IPSJ Journal Vol. 52 No. 3 1010–1020 (Mar. 2011)

Regular Paper

NAT-MANEMO: Route Optimization for Unlimited Network Extensibility in MANEMO

Hajime Tazaki,[†1,†2] Rodney Van Meter,[†1]
Ryuji Wakikawa,[†3] Keisuke Uehara[†1]
and Jun Murai[†1]

MANET for NEMO (MANEMO) is a new type of network that integrates multi-hop mobile wireless networks with global connectivity provided by Network Mobility (NEMO). Two factors limit the scalability of MANEMO: the volatility of topologically correct global addresses, and excessive traffic load caused by inefficient use of nested tunnels and the consequent redundant routing of packets. We propose NAT-MANEMO, which solves both problems by applying NAT for some mobile router addresses, bypassing tunnel nesting. This approach retains global addresses for mobile end nodes, preserving application transparency, and requires only minimal modification to existing specifications. Our ideas are evaluated using simulation and a proof of concept implementation. The simulation shows the additional signaling overhead for the route optimization introduced by our proposal is negligible compare to the bandwidth of an IEEE 802.11 link. The implementation confirms that route optimization reduces latency and improves throughput.

1. Introduction

This paper is motivated by the need to support *unlimited network extensibility*, in which every node can extend global reachability indefinitely to the other nodes. In the rescue operation after a disaster occurs, for example, we require instant connectivity to communicate with services out on the Internet even though the existing infrastructure is only partially available. In such networks, the group of nodes form a multi-hop topology, such as a Mobile Ad-Hoc Network (MANET) [1] for NEtwork MObility (NEMO) [2] (so called MANEMO [3]), while using MANET to extend the connectivity in a small area network, and using NEMO to provide global connectivity to the end node. In MANEMO, a Mobile Router (MR) has the ability to communicate on a multi-hop basis, whereas the original specification of NEMO does not support this scenario. Once MRs connect to each other in an ad-hoc manner, the global reachability can be extended indefinitely. Without any planning or configuration, many MRs can be placed in the target area and possibly provide Internet connectivity, which they may also extend to others as well.

MANEMO seems to be just a combination of two technologies, however its use can be classified into two distinct scenarios: MANET-Centric MANEMO (MCM) and NEMO-Centric MANEMO (NCM) [4]. MCM is a solution that focuses on the problem of MANET. The address auto-configuration for a MANET node could be employed by the gateway node with the topologically correct prefix dissemination at the border of MANET and the Internet. However, the use of an address with this prefix as a communication endpoint breaks the address and session continuity for all the nodes in MANET when the gateway node roams to another access network, as shown in **Fig. 1**. In this case, NEMO helps to provide the global connectivity and the session continuity simultaneously [5].

On the other hand, NCM is a solution that focuses on the problem of NEMO. If MRs form a nested structure, inefficient communication paths are introduced [6]. Since the MR simply forwards the packets to and from the Mobile Network Nodes (MNNs) that it hosts to its Home Agent (HA), the nested MR arrangement introduces a sub-optimal routing path going through multiple HAs, as shown in **Fig. 2**. In this figure, the packet from MNN destined to Correspondent Node (CN) follows the sequence $MNN \Rightarrow MR4 \Rightarrow MR3 \Rightarrow MR2 \Rightarrow MR1 \Rightarrow HA1 \Rightarrow HA2 \Rightarrow HA3 \Rightarrow HA4 \Rightarrow CN$, causing home agent traversals and encapsulations to be performed four times. If the number of MRs is 100 or more, as in our unlimited network extensibility scenario, this path redundancy is a critical problem. In such case, the MANET routing protocol helps to provide an optimized communication path between MNN and CN, bypassing tunnel nesting [7].

MANEMO was expected to satisfy two requirements simultaneously: 1) to provide connectivity to the Internet by communicating via a home agent, and 2) to optimize the routing path for efficient communication. However, since MCM and NCM only solve these individual problems, MANEMO does not perfectly

†1 Keio University
†2 JST/JICA, SATREPS
†3 Toyota InfoTechnology Center, USA

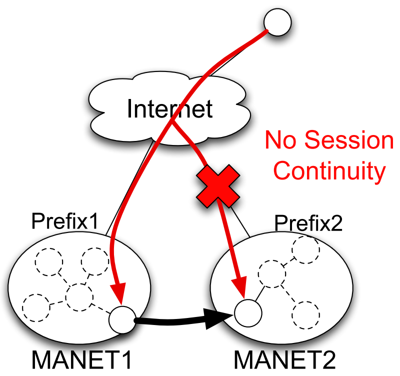

Fig. 1 Inter-MANET roaming breaks the session continuity.

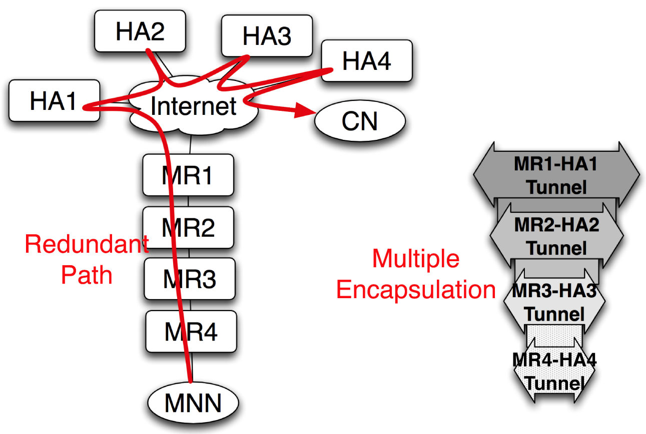

Fig. 2 Nested NEMO results in extra overhead and an inefficient, redundant forwarding path. Packets from MNN to CN first enter the MR4-HA4 tunnel, then are successively encapsulated at MR3, MR2, and MR1.

achieve both goals, leading us to propose NAT-MANEMO.

