A Study On Optimal Hierarchy in Multi-Level Hierarchical Mobile IPv6 Networks

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***Abstract*— Hierarchical Mobile IPv6 (HMIPv6) is an enhanced Mobile IPv6 in order to reduce signaling overhead and to support seamless handoff in IP-based wireless/mobile networks. To support more scalable services, HMIPv6 can be organized as a multi-level hierarchy architecture (i.e., tree structure). However, since the multi-level HMIPv6 results in additional packet processing overhead, it is required to consider the overall cost and to find the optimal level to minimize the overall cost. In this paper, we investigate this problem, namely the design of the multi-level HMIPv6 with the optimal hierarchy. To do this, we formulate the location update cost and the packet delivery cost in the multi-level HMIPv6. Based on the formulated cost functions, we present the optimal hierarchy level in the multi-level HMIPv6 to minimize the total cost. In addition, we investigate the effects of session-to-mobility ratio (SMR) on the total cost and the optimal hierarchy. The numerical results, which show various relationships among network size, optimal hierarchy, and SMR, can be utilized to design the optimal HMIPv6 network.**

I. INTRODUCTION

In wireless/mobile networks, mobile users freely change their service points while they are connected. In this environment, mobility management is an essential technology for keeping track of the users' current location and for delivering data correctly. In terms of cellular networks for voice call services, many schemes have been proposed to support efficient mobility management [1]. However, next-generation wireless/mobile network will be a kind of unified networks based on IP technology, which has different characteristics from the existing cellular networks. Consequently, the design of IP-based mobility management schemes has become necessary.

Hierarchical Mobile IPv6 (HMIPv6) [2] is an enhanced Mobile IPv6 to minimize the signaling cost using a local agent called mobility anchor point (MAP). The MAP is intended to limit the amount of Mobile IPv6 signaling outside the local domain. An mobile node (MN) entering a MAP domain will receive Router Advertisements (RA) containing information on one or more local MAPs. The MN can bind its current CoA (on-link care-of address (LCoA)) with an address on the MAP's subnet (regional care-of address (RCoA)). Acting as a local HA, the MAP receives all packets on behalf of the MN serviced by the MAP and encapsulates and forwards them directly to the MN's current address. If the MN changes its current address within a local MAP domain, it only needs to register a new CoA with the MAP. Hence, only the RCoA needs to be registered with the correspondent nodes (CNs) and the home agent (HA). 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 CNs that the MN is communicating with. A MAP domain's boundaries are defined by means of the access routers (ARs) advertising the MAP information to the attached MNs.

Recently, Xie et al. proposed an analytic model for Mobile IP regional registration [3] which is one of hierarchical mobility management schemes [4]. The proposed analytic model focused on the determination of the optimal size of regional networks, given the average total location update and packet delivery cost. Besides, Woo proposed an analytic model to investigate the performance of Mobile IP regional registration [5]. In [5], Woo measured the registration delay and the CPU processing overhead loaded on the mobility agents to support regional registration. The analytic model proposed in [5] is based on the fluid-flow mobility model. Pack et al. proposed an analytical model for HMIPv6 in IP-based cellular networks [6]. In [6], an analytical model based on the random walk model and numerical results were proposed.

However, these works [4] [5] [6] did not consider a multi-level hierarchical structure. In general, more ARs are needed to support more scalable services and these ARs are organized as a tree structure. To manage this architecture, it is required to design a multi-level HMIPv6 network. Of course, additional packet processing cost may occur due to the multi-level structure. Therefore, it should be investigated to find the optimal hierarchy in the multi-level HMIPv6 to minimize the overall cost.

In this paper, we propose an analytic model for the multi-level HMIPv6, which can be used to evaluate its performance in terms of location update and packet delivery. The proposed analytic model is based on the fluid-flow mobility model. Using the analytical model, we analyze various relationships among network size, session-to-mobility ratio (SMR), and optimal hierarchy. The remainder of this paper is organized as follows. In Section II, we briefly describe the multi-level HMIPv6 networks. Section III formulates the location update cost and the packet delivery cost and Section IV presents a procedure to find the optimal hierarchy level. Section V shows several numerical results based on the analytical model. Section VI concludes this paper.

