Adaptive Local Route Optimization in Hierarchical Mobile IPv6 Networks

Sangheon Pack, Taekyoung Kwon, and Yanghee Choi
School of Computer Science and Engineering
Seoul National University, Seoul, Korea
Email: shpack@mmlab.snu.ac.kr and {tkkwon, yhchoi}@snu.ac.kr

***Abstract*— Hierarchical Mobile IPv6 (HMIPv6) reduces the signaling overhead and the handoff latency associated with Mobile IPv6. Although the HMIPv6 protocol supports route optimization between a mobile node (MN) in the mobility anchor point (MAP) domain and a correspondent node (CN) outside the MAP domain, a non-optimal route is formed when the CN and the MN are located in the same MAP domain. In this case, the route can be optimized by informing the CN of the MN's on-link care-of address (LCoA) when the MN hands off within the domain. However, this optimization may result in a higher binding update cost when the MN hands off frequently. To balance the trade-off between the binding update cost and route optimization, we propose an adaptive local route optimization (ALRO) scheme. In the ALRO scheme, an MN informs the CN of the MN's LCoA if the packet delivery cost is more dominant than the binding update cost. Otherwise, the CN is aware of only the MN's RCoA. Namely, the ALRO scheme minimizes either the packet delivery cost or the binding update cost depending on the session-to-mobility ratio (SMR) of each CN. We analyze the performance of the ALRO scheme and derive the optimal SMR threshold. Numerical results indicate that the ALRO scheme shows a better performance than other RO schemes over a wide range of SMR.**

I. INTRODUCTION

Hierarchical Mobile IPv6 (HMIPv6) [2] was proposed by Internet Engineering Task Force (IETF) to mitigate the high signaling overhead that is incurred in Mobile IPv6 networks when mobile nodes (MNs) perform frequent handoffs. In HMIPv6 networks, a mobility anchor point (MAP) has been introduced in order to handle binding update (BU) procedures due to handoffs within a MAP domain in a localized manner, which reduces the amount of network-wide signaling traffic for mobility management.

In HMIPv6 networks, an MN configures two care-of-addresses (CoAs): a regional care-of-address (RCoA) and an on-link care-of-address (LCoA). The RCoA is an address on the MAP's subnet, whereas the LCoA is an address configured to the MN's current point of attachment. An MN that enters a foreign network first configures its LCoA by the IPv6 address auto-configuration scheme. Also, it will receive an Router Advertisement (RA) message containing information on a MAP. The MN then configures a RCoA and sends a local BU message to the MAP. The local BU message includes the MN's RCoA in the Home Address Option and the LCoA is used as the source address of the BU message. This local BU message binds the MN's RCoA to its LCoA.

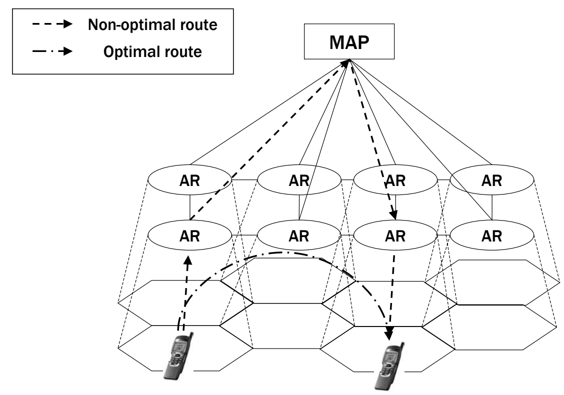

Fig. 1. Non-optimal routing problem in HMIPv6 networks

The MAP will then perform duplicated address detection (DAD) for the MN's RCoA on its link and return a Binding Acknowledgement (BACK) message to the MN. After registering with the MAP, the MN must register its new RCoA with its HA by sending a BU message that specifies the binding (RCoA, Home Address (HoA)) as in Mobile IPv6. The HoA is recorded in the home address option, whereas the RCoA can be found in the source address field. The MN also sends a BU message that specifies the binding information between the HoA and the RCoA to its current correspondent nodes (CNs), which achieves route optimization.