NAT-MANEMO is the first MANEMO-based solution that provides route optimization while using ad-hoc, multi-hop connectivity in the MR, making possible unlimited network extensibility with efficient communication for MANEMO.

The focus of this paper is to optimize the path in the nested MR arrangement while assigning a topologically incorrect care-of address (CoA) to the MR.

Our key contributions are as follows:

(1) We propose a route optimization scheme that minimizes changes to the existing network components and specifications. Our proposal also successfully assigns a unique, globally routable IP address to each end node in the MANET.

(2) Our simulation confirms the low impact on the bandwidth of the wireless link, even when the network size is large.

(3) We prove the concept of our proposal with actual software implementation.

The remainder of this paper is structured as follows. In Sections 2 and 3, we show the requirements derived from our goal and the problems with the existing route optimization for NEMO. Section 4 proposes our solution, NAT-MANEMO. We show the evaluation via qualitative analysis, the simulation of the introduced overhead, and the proof of concept of our proposal in Section 5. We discuss our evaluation and conclude the paper in Section 6.

2. Translating Our Goal into Design Requirements

Establishing a goal of providing *unlimited network extensibility* results in several requirements.

Req-1 Relax the assignment of the address for MRs.
Since an MR may attach to various networks, the address used for the MR should be independent of whether or not it can reach the Internet. The address shall be usable even if the MR forms a multi-hop network.

Req-2 Solution shall not break existing functionality.
Since we cannot assume any specific application for the end node, our solution must be transparent to existing functionality.

Req-3 Required functionality extensions shall be minimized.
As suggested in RFC4889 [8], extending the functionality of existing components should be minimized in order to decrease the deployment overhead.

3. Problems with Route Optimization for MANEMO

In MANET, there are several existing approaches to providing the nodes with global connectivity via an optimized path to the nodes; the two main ones are the Prefix delegation-based approach, and the NEMO tunnel proxy-based approach.

The problem of the redundant path between MR and HA is caused by the use of a topologically incorrect address for the CoA on MR. All of the existing solutions for the path optimization between MR and HA tackle this problem.

3.1 Prefix Delegation-based Approach

Prefix delegation-based address auto-configuration for MANET node has been discussed in the IETF [9]. The goal of this approach is to provide a topologically correct address for each MANET node with the interaction of a gateway node that connects to the access router. MIRON [10] is based on prefix delegation from the access network to assign a topologically correct address for the CoA of each MR. However, the assignment of topologically correct addresses for all MANET nodes is hard: the address (prefix) is owned by the Access Router (AR), therefore whenever the MR directly attached to the AR (called the root-MR) disconnects from the network, the AR should deactivate this prefix. This causes prefix flapping into the access network. Moreover, if the root-MR changes its point of attachment, all of the nodes behind this root-MR also change their IP addresses. This causes a *Binding Update Storm* which may overload the network and nodes.

3.2 NEMO Tunnel Proxy-based Approach

To optimize the redundant path introduced by the nested MR arrangement, the NEMO tunnel proxy-based solution utilizes two separate bi-directional tunnels, between HA and root-MR, and between root-MR and MR in the nested MR cloud. The idea is simple: an MR uses the CoA of the root-MR that is a topologically correct address, and conceals the network in the nested formation to eliminate the redundant path. Thus, MRs in the nested NEMO cloud are reachable from the Internet via an optimized routing path.

Light-NEMO [11] uses a root-MR that provides proxy functionality by advertising its CoA to MRs behind it, and each MR uses this CoA as an alternate CoA to solve the problem of redundant routing path among HAs. However, this tunnel concatenation also needs to be recognized at the HA. This violates Req-3.

4. NAT-MANEMO

In this section, we propose a route optimization scheme, NAT-MANEMO. In this solution, we use Network Address Translation (NAT) as the key component. Although NAT has several drawbacks (discussed in Section 4.4), it works well if the address translation is used in carefully restricted ways. In our proposed solution, *address translation is limited to the address of the MR, leaving packets from the end node (MNN) untouched*. Therefore, it does not break the application transparency for MNN communication.

4.1 System Overview

Figure 3 shows the network configuration and optimized path of our proposed solution, NAT-MANEMO, while the route optimization message sequence is shown in **Fig. 4**. The communication between MNN and Correspondent Node (CN) is performed with the interaction of the root-MR (MR1), MR2, and HAs

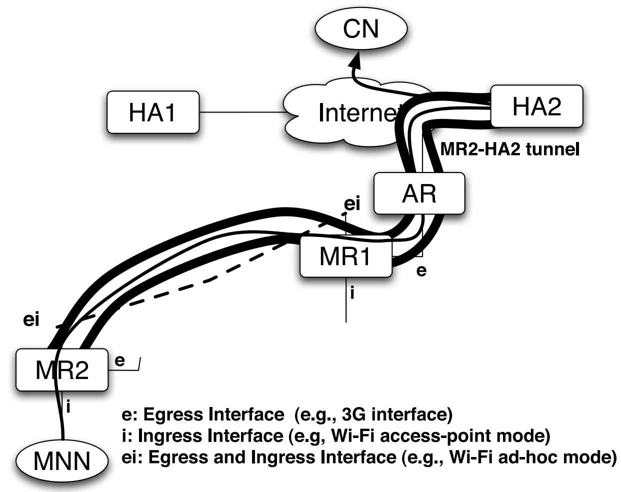

Fig. 3 Overview of NAT-MANEMO, where AR is Access Router, MR is Mobile Router, MNN is one of the Mobile Network Nodes, HA is Home Agent, and CN is a Correspondent Node located in the Internet. MNN communicates with CN via MR2, MR1 (root-MR), AR, and HA2. HA1 is bypassed by route optimization.

