Supporting Route Optimization in NEtwork MObility (NEMO)

Technical Report INC2004-01, Jongkeun Na (jkna@popeye.snu.ac.kr), September 2004, Seoul National University

Abstract—Network Mobility (NEMO) is recently being concerned in IETF but the solution is still premature especially with respect to Route Optimization (RO). NEMO has several problem spaces that need RO over nested mobile networks as well as IP routing infrastructure. However, current approaches are each just for one problem space. There is no solution that can be universally applied as one for all that results in supporting the coherent network mobility. In this paper, we first introduce a generic RO model that acquaints ourselves with the essence of RO. And then, we propose a unified route optimization scheme based on that model that can solve several types of RO problem. In our scheme, Home Agent (HA) does piggyback a special hop-by-hop routing header, i.e. Path Control Header (PCH), on the packet which is reversely forwarded from Mobile Router (MR). That enables any PCH-aware routing facility on the route to make a RO tunnel with MR using MR’s Care-of address which is carried on the PCH. By applying to some already known NEMO RO problems, we show that our PCH based scheme can incrementally optimize the sub-optimal routes induced by default HA-MR tunnel through the simple PCH interpretation.

Index Terms—Network Mobility (NEMO), Route Optimization, Path Control Header (PCH).

I. INTRODUCTION

Along with the proliferation of mobile communication networks such as Wireless LAN (Local Area Network), PAN (Personal Area Network) and VAN (Vehicular Area Network), most of public transportation systems (e.g. ships, buses, trains, aircrafts) are envisioned to have a permanent connectivity to the Internet even while moving around. In these communication environments, new mobility problem occurs because of mobile networks in which network itself, not a mobile node, are moving entirely. The existing host mobility support protocol such as Mobile IPv6 (MIPv6) [5] does not work exactly for network mobility because all nodes moving as part of a mobile network cannot directly handle the handoffs on link layer or not all of them may be sophisticated enough to run such mobility support protocols. These deficiencies have been realized by the IETF, and a working group called NEMO (NEtwork MObility) [8] has been commissioned to extend the existing protocols or develop new ones to support network mobility in an IPv6 network.

With the need of new protocol for network mobility, NEMO basic protocol [11] recently has been proposed. It supports transparent mobility to every node in mobile network by using a bi-directional tunnel between Mobile Router (MR) and Home Agent (HA). As a protocol extending MIPv6, MR registers its network prefix as well as its Care-Of Address (CoA) through the extended binding update (a.k.a Prefix Scoped Binding Update [16]) so that HA can properly intercept and tunnel the packets whose destination address belongs to the mobile network prefix to MR’s CoA. Basically, this protocol can be accepted as a complete network mobility support protocol if we can ignore the routing inefficiency inherently induced by the bi-directional tunneling. However, such tunnel based routing could hinder the deployment of mobile networks since sub-optimal routing has a negative impact not only on the mobile network but also on the Internet as a whole. Therefore, the route optimization should be considered in the literature along with NEMO basic protocol.

There are some efforts for Route Optimization (RO) [10]. Broadly the existing RO approaches can be classified as three categories. First is to RO schemes [13]–[15] which do not need the participation of the nodes within the network. Basically, they require a special router, e.g. correspondent router, which can handle the packet redirection to gain RO effect in IP infrastructure. Second is to RO schemes [22]–[24] with the participation of the nodes within the network, the generic idea of these schemes requires the MR when in a foreign network to obtain a care-of prefix rather then just a single address, and readvertise this location dependent prefix into the mobile network. the mobile network nodes can then auto-configure a location specific care-of address, which when communicated back to the correspondent nodes leads to optimal routing, as per MIPv6. Third is about nested mobility where a smaller mobile network (e.g. WPAN) could be contained in a larger one (e.g. VAN). The schemes [17]–[19] in this category build a flat tunnel over a nested mobile network which consequently avoids multi-level tunneling overhead. In second category, RO is likely accomplished by MIPv6 except for remapping location-specific address to each mobile node so it lacks in describing the benefits of NEMO [10] which can be obtained by introducing MR as a single point of attachment for a mobile network on behalf of all nodes behind MR: reduced handovers, reduced complexity, reduction in bandwidth consumption and location update delays. That makes us to focus on the remaining categories in [12] which defines RO problem spaces of NEMO and briefly analyzes the proposed interim solutions.

As of now, it’s not easy to say how RO problems in NEMO can be best solved in a manner. However, the sure thing is that current proposed solutions can be applied only to one problem space of RO. That is an uncomfortable and unnatural facet in supporting coherent network mobility. We need a simple and effective, unified route optimization solution for network mobility. For the purpose, in this paper, we first introduce a generic route optimization model for the analysis of RO problems and existing interim solutions and then, we propose a route optimization scheme based on the result of
modeling RO problems. The scheme is a unified solution that can solve several types of route optimization problem with applying the same principle to the routing facilities such as HA, MR and Correspondent Router (CR). In the proposed scheme, HA does piggyback the Path Control Header (PCH) on the packet which is reversely forwarded from MR through the bi-directional MR-HA tunnel. PCH is a hop-by-hop option header so that it can be processed by all of the routing facilities on the path that is from HA to Correspondent Node (CN). HA forwards the PCH piggybacked packets toward CN for the route optimization. CR on the path can make a RO tunnel with MR using the information like the CoA of MR contained in the PCH.

Our proposed RO scheme, PCH piggybacking by HA, is a simple and effective one in solving the problems of route optimization without any incompatibility with the basic NEMO protocol [11]. By taking the functional extension of routing facilities such as HA, MR and CR, we can incrementally optimize the routes over CN-HA-MR without the loss of transparency to CN. And also, we expect that the basic concept of this scheme can be used to support other mobility-related route optimizations as a unified solution, not limited to network mobility.

