Nested Network Mobility on Multi-hop Cellular Network

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***Abstract*— In recent years, the *multi-hop cellular network* (MCN) architecture has been actively studied due to its capability to significantly increase the cellular system's capacity and coverage, and at the same time greatly reduce the transmission range of the mobiles. Majority of the literature on MCN, however, is based on the discussions from the physical or link layer's point of view. In this paper, we look into the support of MCN architecture from the IP layer's aspect. We believe that this aspect is critical for the general deployment of Internet applications on MCN because IP is the dominant supporting protocol for such applications. We introduce a new architecture based on the integration of the nested network mobility (nested NEMO), which is a pure IP layer architecture, and MCN, and name the resulting architecture the *nested NEMO on MCN*. We illustrate how nested NEMO on MCN operates and how it realizes the advantages provided by MCN on the IP layer. We also unveil a potential problem specific to the nested NEMO on MCN architecture, namely, recursive IP fragmentation. A simple technique to overcome this problem is also proposed.**

***Index Terms*—Network mobility, IP mobility, IP fragmentation, NEMO, nested NEMO**

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I. Introduction

Multi-hop cellular network (MCN) [1] has been an actively researched topic in recent years due to its potential in boosting the cellular system's capacity and coverage while at the same time reducing the power consumption on the mobile devices. However, the discussions of most literature on MCN are either focusing on the physical layer or link layer [1][3] aspects. However, today's major Internet applications (e.g., email, web browsing, VoIP, etc.) are heavily relying on the convergence of network, or Internet Protocol (IP), layer technologies. The idea of IP convergence effectively provides a universal platform for virtually all the Internet applications to run upon, regardless what physical medium or what link layer technologies are being used. Thus, we believe that, to enable the support of universal Internet applications on the MCN, it is necessary to take into account the IP layer aspect.

Network Mobility (NEMO) is a pure IP layer technology that enables the mobility of the entire network, instead of just a host. NEMO Basic Support Protocol (NBSP) [2] is the current *de facto* standard for NEMO that enables the *mobile network nodes* (MNNs) within the coverage of a mobile router (MR) to move together as a mobile network. It also allows many of these mobile networks, to join each other in an *ad hoc* manner and form a *nested NEMO network*. Generally speaking, a nested NEMO network is hierarchical in nature and is rooted by a top-level MR (so-called the *root-MR*) that connects to the Internet through a fixed *access router* (AR) (refer to Figure 1).

In this paper, we investigate the application of the nested NEMO concept on the *multi-hop cellular network* (MCN) architecture. In other words, we enable the concept of MCN using a pure IP layer technology. We call this *nested NEMO on MCN* architecture hereinafter. Figure 1 depicts a real life example of nested NEMO on MCN. We consider that an MR supporting NBSP installed in a bus and equipped with both the WCDMA (or 3G) and 802.11 WLAN interfaces is acting as the root-MR for its passengers; a laptop computer, containing both 802.11 WLAN and Bluetooth interfaces, of a particular passenger is then acting as a 2nd level MR; and the gadget devices of the passenger (e.g., a MP3 player or a wireless headset) are acting as the MNNs. These devices, namely, the MR in the bus, the laptop computer, and the gadgets together form a nested NEMO on MCN. The passenger's gadgets can then access the Internet in a multi-hop manner through the corresponding Bluetooth interface, then through the WLAN interface of the laptop computer and finally through the WCDMA interface of the root-MR.

