Performance Analysis of Adaptive Mobility Management in Wireless Networks

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Abstract. In this paper, we propose an adaptive mobility management scheme for minimizing signaling costs in Hierarchical Mobile IPv6 (HMIPv6) networks. In our proposal, if the mobile node's mobility is not local, the mobile node sends location update messages to correspondent nodes in the same way as Mobile IPv6 (MIPv6). After the creation of a spatial locality of the mobile node's movement, the mobile node sends location update messages to the correspondent nodes in same way as HMIPv6. Therefore, our proposal can reduce signaling costs in terms of packet transmission delays in HMIPv6 networks. The cost analysis presented in this paper shows that our proposal offers considerable performance advantages to MIPv6 and HMIPv6.

1 Introduction

MIPv6 allows an IPv6 node to be mobile to arbitrarily change its location on the IPv6 Internet and still maintain existing connections. However, MIPv6 causes in a high signaling cost when it updates the location of an Mobile Node (MN) if it moves frequently. Thus, HMIPv6 is proposed by IETF to reduce signaling costs. It is well known that the performance of HMIPv6 is better than that of MIPv6. This is especially true when the basic assumption is that 69% of a user's mobility is local. If the user's mobility is not local, performance of HMIPv6, in terms of delays for packet delivery, is worse than that of MIPv6, due to the encapsulation processing by the Mobility Anchor Point (MAP). Since all packets from a CN to an MN are first delivered through the MAP, it is possible that the MAP can become bottlenecked. Therefore, the load of the search and tunnelling processes increase on the MAP as the number of MNs increase in the foreign or home networks. It is a critical problem for the performance of HMIPv6 networks. In this paper, therefore, we propose an adaptive mobility management scheme, called AHMIPv6, for minimizing signaling costs in HMIPv6 networks. In our proposal, an MN sends a Binding Update (BU) message to the Correspondent Nodes (CN) with either its on-link address (LCoA) or Regional Care of Address (RCoA), depending on the MN's mobility pattern. Thus, our proposal can reduce signaling loads, even if a user's mobility is not local.

The rest of the paper is organized as follows. Section 2 describes the proposed procedures of location update and packet delivery using the adaptive mobility management scheme called AHMIPv6. In Section 3, we propose the analytic mobility model based on the random walk. Section 4 formulates the location update cost and the packet delivery cost using the analytic model. Section 5 shows the evaluation of the proposed system's performance and analysis of the results. Finally, our conclusions are presented in Section 6.

2 Adaptive Mobility Management Scheme

This section describes the location update and packet delivery procedure. In our proposal, each MN has a value of m and T_m. While m is the number of subnet crossings within the MAP domain, T_m is the threshold value which decides whether the MN sends a BU message to the CN with the LCoA or the RCoA. Whenever an MN enters a new MAP domain, it sets the value of m to zero. T_m can be adjusted based on the user's mobility pattern and current traffic load.

The procedures for a location update are as follows:

- If an MN moves to a different MAP domain, then:

1) the MN obtains two CoAs: an LCoA and an RCoA.
2) Then, it registers with its MAP and HA by sending a BU message, and it sets the value of m to zero.

- Otherwise, if an MN moves within the same MAP domain, then:

1) the MN gets a new LCoA.
2) The MN registers with its MAP by sending a BU message.

After registration with the MAP, the MN compares the value of m with T_m.

Case 1. If the value of m is less than T_m, then:

3-1) the MN sends a $BU_{[HoA,LCoA]}$[1] message to the CN.

Case 2. Otherwise, if the value of m is greater than or equal to T_m, then:

3-2) the MN sends a $BU_{[HoA,RCoA]}$[2] message to the CN. After the sending of the $BU_{[HoA,RCoA]}$ message, the MN does not send any other BU messages to the CN before it moves out of the MAP domain.

As a result, the MN performs registration with the CNs using an RCoA or an LCoA, depending on its mobility pattern. In our proposal, the packet delivery procedure is exactly the same to that in MIPv6 or HMIPv6.