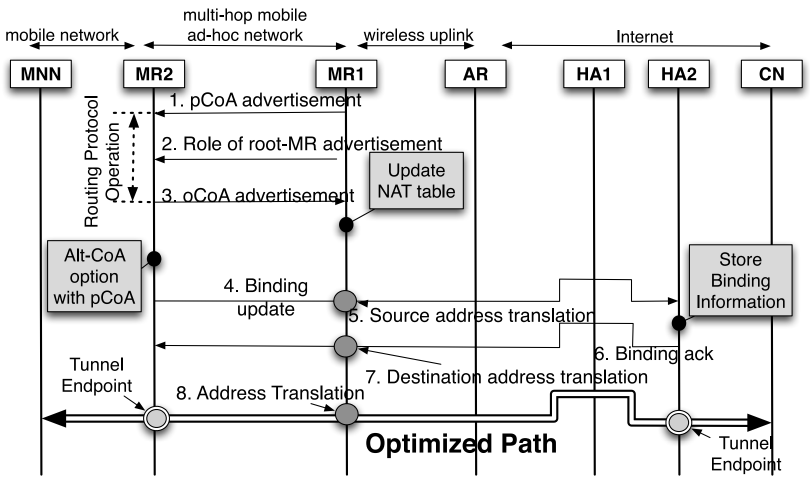

Fig. 4 Sequence of the NAT-MANEMO startup configuration. The dog-leg hop over HA1 indicates that packets bypass HA1 during normal packet forwarding.

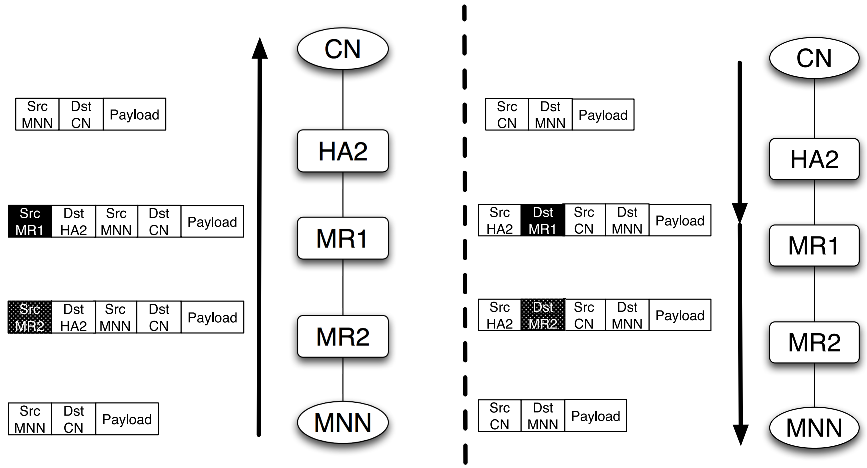

Fig. 5 Packet processing at root-MR. Left: Outbound processing, Right: Inbound processing.

based on the NEMO functionality.

Whenever an MR receives a Router Advertisement message (RA) of the Neighbor Discovery Protocol (NDP) [12] on its egress interface and recognizes the advertiser as a normal AR, the MR becomes a Root Mobile Router (root-MR) for the other MRs, and starts to advertise its role as root-MR with the Public Care-of-Address (pCoA) obtained from the AR. This advertisement is done by the routing protocol as in Section 4.2. If there are multiple root-MRs in a MANET, each MR may select a root-MR based on some routing protocol metric. If the routing protocol supports multiple gateways for the same destination, the MR may select multiple root-MRs and by utilizing Multiple Care-of-Address registrations (MCoA) [13], the MR may also use multiple pCoAs to register its location to multiple HAs.

The root-MR (MR1) also manages an address list of MRs in order to recognize the addresses that should be translated. MR-HA mapping entries with the MR's original CoA (oCoA, "original" meaning before translation) are added when the oCoA is announced by an MR with its home address (HoA). This mapping table is used for the translation of the packets exchanged between HA and MR. The entry is valid only while MR is in the routing table of MR1, as in normal routing protocol operation.

After MR2 detects the root-MR, it transmits a Binding Update (BU) packet to its HA (HA2) using the alternate CoA (Alt-CoA) option encoded with pCoA, which is obtained from MR1. Whenever a BU packet traverses MR1, MR1 rewrites the source address of this packet. **Figure 5** shows the transformation of the packet between MNN and CN. MR1 performs the packet translation as follows.

- Outbound packet processing
  A root-MR performs NAT when it receives a packet sourced from an MR's oCoA. If the source address field of the packet is in the NAT table, the root-MR translates it to the pCoA.
- Inbound packet processing
  When a root-MR receives a packet from the HA bound to an MR, it translates the destination address of this packet to the oCoA. Thus, the path between the MR and its HA is optimized and the IP address of MNN is globally reachable.

4.2 Routing Protocol Operation

In NAT-MANEMO, every MR should run a routing protocol to exchange routing information among the MRs. In addition to normal routing protocol information, the routing protocol should have the ability to advertise pCoA, oCoA and the role of root-MR as described in Section 4.1.

Note that the routing protocol here is not limited to any specific choice. Tree Discovery protocol (TDP), which provides root-MR discovery, with Network In Node Advertisement (NINA), which provides Mobile Network Prefix (MNP) advertisement inside the nested MRs to optimized the path between two MNNs, is a good candidate [7]. Optimized Link State Routing protocol (OLSR) [14] is a good candidate, as well.