Since the MAP acts as a local HA, it receives all packets on behalf of the MNs it is serving and tunnels the received packets to the MN's current address. If the MN changes its current address within a local MAP domain, it only needs to register the new address (i.e., LCoA) with the MAP. The RCoA does not change as long as the MN moves within the same MAP domain. This makes the MN's mobility transparent to the HA and CNs.

Since the HMIPv6 specification is based on Mobile IPv6 [1], it performs route optimization (RO) as follows. Packets sent by the CN are firstly routed to the HA of the MN; then, the HA forwards the packets to the registered RCoA of the MN. Once the MN receives the packets tunneled from the HA, the MN sends a BU message to the CN. In HMIPv6 networks, the BU message informs the CNs of the MN's RCoA. If the

MN changes its RCoA (inter-MAP domain handoff), the MN sends BU messages to CNs listed in the binding update list [1]. The binding update list is maintained by each MN and consists of entries for CNs with active flows. After receiving the BU message, the CN updates its binding cache and sends a BACK message to the MN. When the MN receives the BACK message, the MN updates its binding update list. After the BU procedures are finished, the CN sends subsequent packets to the MAP directly.

However, the RO scheme in the HMIPv6 specification results in a non-optimal route if the CN and the MN are located in the same MAP domain. Although there exist shorter routes between two nodes, all packets are inefficiently routed through the MAP, which results in a longer packet delivery time. Figure 1 illustrates the non-optimal routing problem in HMIPv6 networks. Of course, the HMIPv6 specification considers a special case that two nodes are located in the same access router (AR) area. In other words, the MN may send a BU message containing its LCoA (instead of its RCoA) to CNs which are connected to the same link. Packets will then be routed directly without going through the MAP. However, the HMIPv6 specification does not take into account the another case that two nodes are located in the same MAP domain but not in the same link.

To overcome this problem, a local route optimization (LRO) scheme can be used. In the LRO scheme, the MN sends a BU message with its LCoA to the CN located in the same MAP domain. However, in this scheme, the MN should send the BU message to the CN whenever the MN changes its LCoA. As a result, the LRO scheme may result in a higher binding update cost. In contrast, the global route optimization (GRO), which is the current RO scheme in the HMIPv6 specification, can reduce the binding update cost, but it may result in a longer packet delivery time when the CN and MN are located in the same MAP domain. Based on this trade-off relationship, we propose an adaptive local route optimization (ALRO) scheme. The ALRO scheme adaptively chooses either GRO or LRO considering the session-to-mobility ratio (SMR). The SMR is defined as the ratio of the session arrival rate and the mobility rate. If the SMR is high, the session activity is a more important factor than the mobility rate and it thus needs to reduce the packet delivery cost rather than the binding update cost. Therefore, the LRO scheme is used in the case of the high SMR. In contrast, if the SMR is low, it is better to reduce the binding update cost, so that the GRO scheme is used. The ALRO scheme may result in handoff disruption when the MN performs an intra-domain handoff. Consequently, the ALRO scheme should carefully determine the SMR threshold value (δ), at which the MN determines which RO scheme (either GRO or LRO) is used.

The remainder of this paper is organized as follows. Section II compares the GRO scheme and the LRO scheme. The ALRO scheme will be proposed in Section III. In Section IV, the analytical model is presented and the optimal SMR threshold is derived based on the model. Section V analyze the total cost and the session disruption time in each RO scheme. Section VI concludes this paper.

