Performance Analysis of Hierarchical Mobile IPv6 in IP-based Cellular Networks

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***Abstract*—Next-generation wireless/mobile networks will be IP-based cellular networks integrating Internet with the existing cellular networks. Recently, Hierarchical Mobile IPv6 (HMIPv6) was proposed by the Internet Engineering Task Force (IETF) for efficient mobility management. HMIPv6 reduces the amount of signaling and improves the performance of MIPv6 in terms of handover latency. Although HMIPv6 is an efficient scheme, the performance of wireless networks is highly dependent on various system parameters such as user mobility model, packet arrival pattern, etc. Therefore, it is essential to analyze the network performance when HMIPv6 is deployed in IP-based cellular networks. In this paper, we propose an analytic model for the performance analysis of HMIPv6 in IP-based cellular networks, which is based on the random walk mobility model. Based on this analytic model, we formulate location update cost and packet delivery cost. Then, we analyze the impact of cell residence time on the location update cost and the impact of user population on the packet delivery cost. Also, we investigate the variation in the total cost as the relative session size and the MAP domain size are changed. As a result, we present various analytical results in different environments.**

***Index Terms*—Hierarchical Mobile IPv6, Performance Analysis, Analytic Model, Random Walk Mobility Model.**

I. Introduction

In wireless/mobile networks, users freely change their service points while they are communicating with other users. 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 provide efficient mobility management [1]. However, since next-generation wireless/mobile networks will be unified networks based on IP technology, they have different characteristics from those of the existing cellular networks. Therefore, the design of IP-based mobility management schemes has become necessary.

The Mobile IP working group [2] within the Internet Engineering Task Force (IETF) proposed a mobility management protocol, called Mobile IPv4 [3]. Mobile IPv4 allows the transparent routing of IP packets to mobile nodes (MNs) connected to the Internet. Each MN is always identified by its home address, regardless of its current point of attachment to the Internet. While it is located away from its home network, the MN is also attributed a care-of address (CoA) which provides information about its current point of attachment to the Internet. Generally, a care-of address indicates the address of a foreign agent (FA) as an end point for packet tunneling. The Mobile IP provides for the possibility of registering the care-of address with a home agent (HA). The HA sends packets destined for the MN through a tunnel to the CoA. After arriving at the end of the tunnel, each packet is decapsulated and then delivered to the MN.

In addition to Mobile IPv4, the Mobile IPv6 (MIPv6) protocol [4] was proposed for mobility management in IPv6 wireless networks. In general, the Mobile IPv4 is not a scalable solution because all data packets have to transit via the limited number of nodes, which make up the FAs and HAs. To overcome these drawbacks, Mobile IPv6 utilizes the binding update procedure. In Mobile IPv6, an MN sends Binding Updates messages to its HA and all CNs every time it moves. Although the binding update procedure provides the optimal packet routing, it requires the additional handoff latency so that MIPv6 is not appropriate for environments in which MNs frequently change their point of attachment to the network, in other words the so-called *micro-mobility environments*. For example, the authenticated binding update procedure requires approximately 1.5 round trip times between the MN and each CN. These round trip delays disrupt active connections each time a handoff to a new access router (AR) is performed. Eliminating this additional delay element from the time-critical handoff period provides the improved performance with Mobile IPv6. Moreover, in the case of wireless links, it is required to reduce the number of messages sent over the air interface to all CNs and to the HA. Thus, the existence of a local anchor point allows Mobile IPv6 to benefit from reduced mobility signaling with external networks.

Hierarchical Mobile IPv6 (HMIPv6) [6] is an enhanced Mobile IPv6 to minimize the signaling cost using a local anchor point called Mobility Anchor Point (MAP). The MAP can be located at any level in a hierarchical network of routers, including the AR. The MAP is intended to limit the amount of Mobile IPv6 signaling outside the local domain.