4.3 Address Assignment for the MR

The Wi-Fi ad-hoc mode allows an interface to be configured with a Unique Local Address (ULA) [15] or via an addressing model using unnumbered interfaces [16] in order to avoid using global reachable addresses as CoAs. When using an unnumbered interface, the address of another interface on the router is borrowed; we refer to this as an "unnumbered address". Both approaches leave the MR free to assign topologically correct addresses to its own interfaces. The assigned address is used as the oCoA, which is the source address for the original BU packet and bi-directional tunnel between MR and HA. Although ULA and unnumbered address do not have any global reachability themselves, they can be reachable if root-MR translates this address.

By using an unnumbered address as an oCoA of the MR, the EI-EI (Egress/Ingress and Egress/Ingress) attachment model [3] can be used. The EI-EI attachment model is the advanced topology configuration under MANEMO. It provides flexibility for the MR interface configuration. Under original NEMO basic support, a mobile router is assumed to have two physically different interfaces, however this EI-EI attachment model assigns both egress and ingress interface roles to a single interface. The MR can expose its mobile network prefix to this EI interface and also configure a CoA on the same interface. **Figure 6** shows an example configuration of the unnumbered address on an EI interface, which plays both egress and ingress interface roles. In this figure, MNP1 and MNP2 are mobile network prefixes that belong to the mobile routers R1 and R2

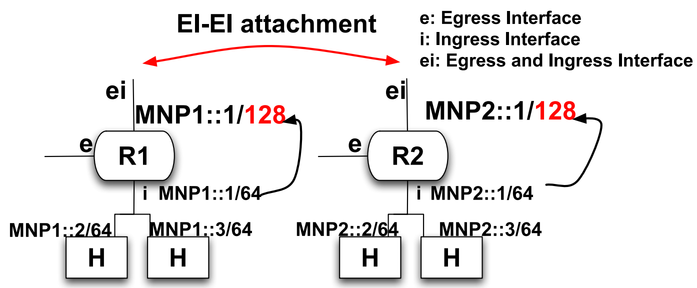

Fig. 6 EI-EI attachment between MRs. An unnumbered address is advertised using the routing protocol, and is globally routable from the Internet since this address is translated at root-MR. MNP1 and MNP2 are mobile network prefixes.

respectively, the IPv6 addresses of the EI interfaces are statically assigned and borrowed from their ingress interfaces (the "unnumbered interface" referred to above, marked with arrows in the figure). However the prefix lengths of the EI interfaces are 128, while the ingress interface has prefix length 64. By using 128 prefix lengths at the EI interface, the neighbor node via ad-hoc interface appears as a different network, avoiding using NDP to resolve for nodes that are two hops away. H represents a normal IPv6 host whose address is configured based on the prefix advertisement by upper router.

4.4 Avoiding the Drawbacks of NAT

Network Address Translation (NAT) [17] was proposed to allow the usage of private addresses in the network due to the limited address space of IPv4. As a result, it introduces several drawbacks: 1) because NAT is stateful, a NAT device is a single point of failure, and 2) NAT prevents application transparency because of the difficulty of handling addresses embedded in the payloads of application datagrams [18]. NAT itself can be considered a type of locator identifier separation: the translated address represents a locator in the network, while the original address represents an identifier in the limited location. This virtualization of the IP address allows the system to avoid requiring modifications in other network entities. By taking advantage of the normal routing protocol operation for the dynamic creation of the NAT table entry, our proposed system can transparently migrate from one NAT device to another, removing the NAT device as a single point of failure: whenever the MR with oCoA disappears from the routing table of the root-MR, the NAT table entry is also removed. Moreover, our proposal does not perform deep packet inspection: since only the tunnel wrapper IP header is affected, the transform engine is carefully constrained, and the impact on packet processing performance is limited. This limited NAT preserves both present and future application transparency and does not require NAT traversal techniques.

5. Evaluation

In this section, we evaluate our proposed scheme using both qualitative analysis (Section 5.1) and simulation (Section 5.2). Finally, we describe our proof of concept software implementation (Section 5.3).

5.1 Qualitative Analysis

We compare the proposed solution with existing solutions in terms of several criteria suggested in Section 2. We consider the following three criteria, as summarized in **Table 1**. In this analysis, we call "Traditional NAT", a network operated with traditional NAT involving port translation without NEMO functionality to provide global connectivity.

Use of topologically incorrect address for CoA Using topologically incorrect address for the CoA of the MR is useful since the MR may be disconnected because of movement. This corresponds to Req-1 described in Section 2.

NAT-MANEMO (our solution) allows the use of a topologically incorrect CoA since this CoA would be translated at root-MR. Light-NEMO, as a representative of the NEMO tunnel proxy-based approach, also allows the use of a topologically incorrect address since the CoA is hidden by the tunnel established with root-MR. In contrast, MIRON, a prefix delegation-based approach, uses a topologically correct address assigned by the DHCP-PD protocol.

Table 1 Summary of the qualitative analysis.

Solution	Use of topologically incorrect CoA (e.g., ULA)	Application Transparency	Required modification
NAT-MANEMO	O	O	MR
MIRON	X	O	MR
Light-NEMO	O	O	MR,HA
Traditional NAT	O	X	N/A

Maintain existing functionality In NAT-MANEMO, unlike traditional NAT, address translation is limited to only the addresses of the MRs. Therefore, packets originating from the MNN are untouched, since they are always encapsulated by the MR, maintaining application transparency (Req-2 in Section 2). Traditional NAT without NEMO functionality can also provide the global connectivity for the MANET node, however, it breaks application transparency and session continuity. MIRON and Light-NEMO also maintain application transparency.