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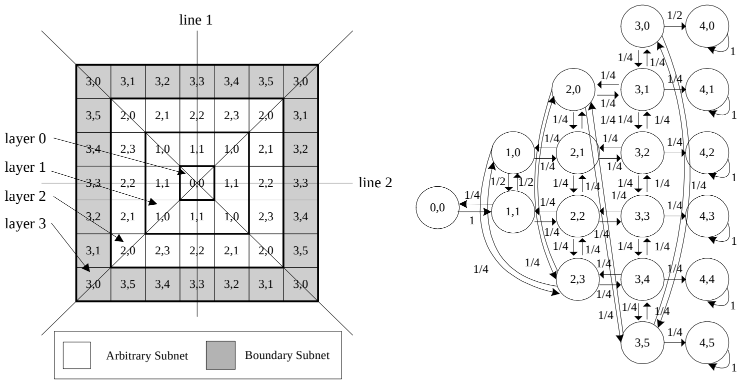
[1] BU with the binding between the MN's Home Address (HoA) and LCoA

[2] BU with the binding between the MN's Home Address (HoA) and RCoA

3 Analytic Mobility Model

Inspired by the initial idea in [1, 2], we will describe a two-dimensional random walk model for mesh planes. Our model is similar to [1] and considers a regular MAP domain/subnet overlay structure. In this model, the subnets are grouped into several n-layer MAP domains. Every MAP domain covers $N = 4n^2 - 4n + 1$ subnets.



3,0	3,1	3,2	3,3	3,4	3,5	3,0
3,5	2,0	2,1	2,2	2,3	2,0	3,1
3,4	2,3	1,0	1,1	1,0	2,1	3,2
3,3	2,2	1,1	0,0	1,1	2,2	3,3
3,2	2,1	1,0	1,1	1,0	2,3	3,4
3,1	2,0	2,3	2,2	2,1	2,0	3,5
3,0	3,5	3,4	3,3	3,2	3,1	3,0

Fig. 1. Type Assignments of the mesh 4-layer MAP domain and the State Diagram

As shown in Fig. 1 (where n = 4), the subnet at the center of a MAP domain is called *layer 0*. An n-layer MAP domain consists of a subnet from layer 0 to layer $n-1$. Based on this domain/subnet structure, we derive the number of subnet crossings before an MN crosses a MAP domain boundary. According to the equal moving probability assumption (i.e., with a probability of 1/n), the subnets in a MAP domain are classified into several subnet types, based on the type classification algorithm in [2]. A subnet type is of the form $< x, y >$, where x indicates that the subnet is in layer x and y represents the $y+1$st type in layer x. Based on the type classification and the concept of absorbing states, the state diagram of the random walk for an n-layer MAP domain is shown in Fig. 1. In this state diagram, state (x, y) represents that the MN is in one of the MAP domains of type $< x, y >$, where the scope of x and y is

$$0 \leq x \leq n, \qquad \begin{cases} 0 \leq y \leq 2x-1 & ,if \quad x \geq 1 \\ y = 0 & ,if \quad x = 0. \end{cases} \tag{1}$$

State (n, y) represents that the MN moves out of the MAP domain from state $(n-1, y)$, where $0 \leq y \leq 2n-3$. For $x = n$ and $0 \leq y \leq 2n-3$, the states (n, y) are absorbing, and the others are transient. For $n > 1$, the total number $S(n)$ of states for the n-layer MAP domain random walk is $n^2 + n - 1$. The transition matrix of this random walk is an $S(n) \times S(n)$ matrix $P = (p_{(x,y)(x',y')})$. Therefore, $P = (p_{(x,y)(x',y')})$ can be defined as the one-stop transition probability from state