An MN entering a MAP domain will receive Router Advertisements containing information on one or more local MAPs. The MN can bind its current CoA (on-link CoA (LCoA)) with an CoA on the MAP's subnet (regional CoA (RCoA)). Acting as a local HA, the MAP receives all packets on behalf of the MN. And then, the MAP encapsulates and forwards them directly to the MN's current address (LCoA). If the MN changes its current address within a local MAP domain, it only needs to register the new address with the MAP. Hence, only the RCoA needs to be registered with the CNs and the 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 it is communicating with. A MAP domain's boundaries are defined by means of the ARs advertising the MAP information to the attached MNs.

Recently, Xie et al. proposed an analytic model for regional registration [5] which is a kind of hierarchical mobility management scheme [7]. The proposed analytic model focused on the determination of the optimal size of regional networks, given the average location update and packet delivery costs. In this study, they assumed the existence of one-level regional networks where there is only one gateway foreign agent (GFA). Although this model is a well-defined analytic model, it is based on Mobile IPv4 and not Mobile IPv6. Furthermore, in this study, a spatial-oriented Internet architecture was used for performance analysis. Currently, the Internet is based on the spatial-oriented location area model, which specifies that the distance between two end points situated on the Internet has nothing to do with the geographic locations of these two points. However, the ARs used in next-generation wireless/mobile networks may utilize a cellular architecture to maximize the utilization of the limited radio resources. Therefore, it is more appropriate for us to analyze network performance in context of IP-based cellular networks.

In this paper, we propose an analytic model for HMIPv6, which can be used to evaluate its performance in terms of location update and packet delivery. We assume wireless IP networks with a hexagonal cell structure and the proposed analytic model is based on the random-walk mobility model. The remainder of this article is organized as follows. In Section II, we propose an analytic model based on the random walk mobility model. Section III formulates location update cost and packet delivery cost using the analytic model. Section IV presents various numerical results which show the impacts of the cell residence time, user population, and MAP domain size on the location update and packet delivery costs. Section V concludes this paper.

II. Analytic Mobility Model

As mentioned above, we assume an IP-based cellular network such as that shown in Fig. 1. Also, we assume each domain managed by a MAP has the same number of rings, R. The innermost cell 0 is called the center cell; cells labeled 1 form the first ring around cell "0" and so forth. A ring r is composed of $6r$ cells except the ring 0 with one cell. Thus, the total number of cells (or access routers) up to ring R, $N(R)$, is calculated by:

$$N(R) = \sum_{r=1}^{R} 6r + 1 = 6\frac{R(R+1)}{2} + 1 = 3R(R+1) + 1 \quad (1)$$

In terms of the user mobility model, we use the random walk mobility model [8] that is appropriate for pedestrian movements. In the random-walk mobility model, the next position of an MN is equal to the previous position plus a random variable whose value is drawn independently from an arbitrary distribution. In addition, an MN moves to another cell area with probability $1-q$ and stays in the current cell with probability q.

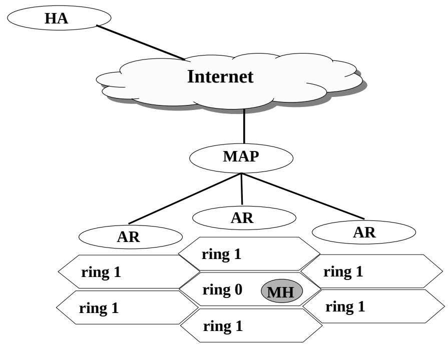


Fig. 1. IP-based cellular architecture based on HMIPv6.

In the cellular architecture shown in Fig. 1, if an MN is located in a cell of ring r ($r > 1$), the probability that a movement will result in an increase ($p^+(r)$) or decrease ($p^-(r)$) in the distance from the center cell is given by

$$p^+(r) = \frac{1}{3} + \frac{1}{6r} \text{ and } p^-(r) = \frac{1}{3} - \frac{1}{6r} \quad (2)$$