Modification of the current specification The prefix delegation-based approach does not require modification of the current specification of NEMO, only enabling the DHCP prefix delegation functionality on MR, root-MR, and AR. Light-NEMO requires modification of the existing functionality on MR and HA, because the proxied tunnel at the root-MR breaks the current specification of NEMO. NAT-MANEMO only requires the modification to MR. Using NAT minimizes modification to the entities in the network (Req-3 in Section 2).

The approach taken in our proposed solution uses NAT for the communication of all MRs. By using NAT, an MR can behave as if the address it is using is globally reachable, and it appears so to nodes on the Internet. Therefore, NAT-MANEMO minimizes modification of the existing protocol.

Light-NEMO and NAT-MANEMO satisfy similar criteria, however, Light-NEMO involves modifications to two system components to support the tunnel, while NAT-MANEMO's use of NAT limits modifications to a single place in the system. Further, modifying the functionality of the home agent involves changes at the service operator's network (e.g., installation of new software to replace the home agent) and also affects the other users sharing the same home agent. Therefore, limiting the modification to the mobile router helps the deployment of the new protocol.

Moreover, although our current proposal is only addressing the optimization of NEMO operation, this approach could also be adopted to optimize communications between the Mobile Node (MN) and the Correspondent Node for Mobile IPv6 [19]. Thanks to the minimal modifications required for the NAT-MANEMO approach, only the MN would have to change.

5.2 Simulation Study for Signaling Overhead

As described in Section 4.2, we need additional signaling messages for NAT-MANEMO. To evaluate the impact of this additional overhead, we conducted network simulations to measure the control traffic generated by the routing protocol. We use Tree Discovery protocol (TDP) with Network In Node Advertisement (NINA) [7] as our routing protocol. We encode the root-MR role in the `tree depth` field and the pCoA in the `TreeID` field, and NINA is used to propagate the oCoA of the MR inside the nested NEMO cloud.

Since the overhead of NINA is dependent on the topology that MRs form [20], we observe the overhead generated by MRs during movement. The Manhattan Grid mobility model [21] is used for the MR movement. This mobility model behaves as though the nodes are only allowed to move on a predefined grid. It aims to imitate the movement of a vehicle equipped with an MR and several MNNs. We choose a 10×10 Manhattan Grid with $200\,\mathrm{m} \times 200\,\mathrm{m}$ area size considering the possible minimum grid size in actual world.

In the simulations, we run an extension of the Zebra routing software ⋆1 for the MR on top of ns-3 [22]. We model an IEEE 802.11b ad-hoc mode wireless interface for the egress/ingress interface of each MR, and a managed mode interface for the ingress interface. MNN is not used in this simulation since the traffic from MNN is not relevant to the overhead. Other parameters for this simulation are shown in **Table 2**.

Figure 7 shows the result of the simulations from 5 repetitions. We observed the packets transmitted by TDP/NINA in every MR, and plotted the distribution of the per-node overhead in bytes per second with a box-and-whisker plot. As shown in the figure, the overhead of TDP/NINA increases as the size of the network grows. Nevertheless, the additional overhead introduced by TDP/NINA is still low, a maximum of about 100 bytes per second. It is negligible compared to the link speed of the wireless interface (e.g., 11 Mbps in IEEE 802.11b mode).

5.3 Proof of Concept

In this section, we show the results of the experiments for our proof of concept.

Table 2 Parameters for the simulation.

Parameters	Value
# of MRs	5, 10, 20, 30, 40, 50, 60, 70, 80, 90
Wi-Fi data rate	11 Mbps
simulation time	200 sec
mobility model	Manhattan Grid
area size	200 m × 200 m
Manhattan Grid size	10 × 10
movement speed	20 m/s
turn probability	1
RA interval	2 sec

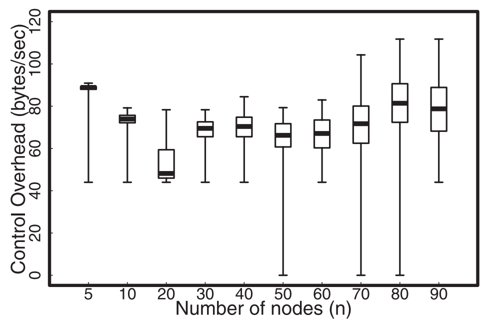

Fig. 7 Distribution of the per-node additional signaling overhead introduced by TDP/NINA for the simulations described in Table 2. The bottom and top of the whiskers are the minimum and the maximum value respectively, the bottom and top of the box represent the first and third quartiles, and the middle bar is the median value.

By using software under a MANET environment, we show the efficiency of communication using the optimized path introduced by NAT-MANEMO. Moreover, we show the performance impact of the handoff operation with our proposal.

5.3.1 Implementation Detail and Experimental Setup

To implement NAT-MANEMO, we implemented IPv6 NAT functionality in the Linux net-next-2.6 ⋆2 kernel as an extension of `netfilter` functionality. This NAT implementation achieves stateless address translation with simplified higher

⋆1 http://www.zebra.org/, our extension is available on http://www.sfc.wide.ad.jp/~tazaki/zebra-mndpd/

⋆2 http://git.kernel.org/?p=linux/kernel/git/davem/net-next-2.6.git, downloaded Aug 19 2010 version.

64-bit prefix translation (i.e., if oCoA is 1:2:3:4:a:b:c:d, it will be translated to 5:6:7:8:a:b:c:d if the prefix of pCoA is 5:6:7:8::) and Neighbor Discovery Proxies [23]. Thus, NAT devices do not have to remember the session state for NAT.

For the routing protocol, we used the same Zebra extension used in the simulation of Section 5.2. This Zebra extension includes NAT entry management on the root-MR based on oCoA information from the MR as described in Section 4.2. Whenever the MR with oCoA disappears from the routing table, the root-MR also removes the NAT entry.

