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DRO: domain-based route optimization scheme for nested mobile networks

Ming-Chin Chuang and Jeng-Farn Lee*

Abstract

The network mobility (NEMO) basic support protocol is designed to support NEMO management, and to ensure communication continuity between nodes in mobile networks. However, in nested mobile networks, NEMO suffers from the pinball routing problem, which results in long packet transmission delays. To solve the problem, we propose a domain-based route optimization (DRO) scheme that incorporates a domain-based network architecture and *ad hoc* routing protocols for route optimization. DRO also improves the intra-domain handoff performance, reduces the convergence time during route optimization, and avoids the out-of-sequence packet problem. A detailed performance analysis and simulations were conducted to evaluate the scheme. The results demonstrate that DRO outperforms existing mechanisms in terms of packet transmission delay (i.e., better route-optimization), intra-domain handoff latency, convergence time, and packet tunneling overhead.

Keywords: network mobility (NEMO), route optimization, *ad hoc* routing protocol, handoff

1. Introduction

Recently, vehicular networks have received a significant amount of attention in the field of wireless mobile networking. On public methods of transportation, such as taxies, trains, buses, and airplanes, many mobile network nodes (MNNs) move together as a large-scale vehicular network. In such environments, people can use mobile devices for accessing services, such as VoIP, video conferencing, web-browsing, and music downloading, anytime-anywhere. With the emergence of vehicular networks, users require seamless and efficient communications on the move. Therefore, developing a route optimization scheme has become an important research issue.

The network mobility (NEMO) basic support protocol [1] was proposed by the Internet Engineering Task Force to support NEMO management, and ensure communication continuity for nodes in mobile networks. A mobile network comprises one or more mobile routers (MRs) that provide access to the Internet. The MR transmits packets to MNNs via the ingress interface, and accesses the Internet/MRs through the egress interface. It also substitutes for MNNs in the mobile network by performing binding updates (BU) to the home agent (HA) without additional registration such that NEMO can reduce the signaling overhead. The main operations of NEMO are extended from Mobile IPv6 (MIPv6) protocol [2], which uses bi-directional tunneling between the MR and the HA to preserve session continuity. However, in nested mobile networks, NEMO suffers from the pinball routing problem [3]. When the level of nesting in a mobile network increases, the packets, which have to pass through HAs at each level, must be encapsulated many times, resulting in long packet transmission delay and high tunneling overhead. Figure 1 illustrates the pinball routing problem in nested mobile networks, where the packets are transmitted from the correspondent node (CN) to MNN1. The data routing path in NEMO is CN → HA3 → HA2 → HA1 → AR → MR1 → MR2 → MR3 → MNN1, which is inefficient. Hence, there is a need for an efficient route optimization scheme [4].

The NEMO routing protocol can be divided into (1) inter-domain routing, which means the MNN and the CN are in different nested mobile networks; and (2) intra-domain routing, where the MNN and the CN are in the same nested mobile network. Most approaches focus on the inter-domain routing problem and use a hierarchical architecture to achieve route optimization.

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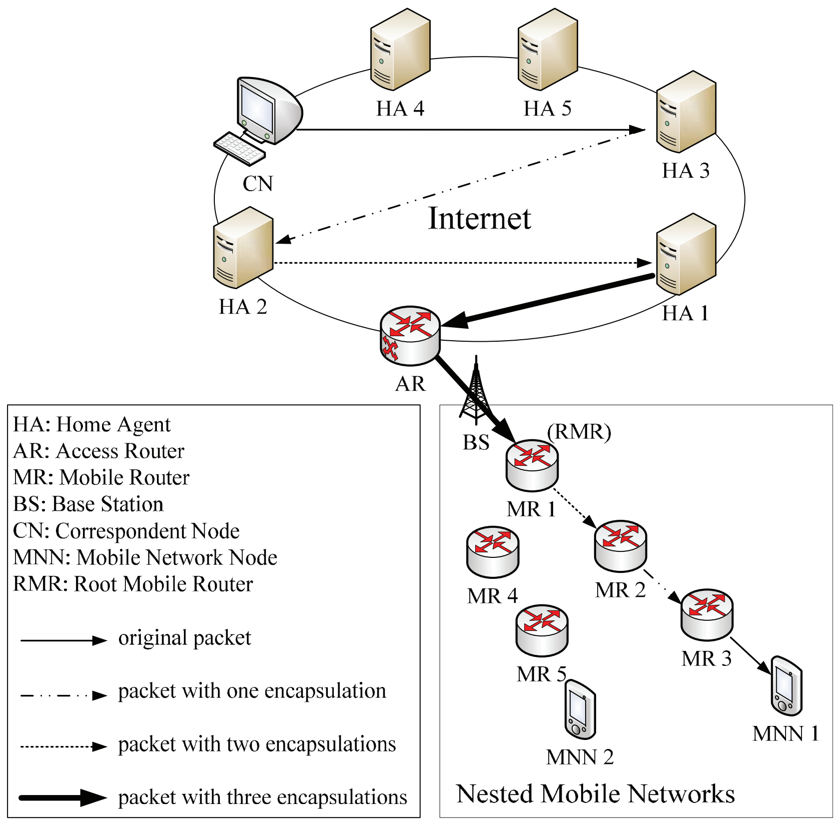

Figure 1 The pinball routing problem in a nested mobile network.

However, hierarchy-based schemes may suffer from the non-optimal route problem when the CN and the MNN are located in the same nested mobile network (i.e., intra-domain routing). Moreover, such schemes do not cope with the handoff procedure well, resulting in long convergence time in route optimization or communication disruption. Actually, the handoff procedure has a substantial impact on the performance of route optimization because it is implemented before route optimization. If the handoff latency (HL) is long, then it disrupts communications or causes long convergence time in route optimization. Therefore, we also consider the handoff problem to reduce the latency in route optimization. Similar to the NEMO routing protocol, inter-domain handoff means that the MR hands off to a different nested mobile network; while intra-domain handoff means the MR hands off within the same nested mobile network. Hence, the proposed mechanism considers route optimization for inter-domain and intra-domain routing, and reduces the HL in both scenarios.

Although route optimization reduces the packet transmission delay, it may suffer from the packet out-of-sequence problem. Out-of-sequence packets degrade the TCP performance by generating duplicate ACKs at the receiver. Although, the MNN can receive the packet successfully, the CN still decreases its sending rate via fast recovery mechanism to avoid congestion. Eventually, the out-of-sequence packets reduce the CN's sending rate, which results in low network performance. Figure 2 illustrates the packet out-of-sequence problem in inter-domain and intra-domain route optimization. In this example, the CN sends a sequence of packets $\{P_1, P_2,...,P_n\}$ to the MNN. The dotted lines represent the old (non-optimal) path and the solid lines represent the new (optimal) path. After the route optimization procedure, the sequence of packets $\{P_{i+1},P_{i+2},...,P_n\}$ traverses the optimal path, but the sequence of packets $\{P_1,P_2,...,P_i\}$ traverses the non-optimal path. Consequently, the packets may arrive at the MNN out of sequence, which would impact the network performance (e.g., TCP applications).

In this article, we propose a domain-based route optimization (DRO) scheme. The domain-based network architecture incorporates the operations of *ad hoc* routing protocols for performing route optimization and reduce HL. Moreover, we use a double buffer mechanism in DRO to prevent the packet out-of-sequence problem during the route optimization procedure. We

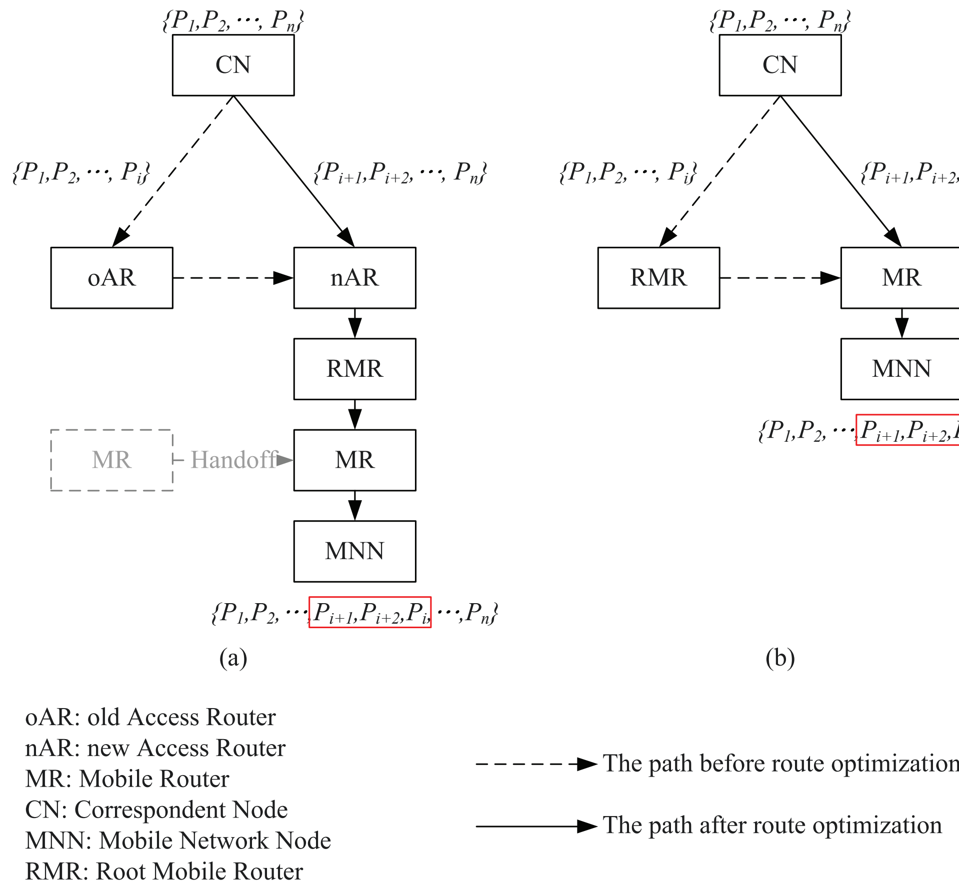

Figure 2 The packet out-of-sequence problem: **(a)** inter-domain route optimization; **(b)** intra-domain route optimization.

compare DRO's performance with that of existing route optimization schemes via analysis and simulations. The results demonstrate that DRO outperforms the compared schemes in terms of packet transmission delay, HL, convergence time, and packet tunneling overhead.

The remainder of this article is organized as follows. Section 2 contains a review of related work. In Section 3, we describe the proposed DRO scheme. In Section 4, we evaluate the scheme's performance in terms of packet delay (PD), HL, packet overhead during tunneling, and total cost (TC). Section 5 contains some concluding remarks.

2. Related work

In this section, we discuss existing schemes for solving the pinball routing problem, out-of-sequence problem, and route optimization using the concepts of mobile *ad hoc* networks (MANETs).