(x, y) to state (x', y') (i.e., which represents the probability that the MN moves from a $< x, y >$ subnet to a $< x', y' >$ subnet in one step). We use the Chapman-Kolmogorov equation to compute $p^{(r)}_{(x,y)(x',y')}$, which is the probability that the random walk moves from state (x, y) to state (x', y') with exact r steps. We define $p_{r,(x,y)(n,j)}$ as the probability that an MN initially resides at a $< x, y >$ subnet, moves into a $< n-1, j >$ subnet at the $r-1$ step, and then moves out of the MAP domain at the r step as follows:

$$p_{r,(x,y)(n,y)} = \begin{cases} p_{(x,y)(n,y)} & , for \quad r = 1 \\ p^{(r)}_{(x,y)(n,y)} - p^{(r-1)}_{(x,y)(n,y)} & , for \quad r > 1. \end{cases} \tag{2}$$

4 Signaling Cost Functions

To investigate the performance of MIPv6, HMIPv6 and AHMIPv6, the total signaling costs given to the HA, CN, and MAP to handle mobility of the MNs are analyzed. We assume that the performance metric is the total signaling cost. It consists of the location update cost and packet delivery cost.

4.1 Mobile IPv6

Location Update Cost in MIPv6 We define the costs and parameters used for the performance evaluation of the location update as follows:

- U_{HA} : The location update cost of a BU for the HA
- U_{CN} : The location update cost of a BU for the CN
- U_{MAP} : The location update cost of a BU for the MAP
- u_{hn} : The transmission cost of a BU between the HA and the MN
- u_{cn} : The transmission cost of a BU between the CN and the MN
- u_{mn} : The transmission cost of a BU between the MAP and the MN
- a_h : The processing cost of a location update at the HA
- a_m : The processing cost of a location update at the MAP
- l_{hn} : The average distance between the HA and the MN
- l_{cn} : The average distance between the CN and the MN
- l_{hm} : The average distance between the HA and the MAP
- l_{mn} : The average distance between the MAP and the MN
- δ_U : The proportionality constant for a location update.

According to the signaling message flows for the BU, each cost of location update can be calculated as follows:

$$U_{HA} = a_h + 2u_{hn}, \quad U_{CN} = u_{cn}, \quad U_{MAP} = a_m + 2u_{mn} \tag{3}$$

For simplicity, we assume that the transmission cost is proportional to the distance, in terms of the number of hops between the source and destination mobility agents, such as the HA, MAP, CN and MN. Using the proportional constant δ_U, each cost of location update can be rewritten as follows:

$$U_{HA} = a_h + 2l_{hn} \cdot \delta_U, \quad U_{CN} = l_{nc} \cdot \delta_U, \quad U_{MAP} = a_m + 2l_{mn} \cdot \delta_U \tag{4}$$

We derive the number of subnet crossings and location updates between the beginning of one session and the beginning of the next session before an MN leaves the first MAP domain. Similar to [1], we define the additional costs and parameters used for the performance evaluation of the location update as follows.

- r : The number of the MN's subnet crossings
- d : The number of subnet crossings before an MN leaves the first MAP domain
- t_d : The time interval between the beginning of one session and the beginning of the next session
- $r(t_d)$: The number of the MN's subnet crossings during t_d
- l : The number of subnet crossings before an MN leaves the first MAP domain during t_d
- N : The total number of subnets within a MAP domain
- $1/\lambda_m$: The expected value for the subnet residence time
- $1/\lambda_d$: The expected value for the t_d distribution
- σ : The number of the CNs that have a binding cache for the MN

We assume that an MN is in any subnet of a MAP domain with equal probability. This implies that the MN is in subnet $< 0, 0 >$ with a probability of $1/N$ and is in a subnet of type $< x, y >$ with a probability of $4/N$, where $N = 4n^2 - 4n + 1$ is the number of subnets covered by an n-layer MAP domain. From (2), we derive d as the number of subnet crossings before an MN leaves the first MAP domain as follows:

$$d = \frac{1}{N}\left(\sum_{k=1}^{\infty} k \cdot \sum_{j=0}^{2n-3} p_{k,(0,0)(n,j)}\right) + \frac{4}{N}\left(\sum_{k=1}^{\infty} k \cdot \sum_{x=0}^{n-1}\sum_{y=0}^{2x-1}\sum_{j=0}^{2n-3} p_{k,(x,y)(n,j)}\right) \tag{5}$$