For the NEMO functionality, we used a modified version of UMIP [⋆1] and Linux net-next-2.6 kernel as is. For UMIP, we implemented the interaction with Zebra in order to encode Alt-CoA learned by TDP/NINA as described in Section 4.1. Note that we only modified MR functionality as described in Section 5.1.

Using all of the above software, we ran the experiments over ns-3 Linux emulation [24] with our enhancements [⋆2]. This environment allows us to use Zebra, UMIP and the Linux kernel in our experiments using ns-3. This approach provides easy control of experiments and achieves good agreement between network simulation and actual deployment.

Figure 8 shows the network configuration for our experiment. MRs are configured with three interfaces and form EI-EI attachments to discover the gateway in the nested NEMO clouds. We use the unnumbered addressing model for address configuration in each MR for the NAT-MANEMO experiment. The address of the ad-hoc interface is borrowed from the address of the ingress interface, which is in the range of the MNP and is used as the node's oCoA. Although this CoA is not reachable from the Internet without conducting a binding registration, NAT-MANEMO provides the connectivity since this CoA would be translated at the root-MR. For the unmodified NEMO experiment, we used managed mode interface for the egress interface (shown as 'e' in Fig. 8) since unmodified NEMO is not able to utilize ad-hoc mode interface for its egress interface because the Neighbor Discovery protocol does not work on ad-hoc mode interfaces [25].

⋆1 USAGI-patched Mobile IPv6 for Linux: http://umip.linux-ipv6.org/, downloaded Jul 7 2010 version.

⋆2 The complete source code of this simulation is available: http://www.sfc.wide.ad.jp/~tazaki/distfiles/ns3/ns-3-simu-quagga-100920.tar.gz

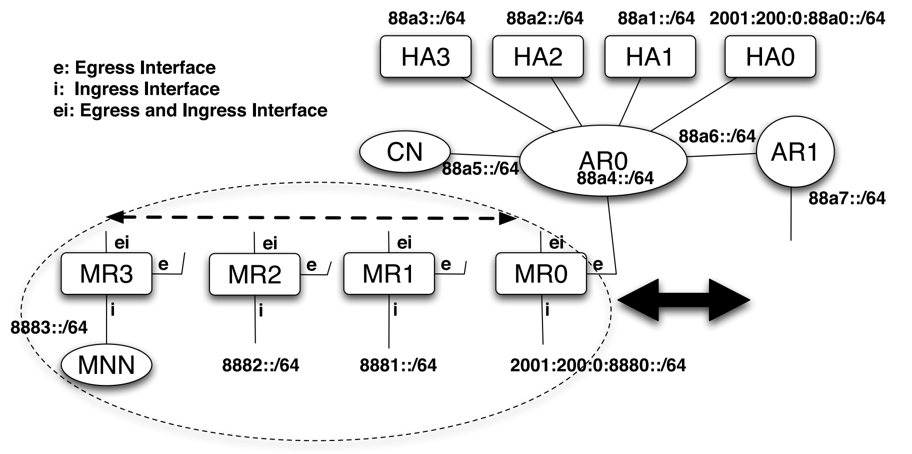

Fig. 8 Network configuration for the experiments.

Table 3 Parameters for the experiment of NAT-MANEMO.

	Parameters	Value
Wi-Fi	Data rate	1 Mbps
Ethernet link	Data rate	5 Mbps
	Delay	20 msec
Routing protocol	RA interval	2 sec

Table 3 shows the set of parameters for this experiment. In each MR, the EI, egress, and ingress interfaces are configured on the Wi-Fi physical interface. The EI interface is configured with ad-hoc mode, egress interface is managed mode client, and ingress interface is configured as an access point. In the NAT-MANEMO experiment, only the root-MR (MR0 in this experiment) uses a managed mode Wi-Fi interface for its CoA; the others use CoAs statically assigned on an ad-hoc mode interface. The Wi-Fi interface is configured with 1 Mbps data rate for the stable link status. All other links for the nodes except MR and MNN are configured with Ethernet links.

5.3.2 Route Optimization Effect

Table 4 shows the mean and standard deviation of the Round Trip Time (RTT) and throughput measurement. RTT is measured by 5000 replications of

Table 4 The optimized traffic measurement between MNN and CN. (±) means standard deviation of each results.

	RTT (ms)	Throughput (Kbps)
NEMO	503.70 (±38.71)	167.28 (±1.08)
NAT-MANEMO	171.71 (±35.64)	191.01 (±1.15)

ICMPv6 echo packet between MNN and CN, at intervals of 100 milliseconds with 64 byte packets. In order to measure the path throughput, MNN sends 1024 byte packets at 10 Mbps, and the CN records the throughput for this transmitted traffic, and replicates this measurement five times. In these measurements, MR0 is attached to AR0 as shown in Fig. 8 and all the MRs do not move. Unmodified NEMO has about 500 millisecond delay because the path between MNN and CN is $MNN \rightarrow MR3 \rightarrow MR2 \rightarrow MR1 \rightarrow MR0 \rightarrow AR0 \rightarrow HA0 \rightarrow HA1 \rightarrow HA2 \rightarrow HA3 \rightarrow CN$, where each Ethernet link between AR and HAs adds a 20 millisecond delay. The optimized path created by NAT-MANEMO results in a smaller delay because it bypasses three HAs.

Both the RTT and throughput results show that NAT-MANEMO improves performance in term of packet delivery because of the optimized path. The results show the possibility of the implementation through the network experiment.

5.3.3 Handoff Performance

This section gives a comparative analysis of handoff performance achieved by the NAT-MANEMO and the unmodified NEMO. In this experiment, an MNN continuously sends ICMPv6 echo requests to the peer node (CN in Fig. 8) to measure the communication latency and the duration of the disruption of communication during a handoff. We simulated five replications with slightly different mobility patterns in two methods of NEMO. The network configuration is the same as the one given in Section 5.3.2, with additional parameters described in **Table 5**.