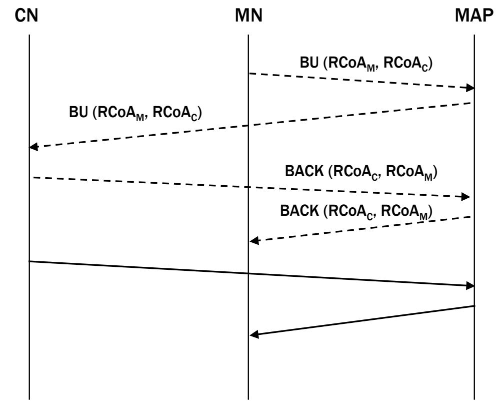

Fig. 2. Packet delivery with the GRO scheme

II. Global Route Optimization (GRO) vs. Local Route Optimization (LRO)

Figure 2 shows the packet delivery procedure in HMIPv6 networks supporting the GRO scheme [1]. In this figure, $RCoA_C$ and $RCoA_M$ stand for RCoAs of the CN and the MN, respectively. In addition, the solid line represents the data packet delivery, whereas the dotted line refers to the signaling packet delivery (e.g., BU and BACK messages). Although route optimization is provided in HMIPv6 networks, the MN informs the CN of its RCoA. Therefore, the packets sent after the BU procedure are delivered to the MAP and the packets are then tunneled to the MN. Consequently, the route by the GRO scheme between nodes in the same MAP domain results in an unnecessary MAP processing time and a longer packet delivery latency.

On the other hand, Figure 3 illustrates the packet delivery procedure in HMIPv6 networks with the LRO scheme. $LCoA_C$ and $LCoA_M$ denote the LCoAs of the CN and the MN. As similar to the GRO scheme, the MN, changing its LCoA or receiving the tunneled packet from the HA, sends a BU message to the CN. In the LRO scheme, the MN notifies the CN of its LCoA. If the CN receives the BU message, the CN responses with the BACK message and directly delivers subsequent packets to the MN without any tunneling at the HA and the MAP. As mentioned above, the LRO scheme is efficient especially when two nodes reside in the same MAP domain. The MN can determine whether the CN is in the same MAP domain or not, by checking the MAP prefix in the RCoA of the CN. Figure 3 illustrates the uni-directional packet delivery procedure, i.e., from the CN and the MN. However, the LRO scheme can be applied to the bi-directional packet delivery[1].

Although the LRO scheme reduces the packet delivery cost, it may result in a higher binding update cost. In the LRO

[1]For simplicity, we consider only the uni-directional packet delivery from the CN to the MN.

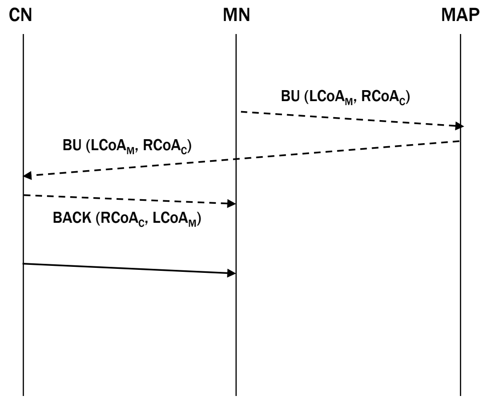

Fig. 3. Packet delivery with the LRO scheme: Uni-directional

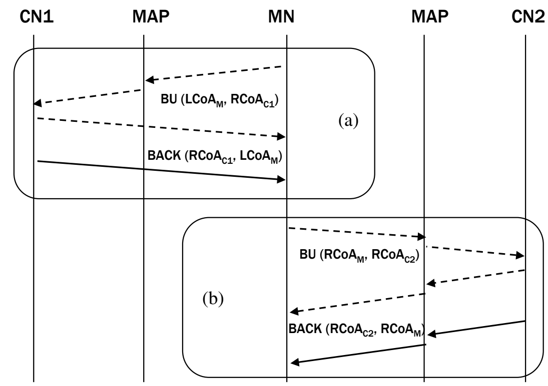

Fig. 4. Packet delivery with the ALRO scheme

scheme, when the MN changes its LCoA with in the same MAP domain, it informs the MAP and CNs recorded in the binding update list of its changed LCoA. If the MN moves from one cell[2] to another frequently, more BU procedures should be performed and this may be high signaling overhead with respect to the entire networks. Therefore, the MN's mobility as well as the session activity between the MN and the CN should be considered when we determine whether the LRO scheme is used or not.