We denote $\alpha(r)$ as the probability that an MN will leave the MAP domain at the rth step provided that the MN is initially in an arbitrary subnet of the MAP domain as follows:

$$\alpha(r) = \frac{1}{N}\left(\sum_{j=0}^{2n-3} p_{r,(0,0)(n,j)}\right) + \frac{4}{N}\left(\sum_{x=1}^{n-1}\sum_{y=0}^{2x-1}\sum_{j=0}^{2n-3} p_{r,(x,y)(n,j)}\right) \tag{6}$$

Note that the above derivations are based on the equal moving probability assumption, thus, we derive the number of subnet updates between the beginning of one session and the beginning of the next session. Fig. 2 shows the timing diagram of the activities for an MN. Assume that the previous session of the MN begins at time t_0, and the next session begins at time t_1. Let $t_d = t_1 - t_0$, which has a general distribution with a density function of $f_d(t_d)$, and expect a value of $1/\lambda_d$, and Laplace Transform

$$f_d^*(s) = \int_{t_d=0}^{\infty} e^{-st_d} f_d(t_d) dt_d \tag{7}$$

We denote $r(t_d)$ as the number of location updates for the MAP during the period t_d. Since an MN needs to register with the MAP whenever it moves in HMIPv6, $r(t_d)$ is equal to the number of subnet crossings during t_d. Assume that

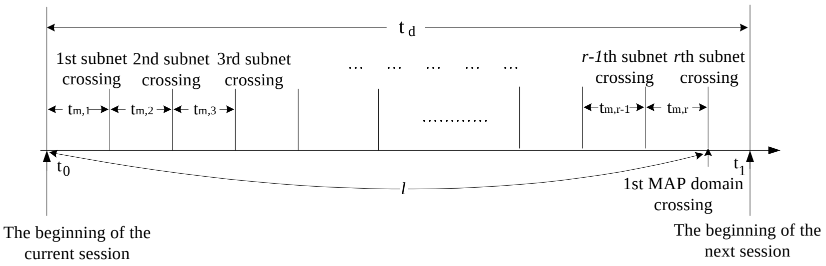


Fig. 2. Time diagram for subnet crossings

the subnet residence time $t_{m,j}$ at j-th subnet has an Erlang distribution, with a mean of $1/\lambda_m = m/\lambda$, variance $V_m = m/\lambda^2$, and density function as follows:

$$f_m(t) = \frac{\lambda e^{-\lambda t}(\lambda t)^{m-1}}{(m-1)!} \ (where \quad m = 1, 2, 3, \cdots) \tag{8}$$

Notice that an Erlang distribution is a special case of the Gamma distribution, where the shape parameter m is a positive integer. Since the subnet crossings of an MN can be modelled as an equilibrium Erlang-renewal process, we can get the probability mass function of the number of subnet crossings $r(t_d)$ within t_d from (7) and (8) as follows:

$$\begin{aligned} Pr[r(t_d) = k] &= \int_{t_d=0}^{\infty} \frac{e^{-\lambda t_d}}{m} \qquad\qquad (9) \\ &\times \Bigg(\sum_{j=km}^{km+m-1} \left[\frac{(km+m-j)(\lambda t_d)^j}{j!} \right] - \sum_{j=km-m}^{km-1} \left[\frac{(j-km+m)(\lambda t_d)^j}{j!} \right] \Bigg) \cdot f_d(t_d)\ dt_d \\ &(where\ k = 1, 2, \cdots) \\ Pr[r(t_d) = 0] &= \int_{t_d=0}^{\infty} \frac{e^{-\lambda t_d}}{m} \sum_{j=0}^{m-1} \left[\frac{(m-j)(\lambda t_d)^j}{j!} \right] \cdot f_d(t_d)\ dt_d \end{aligned}$$