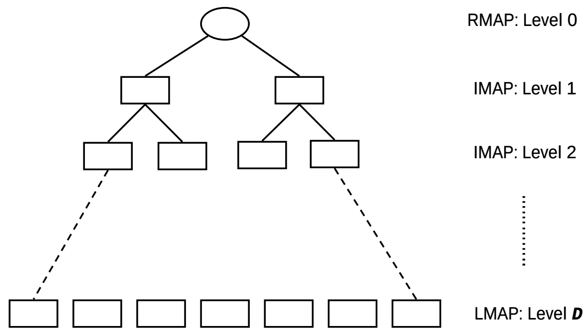

Fig. 1. Abstract architecture for multi-level HMIPv6

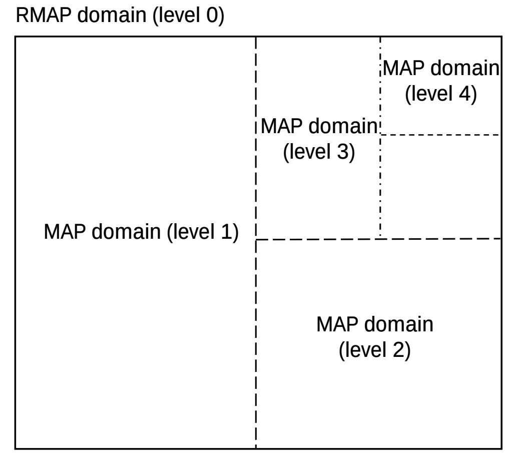

Fig. 2. Rectangular cell configuration in multi-level HMIPv6

II. Multi-Level Hierarchical Mobile IPv6

In HMIPv6 with multiple levels of hierarchy, a Binding Update (BU) message is forwarded to the root MAP (RMAP) by way of one or more intermediate MAPs (IMAPs). When the BU message arrives at the first MAP, the MAP checks its mapping table to see whether the MN is already registered with it or not. If the MN is already registered in the mapping table, local binding update is completed at the MAP. Namely, in this case, the MAP generates a BU reply and sends the message to the next lower-level MAP in the hierarchy. However, if it is not, the MAP forwards the BU message to the next higher-level MAP. This process is repeated in each MAP in the hierarchy until a MAP having the MN in its mapping table can be found. Therefore, in the case of the first binding update in a foreign network, the BU message is forwarded up to the RMAP in the foreign network and the HA.

When the multiple hierarchical level is used, a lot of MAPs can be organized as a form of tree, so that it is possible to provide more scalable services and to support a larger number of MNs. Furthermore, although some nodes (i.e., intermediate MAPs) are failed, only sub-trees rooted from the failed nodes are affected from the failures. Therefore, the multi-level HMIPv6 can be a more reliable solution. However, the multi-level HMIPv6 results in a higher processing cost than the one-level HMIPv6 when a packet is delivered to an MN. This is because the packet goes through more intermediate MAPs and the encapsulation/decapsulation procedures are repeated at each MAP.

In this paper, we develop an analytic model based on HMIPv6 architecture with D-level as shown in Fig. 1. In terms of AR and MAP location, we assume that the total number of ARs in a foreign network is N and these ARs are uniformly located in each leaf MAP (LMAP) domain. For example, let's assume that there are 128 ARs and the hierarchy level is determined as 3 in binary tree architecture. Then, the number of leaf MAPs is $2^3 = 8$ and the number of ARs in a leaf MAP domain is $128/8 = 16$.