We define the state r of a Markovian chain as the distance between the current location of the MN and the center of the location area. This state is equivalent to the index of a ring in which the MN is located. As a result, the MN is said to be in state r if it is currently residing in ring r. The transition probabilities $\alpha_{r,r+1}$ and $\beta_{r,r-1}$ represent the probabilities at which the distance of the MN from the center cell increases and decreases, respectively. They are given as

$$\alpha_{r,r+1} = \begin{cases} (1-q) & \text{if } r = 0 \\ (1-q)\left(\frac{1}{3} + \frac{1}{6r}\right) & \text{if } 1 \le r \le R \end{cases} \quad (3)$$

$$\beta_{r,r-1} = (1-q)\left(\frac{1}{3} - \frac{1}{6r}\right) \qquad \text{if } 1 \le r \le R \quad (4)$$

where q is the probability that an MN stays in the current cell.

Fig. 2 shows a state diagram for random walk mobility model. We denote $\pi_{r,R}$ as the steady-state probability of state r within a MAP domain consisting of R rings. Using the transition probabilities in Eq. 3 and 4, $\pi_{r,R}$ can be expressed in terms of the steady state probability $\pi_{0,R}$ as

$$\pi_{r,R} = \pi_{0,R} \prod_{i=0}^{r-1} \frac{\alpha_{i,i+1}}{\beta_{i+1,i}} \qquad \text{for } 1 \le \mathrm{r} \le \mathrm{R} \quad (5)$$

With the requirement $\sum_{\mathrm{r}=0}^{\mathrm{R}} \pi_{r,R} = 1$, $\pi_{0,R}$ can be expressed by

$$\pi_{0,R} = \frac{1}{1 + \sum_{r=1}^{R} \prod_{i=0}^{r-1} \frac{\alpha_{i,i+1}}{\beta_{i+1,i}}} \quad (6)$$

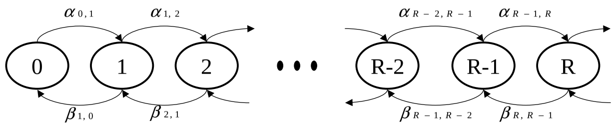


Fig. 2. State diagram for random walk mobility model.

III. Cost Functions

In HMIPv6, there exist two types of cost: *location update cost* and *packet delivery cost*. Let $C_{location}$ and C_{packet} be the location update cost and the packet delivery cost, respectively.

A. Location Update Cost

In HMIPv6, an MN performs two types of binding update procedure: *global binding update* and *local binding update*. Global binding update is a procedure that an MN registers its RCoA with the CNs and the HA. On the other hand, if an MN changes its current address within a local MAP domain, it only needs to register the new address with the MAP. Local binding update refers to this registration. C_g and C_l denote the location update costs in global binding update and local binding update, respectively. In IP networks, the signaling cost is proportional to the distance of two network entities. Thus, the location update cost of the global binding update is larger than that of the local binding update. For the simplicity of analysis, we assumed that the global and local binding update costs are constants.

According to the mobility model proposed in the previous section, the probability that an MN performs the global binding update is as follows:

$$\pi_{R,R} \cdot \alpha_{R,R+1}$$

Namely, if an MN is located in the ring R, the boundary ring of a MAP domain consisted of R rings, and performs a movement from ring R to ring $R+1$, then the MN performs the global binding update procedure. In other cases except this event, the MN performs only the local binding update procedure.

T is the cell residence time that an MN stays in a cell area and $E(T)$ is the average cell residence time. Then, the average location update cost per unit time is

$$C_{location} = \frac{\pi_{R,R} \cdot \alpha_{R,R+1} \cdot C_g + (1 - \pi_{R,R} \cdot \alpha_{R,R+1})C_l}{E(T)} \quad (7)$$

B. Packet Delivery Cost

In HMIPv6, the MAP maintains *a mapping table* for translation between RCoA and LCoA. The mapping table is similar to that of HA and it is used to track the current LCoA of MNs. All packets directed to an MN will be received by the MAP and tunnelled to the MN's LCoA using the mapping table. Therefore, the lookup time required for the mapping table also has to be considered. On the other hand, if the paging function is supported in the networks, it is possible to find the exact current location of the MN using paging functions, so that this additional lookup time is not needed. In this paper. we considered that HMIPv6 does not support the terminal paging because there are no standard IP paging protocols in the current Mobile IP networks.