We denote l as the number of subnet crossings before an MN leaves the first domain during t_d. From (5) and (9), we can get $d(t_d)$ as follows:

$$\begin{aligned} l &= \frac{1}{N} \left(\sum_{k=1}^{l} k \cdot \sum_{j=0}^{2n-3} p_{k,(0,0)(n,y)} \cdot Pr[r(t_d) = k] \right) \\ &+ \frac{4}{N} \left(\sum_{k=1}^{l} k \cdot \sum_{x=0}^{n-1} \sum_{y=0}^{2x-1} \sum_{j=0}^{2n-3} p_{k,(x,y)(n,j)} \cdot Pr[r(t_d) = k] \right) \end{aligned} \tag{10}$$

In MIPv6, an MN sends a BU message whenever it changes its point of attachment transparently to the IPv6 networks. From (4)-(10), we can get the total location update cost before an MN leaves the first MAP domain during t_d in

MIPv6 as follows:

$$U=\Big(U_{HA}+\sigma\cdot U_{CN}\Big)\cdot\sum_{j=0}^{l}\big(j\cdot Pr[r(t_d)=j]\cdot\alpha(j)\big) \tag{11}$$

Packet Delivery Cost in MIPv6 The packet delivery cost consists of transmission and processing costs. First of all, we define the additional costs and parameters used for the performance evaluation of the packet delivery cost as follows:

- f_{ch} : The transmission cost between the CN and the HA
- f_{hn} : The transmission cost between the HA and the MN
- f_{cn} : The transmission cost between the CN and the MN
- l_{ch} : The average distance between the CN and the HA
- v_h : The processing cost of the packet delivery at the HA
- $E(S)$: The average session size in the unit of the packet
- λ_α : The packet arrival rate for each MN
- δ_D : The proportionality constant for the packet delivery
- δ_h : The packet delivery processing cost constant at the HA

In MIPv6, route optimization is used to resolve the triangular routing problem. Thus, only the first packet of a session transits to the HA to detect whether or not an MN moves into foreign networks. Subsequently, all successive packets of the session are directly routed to the MN. As a result, the packet delivery cost during t_d can be expressed as follows:

$$F=\lambda_\alpha(f_{ch}+f_{hn}+(E(S)-1)f_{cn})+\lambda_\alpha\delta_h \tag{12}$$

We assume that the transmission cost of the packet delivery is proportional to the distance between the sending and receiving mobility agents, with the proportionality constant δ_D. Therefore, f_{ch}, f_{hn}, and f_{cn} can be represented as $f_{ch}=l_{ch}\delta_D$, $f_{hn}=l_{hn}\delta_D$, and $f_{cn}=l_{cn}\delta_D$. Also, we define the proportionality constant as δ_h. The δ_h is a packet delivery processing constant for the lookup time of a binding cache at the HA. Therefore, v_h can be represented as $v_h=\lambda_\alpha\delta_h$. Finally, we can get the packet delivery cost during t_d as follows:

$$F=\lambda_\alpha\big(l_{ch}+l_{hn}+(E(S)-1)l_{cn}\big)\delta_D+\lambda_\alpha\delta_h \tag{13}$$

Based on the above analysis, we get the total signaling cost function in MIPv6 from (11) and (13):

$$C_{MIP}(\lambda_m,\lambda_d,\lambda_\alpha)=U+F \tag{14}$$

4.2 Hierarchical Mobile IPv6

To investigate the performance of HMIPv6, we define the additional costs and parameters used for the performance evaluation of location updates as follows.

- l_{cm} : The average distance between the CN and the MAP

- δ_m : The packet delivery processing cost constant at the MAP

In HMIPv6, an MN sends a BU message to the MAP whenever it moves within the MAP domain after the registration with the HA. From (4) and (11), we can get the total location update cost before an MN leaves the first MAP domain during t_d in HMIPv6 as follows:

$$U^{'} = U_{HA} + \sigma \cdot U_{CN} + U_{MAP} \sum_{j=0}^{l} \Big(j \cdot Pr[r(t_d) = j] \cdot \alpha(j) \Big) \tag{15}$$