III. Analytical Modeling

A. Location Update Cost

As mentioned before, we assume that the total number of cells in a foreign network is N. In this paper, a cell refers to a service area of an AR. Also, we use the fluid-flow mobility model in the rectangular cell configuration [8] for user mobility model. Fig. 2 shows the rectangular cell configuration for analytical modeling. Let L_c be the perimeter of a cell. Then, the number of ARs located within the k-level MAP domain, $N(k)$, is as follows:

$$N(k) = \frac{N}{m(k)}, \quad 0 \leq k \leq D \tag{1}$$

where $m(k)$ is the number of k-level MAPs.

Since we assume that there are N cells in a foreign network, the perimeter (L_k) of the domain area of k-level MAP can be calculated as Eq. (2). Besides, the crossing rate (R_k) of k-level MAP domain area in the fluid-flow model can be obtained as Eq. (3).

$$L_k = 4 \times \sqrt{N(k) \times \left(\frac{L_c}{4}\right)^2} = L_c \times \sqrt{\frac{N}{m(k)}} \tag{2}$$

$$R_k = \frac{\rho \upsilon L_k}{\pi} \tag{3}$$

where ρ is the user density and υ is the average velocity.

Then, the location update cost (C_L) can be expressed as Eq. (4), which consists of three long terms. The first term represents the location update cost to the HA caused by moving out a foreign network area (or RMAP domain). The second term refers to the sum of the location update costs occurred by the crossing of the k-level MAP domain area $(1 < k < D)$. The third term shows the location update cost occurred by the cell crossing of MNs.

$$C_L = R_0 \cdot C_L^{HA} + \sum_{k=1}^{D} (R_k \times 2^k - R_{k-1} \times 2^{k-1}) \cdot C_L^{(k)} + (R_c \times N - R_D \times 2^D) \cdot C_L^C \quad (4)$$

where C_L^{HA} is the unit location update cost to the HA. Let C_L^C be the unit location update cost incurred by the cell crossing and $C_L^{(k)}$ be the unit location update cost incurred by the crossing between two k-level MAP domains. When the cell crossing happens, an MN registers its location only to the leaf MAP. On the other hand, the MN crosses the boundary between two k-level domain areas, it should register its location up to $(k-1)$-level MAP. Hence, C_L^C and $C_L^{(k)}$ can be obtained from the following equations.

$$C_L^C = \omega + \eta \cdot d_{AR-LMAP} \quad (5)$$

$$C_L^{(k)} = \omega + \eta \cdot d_{AR-LMAP} + \sum_{i=k}^{D} \eta \cdot d_{i-1,i} \quad (6)$$

where ω and η are the unit costs when a location update procedure is performed in a wireless and a wired link, respectively. $d_{AR-LMAP}$ denotes a distance between AR and LMAP. $d_{i-1,i}$ denotes a distance between $(i-1)$-level MAP and i-level MAP. In addition, the average distance between AR and RMAP, which is expressed as the below equation, is H.

$$H = d_{AR-LMAP} + \sum_{i=1}^{D} d_{i-1,i} \quad (7)$$

B. Packet Delivery Cost

In terms of the packet delivery cost, we consider the transmission cost in packet delivery path and the processing cost at each network entities such as MAP and HA. First, the packet delivery cost from the CN to the RMAP ($C_P^{CN-RMAP}$) is presented in Eq. (8). d_{CN-HA}, $d_{HA-RMAP}$, and $d_{CN-RMAP}$ are hop distances between the CN and the HA, the HA and the RMAP, and the CN and the RMAP, respectively. Since route optimization is supported in HMIPv6, it is assumed that only first packet transits the HA and the subsequent data packets are directly routed to the RMAP.

$$\begin{aligned} C_P^{CN-RMAP} &= \lambda_s \cdot \alpha \cdot (d_{CN-HA} + d_{HA-RMAP}) \\ &+ \lambda_s \cdot (E(S) - 1) \cdot \alpha \cdot d_{CN-RMAP} \\ &+ \lambda_s \cdot P_{HA} \end{aligned} \quad (8)$$

where λ_s is the session arrival rate and $E(S)$ is the average session size in the unit of packet. α is the unit transmission cost in a wired link. P_{HA} denotes the processing cost at the HA.