III. Adaptive Local Route Optimization (ALRO)

As mentioned above, if the session activity of an MN is higher than its the mobility rate, the LRO scheme is a more appropriate RO scheme. On the other hand, the GRO scheme is better than the LRO scheme when the mobility rate is relatively high. Based on this trade-off, we propose an adaptive local route optimization (ALRO) scheme. The ALRO scheme uses a modified binding update list where the SMR value as well as the address of each CN with active flows are maintained.

In the ALRO scheme, if a CN's SMR is higher than the pre-defined threshold (δ), the MN chooses the LRO scheme for route optimization, that is the MN sends the BU message with its LCoA. Then, the CN can send packets to the MN without any MAP processing. In contrast, the SMR of the CN is lower than δ, the MN chooses the GRO scheme for the CN. Likewise, the MN sends the BU message with its RCoA, so that the packets are routed to the MN via the MAP. In short, the LRO scheme is used when the SMR is higher than δ, whereas the GRO scheme is used when the SMR is lower than δ. The optimal threshold value (δ^*) can be obtained by an analytical approach, which will be described in the next section.

The binding update and packet delivery procedures in the ALRO scheme are illustrated in Figure 4. In this figure, $CN1$, $CN2$, and MN are located in the same MAP domain. Also, the SMR of $CN1$ is higher than δ, whereas the SMR of $CN2$ is lower than δ. In the ALRO scheme, MN sends the BU message with its LCoA to $CN1$ (refer to (a)), whereas it sends the binding update message with its RCoA to $CN2$ (refer to (b)). Consequently, the packets from $CN1$ are directly routed to the MN. On the other hand, the packets from $CN2$ are firstly routed to the MAP and then tunneled to MN.

[2]In this paper, a cell represents an IP subnet area.

IV. Analytical Modeling

To evaluate the performance of the ALRO scheme, we develop an analytical cost model of each RO scheme. In the analytical model, we calculate the BU cost (C_{BU}) to the CN and the packet deliver (PD) cost (C_{PD}) from the CN to the MN. The total cost (C_T) is the sum of the BU cost and the PD cost. Since route optimization for a CN is performed until the lifetime (T_{BU}) of binding entry expires [1], we take into account the BU cost and the PD cost during T_{BU}. In addition, the BU cost caused by the MAP domain crossing is not considered because this cost is same regardless of the RO schemes. The cost model is described as follows.

- λ_S: Session generation rate of the CN
- $E(S)$: Average session length (in numbers of packets)
- L_P: Packet length
- $L_{BU}(L_{BACK})$: BU message length (BACK message length)
- d_{A-B}: Hop distance between A and B
- $C_{CN-HA}(C_{CN-MAP})$: Unit packet delivery cost from the CN to the HA (MAP) (= $d_{CN-HA} \cdot L_P$ ($d_{CN-MAP} \cdot L_P$))
- $C_{HA-MN}(C_{MAP-MN})$: Unit packet delivery cost from the HA (MAP) to the MN (= $d_{HA-MN} \cdot L_P$ ($d_{MAP-MN} \cdot L_P$))
- C_{CN-MN}: Unit packet delivery cost from the CN to the MN without visiting the MAP (= $d_{CN-MN} \cdot L_P$)
- BU_{CN}: Unit binding update cost to the CN (= $(d_{MAP-MN} + d_{CN-MAP}) \cdot L_{BU} + d_{CN-MN} \cdot L_{BACK}$))