The reverse routing header [5] uses new extension headers to inform the HAs of an MR in the nested structure. However, this header modification needs to be performed by each MR that an outgoing packet passes through. Moreover, the modification and re-computation overhead of the packet checksum or CRC increases with the level of the nested mobile network. The recursive binding update (RBU) [6] allows the HAs to maintain the binding information for the care-of-address (CoA) of the root mobile router (RMR). Consequently, RBU can use the BU messages to find the optimal route. However, RBU needs long convergence time to find the optimal route when there are many handoff events because the HAs need to repeat the RBU procedure for each event. Calderon et al. [7] propose the Mobile IPv6 route optimization scheme for NEMO (MIRON) based on the protocol for carrying authentication for network access (PANA) [8] and the dynamic host configuration protocol (DHCPv6) [9]. However, MIRON needs to modify all MRs and visiting mobile nodes (VMNs). Moreover, MIRON will not work well if the VMNs do not have PANA client software, or the MR does not have PANA client and server software. SIP-NEMO [10] extends SIP to support NEMO so that the packets can be transmitted directly between the MNN and the CN, but the scheme only applies to applications that use SIP. The route optimization using tree information option (ROTIO) scheme [11] has a fast convergence time during route optimization. However, if an inter-domain handoff event occurs, the communication may be disconnected since ROTIO does not handle inter-domain handoff well. Kuo and Ji [12] proposed an enhanced hierarchical NEMO protocol called HRO+, which reduces the PD in inter-domain and intra-domain routing. In inter-domain routing, the CN sends the packets to the RMR directly without passing through any HA because the MR binds the NEMO prefix of RMR to the CN. In intra-domain routing, each MR records the routing information of sub-MRs. Therefore, the MR can find an optimal path when the sender and receiver belong to its sub-MR. However, HRO+ does not consider inter-domain handoff and it also suffers from the suboptimal routing problem in intra-domain routing (i.e., the sender and the receiver do not have the same parent MR). N-PMIPv6 [13] uses Proxy Mobile IPv6 (PMIPv6) protocol [14] to reduce HL in a NEMO environment, but it does not address the route optimization issue.

During the route optimization procedure, the MNN may receive out-of-sequence packets, as shown in Figure 2. In this situation, receivers will transmit duplicate ACKs so that the performance of TCP will be degraded. Zheng et al. [15] and Tandjaoui et al. [16] anticipate the arrival time of packets from the old link to adjust the transmission time of packets from the new link. The drawback of these schemes is that, since they are based on prediction methods, they suffer from packet loss or inaccurate time estimation when the network environment varies.

MANEMO integrates MANET and NEMO technologies to provide IP connectivity across nested mobile networks. Clausen et al. [17] used the optimized link state routing (OLSR) protocol to support route optimization, but the scheme does not consider the handoff situation of the MR. McCarthy et al. [18,19] introduced the MANEMO concept and identified two key solution areas in the MANEMO problem domain, namely, NEMO-Centric MANEMO (NCM) and MANET-Centric MANEMO (MCM). McCarthy et al. [20,21] and Tsukada and Ernst [22] built testbeds for implementing and experimenting with the MANEMO protocols. Although their results show that MANEMO outperforms the traditional NEMO protocol, they only considered inter-domain route optimization and measured the packet transmission delay between the CN and the MNN. They did not describe the route optimization mechanism in detail or solve the mobility problem in NEMO.

A MANET comprises a collection of mobile nodes that form a temporary network without any infrastructure. Each mobile node in a MANET can act as a sender and cooperate with other nodes and act as a relay in multi-hop transmissions. Moreover, mobile nodes can self-organize and maintain the routing information through routing protocols. In general, the routing protocols for MANETs can be classified as proactive routing protocols [23] and on-demand routing protocols [24,25] based on whether each node maintains the routing tables or finds the route to destination before transmitting data. These routing protocols find the optimal path from the source to the destination based on certain routing metrics. They also have mechanisms to deal with dynamic topology changes because of node mobility or link failures.

The preliminary version of this study was published in WCNC 2009 [26] based on *ad hoc* routing protocol for nested mobile network. In this article, it contains significant contributions not covered by the preliminary version of this study as listed as follows:

(1) We discuss more related work in this journal version.

(2) We describe the proposed scheme in detail such as the intra-domain routing and the inter-domain handoff procedures. Moreover, we propose the double buffer mechanism to avoid the packet out-of-sequence problem. We also correct some flaws of the conference version.

(3) In the preliminary version, we only use the numerical analysis to evaluate the HL and the PD of intra-domain and inter-domain handoff procedures. However, in this version, we add detailed analytical models for 'Convergence Time of Route Optimization during Inter-Domain Handoff', 'Packet Overhead Ratio (POR)', 'TC', and 'Discussion of Double Buffer Mechanism'. Moreover, we use NS-2 simulations to evaluate the performance of DRO compared with existing mechanisms and verify the analytical models.

3. The DRO scheme

Route optimization involves minimizing the packet transmission delay between the sender and the receiver. Although many hierarchy-based route optimization schemes [11,12] support route optimization for inter-domain routing, a non-optimal route is formed when the CN and the MNN are located in the same nested mobile network (i.e., intra-domain routing). Moreover, these schemes do not cope with the handoff procedure well, resulting in a long convergence time during route optimization or communication disruption. To resolve these problems, we propose a novel NEMO support protocol with a DRO scheme. The domain-based network architecture incorporates the routing techniques of MANETs for route optimization. We also use the architecture to reduce intra-domain HL and provide a fast handoff scheme to achieve low inter-domain HL. In addition, we use a double buffer mechanism to avoid the packet out-of-sequence problem during the route optimization procedure.

3.1 MANET routing protocols

Our DRO scheme is based on MANET routing protocols since these routing protocols find the optimal path from the source to the destination. Moreover, they also have mechanisms to deal with dynamic topology changes because of node mobility or link failures. Therefore, we use the protocols to find the shortest/optimal path among MRs in nested mobile networks in order to achieve route optimization. Most hierarchy-based schemes do not adopt these routing protocols because they use tree-based network architectures for mobility management. In contrast, our domain-based network architecture functions like a mesh network; hence, it is compatible with all MANET routing protocols.

3.2 Domain construction

The major differences between our domain-based scheme and other hierarchy-based schemes are the network construction and the MR address schemes. In hierarchy-based schemes, the networks use a top-down approach to form link relations between MRs for mobility management, resulting in a tree-based network architecture, as shown in Figure 3a. Moreover, the descendant MRs configure their CoAs from mobile node prefix (MNP) of their parent-MRs (e.g., the MR3 configures its address according to the prefix of the MR2). In contrast, our domain-based network architecture is like a mesh network, and the descendant MRs configure their CoAs from MNP of the RMR (e.g., the MR3 configures its address according to the prefix of the RMR), resulting in forming a flat network topology (i.e., *ad hoc* domain), as shown in Figure 3b. Moreover, the whole MRs have the same network prefix, and thus they communicate with each other by *ad hoc* routing protocol.

In our domain-based network architecture, when an MR moves in the mobile network, it works as the RMR in the domain if it receives an router advertisement (RA) message from access router (AR). Moreover, the new RMR configures its CoA according to the prefix of the AR, binds its new CoA to the HA, inserts its prefix in RA message, and then broadcasts the RA message. However, if the MR receives an RA message from other intermediate MRs (IMRs), it acts as an IMR, joins this domain, generates its CoA based on the prefix of the RMR, and rebroadcasts the RA message. Then, it finds the shortest path to the RMR based on the routing protocol adopted by the mobile network and binds the CoA of the RMR to its HA. In DRO, each MR sends two kinds of BU messages: a local BU and a global BU. The former is sent to the RMR and other MRs in the domain, and the latter is for the HA and CN of the MR. Finally, every MR follows the routing information recorded in the network's routing protocol so that the network nodes can communicate via the optimal routes.

Figure 4 shows the format of an RA message. We modified the fields highlighted in gray for our domain-based network architecture. The RA message works like a "hello" message in our scheme, and the routing information is included in the RA message. If the MR needs to perform inter-domain handoff, the 'New CoA of RMR' and 'Prefix of new RMR' fields will be inserted in the extended field. Moreover, to prevent a loop, we add a field for the sequence number. The AR sends the RA message periodically. It is noted that the RMR is capable of deciding the domain size, and it inserts the rebroadcast limit into the RA message. (The issue of the most suitable domain size is out of scope of this article.)

We use the following example to describe the advantage of our domain-based network architecture. In hierarchy-based schemes, the CoA of each sub-MR is based on the prefix of its parent-MR, and every parent-MR is responsible for recording the routing information of its sub-MRs. Therefore, hierarchy-based schemes provide shorter routes and reduce the packet transmission delay than NEMO. However, they still suffer from the suboptimal routing problem if the source and destination MRs are in the same nested mobile network (i.e., intra-domain routing), but they have different parent-MRs. Figure 3a illustrates the inefficiency of intra-domain routing in hierarchy-based schemes. The parent-MRs in such schemes are only responsible for managing the routing information of their sub-MRs. Hence, in the figure, MR3 forwards the packets for MR5 to its parent-MR (i.e., MR2), since it only handles the routing to MNN1 and has no routing information about MR5. The packets are forwarded up the tree until the parent-MR has the routing information for the destination MNN. Therefore, if MNN1 wants to communicate with MNN2, the routing path is: MNN1 → MR3 → MR2 → MR1 → MR4 → MR5 → MNN2. However, there are many shorter routing paths, e.g., MNN1 → MR3 → MR7 → MR5 → MNN2 as shown in Figure 3b.

In addition, hierarchy-based schemes still do not cope with intra-domain handoff well in a nested mobile network. If an MR performs intra-domain handoff, then it suffers from long HL since it needs to perform the local duplicate address detection (DAD) procedure and generate a new CoA. Furthermore, the convergence time is directly proportional to the HL. Therefore, hierarchy-based schemes cannot handle the handoff procedure efficiently, so there is a long convergence time during route optimization. In our domain-based scheme, a network domain consists of an RMR and a set of its descendant MRs. The descendant MRs (i.e., MR2-MR7 in

