Fig. 9 of [8] (reproduced in Fig. 9 with an *N-level* nesting configuration), $C(HMIP-RO)$ is equal to $N+2$. As a result, we obtain

$$\Omega(HMIP-RO) = K_B(N+2). \quad (3)$$

6.1.3. IPv6-reverse routing header

Instead of creating multiple levels of IPv6 tunneling, IPv6-RRH embeds multiple "slots" into the IPv6 header to carry the CoAs of upper-level MRs along with the packets. A slot occupies 16 bytes of packet size whereas a full header encapsulation occupies 40 bytes (see Fig. 10). Therefore, a factor of 16/40, or 2/5, should be taken into account when determining the value of $C(IPv6-RRH)$. Ignoring the four-byte fixed IPv6 extension field, and taking into account the original header from the MNN, we have

$$\Omega(IPv6-RRH) = K_B\left(1+\frac{2}{5}(N+1)\right). \quad (4)$$

6.1.4. CUIP for nested NEMO

In CUIP–NEMO, no encapsulation is needed. Therefore, $C(CUIP-NEMO)$ is unity (accounting for the original IPv6 header from the MNN), and so

$$\Omega(CUIP-NEMO) = K_B. \quad (5)$$

Note that we have only considered the $\Omega(X)$ in the uplink direction in (2)–(5). Since $\Omega(X)$ is identical in both the uplink and downlink directions, the total bandwidth overhead at the bottleneck link for a duplex communication channel will be twice of what we have obtained here.

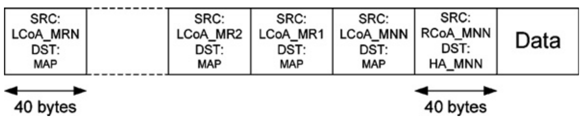

Fig. 9. An IP packet formatted with HMIPv6.

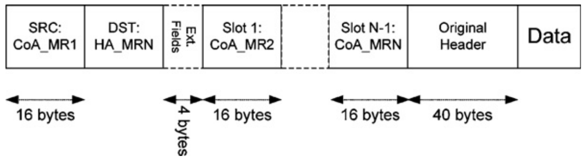

Fig. 10. An IP packet formatted by IPv6-RRH.

6.2. Bandwidth overhead at the bottleneck link (fragmentation taken into account)

In the IPv6 standard [19], fragmentation of IP packets are not allowed at the intermediate routers. Due to the need for tunneling in many occasions (e.g., mobile IPv6), however, the procedures specified in [20] allow fragmentation/reassembly to be done at the entrance/exit router of an IP tunnel. This is because tunneling increases the packet size along the data path, hence the packet size could exceed the fragmentation threshold (i.e., the MTU) after tunneling is performed. Fragmentation will then be needed. Thus, with schemes such as NBSP, HMIP-RO and IPv6-RRH, all the MRs and HA_{MR}'s must be capable of fragmenting and reassembling IPv6 packets because they are the entrances as well as exits of the corresponding tunnels.

Let us again consider the general nested NEMO structure shown in Fig. 8. Let P_j be the probability of a packet being fragmented the first time at level j of the hierarchy, where $1 \leqslant j \leqslant N$ and the root-MR is considered to be at level 1. Note that we only need to consider the probability of the first occurrence of fragmentation because, in a nested NEMO, after a packet gets fragmented the first time at level j, the fragmentation will happen again and again to the packet with probability one all the way up to level 1 of the hierarchy. This is because, according to the IP fragmentation mechanism given in [21], only the excessive part of the packet is fragmented into the second packet. For example, consider a particular network with an MTU of 1500 bytes. Assume the source sends out a packet of the MTU size (e.g., to minimize the header overhead), if the router at the next hop needs to perform tunneling, the packet must be fragmented into two smaller packets of size 1448 bytes and 52 bytes (note that the size of the fragments, except the last one, must be divisible by eight [21]), respectively, at the router. Including the 40-byte IPv6 header in both fragments and the 8-byte IPv6 Fragment header in the first one, an IP packet of size 1496 bytes and an IP packet of size 92 bytes will be transmitted to the next router. For the nested NEMO schemes that require tunneling, tunneling is performed again in the next router (which is an MR). As a result, the 1496-byte packet will have to be fragmented again and the process will repeat itself all the way up to the root MR. However, the smaller fragments generated along the path (they will be 48 bytes long when generated) will not be fragmented again within a reasonably sized nested NEMO (note that the MTU of an IPv6 network must be at least 1280 bytes). In other words, a packet that gets fragmented at level j will eventually turn into $j+1$ fragments when it leaves the root-MR.