The rest of this paper is organized as follows: the problem statement is mentioned together with related works in Section II. In Section III, we introduce a descriptive RO model to understand the nature of RO problems and to describe the common attributes of RO solutions. And, in Section IV, we describe the basic operation and protocol of our propose RO scheme based on PCH. Then, we show how to apply our scheme on RO problem space in Section V and its protocol evaluation is followed in Section VI. Finally, we conclude in Section VIII.

II. PROBLEM STATEMENT AND RELATED WORK

Before entering into the detailed description of NEMO related route optimization problems, we first need to clarify the terminologies used in this paper to help your understanding. For example, in Fig.1, Correspondent Router (CR) means a router in the global Internet that has a capability to provide the packet re-routing service for a globally better route optimization to Correspondent Nodes (CNs) below it on the hierarchical routing topology, CR manages the information of binding route cache for the route optimization as same as HA does its binding cache management for the packet redirection service. It can be an access router or a border router depending on its position in the global Internet. In the other hand, Local Fixed Node (LFN) in Fig.2 is a fixed node (FN), either a host or a router, that belongs to the mobile network and which doesn’t move topologically with respect to the MR. It’s address is taken from a NEMO-prefix. Mobile network may include another type nodes such as Local Mobile Nodes (LMN) or Visiting Mobile Nodes(VMN). Rreferring [9] and [12] is required for the detailed definition if there are some implicitly used terms related to NEMO.

There are some types of route optimization problems. In particular, we can categorize the route optimization problems that related to NEMO into two problem spaces. One is to the route optimization in IP routing infrastructure. The other is to the nested tunnels optimization in the nested mobile networks.

In the former case, the CR based approach was introduced in [15]. That can be conceptually described as in Fig.1. First, the default bi-directional tunnel between HA and MR is established by the basic NEMO protocol at the movement of MR. When MR receive the first packet sent from any CN (in the figure, one in AS300) to a node behind it via the default tunnel, MR tries to find any CR that located in the side of CN through any discovery mechanism. In the case of [15], the IPv6 anycast address is used to locate a CR that is on the path from HA to CN. After the CR discovery process, MR can initiate the Binding Update (BU) to the discovered CR. After the RO tunnel between MR and CR is established, CR provides the same service to all of CN behind it as if MR supports the transparency mobility service to nodes behind it. This approach can eliminate the overhead of applying MIPv6 route optimization to each CN because all of CN behind CR can share the optimized tunnel, i.e. RO tunnel, between MR and CR. Also, for the packets reversely forwarded from MR to any CN behind CR, they can be passed to the optimized tunnel, not to the default tunnel between MR and HA.

In the latter case, it is another type of route optimization problem in NEMO. If the multiple mobile networks are nested as Fig.2, that brings a routing overhead to us which is well known as "pinball" or "dog-leg" routing [12]. As a concrete example, you can imagine that a user with a mobile network such as WPAN consisting of some IP devices goes into a vehicular which is also using NEMO technology. This configuration of mobile networks within another mobile network is called nested mobile networks. The inefficiency routing is incurred since the packets which are sent from CN to Local Fixed Node (LFN) as in Fig.2 get follow the routing path like CN→HA3→HA2→HA1→MR1→MR2→MR3→LFN by IP routing and the basic NEMO protocol. In NEMO context, its desirable to avoid the nested tunneling because it incurs very inefficient routing depending on the relative location of HAs and also an extra IP header for IP tunneling is added per level of nesting to all the packets. Therefore, we want to convert the nested tunnels into a flat tunnel with the path like CN→HA3→MR1→MR2→MR3→LFN. If such a nested tunnels optimization is possible, the packet can be directly reached on MR1 which is topologically co-located with MR3 over the global Internet without visiting HA1 and HA2. This is the reason why we try to make a flat tunnel over the nested mobile networks. For the packets which are reversely forwarded from LFN to CN, the same optimization can be applied.

For nested tunnels optimization, a few of interim solutions are being proposed in IETF NEMO WG. A several of the potential approaches mentioned in [12] is possible, but we try to focus on the flat tunneling scheme using the nested tree information such as MR1-MR2-MR3 because that has an analogy with our proposed scheme in that the nested tree information is collected using a special header and IP source routing is used in the inside of nested mobile networks. First, RRH approach [17] makes a flat tunnel by using a new routing
header, called the reverse routing header. MR3 encapsulates
the packet over its reverse tunnel, i.e. MR3-HA3 tunnel, using
a form of record route header, the RRH. The next MRs, i.e.
MR2 and MR1, simply swap their CoA and the source of the
packet, saving the original source in the RRH. HA3 transforms
the RRH in a routing header [1] to perform a source routing
across the nested mobile networks, along the ingress path to
the target MR3. It is described in details in [17]. On the other
hand, the Access Router Option (ARO) approach is somewhat
similar to the RRH in that only the default tunnel of the first
MR3 in the egress path is maintained. This is done by having
MR3 to send an ARO in Binding Update to inform its HA3 the
address of its access router (i.e. MR2). Using this information,
HA3 can build a routing header to source-route a packet to
the target MR3 within in a nested mobile network. Details can
be found in [18].

As a result of drilling down into the route optimization
problems in NEMO, we feel a unified solution to allow the
route optimization in the infrastructure as well as in the nested
mobile networks to support the coherent network mobility.
By applying a unified route optimization protocol on the
routing facilities such as MR, HA and CR, the general route
optimization can be achieved in terms of the implementation
and deployment under the Internet. This argument is more
elaborated in next section by defining a generic route opti-
mization model.