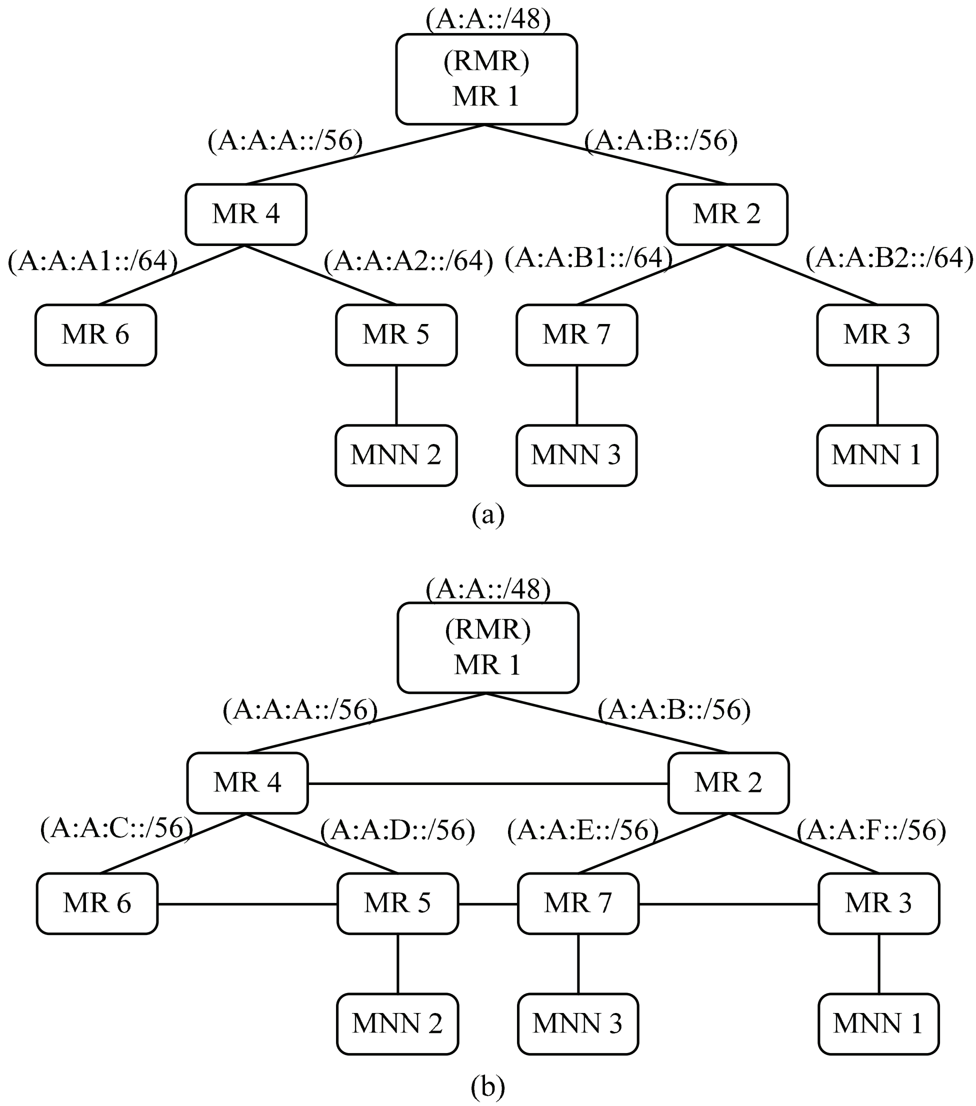

Figure 3 The network architecture (a) hierarchy-based (b) domain-based.

Figure 3b; A:A:A::/56-A:A:F::/56) create their CoAs from the MNP of the RMR (i.e., MR1 in Figure 3b; A:A::/48), rather than the prefix of their parent-MR as in hierarchy-based schemes. The RMR acts as the domain root and manages all descendant MRs in the network domain and every descendant MR records a default routing path to the RMR. It is noted that the RMR will notify the sub-MR to generate a new sub-prefix if the sub-prefix of the sub-MR is not unique in the domain. When an MR moves within the same nested mobile network (i.e., intra-domain handoff), it only updates its RMR with the routing information and it does not need to change its address. Our domain-based scheme reduces the HL substantially because the MR does not need to perform the DAD procedure. Consequently, the nested mobile network in DRO functions like a MANET, and each MR in the network uses existing *ad hoc* routing protocols to find the optimal paths to communicate with other MRs. At present, if the MR3 has a routing entry to MR5 via MR7, the MR3 can find better routing path to achieve the intra-domain route optimization.

3.3 Inter-domain routing

Figure 5 shows the flow chart of the inter-domain route optimization procedure in DRO. As shown in Figure 1, the CN wants to send packets to MNN1 via MR3. The data path is CN $\rightarrow$ HA3 $\rightarrow$ HA1 $\rightarrow$ AR $\rightarrow$ MR1 $\rightarrow$ MR3 $\rightarrow$ MMN1 before the route optimization procedure is performed. When MR3 receives the packets from CN, it checks its binding cache to determine whether the CN's address is on the binding update list.

Type	Length	Reserved	Sequence
Valid lifetime			
Global IP address of RMR			
Prefix of RMR			
New care-of-address of RMR			
Prefix of new RMR			
Routing information			

Figure 4 The format of an RA message in DRO.

If it is not on the list, the MR performs the return routability procedure and sends a BU message to inform the CN about the CoA of RMR (i.e., MR1). The CN replies with a BACK message and then transmits the packets to the RMR directly without passing through any HAs. In DRO, the RMR maintains the routing table, which includes the shortest paths to all descendant MRs. Consequently, the RMR can obtain the shortest path to MR3 from its routing table.

3.4 Intra-domain routing

If both the source and the destination are in the same nested mobile network, then intra-domain routing is performed. In Figure 3, if MNN2 wants to communicate with MNN1, then the packets sent from MNN2 to MNN1 are intercepted by the RMR. The route optimization procedures of hierarchy-based schemes and DRO are shown in Figure 6a,b, respectively. We discussed the procedure of hierarchy-based schemes in Section 3.2. Next, we describe intra-domain routing under DRO.

DRO works in the same way as hierarchy-based routing schemes before the route optimization procedure is performed. Then, the RMR checks its binding cache. If an entry's network prefix field is equal to the destination's prefix, then the destination MR is located in its nested mobile network and intra-domain route optimization is performed. The RMR sends a notification message to the source MR (i.e., MR5) when the source MR and destination MR (i.e., MR3) are located in the same nested mobile network. Then, MR5 implements the return routability procedure and executes the route optimization procedure based on the *ad hoc* routing protocols to find the optimal route. For example, in the route optimization procedure, MR5 can send a route request (RREQ) message to find MR3. Then, MR3 replies by sending a route reply (RREP) message to MR5. Since the domain-based network architecture is compatible with all kinds of *ad hoc* routing protocols, after the route optimization procedure, DRO can find an optimal path from the source to the destination. Moreover, intra-domain route optimization under DRO is not based on tunneling, and the packets for transmission do not require encapsulation from the source to the destination. As a result, DRO reduces the packet transmission delay and the header overhead for encapsulation.

3.5 Inter-domain handoff

Many studies have focused on route optimization for solving the pinball routing problem, but the schemes do not handle inter-domain handoff well. This is a critical problem because the route optimization procedure is performed after the handoff procedure. The convergence time of the route optimization process will be long if the handoff procedure is inefficient. Although fast Mobile IPv6 (FMIPv6) [27] provides seamless handoff, it may suffer from handoff failure since it only uses a simple link layer trigger to assist the handoff procedure [28]. Moreover, FMIPv6 is not suitable for network environments with multiple ARs

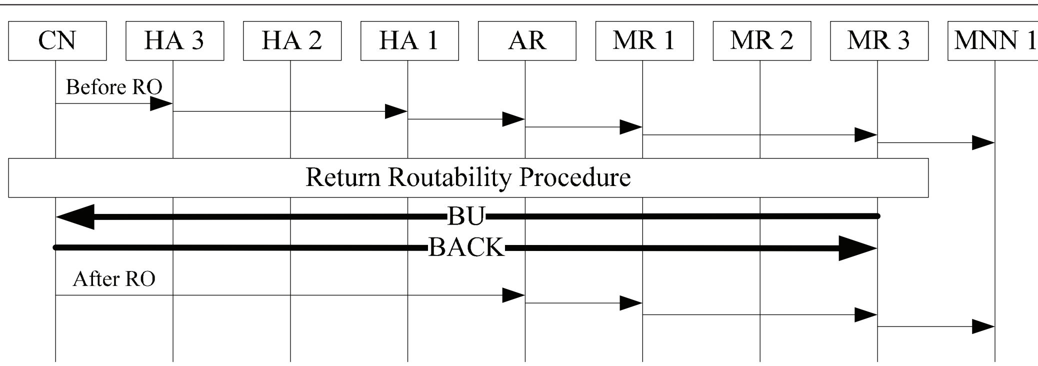

Figure 5 Inter-domain route optimization.

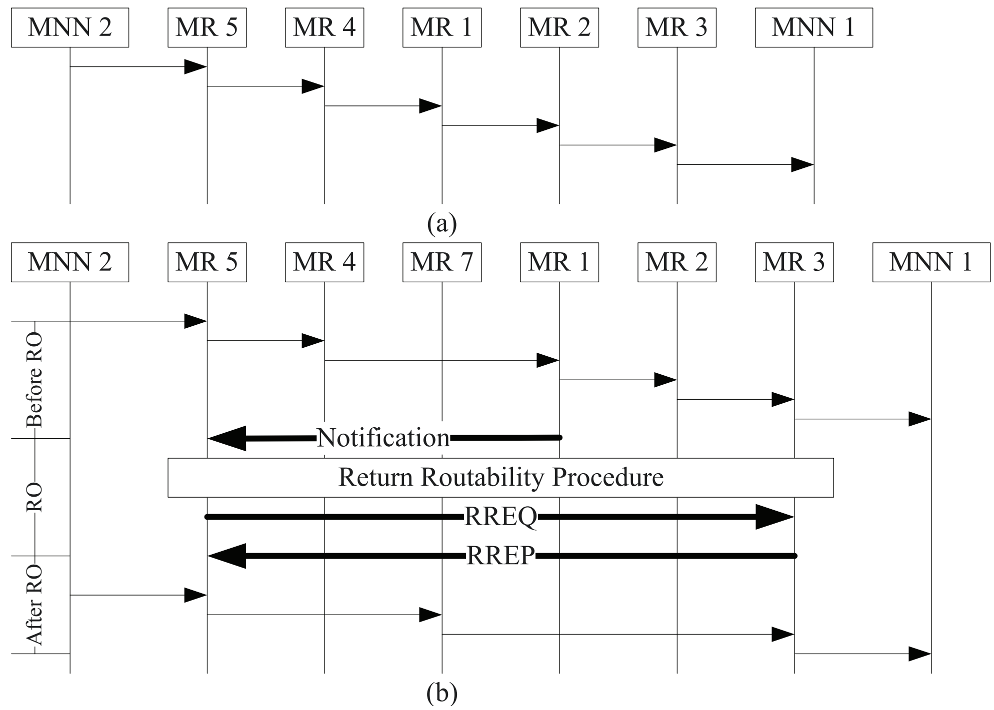

Figure 6 Optimization of intra-domain routing for (a) hierarchy-based route optimization schemes, and (b) our DRO scheme.

because it cannot select the best AR to connect. In contrast, DRO provides reliable and seamless inter-domain handoff by integrating the pre-handoff procedure with the handoff procedure.

The differences between our scheme and FMIPv6 are the number of link layer triggers and the binding update procedure. To overcome the disadvantage of FMIPv6, DRO uses three types of link layer triggers, namely, a link weakness trigger (LWT), a link down trigger (LDT), and a link up trigger (LUT) to ensure successful handoff. In the pre-handoff procedure, the AR broadcasts an RA message, which includes the neighbor advertisement (NB_ADV) periodically. The NB_ADV contains the new CoA of the AR/RMR and the prefix of new AR (NAR)/RMR. When the LWT is triggered, the MR sends a fast binding update (FBU) message to the candidate ARs and performs the DAD procedure using the information of NB_ADV in the RA message before the handoff occurs. The MR confirms that the pre-handoff procedure is finished when it receives the FBACK message. Then, the MR selects the best AR to connect and binds the CoA of NAR to its CN/HA, when the LDT is triggered. At the same time, the packets are forwarded to the NAR from the previous AR (PAR) and the NAR buffers the packets. After the MR connects to the new nested mobile network (i.e., the LUT is triggered), it sends a fast neighbor advertisement (FNA) message to the NAR, and then downloads its packets.