We denote N_{MN} as the total number of MNs located in a MAP domain. In this paper, we assume that the average number of MNs who located in the coverage of an AR is K. Thus, the total number of MNs is as Eq. 8.

$$N_{MN} = N(R) \times K \quad (8)$$

Then, the packet delivery cost (C_{packet}) in HMIPv6 is as follows:

$$C_{packet} = C_{MAP} + C_{HA} + C_T \quad (9)$$

In Eq. 9, C_{MAP} and C_{HA} denote the processing cost at the MAP and the HA, respectively. C_T denotes the packet transmission cost from the CNs to the MNs.

When a packet is arrived at the MAP, the MAP should select the current LCoA of the destination MN from the mapping table. Then, the packet is routed to the MN. Thus, the processing cost at the MAP is divided into the lookup cost (C_{lookup}) and the routing cost ($C_{routing}$). The lookup cost is proportional to the size of the mapping table and the size of the mapping table is proportional to the number of MNs located in the MAP domain. On the other hand, the routing cost is proportional to the logarithm of the number of ARs belonging to a MAP domain. Therefore, the processing cost at the MAP can be expressed as Eq. 10. In Eq. 10, λ_d denotes the packet arrival rate. α and β are weight factors.

$$C_{MAP} = \lambda_d \cdot (C_{lookup} + C_{routing}) = \lambda_d \cdot (\alpha N_{MN} + \beta \log(N(R))) \quad (10)$$

In MIPv6, the route optimization is supported to resolve the triangular routing problem. Therefore, only the first packet of a session transits the HA to detect whether an MN moves into foreign networks or not. After then, all successive packets of the session are directly routed to the MN. Let λ_f be the arrival rate of the first packet in a session. Then, the processing cost at the HA is as follows:

$$C_{HA} = \lambda_f \cdot \theta_{HA} \quad (11)$$

where θ_{HA} refers to a packet processing cost at the HA, which is a constant.

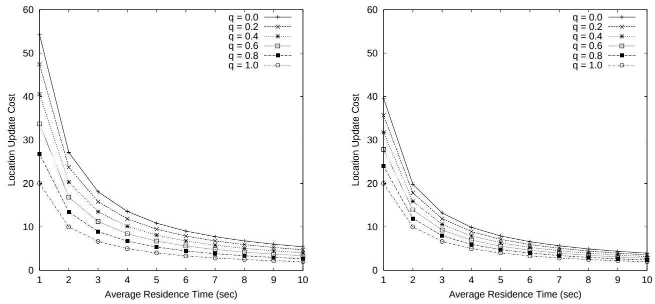
Unlike the processing cost, the transmission cost is associated with the distance between two network entities. In IP networks, the distance is represented as the number of hops. Let D_{CN-HA} , D_{HA-MAP}, and D_{MAP-AR} be the distances in the unit of hops between CN and HA, HA and MAP, and MAP and AR, respectively. Since HMIPv6 supports the route optimization, the transmission cost in HMIPv6 can be obtained by Eq. 12. τ and κ denote unit transmission costs in a wired link and a wireless link, respectively. In general, since the transmission cost in a wireless link is larger than that in a wired link, κ is larger than τ.

TABLE I

SYSTEM PARAMETERS FOR NUMERICAL ANALYSIS.

α	β	θ_{HA}	τ	κ	C_l	C_g
0.1	0.2	20	1.0	2.0	20	100

D_{CN-HA}	D_{HA-MAP}	D_{CN-MAP}	D_{MAP-AR}
6	6	4	2



(a) R = 1 (b) R = 4

Fig. 3. Location update cost as a function of average cell residence time.

$$C_T = \lambda_f \cdot (D_{CN-HA} + D_{HA-MAP} + D_{MAP-AR}) \cdot \tau + (\lambda_d - \lambda_f) \cdot (D_{CN-MAP} + D_{MAP-AR}) \cdot \tau + \kappa \cdot \lambda_d \quad (12)$$

IV. NUMERICAL RESULTS

In this section, we analyze the impact of the cell residence time, the user population, and the relative session size on the signaling cost and the packet delivery cost. Also, we investigate the impact of the MAP domain size on the total cost. The parameter values used in the numerical analysis are shown in Table I.