III. GENERIC ROUTE OPTIMIZATION MODEL

RO problems have a common property that there is an
optimized path, but it cannot be used due to support the
transparent mobility to the IP terminals. While preserving
the goals of MIP and NEMO, it is impossible to realize
RO without introducing tunnel-based virtual path over IP
routing through some extensions or new functionalities of
routing facilities. This is the reason why the existing proposed
solutions [4], [5], [13], [15], [17], [18], [20] for RO at least use
tunnel-based packet redirection or re-routing mechanism in the
extended routing facilities such as CR. IP tunneling is a basic
mechanism to re-route packets at some intermediate points
without any modification on the original packets. We think that
it can well express the purpose of RO such as packet redirec-
tion service. And, the tunneling contains most of procedures
involved in RO, negotiation between two entities, the method
of transferring packets, etc. And also, other optimizations like
eliminating encapsulation overhead can be considered under
the concept of IP tunneling.

As a requirement about RO, we argue that RO in NEMO
should be provided by a unified solution which can solve most
of RO problems by applying the same principle to the routing
facilities such as HA, MR, CR. If each different RO solution
is used to solve each RO problem, it will produce the protocol
redundancy and complexity in the routing facilities.

In this section, we introduce the generic RO model that can
be used as a framework to evaluate the existing RO models.
Then, we analyze typical RO problems by virtue of the generic
RO model. And, we discuss on the feasibility of achieving a
unified RO in NEMO, and enumerate the issues that should
be cleared for the purpose of that.

A. Route Optimization Tunnel (ROT) Model

Route Optimization in NEMO means that one routing entity
uses an IP tunnel to redirect the original packets to the other
routing entity that is most closely located from the destination.
To enable such a route optimization, two routing entities must
recognize each other, in other words, anyone among them
should feel the need of RO tunnel and initiate the signaling
procedure to make an IP tunnel between them. We can define
such an IP tunnel as RO Tunnel (ROT) in NEMO context
because it is established for the purpose of route optimization
in NEMO. This is like the basic principle of Mobile IP
(MIP) [4]. In MIP, mobile node detects its movement and
initiates BU to HA. Such an analogy can be extended to
RO problem in NEMO. In this point of view, we can extract
some of statements characterizing how to achieve RO tunnel.
For example, which routing facilities can initiate RO tunnel? What information does trigger such a RO tunnel? How can the trigger information be delivered to the initiator of RO tunnel? And so on. The answer to those of questions depends on the problem spaces [12] and the proposed solutions in each problem space.

The attributes of RO tunnel can concretely well express the RO context including the purpose of RO, the operation of RO, and the effectiveness of RO. Fig. 3 shows the generalized ROT model. ROT can be made of at least two TEs. In here, TE is a router or host which is allowed to initiate or terminate the RO tunnel in the view of route optimization. According to the type of ROT, ROT can include zero or more TS for switching an incoming tunnel to an outgoing tunnel at that point, zero or more TR for relaying the tunneled packets to next intermediate point. As of TR, the difference is that it operates a routing mechanism, such as Source Routing using RH0 header [10], based on the packet header information without the knowledge of the end-to-end tunneling, while TS processes the tunnel switching based on a given tunnel mapping information that consistently maintained in that point by interacting with other tunnel endpoints.

From the general ROT model, we can drive the following attributes which can be exploited to characterize a specific RO model.

**RO Initiator (ROI):** We need to identify which TE among two TEs can be the initiator in making a RO tunnel. This parameter depends on the applied RO scheme. In one RO scheme, MR is only the initiator, on the other hand, HA and CR can be the initiator in the other RO scheme.

**RO Responder (ROR):** We need to identify which routing facilities can be the responder in making a RO tunnel. This parameter also depends on the applied RO scheme.

**RO Trigger Source (ROTS):** The RO initiator (ROI) is recognized for the need of RO from this information. For example, an explicit RO bit in the packet header can be used to force the receiver to start the RO.

**RO Responder Information (RORI):** This information is used for the RO initiator (ROI) to identify the RO responder (ROR). It would include the address information of the moving entity such as MR, or the address information of the correspondent nodes.

**RO Discovery Mechanism (RODM):** This mechanism describes that how RORI can be delivered to the RO initiator (ROI). In other words, ROI can get RORI by using this discovery mechanism. For example, if ROI itself try to find its ROR using IPv6 anycast address, RORI becomes an address of ROR and we can say that RODM is IPv6 anycasting mechanism.

**RO Tunnel Type (ROTT):** ROTT can be classified as the followings: Simple ROT (SiROT), Switched ROT (SwROT), Relayed ROT (ReROT). SiROT consists of only two TEs. SwROT consists of one or more TS between two TEs. ReROT consists of one or more TR between two TEs. For example, we can say that RRH uses ReROT as RO Tunnel Type, HMIPv6 uses SwROT.

**Table I**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>MR, ORC Router</td>
</tr>
<tr>
<td>ROI</td>
<td>MR</td>
</tr>
<tr>
<td>ROR</td>
<td>ORC Router</td>
</tr>
<tr>
<td>ROTS</td>
<td>the packet sent from any CN via MR-HA default tunnel</td>
</tr>
<tr>
<td>RORI</td>
<td>the global IPv6 address of ORC Router</td>
</tr>
<tr>
<td>RODM</td>
<td>IPv6 anycast addressing</td>
</tr>
<tr>
<td>ROTT</td>
<td>SiROT</td>
</tr>
</tbody>
</table>

Fig. 4. Casting the existing RO approaches into ROT Model

### B. The Analysis of RO Problems in NEMO

In this section, we analyze typical RO problems in NEMO using the generic ROT model.