On the other hand, the packet delivery cost from the RMAP to the AR ($C_P^{RMAP-AR}$) is like as follows:

$$C_P^{RMAP-AR} = \lambda_s \cdot E(S) \cdot (\sum_{k=0}^{D} P_{MAP}(k) + H \cdot \alpha) \quad (9)$$

where $P_{MAP}(k)$ is the processing cost at the k-level MAP.

The processing cost at the MAP includes a lookup cost and a packet encapsulation/decapsulation cost. It is assumed that the lookup cost is proportional to the logarithm of the number of MNs located in the MAP domain [4] and the encapsulation/decapsulation cost is a constant value.

$$P_{MAP}(k) = \delta \cdot \log(N_U(k)) + \kappa \quad (10)$$

where δ is a weighting factor and κ is the encapsulation/decapsulation cost with a constant value. $N_U(k)$ is the number of MNs located in k-level MAP domain so that it can be calculated as follows in the fluid-flow model:

$$N_U(k) = L_k^2 \times \frac{1}{4} \times \rho = L_c^2 \times \frac{1}{4} \times \frac{N}{2^k} \times \rho$$

The last component is the packet delivery cost in the wireless link between AR and MN. This packet delivery cost (C_P^{AR-MN}) is presented in Eq. (11).

$$C_P^{AR-MN} = \lambda_s \cdot E(S) \cdot \beta \quad (11)$$

where β is the unit transmission cost in a wireless link.

Then, the overall packet delivery cost is the sum of all packet delivery costs obtained from Eqs. (8), (9), and (11).

$$C_P = C_P^{CN-RMAP} + C_P^{RMAP-AR} + C_P^{AR-MN} \quad (12)$$

IV. Optimal Hierarchy Minimizing Total Cost

As mentioned before, the total cost is the sum of the location update cost and the packet delivery cost. To investigate the impact of the optimal hierarchy and SMR, we formulate the total cost as a function of the optimal hierarchy and SMR. SMR is an analogous to call-to-mobility ratio (CMR) in cellular networks. In the fluid-flow model, SMR can be defined as λ_s/R_c.

$$C_T = C_L + C_P = C_T(D, SMR) \quad (13)$$

The difference function ($\Delta C_T(D, SMR)$) is also defined in order to find the optimal hierarchy as shown in Eq. (14).

$$\Delta C_T(D, SMR) = C_T(D, SMR) - C_T(D-1, SMR) \quad (14)$$

Using the difference function, it is possible to find the optimal hierarchy when the total number of ARs and SMR are given. If $\Delta C_T(1, SMR)$ is larger than 0, the optimal hierarchy (D^*) is 0. Otherwise, the optimal hierarchy is the largest D in all Ds meeting $\Delta C_T(D, SMR) \leq 0$.

$$D^* = \begin{cases} 0, & \text{if} \Delta C_T(1, SMR) > 0 \\ \max\{D : \Delta C_T(D, SMR) \leq 0\}, & \text{otherwise} \end{cases} \quad (15)$$