A. The Impact of the Cell Residence Time

Fig. 3 shows the variation in the location update cost as the average cell residence time ($E(T)$) is changed. As mentioned above, the cell residence time is the period that an MN stays in a cell area. Thus, as the average cell residence time of an MN increases, the MN performs less movements and the location update cost per unit time decreases. In addition, q stands for the probability that an MN stays in the current cell at the next time slot. Therefore, the MN with a large q refer to the static MN. Namely, the MN performs less movements and requires less location update cost. Fig. 3 shows these characteristics.

In Fig. 3, the location update cost of the ring size of 1 is larger than that of the ring size of 4. This is because an MN located in the MAP domain with small ring size is more likely to perform global binding update procedures.

B. The Impact of the User Population

In general, the location update cost is affected by the user mobility and not by the user population. On the other hand, the packet delivery cost depends on the number of users serviced in a MAP domain. (In this paper, we use the terms "user" and "MN" interchangeably.)

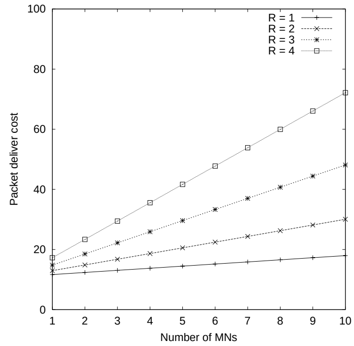


Fig. 4. Packet delivery cost as a function of the MN population.

In HMIPv6 without paging functions, the MAP has to determine whether or not the destination MN belongs to the mapping table. The cost for this lookup procedure (C_{lookup}) is generally proportional to the number of MNs in a MAP domain. Therefore, the packet delivery cost increases as the number of MNs in the MAP increases.

Fig. 4 shows the impact of the MN population in an AR area on the packet delivery cost. The results describe the relationship between the number of MNs and the lookup cost. In addition, the results indicate that it is important to reduce the lookup time in the mapping table for scalable services. For example, if a binary search tree is used for the mapping table lookup, the lookup cost may be proportional to the logarithm of the number of MNs. Furthermore, if the paging is supported in HMIPv6, the packet delivery cost can be reduced. In HMIPv6 with paging functions, the first packet of a session, called the paging request packet, invokes a paging procedure. After the paging procedure is completed, it is possible to find the most suitable AR, and subsequent packets are directly routed to this AR. In this procedure,the paging cost and the routing cost are associated with the number of ARs. Thus, the packet delivery cost in HMIPv6 with paging functions is not affected by the number of MNs. However, in this paper, we didn't consider the impact of the paging function on the packet delivery cost.

C. The Impact of the Relative Session Size

Next, we analyze the packet delivery cost as the relative session size is variable. The relative session size is defined as a ratio, the total packet arrival rate to the first packet arrival rate (λ_d/λ_f). In this analysis, we fixed the total packet arrival rate to 1.0. On the other hand, the first packet arrival rate is variable (0.05, 0.1, 0.2, and 1.0). The ratio of 1, when the total arrival rate is equal to the first packet arrival rate, means that the session is consisted of just one packet. On the other hand, the session with ratio of 20 is consisted of 1 first packet and 19 subsequent packets.

In Fig. 5, the packet delivery cost is maximum when the ratio is one. When the ratio is one, all packets of a session transits the HA and they are tunneled to a suitable MAP. Namely, all packets are routed by the triangular routing. However, in other cases,

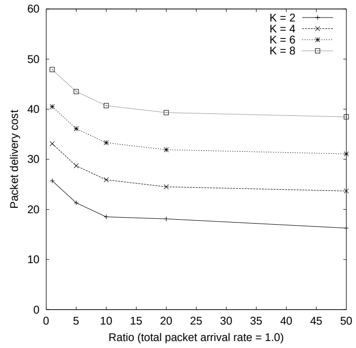


Fig. 5. Packet delivery cost as a function of the relative session size.