1) **RO in the infrastructure:** Fig. 4(a) shows the simple RO in the infrastructure. This RO model was used in ORC [15]. According to the generic ROT model, the formulation like Table I is possible. The attributes in Table I compactly describes that this RO implements ROT between MR and ORC Router, and MR initiates the signaling procedure for ROT to ORC Router after getting the global IPv6 address of ORC Router through IPv6 anycast addressing. This RO model also includes some RO approaches, such as C-Side Router or Correspondent Router (CR), mentioned in RO-Taxonomy [12]. To include those of RO approaches, we can loosely redefine above attributes into Table II.

Fig. 4(b) shows extended RO in the infrastructure. This RO model includes one TS entity and two TEs. Distributed Anchor Routers described in RO-Taxonomy can be expressed as this model like Table III. In this case, most of attributes in the ROT model are not determined, so it is required to deeply
TABLE II
THE REDEFINED RO IN THE INFRASTRUCTURE

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>MR, ORC Router, C-Side Router, CR</td>
</tr>
<tr>
<td>ROI</td>
<td>MR</td>
</tr>
<tr>
<td>ROR</td>
<td>ORC Router, C-Side Router, CR</td>
</tr>
<tr>
<td>ROTS</td>
<td>the packet sent from any CN via MR-HA default tunnel</td>
</tr>
<tr>
<td>RORI</td>
<td>the global IPv6 address of ROR</td>
</tr>
<tr>
<td>RODM</td>
<td>IPv6 anycast addressing</td>
</tr>
<tr>
<td>ROTT</td>
<td>SiROT</td>
</tr>
</tbody>
</table>

TABLE III
THE EXTENDED RO IN THE INFRASTRUCTURE

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>MR, C-Side Anchor Router</td>
</tr>
<tr>
<td>TS</td>
<td>M-Side Anchor Router (a.k.a MAP in HMIPv6)</td>
</tr>
<tr>
<td>ROI</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>ROR</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>ROTS</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>RORI</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>RODM</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>ROTT</td>
<td>SwROT</td>
</tr>
</tbody>
</table>

understand this RO problem and derive its viable solution.

2) Nested Tunnels Optimization (NTO): NTO can be modeled like Fig.4(c) by using the ROT model. For example, the attributes of RRH scheme can be represented as Table IV. Similarly, ARO scheme can be expressed as Table V.

C. Toward a unified route optimization in NEMO

With the help of the ROT model, we can evaluate whether or not there is the feasibility of achieving a unified route optimization in NEMO, and enumerate the issues that should be cleared for the purpose of that. As a unified RO model, let us illustrate one instance as Fig.5. In here, TR can be zero. That is only difference in comparing with Fig.4(c). However, this trivial difference in the model implies that this model can support SiROT based RO in the infrastructure as well as ReROT based NTO. Our route optimization scheme belongs to this model that appears in next section. As an instance of a unified RO, The attributes of our scheme PCH based RO can be summarized as Table VI.

TABLE IV
RRH BASED RO MODEL FOR NTO

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>Mobile Router (MR), Home Agent (HA)</td>
</tr>
<tr>
<td>TR</td>
<td>MR (via Source Routing)</td>
</tr>
<tr>
<td>ROI</td>
<td>CR, HA</td>
</tr>
<tr>
<td>ROR</td>
<td>MR</td>
</tr>
<tr>
<td>ROTS</td>
<td>Receiving the packet with Path Control Header (PCH)</td>
</tr>
<tr>
<td>RORI</td>
<td>Nested Path Information like MR3—MR2—MR1—HA3</td>
</tr>
<tr>
<td>RODM</td>
<td>Using Reverse Routing Header (RRH)</td>
</tr>
<tr>
<td>ROTT</td>
<td>ReROT</td>
</tr>
</tbody>
</table>

TABLE V
ARO BASED RO MODEL FOR NTO

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>Mobile Router (MR), Home Agent (HA)</td>
</tr>
<tr>
<td>TR</td>
<td>MR (via Source Routing)</td>
</tr>
<tr>
<td>ROI</td>
<td>MR</td>
</tr>
<tr>
<td>ROR</td>
<td>HA</td>
</tr>
<tr>
<td>ROTS</td>
<td>BU with ARO option</td>
</tr>
<tr>
<td>RORI</td>
<td>Nested Path Information like MR3—MR2—MR1—HA3</td>
</tr>
<tr>
<td>RODM</td>
<td>Using Access Router Option (ARO) and Recursive BU</td>
</tr>
<tr>
<td>ROTT</td>
<td>ReROT</td>
</tr>
</tbody>
</table>

Fig. 5. A unified RO supporting ReROT as well as SiROT

IV. OUR ROUTE OPTIMIZATION SCHEME

In this section, we first introduce the basic concept and operation of our proposed RO scheme in NEMO context. Then, the detailed protocol description will be followed along with the extensions in the existing NEMO basic protocol.

A. PCH Piggybacking by HA

To the route optimization, HA does piggyback PCH on the packet which is reversely forwarded from MR through a bidirectional MR-HA tunnel. PCH is a hop-by-hop option header so that it can be processed by all of the routing facilities on the path that is from HA to CN. The mentioned routing facility means an entity which can play a role of the transparent routing agent that can support the packet redirection service like HA. The router in the Internet that implements such an agent function provides the packet redirection service to the nodes behind it by intercepting and redirecting the on-going packets to the route-optimized tunnel, i.e. RO tunnel. The RO tunnel between CR and MR can be established when CR gets know the existence of HA by processing the packet with PCH.