As a reference algorithm, the BU cost and the PD cost of the no route optimization (NRO) scheme are given by Eqs. (1) and (2), respectively. Since there are no BU messages to the CN in the NRO scheme, the BU cost is zero. However, all packets transmitted by the CN are routed to the HA and then the HA forwards the packets to the MN in the NRO scheme. Therefore, the unit packet delivery cost is $C_{CN-HA} + C_{HA-MN}$. By Little's law [6], the number of packets delivered during T_{BU} is approximated to $\lambda_S \cdot T_{BU} \cdot E(S)$.

$$C_{BU}^{NRO} = 0 \tag{1}$$

$$C_{PD}^{NRO} = \lambda_S \cdot T_{BU} \cdot E(S) \cdot (C_{CN-HA} + C_{HA-MN}) \tag{2}$$

Similarly, the BU cost of the GRO scheme is also zero. This is because the GRO scheme sends a BU message to the CN only when the MN moves out of the MAP domain. Packets sent by the CN are delivered to the MN through the MAP. Hence, the PD cost of the GRO scheme is given by Eq. (4).

$$C_{BU}^{GRO} = 0 \tag{3}$$

$$C_{PD}^{GRO} = \lambda_S \cdot T_{BU} \cdot E(S) \cdot (C_{CN-MAP} + C_{MAP-MN}) \tag{4}$$

In the case of the LRO scheme, the MN should send a BU message whenever it moves out a cell area. Let μ_C be the cell crossing rate. Then, the average number of cell crossings during T_{BU} is equal to $\mu_C \cdot T_{BU}$. Therefore, the BU cost in the LRO scheme is given by Eq. (5). Although the LRO scheme results in a higher BU cost due to frequent binding updates, it can reduce the PD cost by using the direct path between the CN and the MN. The PD cost of the LRO scheme is calculated as Eq. (6).

$$C_{BU}^{LRO} = \mu_C \cdot T_{BU} \cdot BU_{CN} \tag{5}$$

$$C_{PD}^{LRO} = \lambda_S \cdot T_{BU} \cdot E(S) \cdot C_{CN-MN} \tag{6}$$

In the ALRO scheme, the MN uses the LRO scheme if the SMR of the CN is larger than the threshold value (δ); otherwise, the MN uses the GRO scheme. Therefore, the total cost of the ALRO scheme can be represented by Eq. (7).

$$C_T^{ALRO} = \Pr(SMR > \delta) \cdot C_T^{LRO} + \Pr(SMR \leq \delta) \cdot C_T^{GRO} \tag{7}$$

where SMR is the measured SMR of the CN.

To obtain the optimal SMR threshold value (δ^*) in the ALRO scheme, we define a difference function as follows:

$$\Delta C_T = C_T^{LRO} - C_T^{GRO} \tag{8}$$

At the optimal SMR threshold value, the condition, $\Delta C_T = 0$ is met. To find δ^* satisfying this condition, we replace the terms, C_T^{LRO} and C_T^{GRO}, by Eqs. (3), (4), (5), and (6). Then, the optimal SMR threshold value is derived as follow.

$$\delta^* = \frac{\lambda_S}{\mu_C} = \frac{BU_{CN}}{E(S) \cdot (C_{CN-MAP} + C_{MAP-MN} - C_{CN-MN})} \tag{9}$$

TABLE I

PARAMETER VALUES FOR NUMERICAL ANALYSIS.

d_{CN-HA}	d_{HA-MN}	d_{CN-MAP}	d_{MAP-MN}
8	8	4	4
d_{CN-MN}	T_{BU}	λ_S	$E(S)$
4	1000	0.1	10

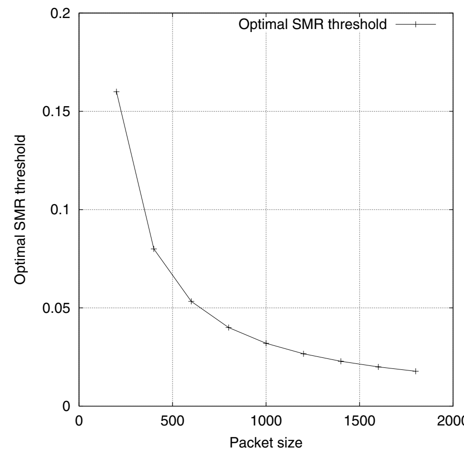

Fig. 5. Optimal SMR threshold as a function of packet size

V. NUMERICAL RESULTS

In this section, we compare the total costs, consisting of the BU cost and the PD cost, in four RO schemes: NRO, GRO, LRO, and ALRO schemes. The session delivery time and the session disruption time are also analyzed.