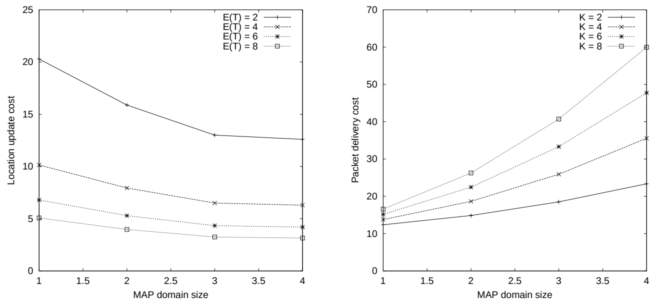
only first packet transits the HA and the subsequent packets are directly routed to the MAP. Thus, the packet delivery cost can be reduced when the ratio is larger than one. In short, this result indicates that the route optimization in HMIPv6 is benefit in reducing the packet delivery cost.

D. The impact of the MAP Domain Size

Fig. 6 show the location update cost and the packet delivery cost as a function of the MAP domain size. In this result, λ_d and λ_f are 1.0 and 0.1, respectively. As mentioned above, the location update cost is inversely proportional to the MAP size. On the other hand, the packet delivery cost increases as the MAP size increases. This is because the processing cost at the MAP is proportional to the number of ARs located in a MAP domain.

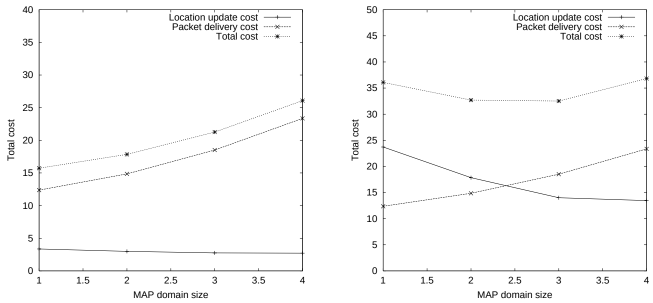
The tradeoff relationship between the location update cost and the packet delivery cost has to be taken into consideration in determining the optimal MAP size. Fig. 7 shows the total cost for the static MN and dynamic MN. The static MN stays in the current cell with probability of 0.8 and the average cell residence time is 8. Therefore, in the case of the static MN, the location update cost is smaller than the packet delivery cost for all MAP domain sizes. In other words, the packet delivery cost has a large effect in the optimal MAP domain size.

However, the dynamic MN stays in the current cell with probability of 0.2 and the average cell residence time is 2. Thus, the location update cost is larger than that of the static MN. In this case, we should find the MAP size to minimize the total cost in order to obtain the optimal MAP domain size. In the case of the dynamic MN presented in Fig. 7, the total cost is minimal when the MAP domain size is 3.



(a) Location update cost (b) Packet delivery cost

Fig. 6. Location update cost and packet delivery cost as a function of MAP domain size.



(a) Static MN (b) Dynamic MN

Fig. 7. Impact of user mobility on the total cost.

V. Conclusion

Hierarchical Mobile IPv6 (HMIPv6) is a novel protocol designed to minimize mobility-related signaling costs. In this paper, we modeled location update cost and packet delivery cost in HMIPv6 using the random walk mobility model. Using this model, we analyzed the impact of the cell residence time and user population on the location update cost and the packet delivery cost, respectively. Also, we studied the variation in the total cost as the relative session size and the MAP domain size are changed. The analytical results indicate that the MAP domain size is a critical performance factor to minimize the total cost in HMIPv6. In addition, an efficient management scheme for the mapping table in the MAP is required to reduce the lookup cost. In future studies, we will intend to the analytic model and analyze HMIPv6 supporting IP paging, which has the advantages in the reduction of signaling overhead and power consumption.

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