In Fig.6, HA de-capsulates the encapsulated packet forwarded from MR via MR-HA tunnel and then forwards the

TABLE VI
A UNIFIED RO MODEL (PCH BASED)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>MR, HA, CR</td>
</tr>
<tr>
<td>TR</td>
<td>MR (via Source Routing)</td>
</tr>
<tr>
<td>ROI</td>
<td>CR, HA</td>
</tr>
<tr>
<td>ROR</td>
<td>MR</td>
</tr>
<tr>
<td>ROTS</td>
<td>Receiving the packet with Path Control Header (PCH)</td>
</tr>
<tr>
<td>RORI</td>
<td>Nested Path Information like MR3—MR2—MR1—HA3</td>
</tr>
<tr>
<td>RODM</td>
<td>Using PCH Piggybacking by HA</td>
</tr>
<tr>
<td>ROTT</td>
<td>SiROT+ReROT</td>
</tr>
</tbody>
</table>
PCH piggybacked packet to CN for the route optimization. Any existing CR on the path from HA to CN can catch the path control information as examining PCH in the packet. Therefore, the CR can initiate the procedure of making RO tunnel between itself and MR using MR's CoA which is contained in PCH. After setting up RO tunnel, the packets of CN will be redirected to RO tunnel at CR. This scheme is simple and effective with respect to NEMO. It only requires a little effort of HA to provide the RO tunnel between CR and MR. The first packet is just piggybacked by HA which is following a non-optimized path of MR-HA tunnel.

Fig.7 shows the structure of PCH. PCH includes an address tree information as an option data. In here, the address tree information represents the list of IPv6 addresses. Each address indexed in the list indicates the CoA of MR in MR-HA relationship. By detecting the packet with PCH, CR gets know the CoA of MR so that it can initiate the signaling for RO tunnel.

Fig.8 shows the case of forming the nested tunnels. In that case, PCH gets contain two CoAs, each of MR1 and MR2. As taking a look at the packet with PCH1, HA2 gets know the fact that its MR2-HA2 tunnel is nested under outer MR1-HA1 tunnel. The nested HA just adds the CoA of its MR on the received PCH to make its own PCH. In other words, HA2 does piggyback PCH which includes and the CoA of MR2 (i.e. the exit point of its tunnel) as well as the CoA of MR1 (i.e. the exit point of the outer tunnel). In this case, one CR on the path between HA2 and CN will be able to make a RO tunnel with the target MR2 by using the nested tree information in PCH.

### C. Protocol Extension

Our proposed scheme requires some protocol extensions for NEMO Basic Protocol [11]. As you see in the previous section, new mobility message, BR, is required. And also, new two mobility options are needed. We briefly describe just only the purpose and usage of them in here.

**Binding Request Message (BR Message):** This message is used to notify MR of the need of RO tunnel. If the sender of this message detects the nested tunneling, it should put NRP(Nested Routing Path), RNP (Reachable Network Prefixes). The initiator of the RO signaling should add NRP mobility option in BR message to set up the nested RO tunnel in which nested MR would be the other exit-point of tunnel. NRP option contains the list of addresses that represents the tree topology of nested MRs. That is used for MR to assign the source routing path that is necessary to nested tunnels optimization. The RNP option is used to let MR know about the network prefixes which are reachable via RO tunnel. By using this prefix information associated with the RO tunnel, MR can select the optimized path (i.e. RO tunnel) for the out-going packets. This option should be contained in BA message.

If the 3-way handshaking RO signaling between MR and CR is done with success, the routing table of both includes new routing entry for directly reachable prefixes via RO tunnel. By referring that entry, the MR can forward the packets to the established RO tunnel because they are destined to the network that is reachable via it. The CR can do the same thing for the prefix of mobile network that is bound through BU from MR. That means the CR intercepts the packets destined to the prefix and redirects them to the RO tunnel.

**Nested Routing Path Option (NRP Option):** The initiator of the signaling of RO tunnel should add this mobility option in BR message to set up the Nested RO Tunnel with nested MR. This option contains the list of addresses that represents the tree topology of nested MRs. That is used for MR to assign the source routing path that is necessary to nested tunnels optimization. The details of nested tunnels optimization will be followed in section V-C.

**Reachable Network Prefixes Option (RNP Option):** This option is used to let MR know about the network prefixes.
which are reachable via RO tunnel. By using this information associated with RO tunnel, MR can select the optimized path (i.e. RO tunnel) for the out-going packets. This option should be contained in BA message.

As an extension to the neighbor discovery protocol [1], we need to use Tree Information Option (TIO) introduced in [17] to help for the nested MR to detect the change of topology inside of nested mobile network. TIO is carried in Route Advertisement (RA) message which is broadcasted by a router to announce its existence to the local subnet. It is used only by the nested MRs. For example, In Fig.2, no receiving RA with TIO Option in the access link gets MR1 know that it is a Root-MR of nested mobile network. MR1 sends periodically RA with TIO Option to its ingress link. MR2 and MR3 each relays its RA with modified TIO Option, in which IPv6 global address of the egress interface is appended, to ingress links. In our scheme, the nested MR can recover the broken RO tunnel by exploiting the nested path information like MR1→MR2→MR3 delivered by TIO option.

D. MR Extension

For route optimization, MR should understand BR message sent from routing facilities such as CR. According to MIPv6 [5], MR must maintain Binding Update List (BU List). In managing BU List, the following information should be additionally maintained to use RO tunnel defined in this proposed scheme.

**RO Tunnel (ROT) flag:** When it is set, it indicates that the associated BU entry is for ROT tunnel. All of ROT tunnel should contain a set of network prefixes that is carried from RNP Option.

**Nested RO Tunnel (NROT) flag:** When it is set, it indicates that the associated BU entry is for NROT tunnel. In this case, the BU entry should contain the nested path information carried from NRP Option.

**Nested Path Information (NPI) Vector:** The address vector information is transferred in NRP Option. This information is only valid when NROT flag is set.

**Network Prefixes (NP) Vector:** The address vector information transferred in RNP Option. This information is only valid when either ROT flag or NROT flag is set.

