RBU+: Recursive Binding Update for End-to-End Route Optimization in Nested Mobile Networks

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Abstract. In this paper, we propose an end-to-end route optimization scheme for nested mobile networks, which we refer to as *Recursive Binding Update plus (RBU+).* A nested mobile network is a hierarchical form of mobile networks. Nested mobile networks suffer from a pinball routing problem with hierarchical mobile routers. This problem becomes more serious in the case of macro mobility, as the routing distance becomes longer. To solve the pinball routing problem of nested mobile networks, in this paper we propose the Recursive Binding Update (RBU) and three distinct solutions for the end-to-end routing in mobile networks using the method of obtaining the route from the Top Level Mobile Router (TLMR) to the destination Mobile Network Node (MNN). The solutions for end-to-end routing include source routing, Table Driven Forwarding (TDF), and Route Request Broadcast (RRB). From the results of the simulations, it was shown that RBU+RRB presents the best performances among the different solutions. When combined with an end-to-end routing capability, RBU+ provides optimal routing in nested mobile networks. RBU+ reduces the pinball routing cost, and this reduction becomes more significant as the degree of nesting becomes higher and the distance between the home agents of the mobile router and its parent/child mobile routers becomes longer. When combined with an appropriate reverse route optimization scheme, the routing costs are independent of the degree of nesting and the distance between the Home Agents (HAs).

Keywords: NEMO, network mobility, pinball routing, route optimization

1 Introduction

With the current trend toward ubiquitous computing, many electronic appliances are being given the capability of communicating through wireless technologies using their own IP address. The Mobile-IP Working Group in the Internet Engineering Task Force (IETF) [1] has proposed Mobile IP [2] to support mobility in IP networks. Mobile IP attempts to maintain transport or higher layer Internet connectivity while a host is moving.

Not only devices, but also vehicles, can be connected to the Internet [3]. Mobile devices can connect to the Internet even from within vehicles. In addition, they can move in groups, e.g. a radio, a mobile phone and a Personal Digital Assistant (PDA) belonging to a single person can interact to form a wireless personal area network (WPAN) that can move in a large vehicle. To route IP packets for such complex applications, nested mobile networks can be used.

Mobile networks can have a very complex hierarchy, e.g. individual mobile networks operating within a larger mobile network, visiting mobile nodes (VMNs) in a mobile network, and so on. This situation is referred to as a *nested mobile network*. Fig. 1 shows a simple nested mobile network. In the beginning, the mobile router (MR) and the visiting mobile node (VMN) are attached to their own home link. After the MR moves to a foreign link (D::), the VMN moves under the supervision of the MR, so the link attached at the ingress interface of the MR (C::) becomes the foreign link for the VMN. The '/p' marks in the binding cache implies that the MR registers its prefix of the ingress interface (nemo prefix).

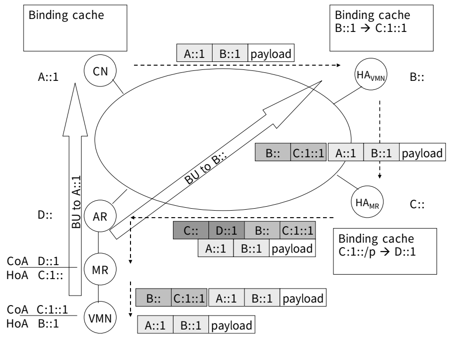

Fig. 1. Pinball routing problem. When the CN wants to send a packet to the VMN, the packet is routed to the HA_{VMN}. The binding cache of the HA_{VMN} has the binding information that the VMN is located under the MR. So the data is tunneled to the HA_{MR}. HA_{MR} also has the binding information that MR is under the AR. The packet is encapsulated again and re-routed to the AR

In this paper, we propose a routing optimization scheme for nested mobile networks called Recursive Binding Update plus (RBU+). RBU+ needs to cooperate with an end-to-end routing algorithm to route packets inside the mobile network, so we also propose three end-to-end routing algorithms and compare them by performing simulations.