Let us see how fragmentation impacts the bandwidth overhead at the bottleneck link. Let P_u be the probability that no fragmentation occurs across the nested NEMO for a particular packet, then we have $P_u + \sum_{j=1}^{N} P_j = 1$. Suppose an MNN sends a packet of arbitrary size into the nested NEMO network, and let Y be the number of fragments generated from this packet at the bottleneck link. Obviously, when no fragmentation occurs, Y will be unity. Then we have

$$E[Y] = P_u + \sum_{j=1}^{N} P_j(j+1). \tag{6}$$

Denote $\Omega_F(X)$ is the average bandwidth overhead at the bottleneck link generated by encapsulations per uplink packet sent by an MNN when scheme X is used, with fragmentation taken into account.

After fragmentation, a packet sent by the MNN, on average, will turn into $E[Y]$ packets at the egress port of the root-MR. Therefore, with the definition of $\Omega(X)$ from the previous subsection, we have

$$\begin{aligned}\Omega_F(X) &= \Omega(X)E[Y] \\ &= \Omega(X)\left(P_u + \sum_{j=1}^{N} P_j(j+1)\right).\end{aligned} \tag{7}$$

According to [22], the IP packet length distribution on the Internet can be assumed as follows.

$$\begin{aligned}&\Pr\{L = 40\ \text{Bytes}\} = 0.6,\\ &\Pr\{L = 576\ \text{Bytes}\} = 0.25,\\ &\Pr\{L = 1500\ \text{Bytes}\} = 0.15.\end{aligned} \tag{8}$$

Note that 1500 bytes is the maximum size a packet can be, and is only determined by the MTU in the network, it will not be affected by the size of IP headers being used. Therefore, although this distribution only considers IPv4 traffic in [22], it is still applicable to our analysis here because we are only interested in $\Pr\{L = 1500\ \text{Bytes}\}$here.

Let us assume that the MTU of the network shown in Fig. 8 is 1500 bytes. From (8), 15% of the packets will get fragmented when the first layer of tunneling is applied (i.e., at level N of the hierarchy). The rest of the packets (i.e., another 85%) will hardly be fragmented within a nested NEMO of a reasonable depth, because Nneeds to be greater than 23 for a packet of size 576 bytes to turn into a packet of size over 1500 bytes through encapsulations. Therefore, we can assume that in a nested NEMO network with $N \leqslant 23$,

$$\begin{aligned}&P_j = \begin{cases} 0.15, & j = N,\\ 0, & j \neq N,\end{cases}\\ &P_u = 0.85.\end{aligned} \tag{9}$$

Substituting (9) into (7), we obtain

$$\Omega_F(X) = \Omega(X)(0.85 + 0.15(N+1)). \tag{10}$$

Note that (10) is applicable to all the nested NEMO schemes that require tunneling performed at the MRs, including NBSP, HMIP-RO and IPv6-RRH. From (10), we can see that, when $N = 2$ (the most common nested NEMO configuration), a 15% probability of fragmentation can already add 30% of bandwidth overhead to the bottleneck link when compared to the results obtained without considering fragmentation.

CUIP–NEMO, on the other hand, does not need tunneling and therefore fragmentation will not occur at all. As a result,

$$\begin{aligned}&P_j = 0 \quad \forall j,\\ &P_u = 1\end{aligned}$$

and therefore,

$$\Omega_F(CUIP) = \Omega(CUIP). \tag{11}$$

In other words, CUIP–NEMO does not suffer from the above-mentioned fragmentation problem.

6.3. Implication of the results

Eqs. (2)–(5), (10) and (11) show that the bandwidth overhead at the bottleneck link, with or without fragmentation considered, for all nested NEMO schemes is dependent on the network size, N, except for CUIP–NEMO. This implies that, among all the existing nested NEMO schemes we know of, CUIP–NEMO is the most scalable one. This is an important advantage because N could increase quickly when the mobile routers move and form nested NEMO networks in an ad hoc manner. When the nesting structure is formed in an ad hoc and non-uniform manner, the nested NEMO could be very unbalanced. Fig. 11 depicts an example of such an unbalanced nested NEMO network formed by non-uniform ad hoc MR movements. With large N, the bandwidth overhead generated by schemes like NBSP, HMIP-RO and IPv6-RRH will easily overload the bottleneck link which will then cause excessive packet delay or packet loss. The bandwidth overhead of CUIP-NEMO, on the other hand, is independent of N, and therefore is more suitable for highly mobile nested NEMO networking.