The differences between our scheme and FMIPv6 are the number of link layer triggers and the binding update procedure. DRO can deal with a network environment containing multiple ARs and it uses multiple link triggers to provide accurate handoff. Moreover, the binding update procedure of DRO is performed in a forward manner such that the MR performs the handoff procedure concurrently in the network and the link layers. This concurrent handoff procedure reduces the handoff delay; thus, the convergence time during route optimization is reduced. Figure 7 shows the flow chart of inter-domain handoff procedure under DRO.

3.6 Intra-domain handoff

When the MR attaches to a different parent-MR in the same nested mobile network, it performs intra-domain handoff. In NEMO, when an MR moves from one subnet to another one, it needs to configure a new CoA and register with its HA, resulting in high HL. Although the hierarchical architecture helps mitigate the problem, each MR still has to configure the new local CoA and register with the RMR. In contrast, when an MR in DRO performs intra-domain handoff, it simply updates the RMR with its routing information and creates a new routing entry between the RMR and itself. The MR does not need to generate a new CoA or send a binding update to its HA because the CoA of each MR is configured according to the prefix of the RMR. Moreover, our

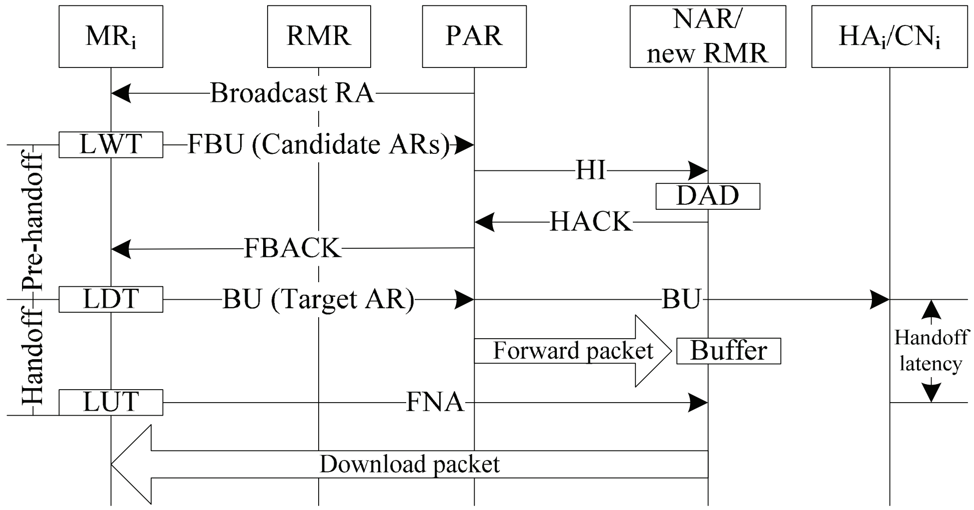

Figure 7 The inter-domain handoff procedure under DRO.

scheme reduces the HL from the RMR to the HA of the MR and therefore saves the local DAD time.

3.7 Double buffer mechanism

The route optimization mechanism may affect the performance of TCP because of the out-of-sequence problem illustrated in Figure 2. Since the anticipation schemes in [15,16] do not fit a dynamic network environment, we use a double buffer mechanism in DRO to avoid the packet out-of-sequence problem. There are two kinds of buffers: a forwarding packet buffer (FPB) and a new packet buffer (NPB). FPB stores the packets from the old link before the optimal route is built, while NPB stores the packets from the new link after the optimal route has been built. The steps of the double buffer mechanism are as follows:

Step 1: The FPB of the MR of the MNN starts to buffer packets when the binding update message is sent by the MR of the MNN.

Step 2: The MR of the CN records a new route entry from the MR of the CN to the MR of the MNN when the MR of the CN receives the binding update message. Then, the MR of the CN replies with a binding update acknowledge (BACK) message to the MR of the MNN. The BACK message includes the sequence number of the last packet that passed through the old link. Then, the packet will be transmitted via the new link.

Step 3: The MR of the MNN receives the packets, checks their sequence numbers, and put them in the corresponding buffer.

Step 4: After the route optimization procedure, the packets in the FPB will be transmitted prior to those in the NPB. Consequently, the MNN receives the packets in sequence.

4. Performance analysis

Figure 8 shows the network topologies used for evaluating DRO. We assume the RMR is in level 1, and the *n* level nested MNN communicates with the *m* level CN. Figure 8a shows the network topology for inter-domain routing; Figure 8b shows the mobile network for intra-domain routing when there is no common parent between the CN and the MNN; and Figure 8c shows the network for intra-domain routing when there are *k* common parents between the CN and the MNN in the nested mobile network. We evaluate the performance of DRO and compare it with the NEMO basic support protocol (NEMO), ROTIO, and HRO+. The performance metrics in our evaluation are PD, HL, POR, and TC.

- PD: The PD is defined as the time interval from the time that the CN transmits the packet to the MNN until the MNN receives the packet.
- HL: The HL is the disrupt time that an MR changes its association. The total HL is the sum of the movement detection (MD) delay, the DAD delay, the registration delay, and the processing time of the network entities.
- POR: The POR means how many packet overheads (i.e., the original packet header plus the tunneling packet header) are occupying in a packet.
- TC: The TC is composed of the signaling cost (SC) (e.g., BU, LBU, etc.) and the packet delivery cost.

For the MD time in the performance evaluation, the study of [2] specifies that the ARs that support mobility should be configured with smaller values for MinRtrAdvInterval (*MinInt*) and MaxRtrAdvInterval (*MaxInt*) to send the unsolicited RA more often. For simplicity, we set the value of D_{MD} in NEMO as half of the mean value

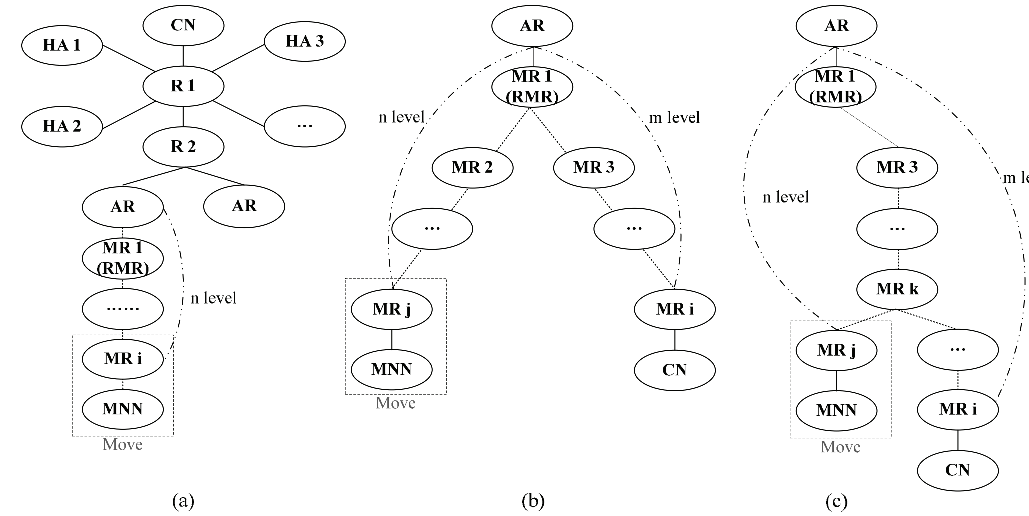

Figure 8 The network topologies used to evaluate DRO: **(a)** inter-domain routing; **(b)** intra-domain routing without a common parent; **(c)** intra-domain routing with *k* common parents.

of unsolicited RA messages (i.e., (*MinInt*+*MaxInt*)/2) and that in ROTIO and HRO+ as a quarter of the mean value of unsolicited RA messages (i.e., (*MinInt*+*MaxInt*)/4) according to [29]. Moreover, based on [30], we set the DAD delay in NEMO at 1,000 ms and that in the hierarchy-based schemes (i.e., ROTIO and HRO+) at 500 ms. We set up the CN as a traffic source with a constant bit rate over UDP. Table 1 shows the descriptions and values of the parameters in the analysis based on [12].

Finally, we evaluate the performance of DRO compared with other existing approaches via NS-2 [31] simulations. The network topologies of the simulation scenarios are shown in Figure 8, which are very general in nested mobile wireless networks. In simulations, we set that only the MR of the MNN moves (i.e., handoff) for observing easily. Moreover, the moving direction of MR is a straight line from left to right to trigger the handoff procedure. Each simulation result is the average of ten runs. The parameters and values used in the simulations are listed in Table 2.

4.1 PD in inter-domain routing

As NEMO does not consider route optimization, all traffic must pass through the bi-directional tunnel between the MR and the corresponding HA. The routing path of NEMO is CN → HA_{MR} → HA_i → HA_{RMR} → AR → RMR → MR_{MNN} → MNN. Therefore, the PD of the NEMO can be composed of the propagation delay between the CN and the HA of the MR (i.e., $LD_{\text{CN-Router}} + LD_{\text{HA-Router}}$), the propagation delay among the HAs of the MRs $\left(\text{i.e., } 2\left(\sum_{i=1}^{n-1} LD_{\text{HA - Router}}\right)\right)$, the propagation delay between the HA and the AR (i.e., $(LD_{\text{HA - Router}} + LD^{i,i+1}_{\text{Router}}) + LD_{\text{AR-Router}}$), the propagation delay between the AR and the RMR (i.e., $LD_{\text{AR-RMR}}$), the propagation delay between the RMR and the MR of the MNN (i.e., $\sum_{i=1}^{n} LD^{i,i+1}_{MR}$), the whole processing delay of entities (i.e., $\sum_{i=1}^{n} (D^i_{HA} + D^i_{MR})$), and the propagation delay between the MR and the MNN (i.e., $LD_{\text{MR-MNN}}$).

Table 1 Parameter values for numerical analysis

Parameter	Description	Value (ms)
D^i_{MR}	The processing delay of MR_i	10
$LD^{i,i+1}_{\text{MR}}$	The propagation delay between MR_i and MR_{i+1}	5
$LD^{i,i+1}_{\text{Router}}$	The propagation delay between $Router_i$ and $Router_{i+1}$	5
D^i_{HA}	The processing delay of HA_i	10
$LD_{\text{CN-Router}}$	The propagation delay between a CN and a router	50
$LD_{\text{HA-Router}}$	The propagation delay between an HA and a router	10-100
$LD_{\text{MR-MNN}}$	The propagation delay between an MR and an MNN	5
$LD_{\text{AR-Router}}$	The propagation delay between an AR and a router	5
$LD_{\text{AR-RMR}}$	The propagation delay between an AR and an RMR	100
$D_{\text{MD\_MinInt}}$	The minimum route advertisement interval	30
$D_{\text{MD\_MaxInt}}$	The maximum route advertisement interval	70
D_{DAD}	The DAD time	500, 1,000

Table 2 The parameter values used in the simulations

Network size	1,600 m*1,600 m
Number of MRs	20-40
Number of MNN in each MR	2
Wired bandwidth	100 Mbps
Wireless link bandwidth	11 Mbps
Packet size	500 bytes
Moving speed (*v*)	5-25 m/s
Route advertisement interval	50 ms
Radius of wireless cell	100 m
Propagation model	TwoRayGround
Simulation time	200 s
MAC protocol	IEEE 802.11 DCF
Hello message interval	500 ms
Packet arrival rate	30 packets/s

Then, we can derive the equation of the PD of the NEMO as follows:

$$PD_{\text{NEMO}} = (LD_{\text{CN-Router}} + LD_{\text{HA-Router}}) + 2\left(\sum_{i=1}^{n-1} LD_{\text{HA-Router}}\right) + (LD_{\text{HA-Router}} + LD^{i,i+1}_{\text{Router}}) + LD_{\text{AR-Router}} + LD_{\text{AR-RMR}} + \sum_{i=1}^{n}(D^{i}_{\text{HA}} + D^{i}_{\text{MR}} + LD^{i,i+1}_{\text{MR}}) + LD_{\text{MR-MNN}}, \quad (1)$$

where n ($n \geq 1$) is the number of nesting level of MNN, $LD_{i\text{-}j}$ is the propagation delay between entities i and j, and D_i is the processing delay of entity i.