The rest of this paper is organized as follows. Section 2 introduces the pinball routing problem in network mobility and section 3 describes the recursive binding search scheme used in the RBU. In Section 4 we propose two additional mechanisms for end-to-end routing in nested mobile networks. In Section 5, we evaluate the performances of the proposed schemes and, in section 6, we consider the use of reverse route optimization to improve the performance of the proposed schemes. Finally, Section 7 concludes this paper with further research issues.

2 Pinball Routing Problem in Nested Mobile Networks

Nested mobile networks suffer from a pinball routing problem. Based on Mobile IPv6 (MIPv6) [2], each mobile router (MR) and mobile network node (MNN) has it's own home agent (HA). So if the correspondent nodes (CNs) want to send data to the leaf MNN which is located at the bottom of the nested mobile network, the packets have to travel to all home agents that are mapped to the MRs of the nested mobile networks.

Fig. 1 shows an example of the pinball routing problem with 2 degrees of nesting. In this case, the original data is encapsulated two times. If the mobile network has a degree of nesting of *N*, the data is encapsulated *N* times. The MR decapsulates the packet and forwards the packet to the VMN. The VMN decapsulates the packet again, thus obtaining the original packet. According to the specification of MIPv6, if the packet is encapsulated by it's HA, the MRs and VMN send a binding update (BU) message to the original sender of that packet for the purpose of route optimization.

Fig. 2 shows the route that packets follow when using the MIPv6 routing optimization capabilities. After the MR sends a BU to the CN, the CN knows that the VMN is under the MR, and that the MR is under the access router (AR). However, the CN cannot deduce the relation between these two pieces of binding information.

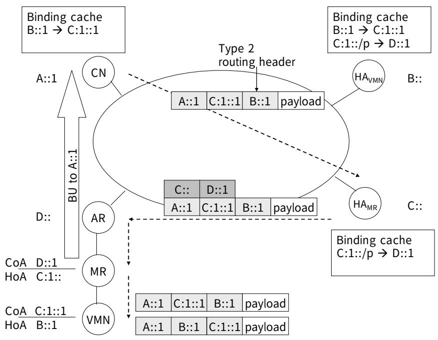

Fig. 2. MIPv6 Route optimization. When a packet is routed using MIPv6 route optimization, the CN knows that the VMN is under the MR, so the data is routed directly to the HA_{MR}. And then the HA_{MR} tunnels the packet to the MR. When the MR receives the packet encapsulated by it's HA, the MR sends a binding update message to the CN

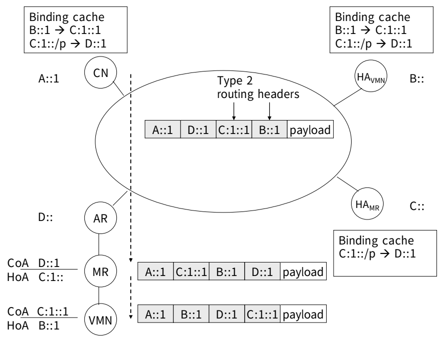

Fig. 3. In the case of the RBU, when the CN wants to send a packet to the VMN, the CN searches its binding cache and finds the binding information of the VMN. Then, the CN adds a type 2 routing header to the packet and searches the binding cache again for the binding information of the CoA of the VMN.

3 Recursive Binding Update

To solve the pinball routing problem of nested mobile networks it is helpful to utilize the binding information of the MR contained in the binding cache of the CN. When the CN wants to send a packet to the VMN, the CN searches its binding cache for the binding information of the VMN, and if the binding is present, the CN adds a type 2 routing header to the packet. The current Mobile IPv6 draft incorporates a restriction which requires that a type 2 routing header must have only one intermediate node.

Fig. 3 is an example of a recursive binding update with source routing for route optimization. We modify the type 2 routing header, in order to be able to use several intermediate nodes, so as to obtain the optimal route from the CN to the VMN by recursive searching of the binding cache. The RBU has an advantage in that it requires no changes to the existing Mobile IP specification, except for the possibility of using multiple type 2 routing headers.