7. Other design considerations in CUIP for nested NEMO

7.1. Routing table scalability of CUIP-NEMO

As discussed in the previous section, the bandwidth overhead at the bottleneck link of CUIP-NEMO is a constant regardless of the size of the nested NEMO network. Therefore, the scalability of CUIP-NEMO is a non-problem in terms of bandwidth overhead. However, one may see that the CUIP–NEMO mechanism is to deal with the network mobility problem through updating the routing tables inside the hierarchical network architecture. Obviously, the efficiency of data delivery and bandwidth consumption are achieved at the expense of additional routing table operations (e.g., lookup of additional route entries for visiting MRs (VMRs)). Since the overall routing table size in the routers is usually an important measure of the scalability of a network, we now discuss how ad hoc network mobility impacts the routing table size in a CUIP–NEMO enabled MR.

As discussed earlier, the hybrid prefix/flat MRT structure used in CUIP can enhance the scalability of routing-table in fixed-line mobility networks. It turns out that in nested CUIP-NEMO networks, prefix aggregation makes MRT even more scalable. We explain this in more detail as follows, with Fig. 12 as illustration.

We can see from Figs. 5 and 6 that each VMR creates one additional route entry in the MRs along the new route, including the COR. As a result, for any particular MR of a CUIP–NEMO network, the number of additional route entries created by ad hoc network mobility therefore grows with the number of VMRs underneath it. However, due to the effect of prefix aggregation, the additional route entries inserted into an MR along the new route under concern are actually route prefixes of the VMRs beneath it, for which one entry of route prefix can represent tens or even hundreds of MNNs underneath the VMRs. Furthermore, a VMR is assumed to move along with all the lower-level MRs underneath it. This can be seen as a second tier

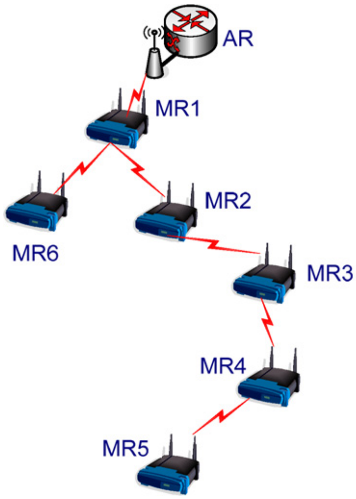

Fig. 11. An unbalanced nested NEMO network.

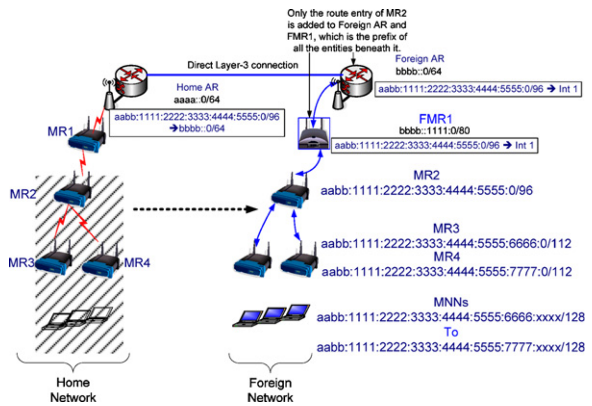

Fig. 12. Illustration of multi-tier aggregation effect.

prefix aggregation for which one additional route entry of the VMR actually represents multiple lower-level MRs underneath it. Fig. 12 illustrates the effect of the multi-tier prefix aggregation. When MR2 moves into a foreign network rooted by FMR1, only the prefix entry of MR2 is added to the routing table of FMR1 and Foreign AR. Since the route entry of MR2 (i.e., aabb:1111:2222:3333:4444:5555:0/96) is the prefix of all entities below it (i.e., including the MNNs underneath MR3 and MR4), packets addressed to any of these MNNs can be routed accordingly as long as FMR1 has the /96 prefix of MR2 in its routing table. After these packets are routed to MR2 from FMR1, MR2 will route them based on the longer prefix appropriately. Therefore, one additional route entry in FMR1 already represents many MNNs from another network.

Generally speaking, this multi-tier route aggregation is important to universal addressing schemes (i.e., CUIP–NEMO) because it allows one route entry to be associated with many lower-level MRs and MNNs. Therefore, routing tables inside any MR should just contain route entries for its own MNNs and a number of entries for the lower-level MRs, but not the MNNs underneath these lower-level MRs. With today's advanced routing technologies, the routing table scalability will hardly be a major issue for a CUIP–NEMO network of any size.