A. Total Cost

To calculate the BU cost of the four RO schemes, the unit PD and BU costs should be determined in advance. The unit PD and BU costs can be represented as the unit of $Kbytes * number\ of\ hops$ [3], [4]. The minimum length of BU (L_{BU}) and BACK (L_{BACK}) messages in the HMIPv6 specification are 112 bytes and 96 bytes, respectively. The average packet size (L_P) is assumed to be 1500 bytes. Table I shows the parameter values used in the numerical analysis.

The optimal SMR threshold as a function of the average packet size is depicted in Figure 5. As shown in Figure 5, the optimal SMR threshold is inversely proportional to the average packet size. When the average packet size is small, it is more efficient to reduce the BU cost rather than the PD cost. In order to reduce the BU cost, the probability using the GRO scheme should be increased by enlarging the SMR threshold. On the contrary, if the packet size is large, the PD cost is a more dominant factor with respect to the total cost. Hence, the SMR threshold should be decreased in order to use the LRO scheme more frequently.

Figure 6 shows the total cost as the SMR is varied. When the SMR is small, the mobility rate is relatively higher than the session arrival rate. Therefore, the GRO scheme is better because the GRO scheme provides the CN with the transparent mobility. In other words, in the GRO scheme, the MN does

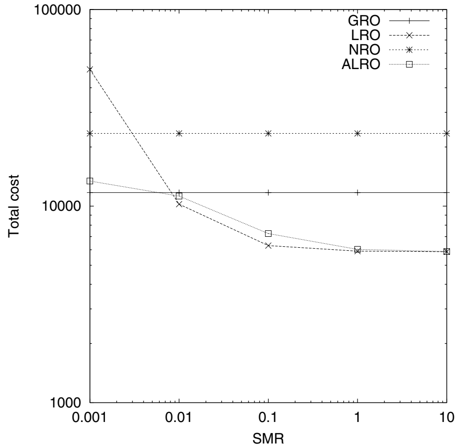

Fig. 6. Total cost as a function of SMR

not inform the CN of its LCoA change. Hence, it is possible to reduce the BU cost. However, as the SMR increases, the total cost of the LRO scheme is drastically reduced. This is because the LRO scheme uses the optimized local route between the CN and the MN, so that the PD cost is minimized. When we compare the ALRO scheme with the LRO scheme, the ALRO scheme shows a low total cost in a wide SMR range. Although the SMR is extremely small (say less than 0.01), the ALRO scheme shows the comparable total cost with the GRO scheme. As shown in Figure 6, the GRO and NRO schemes have the constant total cost, since two schemes do not perform any BU procedures to the CN for local movements within the MAP domain (i.e., the cell crossing).

B. Session Delivery Time

In addition to the total cost, we compare the session delivery time in each RO scheme. We define the session delivery time as the total time that packets sent by the CN during T are delivered to the MN. Followings show the notations and their meaning used in this analysis [3].

- $T(i, j)$: Total session delivery time between i and j
- BW: Link bandwidth of the wired link (100 Mbps)
- BW_W: Link bandwidth of the wireless link (11 Mbps)
- T: Total packet sending time
- P_R: Processing time in the router: routing table lookup and packet processing time (0.001 msec)
- P_{HA}: Processing time in the HA (0.005 msec)
- P_{MAP}: Processing time in the MAP (0.003 msec)
- l: Latency of the wired link: propagation delay and link layer delay (0.5 msec)
- l_W: Latency of the wireless link: propagation delay and link layer delay (2 msec)

The session delivery time consists of the packet delivery time among several network entities (e.g., CN, MN, HA, and MAP). The packet delivery time is the sum of the packet transmission delay and the link delay [3], [4], [5]. For example, if a packet with size of L_P is delivered over a wired link, the delivery time is equal to $L_P/BW + l$. Table II shows the packet delivery time among network entities.