4 End-to-End Recursive Binding Update

The RBU ensures optimal routing from the CN to the VMN using source routing. However the RBU is not scalable, because if a mobile network has *N* degrees of nesting, a CN must search the entire binding cache *N* times. Searching the binding cache and inserting a routing header per packet constitute overhead for the CN. So we propose another route optimization scheme which we call Recursive Binding Update plus (RBU+).

Our RBU+ scheme maintains the optimal route to the Top Level Mobile Router (TLMR) by updating its binding information recursively when it receives a binding update (BU) message. In the case of nested mobile networks, both MRs and VMNs send BU messages to a CN. So the binding cache in the CN involves more than one entry per session, and the CN uses this redundant entry to optimize the route to the nested mobile networks. The recursive binding update is performed as follows.

```
Received BU(HoA:CoA)
for each BE(HoA:CoA) binding_entry in binding_cache
  if BE.CoA equals BU.HoA then
    BE.CoA ← BU.CoA
insert BU(HoA:CoA) to binding_cache
```

In the RBU algorithm, the BU message and binding entries (BE) in the binding cache contain a Home Address (HoA) and Care-of Address (CoA) pair of MRs or VMNs. When an home agent (HA) receives a new BU message from a mobile node, the HA searches all of the binding entries in its binding cache. So if the CoA of the BE is equal to the HoA of the BU, the HA updates the CoA of the BE to the CoA of the BU. Finally, HA inserts a received binding update message in its binding cache.

However RBU+ should work with an end-to-end route optimization algorithm. As mentioned above, using the recursive binding update, the CN can maintain the optimal route not to the destination, but to the top level mobile router (TLMR) of the mobile network. So the packet arriving from the CN to the VMN is routed directly to the MR, but the MR cannot forward this packet, since the MR doesn’t know the HoA of the VMN.

In the following sections, we propose two end-to-end route optimization mechanisms for nested mobile networks. One uses a forwarding table to route packets inside the mobile network, that is Table Driven Forwarding (TDF). The other uses restricted broadcasting to request the route to the mobile network nodes (MNNs), that is Route Request Broadcasting (RRB).

4.1 RBU+ TDF

Fig. 4 shows the basic idea of using Table Driven Forwarding (TDF) for end-to-end route optimization in nested mobile networks. Every mobile router (MR) except for the TLMR sends a route summary (RS) to the parent MR. The RS contains the CoA, HoA and nemo prefix of the MR. Every VMN also sends an RS which contains the CoA and HoA of the VMN. When an MR receives an RS from a child MR or VMN, the MR records the RS in its table and relays the received RS to the parent MR, after overwriting the CoA of the RS to its own CoA. When a TLMR receives a packet from CN and doesn't know the destination, the TLMR searches the forwarding table for the destination and forwards the packet to the appropriate child MR. The intermediate MRs along the path toward the destination repeat the same operation, and in this way the packet can be delivered to the destination.

In this method, all MRs and VMNs have to advertise a RS to their egress interface, and the nodes inside the mobile network use Table Driven Forwarding (TDF) to forward data. If there are not many MNNs and the movement of MNNs is not frequent, TDF is efficient for end-to-end route optimization in nested mobile networks. Trains or airplanes are applicable examples. In this case, the number of nodes is limited to a few hundred, and the movement of nodes is not frequent, since passengers spend most of their time in their assigned seat.

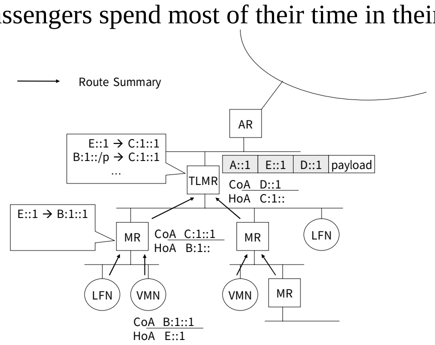

Fig. 4. In RBU+TDF, when the TLMR receives the packet destined for E::1, the TLMR searches its forwarding table and forwards the packet to C:1::1. The MR that receives the packet also searches its forwarding table and forwards the packet to B:1::1. Finally, the VMN accepts the packet, which is destined for itself