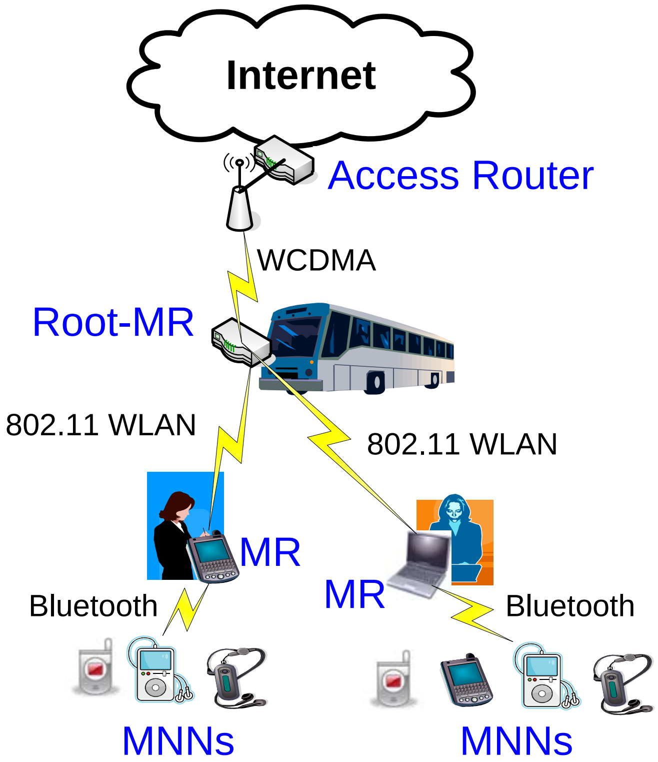

Figure 1. A daily example of the nested NEMO on MCN architecture

Due to its root on mobile IPv6 (MIPv6) [9], NBSP enables nested NEMO networking with the concept of two-tier addressing, including the need of *care-of address* (CoA) acquisition and *IP tunneling* through the home agent after handoff. In brief, after moving into the coverage of a foreign nested NEMO, a visiting MR first acquires a CoA from its upper-level MR in the foreign nested NEMO, and then performs a binding update with its *home agent* at its home network. The major difference between NBSP and MIPv6 is NBSP's usage of *prefix aggregation*. That is, all the entities, including the MNNs and lower-level MRs, underneath the visiting MR are all "represented" by one CoA and registered to the corresponding home agent (of the visiting MR) through one binding update procedure. As a result, after the binding update is done at the home agent of the visiting MR, the home agent will intercept all the packets addressed to all the entities underneath the visiting MR, and tunnel these packets to the visiting MR. Once these tunneled packets are received at the visiting MR, the tunnel will be decapsulated and the packets will be forwarded to the appropriate entities. This *prefix aggregation* therefore avoids the problem of "binding update (BU) storm," which refers to the consequence when all MNNs underneath the visiting MR are required to perform the binding update individually as when MIPv6 is used. When we consider the IP layer communications under the MCN architecture, NBSP significantly helps improve the performance and scalability of the network because such a BU storm will inevitably place a huge burden on the cellular link.

On the other hand, many problems associated with NBSP are also problems for nested NEMO on MCN. Fortunately, the most well known problem in NBSP, namely, the *routing sub-optimality* problem [2], has already been well addressed in the literature. In this paper, we focus our discussions on another problem that has not received much attention in the research community while the resource overhead induced can be significant in the MCN architecture. This problem, and its simple solution, will be discussed in detail in section III and IV, respectively.

II. NESTED NEMO ON MCN

Figure 2 illustrates how NBSP handles the packet routing in an MCN architecture. Suppose the mobile devices identified as 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. In this example, MR1 is the root MR connecting to the AR through a particular cellular network technology such as WCDMA, and MR2 and MR3 are connected to each other with 802.11 wireless LAN or Bluetooth and are acting as the intermediate MRs in the network.