TABLE I

SYSTEM PARAMETERS FOR NUMERICAL ANALYSIS

α	β	ρ	ω	η	δ	κ	L_c	C_L^{HA}	H
1.0	2.0	0.002	2.0	1.0	0.5	2.0	400	40	8

$E(S)$	P_{HA}	d_{CN-HA}	$d_{HA-RMAP}$	$d_{CN-RMAP}$
10	40	4	4	6

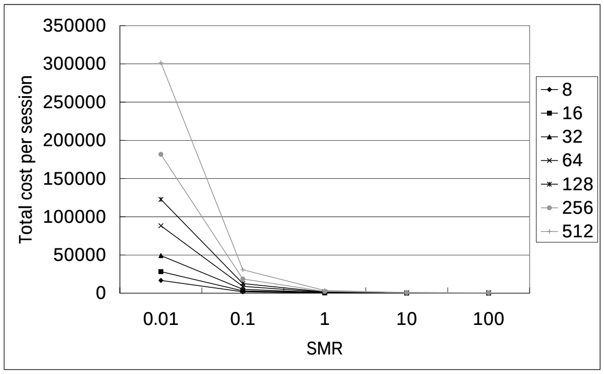

Fig. 3. Total cost as a function of SMR

V. NUMERICAL RESULT

Using the analytic model for the multi-level HMIPv6, we conducted various numerical results. In terms of unit costs for transmission and location update, a number of value sets are evaluated in Subsection D. Other parameter values are set to reasonable values based on [4] and [8]. Table I shows the used parameter values. The average velocity of MN is used to adjust the crossing rate and SMR. In addition, we assume that $d_{i-1,i}$ is 1 and the $d_{AR-LMAP}$ is $H-D$, without loss of generality.

A. SMR vs. Total Cost per Session

First, we analyze the variation of the total cost per session as SMR is changed. Fig. 3 shows the analysis result. Network hierarchy for each network size is chosen as the optimal value, which is obtained from Eq. (15). As shown in Fig. 3, the total cost per session decreases as SMR increases. The total cost per session is the sum of the packet delivery cost for a session and the location update costs occurred during an inter-session arrival time. In the case of the total cost per session, session arrival rate can be assumed to be 1. Therefore, as SMR increases, mobility ratio decreases and the location update cost also decreases. Consequently, the total cost per session is inversely proportional to SMR. In addition, Fig. 3 shows that the total cost per session increases as the number of ARs in the foreign network increases.

B. Network Size vs. Optimal Hierarchy

Fig. 4 shows the optimal hierarchy with increasing of network size. The network size is represented as the number of ARs located in the foreign network. Using the analytical result as shown in Fig. 4, it is possible to get the necessary network level when the network size is given. For example, when the number of AR is between 8 and 104, the optimal hierarchy is 0. However, as the number of ARs increases, the optimal hierarchy also increases. As shown in Fig. 4, the network size range with the same optimal hierarchy increases as the network size increases.

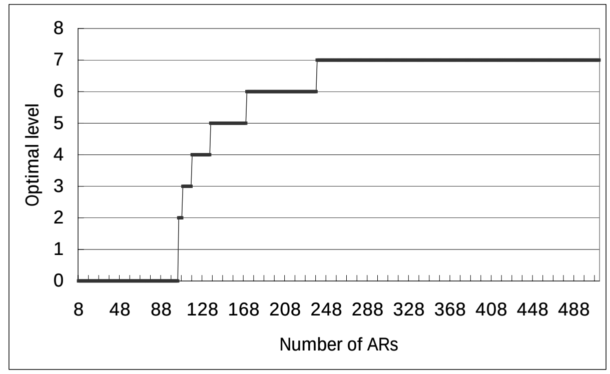

Fig. 4. Optimal hierarchy level as a function of the number of ARs

C. SMR vs. Optimal Hierarchy

Fig. 5 shows the optimal hierarchy as SMR is varied. As shown in Fig. 5, the optimal hierarchy decreases as SMR increases. A higher SMR means that the session arrival rate is larger than the mobility ratio (i.e., crossing rate). In other words, the packet delivery cost has a larger portion of the total cost than the location update cost does, in the case of a higher SMR. Therefore, if SMR is high, it is more advantageous to reduce the network hierarchy in order to minimize the packet delivery cost. On the other hand, when SMR is low, the location update cost is a more dominant factor than the packet delivery cost, so that the optimal network hierarchy, minimizing the total cost, increases to enhance the localization of registration process. In addition, the optimal network hierarchy increases as the network size increases. However, the difference between different network sizes is reduced as SMR increases.

Based on the results shown in Fig. 5, it is possible to adapt the network hierarchy according to the current SMR. In other words, an MN can select one MAP, which is located in the optimal network hierarchy, among a number of MAPs located in a foreign network by estimating the current SMR. This adaptive MAP selection scheme is under our study [7].