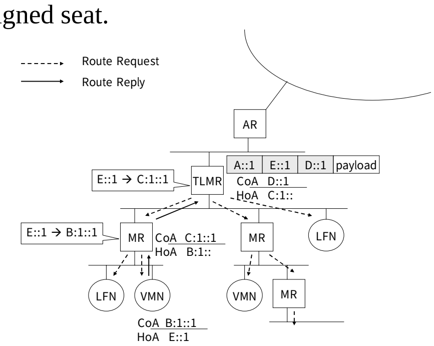

Fig. 5. In RBU+RRB, when the TLMR receives a packet destined for E::1, the TLMR broadcasts the a RReq with E::1 and the intermediate MRs relay the request. When the request reaches at B:1::1, the VMN knows the request is destined for itself and, consequently, it replies by sending a RRep with B:1::1. The intermediate MRs cache the reply and replay the reply after overwriting B:1::1 with C:1::1

4.2 RBU+ RRB

Fig. 5 illustrates the basic concept of Route Request Broadcasting (RRB) for end-to-end route optimization in nested mobile networks. When the TLMR receives a packet from CN and doesn't know the destination, the TLMR broadcasts a Route Request (RReq) with the destination address. The intermediate MRs relay the RReq from the egress interface to the ingress interface. Finally, the VMN receives the request, and replies to the Route Reply (RRep) so as to provide it with VMN_{CoA}. Then, the intermediate MR caches this reply and makes a new RRep message with MR_{CoA}. Subsequently, when the TLMR receives this RRep message, the TLMR sends the packet to the MR and the MR forwards it to the VMN.

If there are many mobile network nodes (MNNs) and the movement of MNNs is frequent, RRB is efficient for the end-to-end route optimization of nested mobile networks. The subway is a good example. In the subway, thousands of nodes exist and these nodes move very frequently.

5 Performance Evaluation

We simulated RBU+ using Network Simulator 2 (NS2) [5] and the MobiWan [6] extension for MIPv6. We measured the round trip time (RTT) and end-to-end delay from the CN to the MNN.

5.1 Operation Modes

Each simulation is performed for five different operation modes, bi-directional tunneling, MIPv6 route optimization, RBU, RBU+ TDF, and RBU+ RRB.

Bi-directional tunneling: Nemo basic support protocol [4] adopts this method to support mobile networks. In this mode, route optimization is not taken into consideration. The CN has no binding information about the MNN, and packets heading toward the MNN have to traverse all of the HAs, that is pinball routing.

MIPv6 route optimization: MIPv6 has route optimization capabilities. When an mobile node (MN) receives a packet encapsulated by its HA, the MN sends a binding update to the original source of the packet. So the CN can possess binding information about the MRs. However, if the degree of nesting is more than 3, this mode also suffers from the pinball routing problem.

RBU: If MIPv6 route optimization capabilities are enabled, the CN can keep information regarding binding information for intermediate MRs. By searching its binding cache recursively and adding bindings to source routing headers, packets can be routed directly to the TLMR of the mobile network. Then, the routing inside the mobile network is performed by the source routing mechanism.

RBU+: In RBU, the CN searches its binding cache recursively whenever packets arrive. For higher degrees of nesting, searching the binding cache can constitute substantial overhead. So in RBU+, the CN updates its binding cache recursively whenever a new binding update message arrives. However, in this mode, the CN knows only the location of the TLMR, so that an end-to-end route optimization algorithm inside the nested mobile network is also needed. In section 4, we propose two end-to-end route optimization methods: these are RBU+TDF and RBU+RRB.

5.2 Degrees of nesting

The routing cost is defined as the hop count or link delay. Route optimization is essential for longer routing distance, since HAs can be scattered all over the world, so we defined the *cost* as the link delay. Also, we assume that the routing cost from the TLMR to the MNN is trivial in comparison with the routing cost from the CN to the TLMR.