In ROTIO, the packets need to be passed through the MR's HA and the RMR's HA. The routing path of ROTIO is CN → HA_{MR} → HA_{RMR} → AR → RMR → MR_{MNN} → MNN. The PD of the ROTIO can be composed of the propagation delay between the CN and the HA of the MR (i.e., $LD_{\text{CN-Router}} + LD_{\text{HA-Router}}$), the propagation delay between the HA of the MR and the HA of the RMR (i.e., $2LD_{\text{HA-Router}}$), the propagation delay between the HA and the AR (i.e., $(LD_{\text{HA-Router}} + LD^{i,i+1}_{\text{Router}})+LD_{\text{AR-Router}}$), the propagation delay between the AR and the RMR (i.e., $LD_{\text{AR-RMR}}$), the propagation delay between the RMR and the MR of the MNN (i.e., $\sum_{i=1}^{n} LD^{i,i+1}_{\text{MR}}$), the whole processing delay of entities (i.e., $2D^{i}_{\text{HA}} + \sum_{i=1}^{n} D^{i}_{\text{MR}}$), and the propagation delay between the MR and the MNN (i.e., $LD_{\text{MR-MNN}}$).

$$PD_{\text{ROTIO}} = (LD_{\text{CN-Router}} + LD_{\text{HA-Router}}) + 2LD_{\text{HA-Router}} + (LD_{\text{HA-Router}} + LD^{i,i+1}_{\text{Router}}) + LD_{\text{AR-Router}} + LD_{\text{AR-RMR}} + 2D^{i}_{\text{HA}} + \sum_{i=1}^{n}(D^{i}_{\text{MR}} + LD^{i,i+1}_{\text{MR}}) + LD_{\text{MR-MNN}} \quad (2)$$

In HRO+ and DRO schemes, the CN transmit packets to the MNN directly without passing through any HA. Therefore, the routing paths of HRO+ and DRO are CN → AR → RMR → MR_{MNN} → MNN. The PD of the HRO+ and the DRO can be composed of the propagation delay between the CN and the AR (i.e., $LD_{\text{CN-Router}} + LD^{i,i+1}_{\text{Router}}+LD_{\text{AR-Router}}$), the propagation delay between the AR and the RMR (i.e., $LD_{\text{AR-RMR}}$), the propagation delay between the RMR and the MR of the MNN (i.e., $\sum_{i=1}^{n} LD^{i,i+1}_{\text{MR}}$), the whole processing delay of entities (i.e., $\sum_{i=1}^{n} D^{i}_{\text{MR}}$), and the propagation delay between the MR and the MNN (i.e., $LD_{\text{MR-MNN}}$).

$$PD_{\text{HRO+}} = PD_{\text{DRO}} = LD_{\text{CN-Router}} + LD^{i,i+1}_{\text{Router}} + LD_{\text{AR-Router}} + LD_{\text{AR-RMR}} + \sum_{i=1}^{n}(D^{i}_{\text{MR}} + LD^{i,i+1}_{\text{MR}}) + LD_{\text{MR-MNN}} \quad (3)$$

Figure 9 shows the PD for different levels of nesting of the mobile network (i.e., parameter n). In NEMO, the PD increases rapidly because of the pinball routing problem. The ROTIO scheme improves the inter-domain routing performance, but it needs at least two levels of nested tunneling. HRO+ and DRO achieve the shortest PD because the MNN uses a binding update to inform the CN such that packets can be routed from the CN to the MNN directly. Figure 10 shows how the PD changes as the distance between the AR and HA increases. When the distance increases under NEMO and ROTIO, the PD between the CN and the MNN also increases significantly. However, the PD remains constant under HRO+ and DRO because the CN transmits packets to

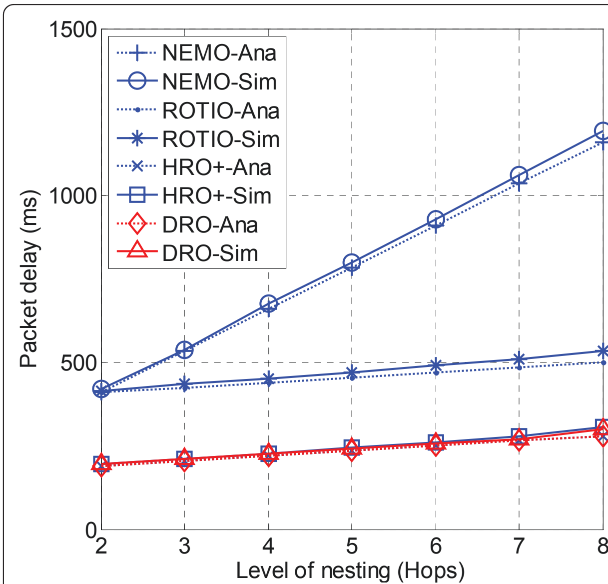

Figure 9 PD with different levels of nesting ($LD_{\text{HA-Router}}$ = 50 ms).

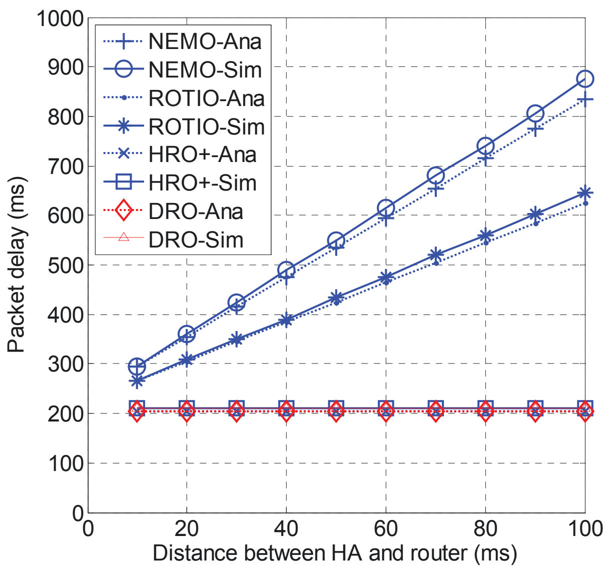

Figure 10 The impact of the distance between the HA and the AR (*n* = 3).

the MNN directly without passing through any HA. Although HRO+ achieves low inter-domain routing delay for like DRO, it suffers from the suboptimal routing problem in intra-domain routing, as we explain in the following sections.

4.2. PD in intra-domain routing

In intra-domain routing, we consider two scenarios in hierarchy-based schemes: (1) there is no common parent-MR for the MNN and the CN (e.g., Figure 8b); and (2) the MNN and the CN have *k* common parent-MRs (e.g., Figure 8c).

In NEMO, all traffic always passes through the bi-directional tunnel between the MR and the corresponding HA. Therefore, the routing path of NEMO is CN → MR_{CN} → RMR → AR → HA_{RMR} → HA → HA_{MR} → AR → RMR → MR_{MNN} → MNN. The PD of the NEMO can be composed of the propagation delay between the RMR and the MR of the CN (i.e., $\sum_{j=1}^{m} LD_{MR}^{j,j+1}$), the propagation delay between the AR and the RMR (i.e., $2LD_{AR\text{-}RMR}$), the propagation delay among the HAs of the MRs $\left(\text{i.e., } 2\left(\sum_{i=1}^{n-1} LD_{HA\text{ - Router}} + \sum_{j=1}^{m-1} LD_{HA\text{ - Router}}\right)\right)$, the propagation delay between the HA and the AR (i.e., 2 $(LD_{HA\text{ - Router}} + LD_{Router}^{i,i+1}) + 2LD_{AR\text{-Router}}$), the propagation delay between the RMR and the MR of the MNN (i.e., $\sum_{i=1}^{n} LD_{MR}^{i,i+1}$), the propagation delay between the MR and the MNN/CN (i.e., $2LD_{MR\text{-}MNN}$), and the whole processing delay of entities (i.e., $\sum_{i=1}^{n}(D_{HA}^{i} + D_{MR}^{i}) + \sum_{j=1}^{m}(D_{HA}^{j} + D_{MR}^{j})$). Then, the PD under NEMO is shown in Equation 4.

$$\begin{aligned} PD_{NEMO} = &\sum_{i=1}^{n}(D_{HA}^{i} + D_{MR}^{i} + LD_{MR}^{i,i+1}) \\ &+ \sum_{j=1}^{m}(D_{HA}^{j} + D_{MR}^{j} + LD_{MR}^{j,j+1}) + 2\sum_{i=1}^{n-1} LD_{HA\text{ - Router}} \\ &+ 2\sum_{j=1}^{m-1} LD_{HA\text{ - Router}} + 2LD_{HA\text{ - Router}} + 2LD_{AR\text{ - Router}} \\ &+ 2LD_{Router}^{i,i+1} + 2LD_{AR\text{ - RMR}} + 2LD_{MR\text{ - MNN}} \end{aligned} \quad (4)$$

In ROTIO, the RMR is responsible for the whole packet routing. Therefore, the routing paths of ROTIO and RMR are CN → MR_{CN} → RMR → MR_{MNN} → MNN. The PD of the ROTIO can be composed of the propagation delay between the RMR and the MR of the MNN (i.e., $\sum_{i=1}^{n-1} LD_{MR}^{i,i+1}$), the propagation delay between the RMR and the MR of the CN (i.e., $\sum_{j=1}^{m-1} LD_{MR}^{j,j+1}$), the whole processing delay of entities (i.e., $\sum_{i=1}^{n-1} D_{MR}^{i} + \sum_{j=1}^{m-1} D_{MR}^{j}$), and the propagation delay between the MR and the MNN/CN (i.e., $2LD_{MR\text{-}MNN}$). The PD under ROTIO is shown in Equation 5.

$$PD_{ROTIO} = \sum_{i=1}^{n-1}(D_{MR}^{i} + LD_{MR}^{i,i+1}) + \sum_{j=1}^{m-1}(D_{MR}^{j} + LD_{MR}^{j,j+1}) + 2LD_{MR\text{ - MNN}} \quad (5)$$

The PD under HRO+ is shown in Equations 6 and 7. Equation 6 presents the delay of HRO+ with no common parent-MR for the MNN and the CN. This situation that results in the RMR is responsible for the whole packet routing, and besides the PD is similar to ROTIO. Equation 7 expresses that MNN and the CN have *k* common parent-MRs. Therefore, the PD of HRO+ can reduce the overlapping time (i.e., $2 \cdot \sum_{k=1}^{k}(D_{MR}^{k} + LD_{MR}^{k,k+1})$) since the IMRs assist the packet routing.

$$PD_{HRO+}^{worst} = \sum_{i=1}^{n-1}(D_{MR}^{i} + LD_{MR}^{i,i+1}) + \sum_{j=1}^{m-1}(D_{MR}^{j} + LD_{MR}^{j,j+1}) + 2LD_{MR\text{ - MNN}} \quad (6)$$

$$\begin{aligned} PD_{HRO+}^{normal} = &\sum_{i=1}^{n-1}(D_{MR}^{i} + LD_{MR}^{i,i+1}) + \sum_{j=1}^{m-1}(D_{MR}^{j} + LD_{MR}^{j,j+1}) \\ &- 2 \cdot \sum_{k=1}^{k}(D_{MR}^{k} + LD_{MR}^{k,k+1}) + 2LD_{MR\text{ - MNN}} \end{aligned} \quad (7)$$

where *k* (*k* ≥ 1) is the number of common parent-MRs.