Figure 9 shows the typical results of the handoff performance achieved by different types of MRs. RTT decreases slightly after handoff since the number of links between MR0 and HA0 decreases. The duration of the disruption of communication during a handoff, which is described in the X-axis, is used as the indicator of handoff performance. Note that the figure also shows the Round-Trip Time (RTT) between the MNN and the peer node in the Y-axis. The mean value of the duration of the disruption in unmodified NEMO is 5.19 (stddev: ± 2.21) seconds while 9.95 (stddev: ± 1.47) seconds in NAT-MANEMO. As the figure shows, NAT-MANEMO adds additional handoff latency. The latency is due to the time for the root-MR (MR0 in Fig. 8) to signal MRs in the lower hierarchy that its pCoA has been changed and the time for the MRs to perform binding registration.

The results show that our proposed solution (NAT-MANEMO) has a performance tradeoff between the communication latency and the handoff latency compared to the unmodified NEMO. The user will benefit most from our proposed solution when the frequency of handoff is relatively low, and applications require shorter communication latency.

Table 5 Additional parameters for the handoff experiment.

Parameters	Value
mobility model	Random Walk
movement speed	5 m/s
simulation time	500 sec

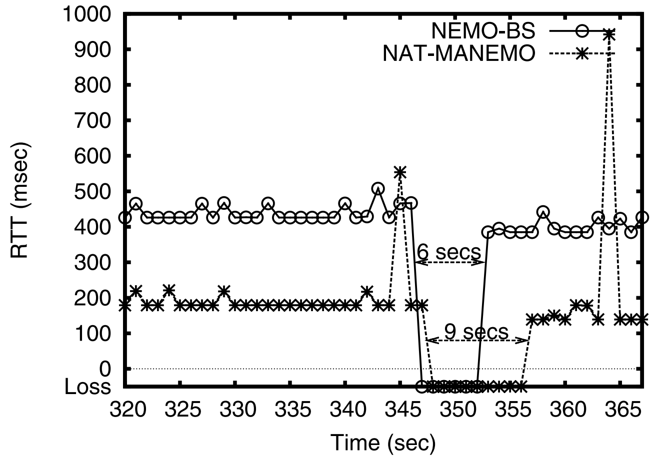

Fig. 9 Handoff operation with connectivity measurement. An RTT value less than 0 seconds means the reply packet is lost because of connectivity loss.

6. Conclusion

We propose a NEMO route optimization scheme, NAT-MANEMO, to achieve global reachability for MANET nodes. To the best of our knowledge, this is the first design for the route optimization, decreasing the number of home agents while MR is using ad-hoc, multi-hop connectivity in a MANEMO configuration. We compared our proposed scheme with existing approaches using simulation and a proof-of-concept implementation, as well as qualitatively. Our proposal meets all of the requirements we established in Section 2, and improves on existing solutions to the nested NEMO problem by: 1) relaxing the assignment of the address for MR, 2) maintaining the application transparency and 3) minimizing modification to the network components and functionality. Although NAT is performed to optimize the route, address translation is limited to the address of MR, leaving packets from the end node (MNN) untouched. Moreover, simulation using a Manhattan Grid mobility model confirms that the additional signaling overhead has only minimal impact on bandwidth consumed. Finally, we show the actual software implementation and the proof of our concept with optimized communication among the nested MRs. Our proposal encourages unlimited network extensibility of MANET nodes by eliminating concerns about the addresses used by MRs.

Another NAT based mobile protocol, MAT [26], has been proposed. Since MAT is not based on the IETF mobile protocol, we have not investigated it in this paper. For future work, we plan to investigate non-standardized mobile protocols and to extend the evaluation with system-wide experiments including handoff operation in the large numbers of the nodes to confirm the scalability of our proposal.

Acknowledgments The authors wish to thank Shinta Sugimoto from Nippon Ericsson K.K. for his insightful technical comments on this paper.

This research was supported by JST/JICA, SATREPS (Science and Technology Research Partnership for Sustainable Development).

References

1) Corson, S. and Macker, J.: Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations, RFC 2501 (Informational) (1999).
2) Devarapalli, V., Wakikawa, R., Petrescu, A. and Thubert, P.: Network Mobility (NEMO) Basic Support Protocol, RFC 3963 (Proposed Standard) (2005).
3) Moustafa, H. and Zhang, Y. (Eds.): *Vehicular Networks: Techniques, Standards, and Applications*, Auerbach Publications (2009).
4) McCarthy, B., Edwards, C. and Dunmore, M.: Network transparency in a mountain rescue domain, *Internet Research*, Vol.17, No.5, pp.465–478 (2007).
5) McCarthy, B., Edwards, C. and Dunmore, M.: Using NEMO to Support the Global Reachability of MANET Nodes, *The 28th Conference on Computer Communications* (*IEEE INFOCOM 2009*), pp.2097–2105 (2009).
6) Ng, C., Thubert, P., Watari, M. and Zhao, F.: Network Mobility Route Optimization Problem Statement, RFC 4888 (Informational) (2007).
7) McCarthy, B., Jakeman, M., Edwards, C. and Thubert, P.: Protocols to efficiently support nested NEMO (NEMO+), *Proc. 3rd International Workshop on Mobility in the Evolving Internet Architecture* (*MobiArch '08*), New York, NY, USA, ACM, pp.43–48 (2008).
8) Ng, C., Zhao, F., Watari, M. and Thubert, P.: Network Mobility Route Optimization Solution Space Analysis, RFC 4889 (Informational) (2007).
9) Internet Engineering Task Force: IETF Ad-Hoc Network Autoconfiguration Working Group Charter Homepage (online), http://datatracker.ietf.org/wg/autoconf/charter/ (accessed 2010-09-13).
10) Bernardos, C., Bagnulo, M. and Calderon, M.: MIRON: MIPv6 route optimization for NEMO, *4th Workshop on Applications and Services in Wireless Networks* (*ASWN 2004*), pp.189–197 (2004).
11) Sabeur, M., Jouaber, B. and Zeghlache, D.: Light-NEMO+: Route Optimization for Light-NEMO Solution, *14th IEEE International Conference on Networks* (*ICON '06*), Vol.2, pp.1–6 (2006).
12) Narten, T., Nordmark, E., Simpson, W. and Soliman, H.: Neighbor Discovery for IP version 6 (IPv6), RFC 4861 (Draft Standard) (2007). Updated by RFC 5942.
13) Wakikawa, R., Devarapalli, V., Tsirtsis, G., Ernst, T. and Nagami, K.: Multiple Care-of Addresses Registration, RFC 5648 (Proposed Standard) (2009).
14) Clausen, T. and Jacquet, P.: Optimized Link State Routing Protocol (OLSR), RFC 3626 (Experimental) (2003).
15) Hinden, R. and Haberman, B.: Unique Local IPv6 Unicast Addresses, RFC 4193 (Proposed Standard) (2005).
16) Clausen, T.H.: MANET Router Configuration Recommendations, Research Report RR-6852, INRIA (2009).