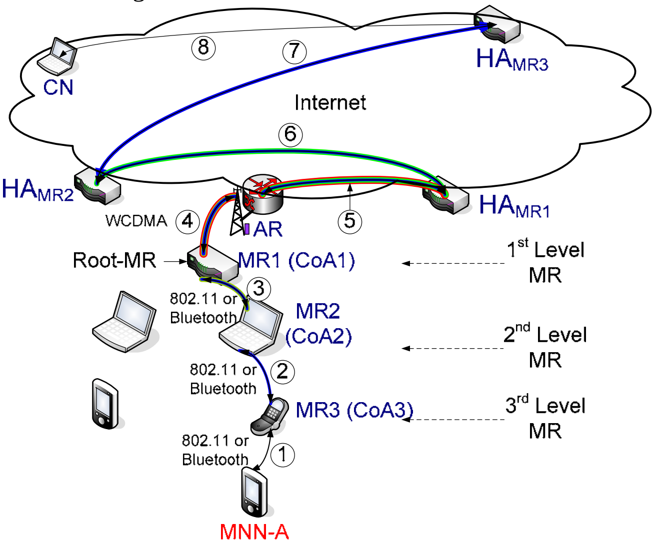

Figure 2. Illustration of nested NEMO under MCN

Suppose a mobile device, labeled MNN-A in Figure 2, is connected to MR3 as an MNN (i.e., the MNN-A belongs to MR3's mobile network). Assume that MNN-A is involved in an ongoing session with a correspondent node (CN) located outside the nested NEMO. Let us also assume that the CoA acquisitions and the binding update procedures have been completed for all the MRs inside the nested NEMO, and now MNN-A sends an uplink data packet to the CN. The packet must then traverse the following path before reaching the CN.

1. MNN-A → MR3: The MNN-A 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 (i.e., CoA3) 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 (i.e., CoA2) 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. The outermost layer now contains the HA_{MR1} as the destination and MR1's own CoA (i.e., CoA1) 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}→ CN: HA_{MR3} decapsulates the outermost IPv6 header from the received packet. The packet now 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 will traverse the same path in reverse order. That is, the opposite of the above eight route segments will be followed.

We can see from Figure 2 that the fundamental MCN characteristic, namely, enhancing the system capacity and coverage while reducing the transmission range of the mobile devices at the same time, is retained on the IP layer through nested NEMO. Too see this, we note that the hierarchy shown in Figure 2 can theoretically be extended indefinitely, and therefore the system capacity and coverage is only limited by the bandwidth of the wireless interfaces. Secondly, it is obvious that the transmission ranges of the mobile devices are also reduced. For example, the MNN-A can be far away from the AR, but it can still connect to the AR through the intermediate MRs in a multi-hop manner.

III. A PROBLEM IN NESTED NEMO ON MCN -- RECURSIVE IP FRAGMENTATION

It is important to note that, under the nested NEMO on MCN architecture, the root link (i.e., the WCDMA interface) is the *"bottleneck link"* of the entire MCN because each packet entering or exiting the network must pass through this expensive and bandwidth-limited link. Therefore, the bandwidth efficiency on this link largely determines the scalability of the entire nested NEMO on MCN architecture. The following discussions will be focused around the bandwidth efficiency of this link.

In the IPv6 fragmentation standard [5], packet fragmentation/reassembly is only allowed 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 may exceed the fragmentation threshold (i.e., the maximum transmission unit or MTU) after tunneling is performed. Fragmentation will then be needed. Thus, under nested NEMO for MCN, 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.

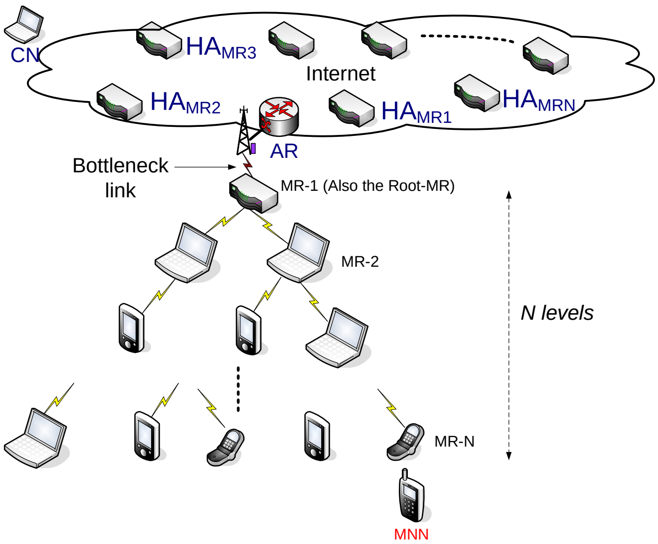

Figure 3. A *N*-level nested NEMO on MCN architecture

Let us consider a general N-level nested NEMO on MCN architecture shown in Figure 3. In this case, the cellular link between MR1 and the AR is the *bottleneck link*. Since an arbitrary packet sent by the MNN must undergo recursive tunneling as it traverses up the hierarchy, the size of the packet will inflate and may reach the MTU of the network at some point within the nested NEMO structure.