In HMIPv6, all packets destined for the MN are forwarded by the HA and the MAP using the encapsulation and decapsulation process. In a similar manner to HMIPv6, we define a proportionality constant of δ_m. The δ_m is a packet delivery processing constant for the lookup time of a binding cache at the MAP. From (12), we can get the total packet delivery cost during t_d in HMIPv6 as follows:

$$F^{'} = \lambda_\alpha \Big((l_{ch} + l_{hm} + l_{mn}) + (E(S) - 1)(l_{cm} + l_{mn}) \Big) \delta_D + \lambda_\alpha (\delta_h + E(S)\delta_m) \tag{16}$$

Based on the above analysis, we get the total signaling cost function in HMIPv6 from (15) and (16) as follows:

$$C_{HMIP}(\lambda_m, \lambda_d, \lambda_\alpha) = U^{'} + F^{'} \tag{17}$$

4.3 Adaptive Hierarchical Mobile IPv6

The optimal value of T_m is defined as the value of l that minimizes the cost function derived in Section 4.1 and 4.2. To get the value of T_m, we define the cost difference function between MIPv6 and HMIPv6 as follows:

$$\Delta(l, \lambda_m, \lambda_d, \lambda_\alpha) = C_{MIP} - C_{HMIP} \tag{18}$$

Given Δ, the algorithm to find the optimal value of l is defined as follows:

$$T_m(\lambda_m, \lambda_d, \lambda_\alpha) = \begin{cases} 0 & , if\ \Delta(l, \lambda_m, \lambda_d, \lambda_\alpha) > 0 \\ maximum(l : \Delta(l, \lambda_m, \lambda_d, \lambda_\alpha) \leq 0) & , otherwise \end{cases} \tag{19}$$

The optimal value of T_m is a designed value. It is computed before the communications based on the average packet arrival rate λ_α, average mobility rate λ_m, and average λ_d. In the AHMIPv6, an MN sends the BU message to the CN with either an LCoA or an RCoA. If the number of subnet crossings, m, is less than T_m, the MN sends the BU message to the CN with an LCoA after the registration with the HA and MAP. Otherwise, the MN sends a BU message to the CN with an RCoA. From (11),(15) and (19), we can get the total location update cost before an MN leaves the first MAP domain during t_d in the AHMIPv6 as follows:

$$U^{''} = \begin{cases} U_{HA} + (U_{MAP} + \sigma \cdot U_{CN}) \sum_{j=0}^{T_m} \big(j \cdot Pr[r(t_d) = j] \alpha(j) \big), \ if \ \ T_m < j \\ U_{HA} + U_{MAP} \sum_{j=0}^{l} \big(j \cdot Pr[r(t_d) = j] \alpha(j) \big) + \sigma \cdot U_{CN} \\ \times \sum_{j=0}^{T_m} \big(j \cdot Pr[r(t_d) = j] \alpha(j) \big) \qquad , if \ \ T_m \geq j \end{cases} \tag{20}$$

In the AHMIPv6, when a CN sends a packet to the MN, the packets are directly forwarded to the MN using an LCoA, if m is less than T_m. Otherwise, the packets are indirectly forwarded to the MN via the MAP using the RCoA. From (12) and (16), therefore, we can get the total packet delivery cost during t_d in AHMIPv6 as follows:

$$F^{''} = \begin{cases} F, & if \;\; T_m < j \\ \\ F^{'}, & if \;\; T_m \geq j \end{cases} \tag{21}$$

Based on the above analysis, we get the total signaling cost function in AHMIPv6 from (20) and (21) as follows:

$$C_{AHMIP}(\lambda_m, \lambda_d, \lambda_\alpha) = U^{''} + F^{''} \tag{22}$$

5 Numerical Results

Table 1. Performance Analysis Parameters

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
N	49	L	28	α	1.5	κ	1-10
λ_α	0.01-10	λ_i	0.01-10	λ_m	0.01-10	λ_d	0.01-10
a_m	20	a_h	30	δ_m	10	δ_D	0.2
δ_U	15	δ_h	15	n	1-10	σ	1-10

In this section, we will demonstrate some numerical results. Table 1 shows some of the parameters used in our performance analysis that are discussed in [1]. For simplicity, we assume that the distance between the mobility agents is fixed and has the same number of hops (i.e., $l_{ch} = l_{cm} = l_{hm} = l_{mn} = l_{cn} = 10$).