The successful establishment of RO tunnel means the ready of RO-enabled tunnel interface that would be associated with the corresponding entry in BU List. That tunnel interface should be setup to add IPv6 RH0 (Routing Header Type 0) optional header [1] at the encapsulation of tunneled packets if its NROT flag is set. The reason is that the normal IP routing is not allowed in nested mobile networks. RH0 enables the packets to be routed in the inside of nested mobile network by the hop-by-hop source routing. For NROT, MR needs to update the route information being used in the source routing when it has detected the change of topology by comparing the previous TIO option to the current TIO option. If not updated, the NROT will be broken because the source routing does not work. Therefore, MR should rebind its changed topology to the tunnel-exit points of NROT through BU/BA. Although its point of attachment is not changed, MR has to initiate the binding procedure to recover its NROTs if the TIO option is changed. All of this is attributed to the source routing used in NROT.

MR should maintain the number of RO tunnels in its own context. In other words, MR can tear down less necessary RO tunnels according to its own criterion such as Least Recently Used (LRU) in case of the resource shortage.

E. HA Extension

To the route optimization, HA should maintain the state of PCH piggybacking per traffic flow. The traffic flow can be classified by the destination address of the packets. HA does only piggyback PCH on the first packet which belongs to each traffic flow. The piggybacking state should be managed by the soft-state. The piggybacking state of per traffic flow comes to be set when the first packet is piggybacked and reset when the state timer is expired. HA doesn’t need to piggyback PCH on the packets belong the traffic flow while the correspondent piggybacking state is set. The overhead of managing the piggybacking state can be minimized by the careful implementation.

According to MIPv6 [5], HA must maintain Binding Cache (BC). Like MR extension, HA should manage the following information in the associated BC entry for route optimization.

**Route Optimization (RO) flag:** When it is set, it indicates that the associated BU entry is RO enabled. RO may be enabled or disabled by some administrative means.

**Piggybacking State Table (PST):** An entry of this table represents a record that contains \((\text{fid} = \text{destination address})\),
ts = UTC time). It indicates that the first packet belong traffic flow fid was piggybacked with PCH at ts time. This table should be cleared when the binding update occurs from MR.

For the packets forwarded via RO enabled tunnel from MR, HA decapsulates them, and checks whether or not PCH should be piggybacked. If an entry that contains the destination address of the packet exists in PST, PCH is not piggybacked to the packet at forwarding. Otherwise, HA creates new entry in PST for that traffic flow and piggybacks PCH on the packet at that time. We just can use one global timer to delete the records which were long sustained in PST.

V. ROUTE OPTIMIZATION USING PCH

In this section, we illustrate how to apply our proposed scheme on several types of route optimization in NEMO context. For easy understanding, each of route optimization procedures is described together with network configuration and packet flow diagram.

A. Route Optimization in IP routing infrastructure

Depending on the location of CR and how many CRs on the path between CN and HA, the various types of route optimization can be reflected. In here, we typically show two cases that expose the effect of PCH based RO. First, we assume the network configuration like Fig.10(a). There is one CR on HA-CN path in the border side of AS in which CN exists. In this case, all of other CNs belong the AS can get the gain of route optimization through CR-MR RO tunnel that is pre-established by the PCH piggybacked packet forwarded from HA to CN. Once established, the communication between CNs behind CR and nodes behind MR will be realized through the CR-MR RO Tunnel. It is transparent to all of nodes except for CR and MR.

In case of Fig.10(b), it shows how we can get the incremental route optimization from multiple CRs which are widely scattered in the Internet. CR1 and CR2 can almost simultaneously establish a RO tunnel with MR through one PCH piggybacking by HA. This is possible because both are on the path that is from HA to CN1. In that case, the packets sent from CNs in all of subnets attached to CR2 are redirected to the RO tunnel at CR2 if they are destined to the mobile network of MR. CR1 can serve the packets sent from any CNs (in the figure, CN) that are located in the outside of AS100. The packets reached on CR1 indicate that there is no CR in the path that is from CN to CR1, or CR but still have not received PCH. The packets from CN are redirected at CR1 and reversely the packets from MR are forwarded via HA. At the next time, the CR in AS400 on the CR1-CN path can make a RO tunnel by picking up PCH on the reversely forwarded packets from HA. As a result of PCH piggybacking by HA, we can serve the incremental route optimization to all of CNs.

B. Route Optimization over MR-to-MR

As in Fig.12, we can get the RO tunnel over MR-to-MR by using PCH piggybacking. MR per se interprets PCH piggybacked from the HA of the other MR and initiates the signaling for RO tunnel with the other MR. As a result of that, the nodes behind one MR can directly communicate with the nodes behind the other MR without any routing overhead.

C. Nested Tunnels Optimization (NTO)

Our scheme can also be applied to solve the nested tunnels problem without the loss of generality. We assume the 3-level nested network configuration as Fig.13 to show two cases of NTO using PCH based scheme. One is NTO by CR and the other is NTO by HA. In nested mobile networks, the RO tunnel is specially called Nested RO Tunnel (NROT). It should be distinguished from normal RO tunnel because we introduce the source routing concept in handling the nested tunnels optimization. To the correct routing in the nested network configuration, we take advantage of IPv6 Routing Header Type 0 (RH0) in NROT.

In Fig.13, CR gets to know the existence of nested tunnels through PCH information (MR1’s CoA and MR2’s CoA, MR3’s CoA) and then initiate the signaling for NROT to MR3 via nested tunnels. At this time, the Binding Request (BR) message contains the NRP Option. The NRP Option is used to inform MR3 of the nested path information. If MR3 receives the BR message having the NRP option, MR3 also gets know that it is nested. Therefore, the tunnel between CR and MR3 becomes a NROT.