First, the session delivery time of the NRO scheme is given by Eq. (10). Namely, all packets are routed to the MN via the HA. The total number of packets sent by the CN is $\lambda_S \cdot T \cdot E(S)$ by Little's law [6].

$$\begin{aligned} T^{NRO} &= \lambda_S \cdot T \cdot E(S) \cdot (T(CN, HA) + T(HA, MAP) \\ &+ T(MAP, MN)) \end{aligned} \tag{10}$$

On the other hand, in the GRO scheme, packets are delivered to the MN through the MAP. Therefore, the session delivery time is given by Eq. (11).

$$T^{GRO} = \lambda_S \cdot T \cdot E(S) \cdot (T(CN, MAP) + T(MAP, MN)) \tag{11}$$

In the LRO scheme, packets are directly delivered to the MN without visiting the MAP. This is because the MN informs the CN of its LCoA along with the BU message. Hence, the session delivery time is given by Eq. (12).

$$T^{LRO} = \lambda_S \cdot T \cdot E(S) \cdot T(CN, MN) \tag{12}$$

In the ALRO scheme, the session delivery time can be obtained from Eq. (13) by combining Eqs. (11) and (12).

$$T^{ALRO} = \Pr(SMR > \delta) \cdot T^{LRO} + \Pr(SMR \leq \delta) \cdot T^{GRO} \tag{13}$$

Figure 7 shows the session delivery time as the SMR increases. In here, T is set to 100 sec. As shown in Figure 7, the session delivery time increases as the SMR increases. This is because the session arrival rate is proportional to the SMR. Therefore, when the SMR is high, more packets are transmitted and a longer delivery time is required. When the SMR is equal to 10, the session delivery time of the LRO scheme is 0.8046 sec, whereas those of the NRO and GRO schemes are 1.4570 sec and 1.1153 sec, respectively. Namely, the LRO scheme shows the best performance in terms of the session delivery time. On the other hand, the session delivery time of the ALRO scheme is 0.8049 sec, which is slightly larger than that of the LRO scheme. In short, the ALRO scheme provides a similar session delivery time to the LRO scheme, especially when the SMR is high. At the same time, the ALRO scheme can increase the throughput as highly as the LRO scheme does.

C. Session disruption time

Unlike the NRO and GRO schemes, the LRO scheme always performs the BU procedure for local movements. This BU procedure results in session disruption and some packet losses. The session disruption time with respect to the MN is how long it takes to finish the BU procedure. Therefore, the session disruption time is given by Eq. (14). In Eq. (14), first and second terms represent the delivery time of the BU message from the MN to the CN via the MAP. Third and fourth terms

TABLE II

SUMMARY OF THE DELIVERY TIME

Term	Calculation
$T(CN, HA)$	$(d_{CN-HA} - 1) \times (\frac{L_P}{BW} + l) + (\frac{L_P}{BW_W} + l_W) + (d_{CN-HA} - 1) \times P_R + P_{HA}$
$T(HA, MAP)$	$d_{HA-MAP} \times (\frac{L_P}{BW} + l) + (d_{HA-MAP} - 1) \times P_R + P_{MAP}$
$T(MAP, MN)$	$(d_{MAP-MN} - 1) \times (\frac{L_P}{BW} + l) + (\frac{L_P}{BW_W} + l_W) + (d_{MAP-MN} - 1) \times P_R$
$T(CN, MAP)$	$(d_{CN-MAP} - 1) \times (\frac{L_P}{BW} + l) + (\frac{L_P}{BW_W} + l_W) + (d_{CN-MAP} - 1) \times P_R + P_{MAP}$
$T(CN, MN)$	$(d_{CN-MN} - 2) \times (\frac{L_P}{BW} + l) + 2 \times (\frac{L_P}{BW_W} + l_W) + (d_{CN-MN} - 1) \times P_R$