N: degrees of nesting
C_i: routing costs of link delay from the HA of the MR_i to the HA of the $MR_{(i+1)}$
C_N: routing cost of link delay from the HA of the TLMR to the TLMR of the mobile network
c_i: routing cost of link delay from the CN to the HA of the MR_i (MR_N is TLMR)
c_{direct}: routing cost of link delay from the CN to the TLMR of the mobile network

Table 1. Routing Costs

Mode	Routing cost
Bi-directional tunneling	$c_1 + \sum_{i=1}^{N} C_i$
MIPv6 route optimization	$c_2 + \sum_{i=2}^{N} C_i$
Recursive binding update	c_{direct}
RBU+ TDF	c_{direct}
RBU+ RRB	c_{direct}

As shown in Table 1, for higher degrees of nesting, the routing cost for bi-directional tunneling and MIPv6 route optimization increases linearly. However, for RBU and RBU+ the routing cost remains constant.

Fig. 7 shows the simulation result of the routing costs according to the degrees of nesting. The simulation was performed for five operation modes and lasted for 30 seconds. The degree of nesting was varied from 2 to 6. The link delays between the HAs were fixed at 100ms and the link delay from the CN to the TLMR is set to 4ms. The return packets from the MNN to the CN are routed by reverse tunneling for all modes. If the return packet is routed directly, the MR drops packets by ingress filtering. So, in the case of RBU and RBU+, the RTT increases because the return packets are routed by reverse tunneling. In section 6, we will discuss about the reverse route optimization problem.

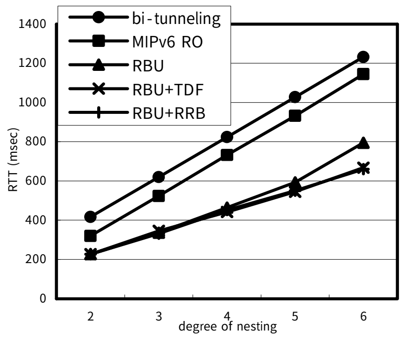

Fig. 7. Routing costs according to the degrees of nesting

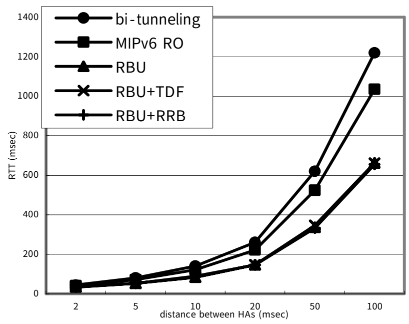

Fig. 8. Routing costs according to the distances between the HAs of the parent and child MRs

5.3 Distances between HAs

Route optimization is especially important when the routing distance is long. In this section, the simulation result shows the relation between the routing distances and the RTT for each operation mode. The routing distances are parameterized by the link delay between the HAs. The degree of nesting is fixed at 3 and the other conditions are the same as for the simulation in section 5.2.

Fig. 8 shows that when the routing distance is longer, the effect of route optimization is bigger. This simulation also adopts reverse tunneling for the return packets. In the view of RTT, RBU and RBU+ present similar performances, but from the viewpoint of the number of binding cache searches, RBU+ is more efficient than RBU.

5.4 Convergence time

Fig. 9 shows the end-to-end packet delay from the CN to the MNN. Probes are started at 1 second and ended at 5 seconds. The decreasing behavior of delay shows discrete levels and each level represents the routing phase.

Phase I (Pinball routing): If the CN has no binding information about the MNN, packets from the CN traverse all of the HAs of the intermediate MRs. In this process, each MR sends a BU to its HA and CN for the sake of routing optimization.
Phase II (Transit state): In this phase, the CN has binding information about the MNN, and the HAs also have new binding information about the intermediate MRs. So packets can be routed through a semi-optimal route.
Phase III (Optimal routing): The CN knows the binding information about all of the intermediate MRs. Using this information, the CN sends packets to the TLMR directly, and this route is the optimal route to the mobile network.