Finally, let l be the shortest hop-count from the MR of CN to the MR of the MNN; then we can derive the PD of DRO, as shown in Equation 8. It is noted that the value of l must be less than or equal to $(n + m - k)$ because DRO uses an *ad hoc* routing protocol to achieve route optimization. In addition, the worst case of DRO is equal to Equation 7.

$$PD_{\text{DRO}}^{\text{normal}} = \min\left(\sum_{i=1}^{l}(D_{\text{MR}}^{i} + LD_{\text{MR}}^{i,i+1})\right) + 2LD_{\text{MR - MNN}}, \text{ where } l \le n + m - k \quad (8)$$

Figure 11 shows the PD during intra-domain routing. The results show that DRO can reduce the delay by approximately 90% compared to NEMO. Moreover, DRO outperforms ROTIO and HRO+ because the hierarchy-based schemes suffer from the suboptimal routing problem and we use *ad hoc* routing protocols to find the shortest path. Figure 12 shows the PD with different numbers of common parent-MRs. According to the result, ROTIO has the longest PD because all routes need to pass through the RMR. The PD in intra-domain routing under HRO+ decreases when the number of common parent-MR increases because the IMRs record the routing information of the descendant MRs. The proposed DRO scheme yields the shortest PD during intra-domain routing because it always finds the shortest path.

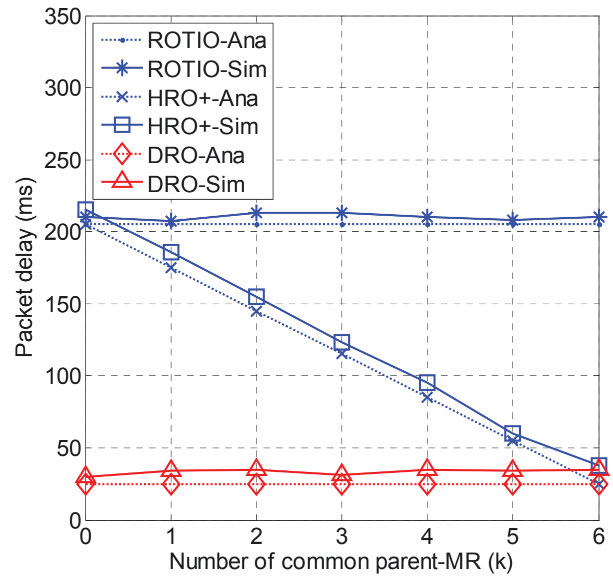

Figure 12 The impact of delays with different numbers of common parent-MR (k) (m = 7, n = 8).

4.3 Convergence time of route optimization during inter-domain handoff

The NEMO and HRO+ schemes do not support inter-domain handoff, so communications will be disrupted when it occurs. The ROTIO scheme uses a tunnel chain to cope with inter-domain handoff; however, if handoff occurs frequently, the tunnel/encapsulation overhead and PD will increase substantially. Moreover the communication link may be disconnected since ROTIO's handoff scheme is temporary. DRO provides a fast handoff scheme to reduce the delay for inter-domain handoff. The difference between DRO and FMIPv6 is that, under DRO, the binding update procedure is performed in a forward manner such that the MR implements the handoff procedure concurrently in the network and link layers. Therefore, DRO can reduce the convergence time of route optimization more than FMIPv6. In other words, the sender spends less time searching for the optimal route to the receiver if the convergence time is lower. Moreover, DRO uses multiple triggers to facilitate accurate handoff. In Figure 13, t_0 denotes the handoff start time of the MR; and t_1 and t_2 represent the finishing times of the route optimization procedure under DRO and the FMIPv6, respectively. The convergence times of DRO and FMIPv6 are derived by Equations 9 and 10, respectively:

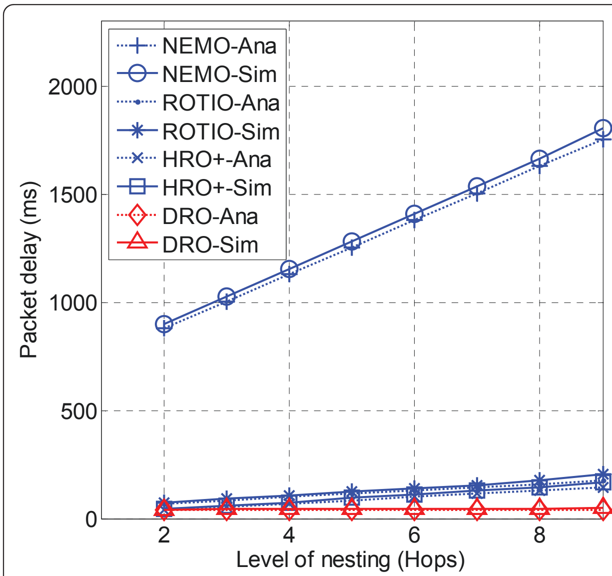

Figure 11 PD during intra-domain routing with different levels of nesting (n = 4, k = 1, $LD_{\text{HA-Router}}$ = 50 ms).

$$\Delta t_1 = t_1 - t_0 = \max\{D_{\text{BU}}, D_{L2} + D_{\text{FNA}} + LD_{\text{RMR - PAR}}\} \quad (9)$$

$$\Delta t_2 = t_2 - t_0 = D_{L2} + D_{\text{FNA}} + LD_{\text{RMR - PAR}} + D_{\text{BU}} \quad (10)$$

Based on Equations 10 and 11, we can derive the result intuitively (i.e., $\Delta t_1 < \Delta t_2$). Figure 14 shows the average convergence time of route optimization after inter-domain handoff. We observe that when the MR moves rapidly, both mechanisms need a longer convergence time, but the convergence time of DRO is shorter than that of FMIPv6. This is because the FMIPv6

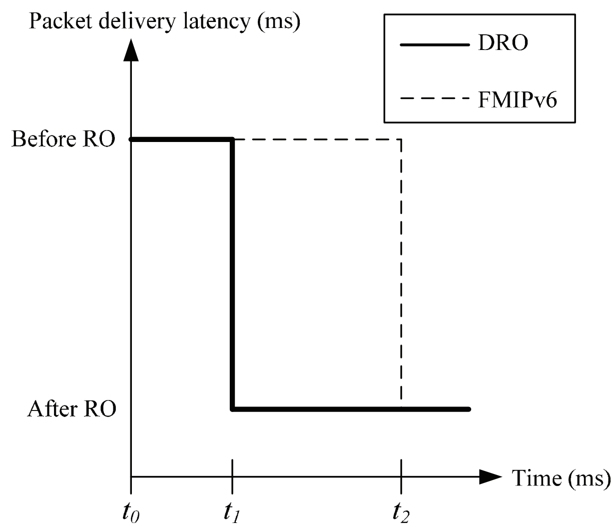

Figure 13 The convergence time of route optimization.

protocol is susceptible to handoff failure in a high-speed environment, which results in high HL. Hence, DRO needs less processing time for route optimization than FMIPv6 when an inter-domain handoff occurs.

4.4 Intra-domain HL

When the MR moves within the same nested mobile network, it performs the intra-domain handoff procedure. The HL is comprised of MD delay (i.e., D_{MD}), DAD delay (i.e., D_{DAD}), registration delay, and the processing time of the network entities. Because NEMO does not consider intra-domain handoff, its HL is the longest among the compared schemes. The HL of NEMO is formulated as follows:

$$HL_{NEMO} = D_{MD} + D_{DAD} + 2n \cdot LD_{AR-HA} + 2n \cdot LD_{AR-RMR} + \sum_{i=1}^{n} D_{MR}^{i} + \sum_{i=1}^{n-1} LD_{MR}^{i,i+1} \quad (11)$$

The ROTIO and HRO+ use the hierarchical architecture to reduce intra-domain HL, and they only perform the local DAD, which is expressed as follows:

$$HL_{ROTIO} = HL_{HRO+} = D_{MD} + D_{DAD} + \sum_{i=1}^{n} D_{MR}^{i} + \sum_{i=1}^{n-1} LD_{MR}^{i,i+1} \quad (12)$$

Equation 13 shows the intra-domain HL of DRO.

$$HL_{DRO} = D_{MD} + \sum_{i=1}^{n} D_{MR}^{i} + \sum_{i=1}^{n-1} LD_{MR}^{i,i+1} \quad (13)$$

Figure 15 shows the results of intra-domain HL. NEMO has the longest HL because it does not support micro-mobility management. The DRO scheme has the lowest HL because the MR generates its CoA according to the prefix of the RMR; hence, it does not perform the DAD procedure in the intra-domain handoff. Moreover, the MR only updates the RMR with the routing information. Clearly, the shorter HL, the lower convergence time during route optimization and the smaller buffer size at the MR; therefore, we can infer that the DRO scheme achieves the lowest convergence time of route optimization and the smallest buffer size in intra-domain handoff. Figure 16 shows the impact of velocity on intra-domain HL. The HL of all schemes increases when the MR moves at high speed, but the DRO scheme still achieves the best result.

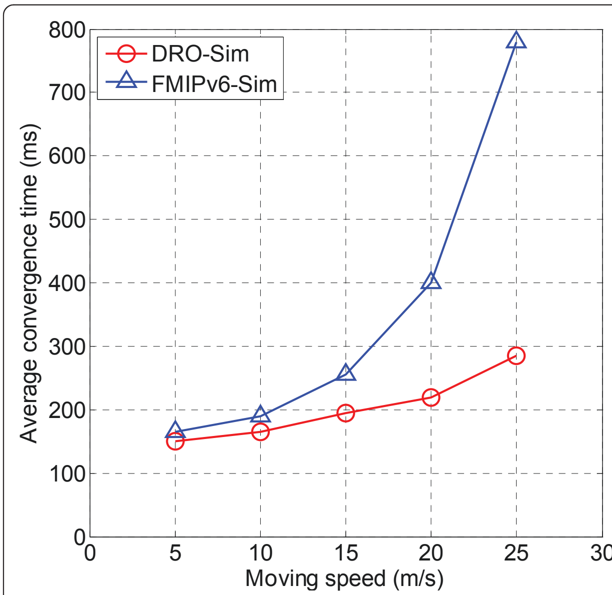

Figure 14 The average convergence time of route optimization with different moving speed.