17) Srisuresh, P. and Egevang, K.: Traditional IP Network Address Translator (Traditional NAT), RFC 3022 (Informational) (2001).
18) Srisuresh, P. and Holdrege, M.: IP Network Address Translator (NAT) Terminology and Considerations, RFC 2663 (Informational) (1999).
19) Johnson, D., Perkins, C. and Arkko, J.: Mobility Support in IPv6, RFC 3775 (Proposed Standard) (2004).
20) Tazaki, H., Van Meter, R., Wakikawa, R., Wongsaardsakul, T., Kanchanasut, K., Dias de Amorim, M. and Murai, J.: MANEMO Routing in Practice: Protocol Selection, Expected Performance, and Experimental Evaluation, *IEICE Trans. Communications*, Vol.93, No.8, pp.2004–2011 (2010).
21) Bai, F., Sadagopan, N. and Helmy, A.: IMPORTANT: A Framework to Systematically Analyze the Impact of Mobility on Performance of Routing Protocols for Adhoc Networks, *22nd Annual Joint Conference of the IEEE Computer and Communications Societies* (*INFOCOM 2003*), Vol.2, pp.825–835 (2003).
22) NS-3 project: The ns-3 network simulator (online), available from http://www.nsnam.org/ (accessed 2010-05-17).
23) Thaler, D., Talwar, M. and Patel, C.: Neighbor Discovery Proxies (ND Proxy), RFC 4389 (Experimental) (2006).
24) Jansen, S. and McGregor, A.: Simulation with real world network stacks, *Proc. 37th Conference on Winter Simulation* (*WSC '05*), Winter Simulation Conference, pp.2454–2463 (2005).
25) Baccelli, E., Clausen, T.H. and Jacquet, P.: Ad Hoc Networking in the Internet: A Deeper Problem Than It Seems, Research Report RR-6725, INRIA (2008).
26) Aibara, R., Fujita, T., Maeda, K. and Nomura, Y.: Mobile Internet Architecture with Address Translation (in Japanese), *Journal of Information Processing*, Vol.43, No.12, pp.3889–3897 (2002).

(Received May 21, 2010)
(Accepted December 1, 2010)
(Original version of this article can be found in the Journal of Information Processing Vol.19, pp.118–128.)

Hajime Tazaki received his B.E and M.E. from Chiba University, Japan, in 1998 and 2000 respectively. In 2000, he joined PFU Limited and worked in software development division for networking products. He is presently a Ph.D. candidate of Graduate School of Media and Governance at Keio University. His research interests are mobile ad-hoc networks and network architecture for mobile networks.

Rodney Van Meter received a B.S. from the California Institute of Technology in 1986, an M.S. from the University of Southern California in 1991, and a Ph.D. from Keio University in 2006. His research interests include storage systems, networking, post-Moore's Law computer architecture, and quantum computing. He is an Associate Professor of Environment and Information Studies at Keio University's Shonan Fujisawa Campus.

Ryuji Wakikawa received his Ph.D. degree in Media and Governance from Keio University in 2003 and M.E. degree in Media and Governance from Keio University in 2001. He is a Senior Researcher at Toyota InfoTechnology Center, USA, Inc from 2009. His research interests are mobile computing, Mobile IP, Mobile Ad-hoc Networks, and Mobile Networks. He received The 10th Ericsson Young Scientist Award in 2007.

Keisuke Uehara is an Associate Professor at Keio University. He received his Ph.D. from Keio University in 2003. His interests in research are Internet Mobility, Intelligent Transport Systems (ITS) and Ubiquitous computing. He is working on standardization as an expert of ISO/TC204 and ISO/TC211. He is a member of ACM, IEEE Computer Society and IPSJ.

Jun Murai was born in March 1955 in Tokyo. Graduated Keio University in 1979, Department of Mathematics, Faculty of Science and Technology. He received his M.S. for Computer Science from Keio University in 1981, and received his Ph.D. in Computer Science, Keio University in 1987. He specializes in computer science, computer network, and computer communication. He is currently the Dean, Faculty of Environment and Information Studies, Keio University since October 2009. Former Vice-President of Keio University from May 2005 to May 2009. He was an Executive Director of the Keio Research Institute at SFC, Keio University from 1999 to 2005.