Let P_j be the probability of a packet being fragmented the first time at level j of the hierarchy, where $1 \le j \le N$ 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 need to be performed again and again to the packet with probability one all the way up to level 1 of the hierarchy. The reason is the following. According to the IP fragmentation mechanism given in [6], 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. Let us assume that the source sends out a packet of the MTU size (because the source also needs to fragment the packets according to the MTU size). Since the next hop router, which is an MR, needs to perform tunneling, the packet must be fragmented into two smaller packets of size 1448 bytes and 52 bytes at the router (note that the size of the fragments, except the last one, must be divisible by eight [6]). 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. With NBSP, tunneling is performed again in the next router (which is also 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 consider 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. We have $P_u + \sum_{j=1}^{N} P_j = 1$. Suppose an MNN sends a packet of arbitrary size into the nested NEMO on MCN architecture, and let *Y* be the number of fragments generated from this packet when it reaches the bottleneck link. When no fragmentation occurs, *Y* will simply be unity. Then we have

$$E[Y] = P_u + \sum_{j=1}^{N} P_j \left(j+1 \right) \qquad (1)$$

Obviously, the bandwidth overhead due to fragmentation seen at the bottleneck link is proportional to $E\left[Y\right]$ obtained in (1). We now estimate this value based on some published characteristics of the current Internet. According to [7], the IP packet length distribution on the Internet can be assumed as follows.

$$\Pr\left\{L = 40\,Bytes\right\} = 0.6$$
$$\Pr\left\{L = 576\,Bytes\right\} = 0.25$$
$$\Pr\left\{L = 1500\,Bytes\right\} = 0.15$$

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 [7], it is still applicable to our analysis here because we are only interested in $\Pr\left\{L = 1500\,Bytes\right\}$. Let us assume the MTU of the network shown in Figure 3 is 1500 bytes. As a result, 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 *N* needs 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 on MCN architecture with $N \le 23$,

$$P_j = \begin{cases} 0.15 & j = N \\ 0 & j \ne N \end{cases}$$
$$P_u = 0.85$$

From (1), we can obtain

$$E\left[Y\right] = 0.85 + 0.15\left(N+1\right) \tag{2}$$

Note that (2) is also applicable to packets entering from the core network in the reverse direction. From (2), we can see that, when *N=2* (e.g., the sample nested NEMO shown in Figure 1), a 15% probability of fragmentation can readily add 30% of bandwidth overhead to the bottleneck link ($E\left[Y\right]=1.3$). When $N \geqq 7$, the IP fragmentation overhead will be over 100%.

To the best of our knowledge, this problem mentioned has not been not well studied yet.

IV. The Simple Solution

A. *Evenly distributed fragmentation*

We note that the recursive fragmentation problem described in section III.III is due to the uneven distribution of the sizes of the two resulting packets formed after fragmentation – one with the size of the MTU and the other with a much smaller size.

Our solution to this problem is simple. The MNNs and CNs continue to fragment large packets in the "traditional" way, and therefore no change is needed for these devices. On the other hand, the MRs and the home agents should divide the packets into two evenly sized fragments when fragmentation is necessary. For example, when a packet of size 1500 bytes is received at an MR (assuming the path MTU is 1500 bytes), then the MR should divide the packet into a fragment of 752-byte long and the other fragment of 748-byte long (recall that the size of the first fragment must be divisible by eight). 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 800 bytes and an IP packet of size 788 bytes will be transmitted to the next MR. Consider that each additional level in a nested NEMO traversed by the packet adds one extra layer of 40-byte IPv6 header to the packet, an IP packet of 800 bytes will not be fragmented again for another 17 levels of tunneling. That is, inside any nested NEMO of a depth of less than 17 levels, at most one fragmentation will be performed for any packets traversing the network. With this simple solution, (1) becomes