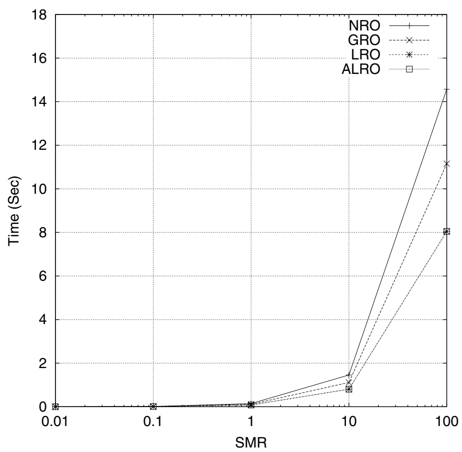

Fig. 7. Session delivery time vs. SMR

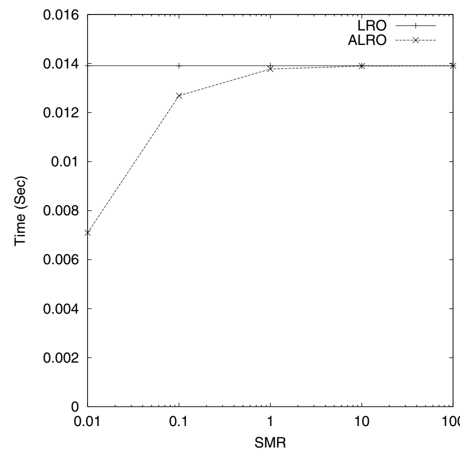

Fig. 8. Session disruption time vs. SMR

refer to the delivery time of the BACK message from the CN to the MN. (Note that the BACK message is directly delivered from the CN to the MN, as shown in Figure 3.) In contrast, the session disruption time of the ALRO scheme can be represented by $S^{ALRO} = S^{LRO} \cdot Pr(SMR > \delta)$.

$$S^{LRO} = (d_{MAP-MN} + d_{CN-MAP} - 2) \times \left(\frac{L_{BU}}{BW} + l + P_R\right) + 2 \cdot \left(\frac{L_{BU}}{BW_W} + l_W\right) + 2 \cdot \left(\frac{L_{BACK}}{BW_W} + l_W\right) + (d_{CN-MN} - 2) \times \left(\frac{L_{BACK}}{BW} + l + P_R\right) \quad (14)$$

As shown in Figure 8, the session disruption time of the LRO scheme is independent of the SMR changes, whereas the disruption time of the ALRO scheme is proportional to the SMR. However, the average session disruption time of the ALRO scheme is less than that of the LRO scheme.

VI. CONCLUSION

Although HMIPv6 can reduce the signaling overhead and the handoff latency, it results in the non-optimal local routing problem when two MNs communicate in the same MAP domain. To address this problem, we propose an adaptive local route optimization (ALRO) scheme. The ALRO scheme chooses either the GRO scheme or the LRO scheme depending on the SMR. Based on the proposed analytical model, we find the optimal SMR threshold, at which the ALRO scheme shows the best performance. Numerical results demonstrate that the ALRO scheme shows a good performance in terms of the total cost, session delivery time, and session disruption time. In our future work, we will evaluate the throughput of the ALRO scheme using the ns-2 simulator [7] and extend the ALRO scheme for the general case that two mobile nodes reside in different MAP domains.

ACKNOWLEDGMENT

This work was supported in part by the Brain Korea 21 project of the Ministry of Education and in part by the National Research Laboratory project of the Ministry of Science and Technology, 2004, Korea.

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