In a NROT, the entry point of tunnel adds RH0 at encapsulation. Reversely, the exit point of tunnel deletes RH0 at decapsulation. For the packets tunneled from CR to MR3, the packet forwarding is done with the source routing of RH0 (MR1→MR2→MR3). For the packets tunneled from MR3 to CR, the reverse source routing (MR2→MR1→CR) occurs. Fig.14 shows the message flow for nested tunnels optimization by CR. Fig.15(a) and Fig.15(b) show the content of RH0 packet at the packet delivery via NROT.

As well as CR, the nested HA can also attend in nested tunnels optimization to directly support NROT to its all of CNs. That case makes the equivalent optimization effect with the nested tunnels optimization by RRH/or ARO. As in Fig.16, HA3 makes a NROT with MR3 that is triggered by CN1. And then, HA3 does PCH piggybacking for NROT in the case of CN2. That of PCH piggybacking would make a possible for any CR to make its NROT which may be located in the CN2-HA3 path.

VI. PROTOCOL EVALUATION

In this section, we evaluate our proposed scheme in some respects. First, the signaling cost is qualitatively compared with other schemes. And next, consider the operation of our proposed scheme under various handover scenarios, and how much we can get the gain of throughput through incremental route optimization, lastly how MR can manage RO tunnels in respect of scalability.

A. Signaling Cost

In our scheme, the signaling cost for a ROT can be represented by the following equation.

\[ C_{TOTAL}^{PCH} = C_{PCH} + C_{BR} + C_{BU} + C_{BA} \]
where $C_{PCH}$ means the cost of piggybacking PCH at HA, $C_{BR}$ the cost of notifying the need of the optimized tunnel to MR at a routing facility (hereafter CR), $C_{BU}/C_{BA}$ the cost of exchanging BU/BA between them. In case of ORC, its...
The signaling cost can be defined by $C_{ORC_{TOTAL}} = C_{DM} + C_{BU} + C_{BA}$ where $C_{DM}$ means the cost of discovering CR using IPv6 anycast address. In comparison with ORC, our proposed protocol does not require more signaling cost since the cost of $C_{PCH} + C_{BR}$ is less or equal than $C_{DM}$. The cost of processing PCH at HA is ignorable because HA does always decapsulate the reversely forwarded from MR via the default tunnel. And, our proposed protocol requires the one-way time represented by $C_{BR}$ while $C_{DM}$ requires the turn-around time between MR and CR in the form of ICMP request/reply for the CR discovery.

In the case of the signaling cost for a NROT, it can be roughly represented by the following equation.

$$C_{PCH_{TOTAL}} = \eta \times C_{PCH} + C_{BR} + C_{BU} + C_{BA}$$

where $\eta$ means the number of nested tunnels. This cost is the same as the case of a ROT except for $(\eta - 1) \times C_{PCH}$ in addition. In considering other approaches for nested tunnels...
optimization, that is fairly comparable since the case of RRH requires piggybacking RRH in all reversely forwarded packets from MR, and ARO requires \((\eta - 1) \times (C_{BU} + C_{BA})\) as the upper Access Routers recursively do the binding update to make a NROT.

With respect to the signaling cost, we can say that our protocol at least requires less than the existing approaches [15], [17], [18] in each case of optimizing the route in IP routing infrastructure, and in nested tunnels optimization.

B. Movement and Handover

The various handover scenarios are possible in NEMO. We need to consider how our RO scheme well works when the handover of mobile network occurs. As a basic handover scenario, the MR with RO tunnels can be moved into another access networks. At that movement, MR will detect its movement by receiving Route Advertisement (RA) message from the Access Router (AR), and then re-bind its new CoA to the tunnel-exit points in BU List. In this case, the RO tunnels can be continuously maintained without the loss of connectivity. Although explicitly not mentioned, our protocol includes the implicit use of Binding Refresh message and Re-binding procedure at the movement [5]. Therefore, our protocol has no trouble with supporting this type of basic handover scenario.

On the other hand, there is more complex handover scenario in NEMO. Assume there is a nested mobile network in which MR1 plays a role of AR for MR2 and MR2 also does for MR3, here MR1 is top-level mobile router. In that case, what would happen to MR3 if MR2 leaves to other site without any notification while MR3 is communicating via NROT in which MR2 is included as a hop used in the source routing. The communication by MR3 becomes impossible until MR3 detects the movement of its parent MR2 by TIO option, and recovers this abnormal situation. The detection and recovery of broken tunnel is almost same in the basic scenario except for considering its nesting. After the movement of MR2, MR3 gets detect the change of its AR by receiving new RA message broadcasted from its parent AR, i.e., MR1. After detecting the change of its point of attachment, MR3 reconfigures its CoA and tries to reflect its change to the tunnel-exit points in BU List as well as its HA. At this time, MR3 configures its CoA and tries to reflect its change to the tunnel-exit points in BU List as well as its HA. At this time, MR3 can not use the source routing using NPI Vector associated with each NROT since the content of NPI Vector is invalidate due to the change of nested topology. However, right after the change of topology, the NPI Vector can be adjusted by TIO information that correctly reflects the current topology. Therefore, MR3 can directly send its BU to the tunnel-exit points with NROT flag. For the case of the movement of MR1, MR3 can detect its change of topology and recover its tunnels on the same way except the CoA of MR3 not changed.

C. Incremental Route Optimization

In Fig.11, We showed how our protocol can realize the incremental route optimization in the infrastructure by using multiple CRs. And also, we mentioned the possibility of the incremental nested tunnels optimization with describing Fig.16. The incremental route optimization is an important feature of our protocol in respect that can give us a fair amount of throughput gains. Lets see the effect of that in nested mobile network. In Fig.16, HA2 can also have a NROT with MR2 before MR3 is attached into the subnet of MR2. After then, the NROT between HA2 and MR2 can be used instead of MR2-HA2 default tunnel so that all of traffic between HA2 and MR2 including the packets sent from MR3 can be bypassed from HA1. By using PCH, the nested HA can sequentially make a NROT with its MR, that makes a possible for the throughput gains to be accumulated over the nested tunnels.