7.2. Backward compatibility of CUIP for NEMO

As mentioned in Section 3, the signaling and routing of CUIP do not involve the legacy routers or devices on the core Internet at all. CUIP–NEMO inherits this feature so that it is fully compatible with any legacy devices on the Internet. Consequently, the CNs can virtually be any legacy devices, including IPv4 devices or even devices behind network address translation (NAT) gateways.

On the other hand, under a CUIP–NEMO based MR, the MNNs are not required to support of CUIP or even IPv6 at all as long as they stay within the MR's coverage and move along with the MR. When necessary, the MR may serve as a NAT gateway for its MNNs, which allows the MNNs to access the Internet with the minimum network configuration (e.g., being DHCP capable). This, of course, complies with the original purpose of NEMO that is to allow devices with basic network configuration to access the Internet while moving

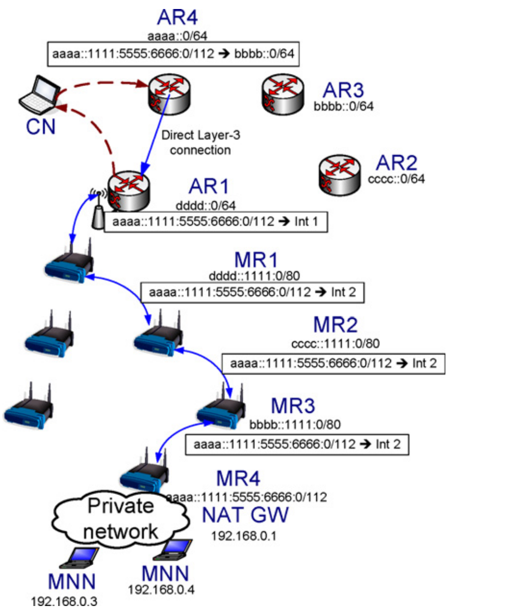

Fig. 13. Illustration of legacy compatibility of CUIP–NEMO.

along with its associated MR. Extending from the example shown in Figs. 6 and 13 illustrates the legacy compatibility of CUIP–NEMO by adding IPv4 NAT gateway support to MR4 and converting the universal addresses of the MNNs to IPv4 private addresses. Note that the CUIP–NEMO operation for all the MRs still applies without modification.

Furthermore, CUIP–NEMO is backward compatible with NBSP. Assuming that a CUIP–NEMO based MR and the corresponding home AR are also NBSP capable. When the NBSP mode is enabled, the universal address will serve as the home address and the home AR will serve as the home agent of the MR. For example, imagine that a CUIP–NEMO enabled MR moves into a foreign network that supports NBSP, but not CUIP–NEMO. All the CUIP signaling packets will be dropped by the non-supporting routers, but the MR will then receive the periodic router advertisements [23] from this foreign network. The MR can switch to NBSP mode and begin the CoA acquisition, home agent binding update (with its home AR) and other NBSP procedures defined in [3].

8. Conclusion

Route sub-optimality has been a major problem of nested NEMO deployment because of the pinball routing effect and the excessive bandwidth consumption involved in supporting ad hoc network mobility. This paper has proposed a new nested NEMO scheme based on CUIP. The major characteristic of CUIP is universal addressing which completely eliminates the major causes of route sub-optimality – CoA acquisition and IP tunneling. Furthermore, CUIP is based on a hierarchical architecture, which is also how nested NEMO is structured by definition. In this paper, we have testified how the new scheme, namely CUIP–NEMO, eliminates the pinball routing effect on the common nested NEMO scenarios. Also, we have quantitatively shown that CUIP–NEMO outperforms the most popular existing nested NEMO schemes in terms of the bandwidth overhead at the bottleneck link, which reveals scalability of the various schemes. In addition, we have further investigated the negative impact of IP fragmentation on scalability for nested NEMO. We showed that, with just two layers of nesting, IP fragmentation already adds 30% of bandwidth overhead, on top of tunneling, to the bottleneck link. CUIP–NEMO, however, is free of IP fragmentation and therefore is immune to its impact. The results therefore suggest that CUIP–NEMO is a scalable scheme to enable nested NEMO networks which are usually formed by highly mobile MRs in ad hoc manner. Last but not least, we have discussed the routing table scalability and backward compatibility concerns of CUIP–NEMO.

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