Fig. 3 (a) and (b) show the effect of the mobility rate λ_m on the total signaling cost for $\lambda_\alpha = 1$ and $\lambda_d = 0.01$. As shown in Fig. 3 (a) and (b), the total signaling cost increases as the mobility rate λ_m increases. We can see that the performance of the AHMIPv6, on the whole, results in the lowest total signaling cost, compared with MIPv6 and HMIPv6. These results are expected because the AHMIPv6 scheme tries to reduce the signaling loads at the MAP for the small value of λ_m in the same way as MIPv6. For the large value of λ_m, the AHMIPv6 scheme tries to reduce the location update costs by sending a BU message to the CN with an RCoA in the same way as HMIPv6.

Fig. 3 (c) and (d) show the effect of the packet arrival rate λ_α on the total signaling cost for $\lambda_m = 1$ and $\lambda_d = 0.01$. As shown in Fig. 3 (c) and (d), the total signaling cost increases as the packet arrival rate λ_α increases. We can see that the performance of the AHMIPv6, on the whole, results in the lowest total signaling cost compared with MIPv6 and HMIPv6. From the above analysis of the results, the AHMIPv6 scheme has a considerable performance advantages over

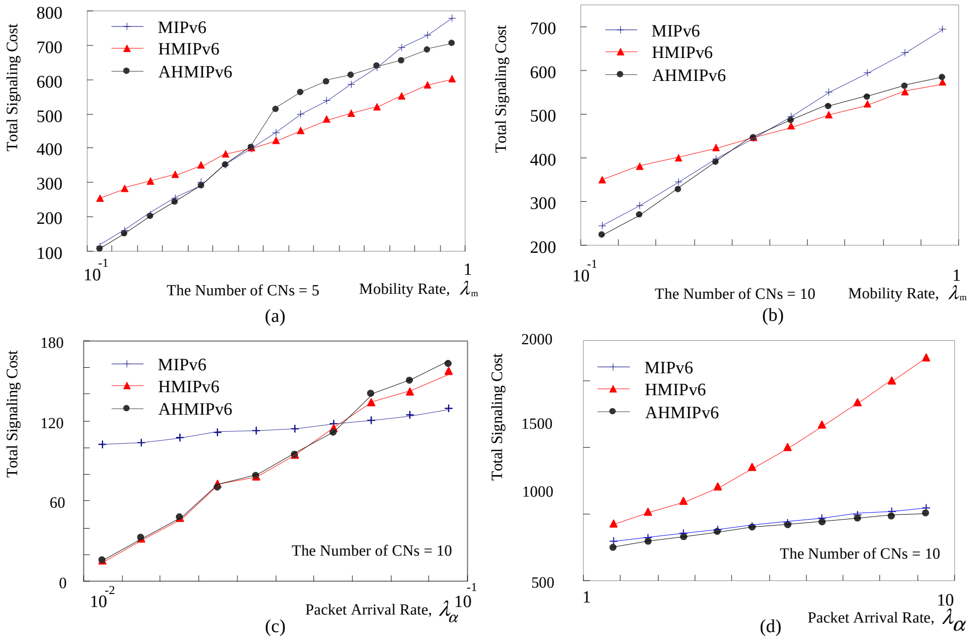


Fig. 3. Effects of Mobility Rate and λ_α on the Total Signaling Cost

MIPv6 and HMIPv6. So, we conclude that the AHMIPv6 achieves significant performance improvements by using the MN's selection to send a BU message to the CN, either with an LCoA or an RCoA.

6 Conclusions

In this paper, we proposed an adaptive mobility management scheme for minimizing signaling costs in HMIPv6 networks. In our proposal, location registration with the HA and MAP is exactly the same as that in HMIPv6. However, the MN sends a BU message to the CN with either an LCoA or an RCoA, based on the geographical locality properties of the MN's movements. The cost analysis presented in this paper shows that the AHMIPv6 scheme achieves significant performance improvements by using the MN's selection to send a BU message to the CN, either with an LCoA or an RCoA.

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