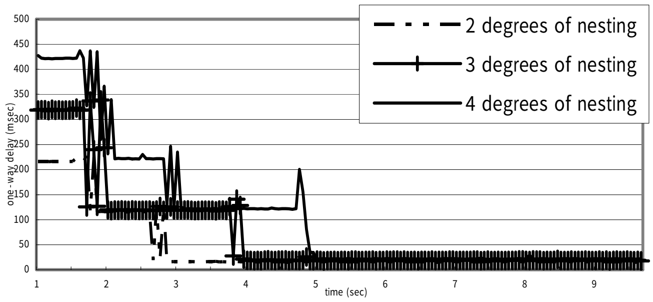

Fig. 9. Convergence time according to the degrees of nesting

The convergence time required to obtain the optimal route means the interval from the start time of *Phase I* to the start time of *Phase III*. In this simulation, the convergence time is related to the degree of nesting of the mobile network. If the binding update is performed at every t seconds and the network is an N-degree nesting mobile network, the convergence time T can be expressed as follows:

$$T = N \times t\,. \tag{1}$$

6 Reverse route optimization

RBU and RBU+ are designed for route optimization from the CN to the MNN. However, we also need the reverse route optimization scheme, because the return packets are routed through reverse tunneling, and this also causes a pinball routing problem. If the return packets are routed directly, the MR drops packets by ingress filtering. So, if an appropriate reverse route optimization method is used, the performances of RBU and RBU+ can be improved dramatically.

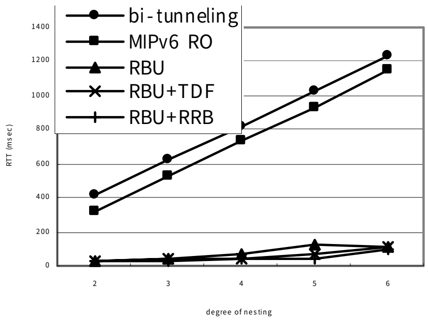

Fig. 10. Routing costs according to the degree of nesting with reverse route optimization

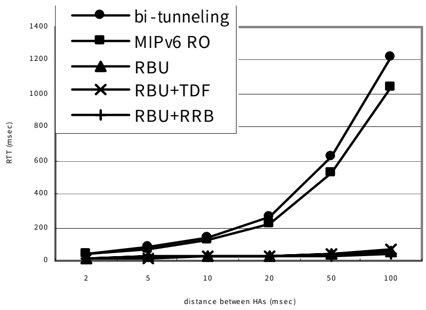

Fig. 11. Routing costs according to the distance between the HAs with reverse route optimization

Fig. 10 and Fig. 11 are the simulation result when a MR doesn't perform ingress filtering so the return packets can be routed directly to the CN. The other conditions of simulation are the same for that of section 5.2 and 5.3.

The simulation result represents that the routing costs are independent from the degree of nesting or the distances between HAs when using forward route optimization and reverse route optimization. In this simulation we assume that an intermediate MR does not drop packets by ingress filtering. But to apply this to the real situation we need an appropriate reverse routing optimization method.

7 Conclusion

Through the simulation of a nested mobile network, this paper compares the effect of route optimization for different mechanisms and proposes two end-to-end route optimization schemes. Based on the proposed Route Optimization schemes in nested mobile networks, a minor modification to the Binding Cache update process and the introduction of end-to-end route optimization algorithms, RBU+ reduces the pinball routing cost. Furthermore, when combined with an appropriate reverse route optimization scheme, RBU+ renders the routing costs independent of the degree of nesting and the distances between the HAs of the parent and child MRs. The RBU+ scheme is useful when the degree of nesting is high and the routing distance becomes longe. RBU+ is particularly well suited for large vehicular network mobility with wireless PANs of passengers. So, RBU+ assumes nested network mobility with long distance movement. It also assumes infrequent handoff for satellite access networks, since large vehicles traveling between different nations will have to access satellite networks for their long range access.

Acknowledgement

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