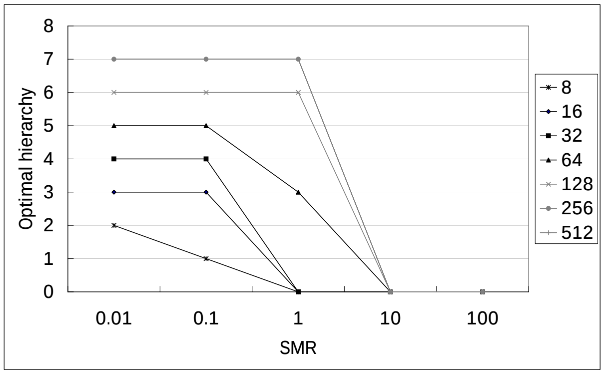

Fig. 5. Optimal hierarchy level as a function of SMR

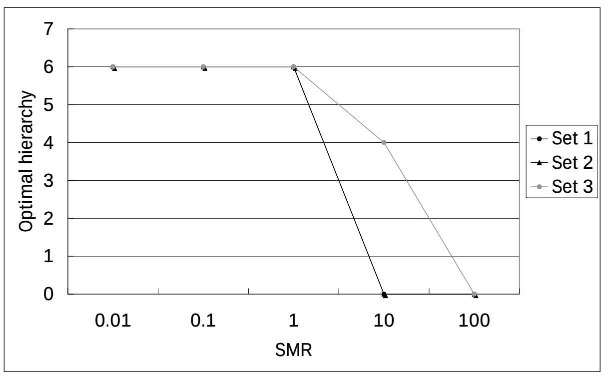

Fig. 6. Optimal hierarchy level for different cost sets

D. *Effect of Unit Transmission/Update Costs*

In the previous numerical results, we assumed that the unit location update cost is the same as the unit transmission cost. Namely, η and α are set at 1.0 and ω and β are set at 2.0. However, the unit location update and transmission costs are affected by several factors. In the case of the unit location update cost, which procedures are performed for location registration determines the unit update cost. On the other hand, in the case of the unit transmission cost, packet size is one of the important factors to be considered. Therefore, we analyze various results for different cost sets. Table II shows the different cost sets.

Fig. 6 shows the optimal network hierarchy when different unit cost sets are used. In this result, N is assumed as 128. As shown in Fig. 6, the optimal network hierarchies for the cost sets 1 and 2 are same although SMR is changed. However, the cost set 3 shows a different optimal hierarchy from the cost sets 1 and 2. Namely, the optimal hierarchy for the cost set 3 is 4 when SMR is 10, whereas the optimal hierarchy for the cost sets 1 and 2 is 0. This is because the cost set 3 has a higher unit location update cost than the cost sets 1 and 2, as shown in Table II. Therefore, when the cost set 3 is used for numerical results, it is of benefit to reduce the location update cost. Hence, the optimal hierarchy for the cost set 3 is equal to or larger than those of cost sets 1 and 2 in order to reduce the location update cost.

TABLE II
DIFFERENT COST SETS

set	η	ω	α	β
1	1.0	2.0	1.0	2.0
2	1.0	2.0	5.0	10.0
3	5.0	10.0	1.0	2.0

VI. CONCLUSION

When various mobility management schemes are deployed in mobile networks, it is one of the most essential works to evaluate the performance and to optimize the performance of these schemes. Hierarchical Mobile IPv6 (HMIPv6) is an efficient mobility management to minimize signaling overhead and handoff disruption. In this paper, we analyzed the multi-level HMIPv6, which can support more scalable services, but has a tradeoff relationship between the location update cost and the packet delivery cost. We developed an analytic model consisting of the location update cost and the packet delivery cost in the multi-level HMIPv6. Based on the model, we studied the optimal hierarchy level in the multi-level HMIPv6 to minimize the total cost. Specifically, we investigated the effects of SMR on the total cost and the optimal network level. In addition, we studied the optimal network level as a function of network size and the effects of different unit cost sets. We believe that it is possible to deploy optimal HMIPv6 networks by utilizing these various analytical results.

VII. ACKNOWLEDGMENTS

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