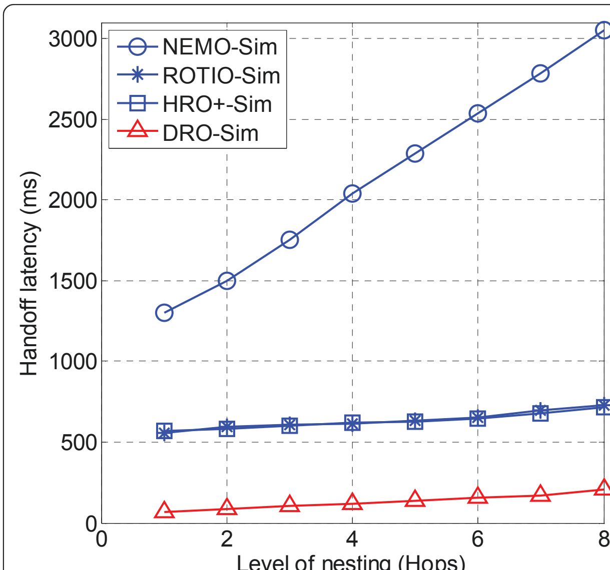

Figure 15 Intra-domain HL (*v* = 15 m/s).

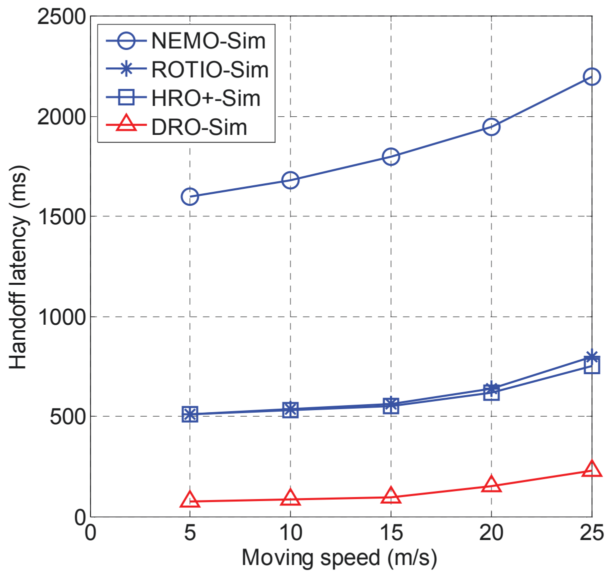

Figure 16 The impact of velocity on intra-domain HL (nested level = 3).

4.5 Packet overhead ratio (POR)

DRO can provide the shortest path between a CN and an MNN because direct routes can be found in the same domain using the *ad hoc* routing protocols. Moreover, the path is free from the NEMO tunnel overhead. In this section, we analyze the POR in inter-domain and intra-domain route optimizations. We define the POR in Equation 14 as the percentage of packet header (i.e., the original packet header plus the tunneling packet header[a]) occupying the total packet. The POR is in inverse proportion to the network performance. We consider the same network topology (i.e., Figure 8) for the evaluation, and compare the PORs for inter-domain route optimization under NEMO, ROTIO, HRO+, and DRO.

$$\text{POR} = \frac{\text{Packet header}}{\text{Packet header} + \text{Payload}} \tag{14}$$

In inter-domain routing, NEMO uses bi-directional tunneling between MR and HA to preserve session continuity. Therefore, it incurs a high POR, which is expressed as follows:

$$\text{POR}_{\text{NEMO}} = \frac{(n+1)\cdot 40}{(n+1)\cdot 40 + \text{Payload}} \tag{15}$$

where n ($n \geq 1$) is the number of nesting levels of the MNN. Equations 16 and 17 express the PORs of the enhanced schemes (i.e., ROTIO, HRO+, and DRO) for inter-domain route optimization.

$$\text{POR}_{\text{ROTIO}} = \begin{cases} \dfrac{2\cdot 40}{2\cdot 40 + \text{Payload}}, & n = 1 \\ \dfrac{3\cdot 40}{3\cdot 40 + \text{Payload}}, & n > 1 \end{cases} \tag{16}$$

$$\text{POR}_{\text{HRO+}} = \text{POR}_{\text{DRO}} = \frac{2\cdot 40}{2\cdot 40 + \text{Payload}} \tag{17}$$

Moreover, Equations 18-20 show the PORs for intra-domain route optimization, where we also assume that the RMR is at level 1, and the n level nested MNN communicates with the m level CN. The NEMO protocol uses the tunneling scheme to ensure the communication continuity resulting in the packet is encapsulated ($n + m + 1$) times. However, ROTIO and HRO+ only need to encapsulate the packets once. It is noted that the packet header of DRO includes the original packet header and an extension with the destination address in the domain.[b]

$$\text{POR}_{\text{NEMO}} = \frac{(n+m+1)\cdot 40}{(n+m+1)\cdot 40 + \text{Payload}} \tag{18}$$

$$\text{POR}_{\text{ROTIO}} = \text{POR}_{\text{HRO+}} = \frac{2\cdot 40}{2\cdot 40 + \text{Payload}} \tag{19}$$

$$\text{POR}_{\text{DRO}} = \frac{40+16}{40+16+\text{Payload}} \tag{20}$$

There are two payload sizes in our analysis: 100 and 500 bytes. Figures 17 and 18 show the POR in inter-

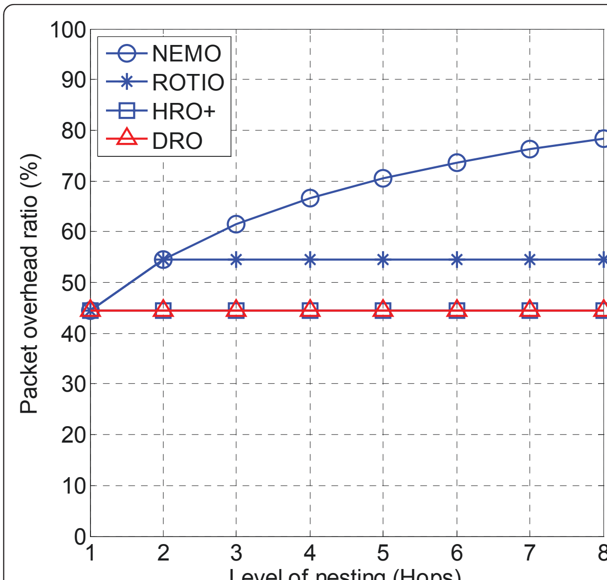

Figure 17 POR with different levels of nesting (payload size = 100 bytes).

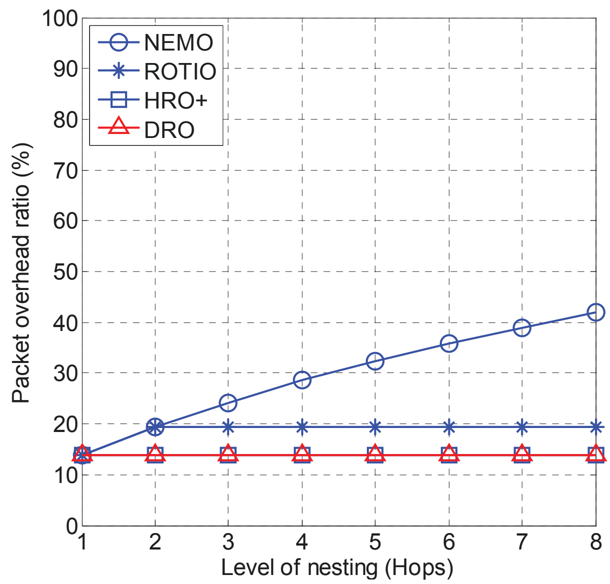

Figure 18 **POR with different levels of nesting (payload size = 500 bytes)**.

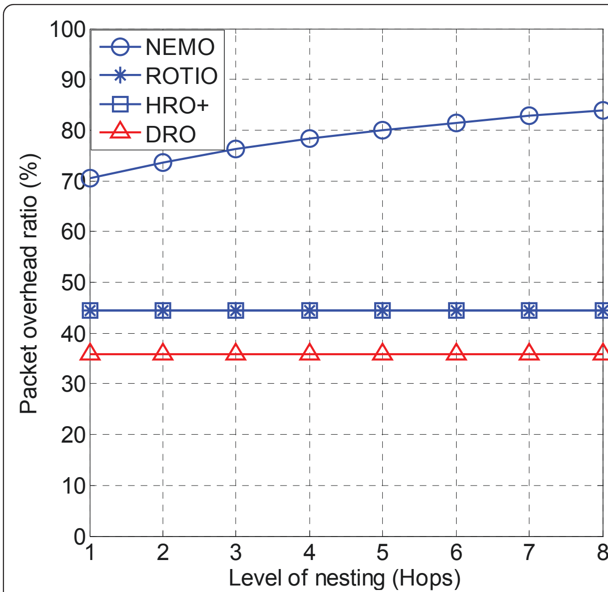

Figure 19 **POR with different levels of nesting (payload size = 100 bytes and *m* = 4)**.

domain route optimization. The NEMO scheme has the highest POR because it suffers from the pinball routing problem and thus needs multiple tunnel headers. Besides, the high POR becomes worse when the level of nesting in a mobile network increases or the payload size decreases. For example, when the level of nesting is 8, the POR of a small packet is 78% while that of a big packet size is 42% The POR of ROTIO is fixed because it always encapsulates packets twice. Both of HRO+ and DRO have the lowest POR since they only encapsulate the packets once. Figures 19 and 20 show the POR during intra-domain route optimization. NEMO still yields the worst result. ROTIO and HRO+ improve on the performance of NEMO, but they also need to encapsulate the packets once. The proposed scheme yields the best result because it uses the *ad hoc* routing protocols to achieve route optimization without encapsulation.[c] It is noted that the POR increases as the payload size decreases, as shown in Figures 17, 18, 19 and 20.

4.6 Total Cost (TC)

In this section, we discuss the TC of route optimization under NEMO, ROTIO, HRO+, and DRO schemes. The TC is composed of the SC and the packet delivery cost. The SC is the sum of the signaling messages for handoff and route optimization procedures, and the packet delivery cost is the sum of data packets sent from the network entities. Moreover, the packet delivery cost is proportion to the hops between the CN and the MNN.