$$E[Y] = P_u + 2\sum_{j=1}^{N} P_j \tag{3}$$

Substituting the data given in [7] (shown in section III.III) into (3), $E\left[Y\right]=1.15$. In other words, $E\left[Y\right]$ does not grow with the depth of the nested NEMO for $N \leqq 17$.

Note that only the MRs and the home agents, which are the entrances and exits of the tunnels inside a nested NEMO, are needed to support this solution. Nothing in the core network, nor the end devices, is modified. In addition, these "new" MRs and home agents are perfectly interoperable with other "traditional" MRs and home agents, because the way one MR performs fragmentation does not affect in any way how another MR performs fragmentation. Therefore, backward compatibility is guaranteed.

V. Discussions and Future Work

We believe that, with the nested NEMO on MCN architecture, virtually all the Internet applications can now take the full advantages that MCN is meant to offer. One might have noticed that, however, pure multi-hop ad hoc networking is not supported with nested NEMO. That is, connection between two wireless nodes separated by multiple hops is not possible without an AR under nested NEMO on MCN. The main reason of this limitation is that the packets are encapsulated as they traverse the hierarchy in the nested NEMO. As a result, the "true" destinations of the packets are hidden to the MRs and therefore they must go through the home agents for decapsulation before they can be forwarded to the correct destinations. This kind of wireless ad hoc networking, however, is not a critical feature for MCN anyway. For pure ad hoc communications that require absolutely no infrastructure in place, the ad hoc networking techniques used in traditional MCN should be used instead.

Furthermore, the performance of nested NEMO on MCN relies heavily on the stability of the hierarchy constructed among the MRs in an ad hoc manner. In this paper, we focus on scenarios that are characterized by a relatively stable hierarchical structure among the MRs (e.g., passengers inside a bus or train). In the future, to take the full advantage of the MCN concept, a specific routing protocol should be deployed among the MRs to keep track of the ever-changing hierarchical structure and to enhance the stability of the structure so formed. In addition, frequent encapsulations and decapsulations are required to be performed on the MRs, which could place a burden of power consumption on the MRs relying on battery power. Again, in this paper we are focusing on scenarios that can "distribute" the power consumption in a reasonable manner within the nested NEMO on MCN architecture. For example, to handle high volume of traffic from and to many passengers, the MR installed in the bus should be powered directly from the electricity generated from the bus. On the other hand, the cellular phone of a passenger, which acts as an MR for his/her wireless gadget devices, is only required to handle small among of traffic for that particular passenger. As a future work, we should also design the routing protocols among the MRs in a way to minimize power consumption.

VI. Conclusions

In this paper, we have introduced a pure IP architecture, namely, the nested NEMO on MCN, to enable the MCN concept at the network (or IP) layer. Enabling the MCN concept on the IP layer is critical for the general acceptance of MCN because the IP layer is also the common platform for virtually all the Internet applications nowadays. We illustrated how the nested NEMO on MCN architecture operates. Furthermore, we have unveiled a problem specific to the nested NEMO on MCN architecture, namely, the recursive IP fragmentation. We have also identified the source of the problem to be the uneven distribution of the size of the two resultant packets after traditional fragmentation. Our solution simply requires the MRs and the home agents to divide the packet into two evenly sized packets during fragmentation. We show that this simple technique ensures that fragmentation will be performed at most once under any reasonably sized nested NEMO on MCN architecture. Finally, we have discussed a few other limitations in the nested NEMO for MCN architecture, and have suggested some future work to address them.

This paper is our first attempt to apply the concepts introduced by MCN onto a pure IP layer architecture. We may have not addressed all the issues on this topic, but we certainly hope that this point of view will generate further discussions in the MCN community in the future.

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