D. RO Tunnel Management

As shown in incremental route optimization in Fig.10(b), Many of ROTs can be established at MR. However, the number of ROT that MR can capable of is limited due to its available resource. We denote \(\max_{rot}\) to the maximum number of ROT for which MR can maintain. In this case, MR needs to make a decision about which ROT should be released when the number of requested ROTs exceeds \(\max_{rot}\). MR can rank each ROT by calculating the gain of RO \(\rho\) per ROT. That can be formulated as the following equation.

\[
\rho = (\chi_1/\chi_2)\alpha + \mu(1 - \alpha)
\]

where \(\chi_1\) means packet delay which is measured via the default tunnel, \(\chi_2\) packet delay via ROT, \(\mu\) is a tunnel utilization factor, e.g., the averaged packet rate (per sec) of RO tunnel, \(\alpha\) is a weight constant. As a result of ordering each ROT by the utilization as well as the throughput gain of ROT, MR can maintain the list of ROTs that totally ensure the best gain of route optimization.

E. Security Consideration

In particular, considering security concerns is very important in applying the Internet protocol. At this moment, Public Key Infrastructure (PKI) can be a solution to support the integrity and the origin-authentication of PCH because the participants in our scheme are limited to some of routing facilities. All of security mechanisms provided by IPSEC can be applied to protect the integrity of PCH header under PKI infrastructure. We know that the potential security problem of our scheme must be deeply considered. We leave the detailed security consideration into the future work item.

VII. SIMULATION RESULTS

We implemented NEMO simulator on ns-2 wired-cum-wireless extension (Mobile IP) [7] to show the effect of our proposed scheme. In our simulator, Network Dynamics of ns2 was used to make the simulation topologies dynamic, and new instances, i.e., MR, CR, HA/FA, were implemented to support NEMO basic protocol. As simulation parameters, default RA (Route Advertisement) interval in agents (HA/FA) is 1 second, default packet size is 1000 bytes, traffic rate of each flow (UDP and TCP) is 200 kbps, 2 Mbps or 11 Mbps link capacity is randomly used for each link, typically two topologies are considered, one to show the effect of incremental route
optimization, the other to show the effect of nested tunnels optimization.
the simulation topology in 17(a) represents the scenario of Fig.10(b) already mentioned together with Fig.11. Even some labels are different but the semantics of that is same. MR handoff is simulated as link on/off, i.e link(MR, HA) is down and simultaneously link(MR, BS3) is up, at simulation time 5sec. Fig.18(a) and Fig.18(b) will illustrate the effect of incremental route optimization. In UDP traffic, we can see the difference of packet delay between before RO and after RO. Second CN2-LFN flow starts at 7.5sec. That flow uses CR3-MR RO tunnel already established by CN1-LFN flow, so it can decrease the initial delay that is incurred by visiting HA of MR. And then, after PCH piggybacked for that flow, the packet delay of CN2-LFN flow is much reduced by CR2-MR RO tunnel. The behavior of TCP traffic shows the gradual change of RTT (Round-Trip Time) in before RO and after RO, as well as packet loss in the handoff period.

Fig.17(b) shows the simulation topology according to the scenario of nested mobile network shown in Fig.13 and Fig.14. Initially, link(HA3, MR3) and link(HA2, MR2) are down, other links are in up so MR3 and MR2 are the state of nested, and then CN-LFN traffic flow starts. At 8sec, MR1 hand-off occurs by making link(HA1, MR1) down, simultaneously link(MR2, MR3) up. That results 3-level nested configuration as MR1 is attached behind MR2. As you see in Fig.19, the packet delay of UDP traffic is steeply decreased after NROT between MR1 and CR. TCP traffic with PCH-based RO shows the throughput (i.e. fast TCP sequence number increasing) higher than before RO after the handoff.

The throughput gain of RO will be different depending on the assumed network topology. However, as in this packet-level simulation, we sure the throughput gain through applying RO can fully compensate the cost of installing CRs in the Internet somewhere. As mentioned in VI, the processing overhead of PCH piggybacking at HA is negligible in comparing with IP tunneling process, and the signaling overhead of RO tunnel is also nothing much in case of considering MIPv6 BU/BA. Therefore, the exact quantitation of those of metrics in our simulation was not measured but will be required in practical experimentation.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we explored on the problems and solutions of NEMO route optimization. For easy understanding of RO characteristics under NEMO context, we introduced ROT model as a generic RO model and got acquainted with the essence of a unified RO concept from it. In our opinion, we can use this model as a descriptive framework to describe some sort of things like which situation want RO, which entities involved in RO, how RO can be achieved, etc. It also could be used to evaluate some existing RO solutions, in what range does it support RO, does it satisfy the minimum requirement in performance or some operational restrictions. So we think that it can help us devise new universal RO solution.

And next, we described the concept and basic operations of our proposed scheme which is implemented by PCH Piggybacking in HA. We proved that the proposed scheme can be used to solve most of the RO problems defined in [12] as a unified solution by showing the RO cases based on PCH in Section V. Additionally, we evaluated our proposed protocol with some considerations about signaling cost, handovers, and tunnel management. We expect that the basic concept of our scheme can be used to support other mobility-related route optimizations as a unified approach in IP routing, not limited to NEMO. Lastly, the implementation and practical evaluation of our proposed scheme will be more elaborated in future work.

ACKNOWLEDGMENT

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