We adopt the session-to-mobility ratio (SMR), which is similar to the call-to-mobility ratio in wireless cellular networks [32], to indicate the ratio of the number of sessions per unit of time to the number of changes of location areas per unit of time for an MR. The SMR is an important factor for SC. SMR is equal to λ/μ, where λ is the ratio of the number of sessions per unit of time and μ is the number of changes of location areas per unit of time for an MR. Thus, if an MR has high moving speed and changes its attachment point quickly, it has

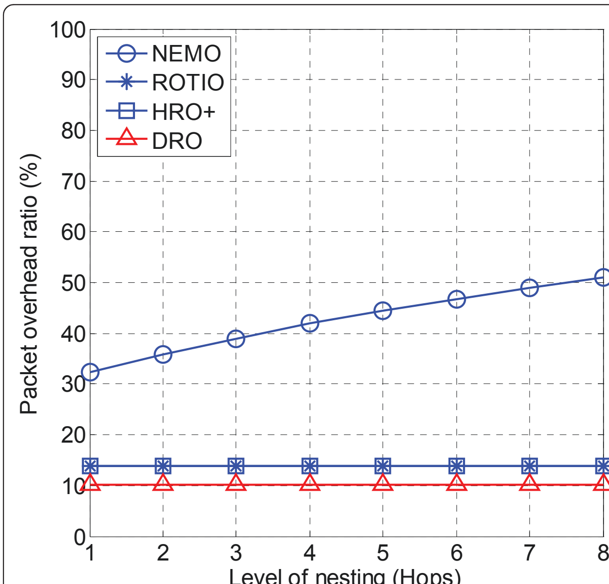

Figure 20 **POR with different levels of nesting (payload size = 500 bytes and *m* = 4)**.

more SMR value. Because handoff is divided into the intra-domain and inter-domain handoff, Thus, μ is composed of μ_G and μ_L, where μ_G and μ_L mean the rate of inter-domain and intra-domain handoff for an MR, respectively. The SC is defined as the total number of signaling messages, as shown in Equation 21.

$$SC = \frac{\sum M}{SMR} = \frac{\mu_G \cdot (\sum M_G) + \mu_L \cdot (\sum M_L)}{\lambda} \quad (21)$$

where M denotes the total number of signaling messages which include the global signaling messages (i.e., M_G) and the local signaling messages (i.e., M_L). NEMO sends the BU message each time when the MR attaches to the different point. Therefore, the global and the local signaling messages are the same. Equation 22 shows the SC of NEMO protocol.

$$SC_{NEMO} = \frac{1}{\lambda} \times [\mu_G (SC_{BU} + SC_{BACK}) + \mu_L (SC_{BU} + SC_{BACK})] \quad (22)$$

In contrary, ROTIO, HRO+, and DRO support the micro-mobility management. The MR sends the global BU and local BU messages when it first moves into the new domain. Afterwards, the MR only sends the LBU message when it moves around the same domain. Thus, the SC of ROTIO and HRO+ schemes can be expressed as follows:

$$SC_{ROTIO} = \frac{1}{\lambda} \times [\mu_G (SC_{BU} + SC_{BACK} + SC_{LBU} + SC_{LBACK}) + \mu_L (SC_{LBU} + SC_{LBACK})] \quad (23)$$

$$SC_{HRO+} = \frac{1}{\lambda} \times [\mu_G (SC_{BU} + SC_{BACK} + SC_{LBU} + SC_{LBACK}) + \mu_L (SC_{LBU} + SC_{LBACK})] \quad (24)$$

DRO needs a notification message to start the intra-domain route optimization. Therefore, the SC of DRO is shown in Equation 25.

$$SC_{DRO} = \frac{1}{\lambda} \times [\mu_G (SC_{BU} + SC_{BACK} + SC_{LBU} + SC_{LBACK}) + \mu_L (SC_{LBU} + SC_{LBACK} + SC_{Notify})] \quad (25)$$

Figure 21 depicts the trend of the SC for various SMR during handoff. The range of SMR is set between 0.2 and 2. NEMO has the lowest SC because it does not send any route optimization information to the CN. Moreover, we observe that the SC of ROTIO, HRO+, and DRO declines quickly as the SMR increases. In ROTIO, HRO+, and DRO, MRs send two kinds of binding update messages (i.e., local BUs and global BUs) to initiate route optimization. The local BU is sent to the RMR and the global BU is sent to the HA or the CN. Therefore, ROTIO, HRO+, and DRO schemes generate more signaling messages (i.e., BU, BACK, LBU/RREQ, LBACK/RREP, and notification messages) than NEMO.

Figure 22 depicts the TC with different number of MRs. The TC of DRO enlarges obviously when the number of the MR increases. This is because DRO uses the *ad hoc* routing protocol for achieving the route optimization. Therefore, DRO needs the other signaling messages to find or maintain the optimal routing path. We can see that NEMO has the worst results since the data packets are passed through the whole HAs of the MRs, which means the hops between the CN and the MNN is large, resulting in the high packet delivery cost. Although DRO has more SC than ROTIO and HRO+, it

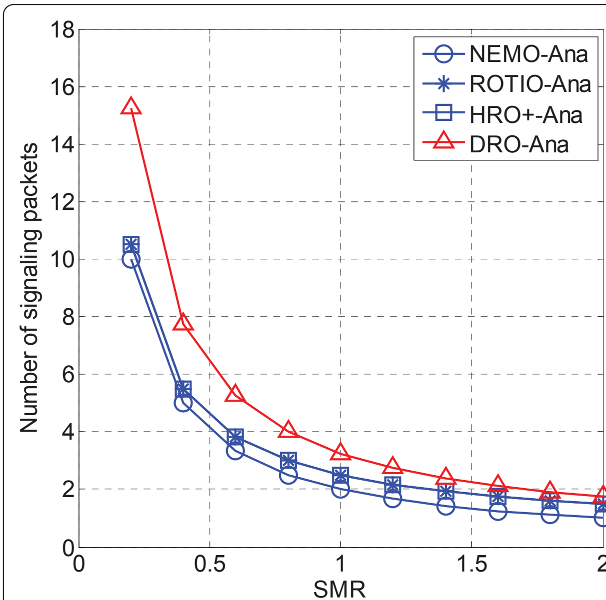

Figure 21 The SC with different SMR (λ = 1, μ_G = 0.25).

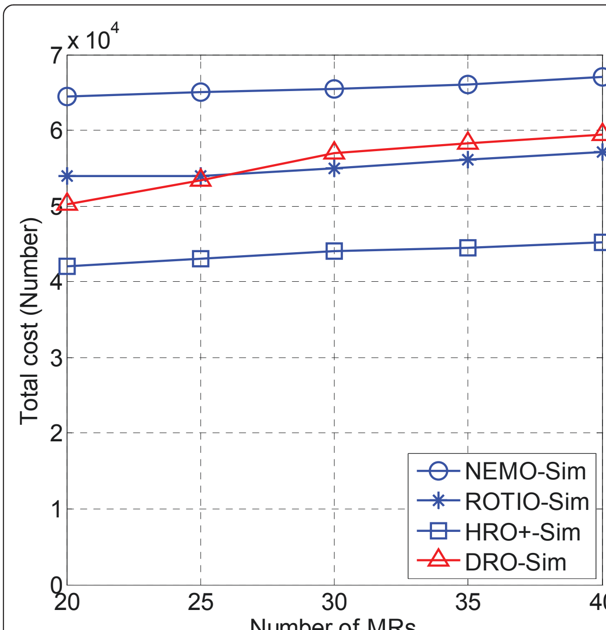

Figure 22 The TC with different number of MRs (v = 10 ms, nested level = 4).

can find the optimal routing path between the CN and the MNN (i.e., low packet delivery cost, and thus low HL). Figure 23 depicts the TC with different levels of nesting. NEMO still yields the worst result since the ping-pong routing problem resulting in the large packet delivery cost. The TC of DRO, ROTIO, and HRO+ are closed. From this result, we obtain an indirect reason to prove that the routing path of the DRO is shorter than other schemes (i.e., low packet delivery cost).

Compared with HRO+ and ROTIO, although our proposed DRO has more TC, their difference is not high. Therefore, we believe it is worth incurring a little extra SC to achieve a better performance (i.e., low PD, low HL, and low POR) for DRO.

4.7 Discussion of double buffer mechanism

Out-of-sequence packets degrade the performance of TCP by generating duplicate ACKs at the receiver. If the number of duplicate ACK is more than 3, the receiver takes the fast recovery mechanism which cuts down the congestion window into half and thus decreases the throughput. Recall that we incorporate a double buffer mechanism into DRO to avoid the packet out-of-sequence problem. Figure 24 shows the impact of the double buffer mechanism during handoff. The out-of-sequence packet problem occurs if DRO does not activate the double buffer mechanism. When the receiver replies with triple ACKs, the sender starts to execute the fast recovery mechanism, which reduces the congestion window as well as the sending rate.

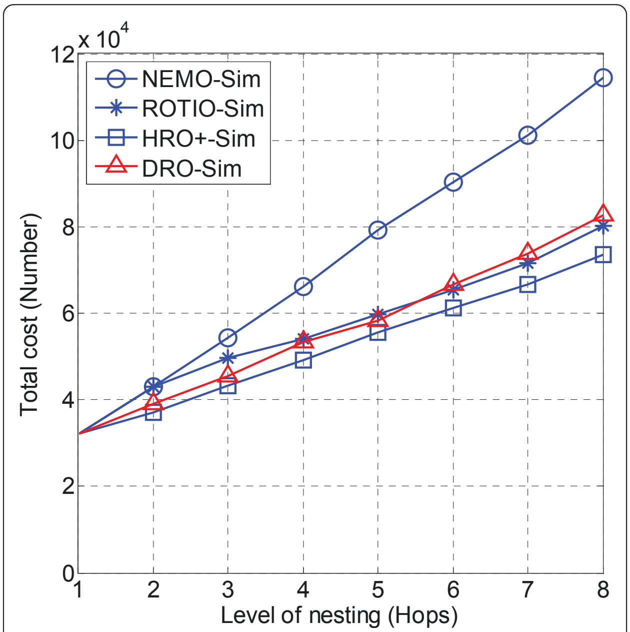

Figure 23 The TC with different levels of nesting (*v* = 10 ms, MR = 30).

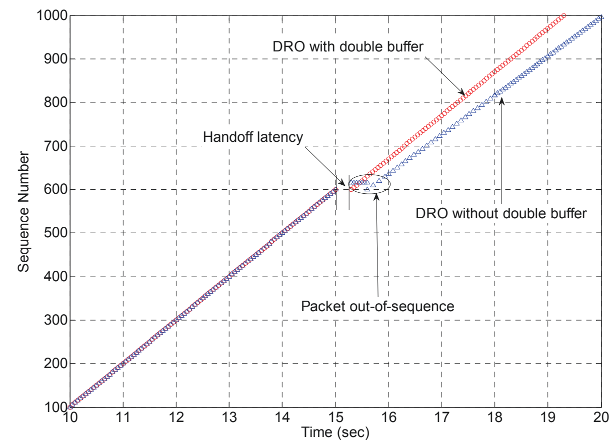

Figure 24 The impact of the double buffer mechanism during handoff.

5. Concluding remarks

We have proposed a DRO scheme for nested mobile networks. The scheme utilizes a domain-based network architecture and incorporates *ad hoc* routing techniques to solve the pinball routing problem, reduce HL, and achieve route optimization for NEMO. Moreover, the scheme uses a double buffer mechanism to prevent the out-of-sequence packet problem during the route optimization procedure. We compare the DRO scheme with existing route optimization schemes via numerical analysis and simulations. The results demonstrate that it outperforms the compared schemes in terms of packet transmission delay, inter-domain and intra-domain HL, the convergence time required for route optimization, and the POR.

In our future study, we will investigate two issues. (1) Adjustment of the domain size: we will investigate the optimum domain size to reduce the SC and improve the scheme's performance. (2) Route optimization for new mobility management model: we will consider the route optimization mechanism for network-based localized mobility management (e.g., PMIPv6) in a nested mobile network environment.

Endnotes

[a]The lengths of the tunneling header and the original IP header in IPv6 are both 40 bytes. [b]The length of address in IPv6 is 16 bytes. [c]According to the CoA of the MR of CN, the MR of the MNN can determine if the MR and the CN are located in the same domain.

Competing interests
The authors declare that they have no competing interests.

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