Mobility in IPv6: Whether and How to Hierarchize the Network?

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Abstract—Mobile IPv6 (MIPv6) offers a basic solution to support mobility in IPv6 networks. Although Hierarchical MIPv6 (HMIPv6) has been designed to enhance the performance of MIPv6 by hierarchizing the network, it does not always outperform MIPv6. In fact, two solutions have different application scopes. Existing work studies the impact of various parameters on the performance of MIPv6 and HMIPv6, but without analyzing their application scopes. In this paper, we propose a model to analyze the application scopes of MIPv6 and HMIPv6, through which an Optimal Choice of Mobility Management (OCMM) scheme is designed. Different from the existing work that either propose new mobility management schemes or enhance existing mobility management schemes, OCMM chooses the better alternative between MIPv6 and HMIPv6 according to the mobility and service characteristics of users, addressing *whether* to hierarchize the network. Besides that, OCMM chooses the best mobility anchor point and regional size when HMIPv6 is adopted, addressing *how* to hierarchize the network. Simulation results demonstrate the impact of key parameters on the application scopes of MIPv6 and HMIPv6 as well as the optimal regional size of HMIPv6. Finally, we show that OCMM outperforms MIPv6 and HMIPv6 in terms of total cost including average registration and packet delivery costs.

Index Terms—Mobile IPv6, hierarchical mobile IPv6, application scope, regional size.

1 Introduction

To accommodate mobility for IPv6 Internet, the Internet Engineering Task Force proposed MIPv6 [1] protocol, which enables mobile nodes (MNs) to move from one subnet to another while maintaining reachability and all ongoing communications. MIPv6 deploys a home agent (HA) in a network to bind an MN's identifier with locator. Once the MN changes its point of attachment in a visited network, it is required to register the HA to inform its new locator. In the case that the MN moves far from the HA and performs frequent handovers within a local region, the delay for registering the HA prolongs and thus increasing handover latency.

A common approach to the above problem is to hierarchize the network, thus separating macromobility (handovers across regions) from micromobility (handovers within a region). Here, MIPv6 is employed to manage macromobility whereas some specific micromobility schemes are employed to cope with micromobility. When an MN performs handovers within a region, it need not to notify its correspondent nodes (CNs) and HA, hence reducing handover latency.

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As a well-known micromobility scheme, HMIPv6 [2] has attracted significant attention owing to its simplicity and efficiency. In an HMIPv6 network, a mobility anchor point (MAP) is deployed as a local HA for handling micromobility. As shown in Fig. 1, each MAP administers a set of access routers (ARs) that form a region. The number of different ARs managed by an MAP is defined as regional size. When an MN enters a new region, it needs to register the MAP and HA. If the MN moves within the region, it only needs to register the MAP. The MAP intercepts all packets destined to the MN and tunnels packets to it. In HMIPv6, more than one MAP can be deployed in a domain to avoid the single point of failure.

HMIPv6 is proposed to enhance the performance of MIPv6 by shielding an MN's micromobility from the CNs and HA. But can it realize the aim in all scenarios? Let us analyze this problem. When MNs roam within the region, the handover latency using HMIPv6 is smaller than that using MIPv6. However, this profit is obtained by paying two costs. The first cost is double-registration, which means an MN needs to launch not only a regional registration to its MAP, but also a home registration to its HA when it roams across regions. Double-registration undoubtedly increases handover latency. The second cost is long packet delivery time. Because all packets destined to MNs will be tunneled by the MAP, the packet processing delay of the MAP prolongs packet delivery delay. If the MAP is not the gateway, the packet delivery path will not be optimal, further lengthening packet delivery latency. If these two costs are greater than the profit, HMIPv6 cannot outperform MIPv6.

In addition, MAP and regional size are critical to the performance of HMIPv6. The heavier the load of MAP, the longer is its packet processing latency. Moreover, a smaller regional size leads to a more frequent macromobility of MNs, which triggers a more frequent double-registration; a

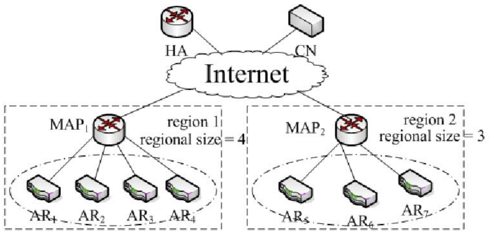


Fig. 1. Framework of HMIPv6.

larger regional size generates a higher traffic load on an MAP, which, in turn, delays its packet processing time, thus prolonging packet delivery latency.

In summary, although HMIPv6 is an extension of MIPv6, it does not always outperform MIPv6. Two protocols have different application scopes. Hence, how to minimize the overall registration and packet delivery time through selecting the better alternative between them becomes an interesting problem. Furthermore, in the case that HMIPv6 turns out to be better, MAP and regional size should be well chosen to optimize network performance.

In this paper, we propose a new scheme, called the *Optimal Choice of Mobility Management* (OCMM). The "Optimal Choice" has two meanings: 1) it chooses the better alternative between MIPv6 and HMIPv6 according to the mobility and service characteristics of MNs, addressing *whether* to hierarchize a network; and 2) it chooses the best MAP and regional size when HMIPv6 is adopted, addressing *how* to hierarchize a network.

To realize our purposes, a model is proposed to analyze the relative cost of HMIPv6 against MIPv6 in terms of average registration and packet delivery delay. To quantitatively derive the impact of regional size on the relative cost of HMIPv6 against MIPv6, a Markov model is used to analyze the mobility of MNs, where MNs can move with arbitrary direction probabilities. After proving that the value of regional size minimizing the relative cost of HMIPv6 against MIPv6 is the same as that the one minimizing the absolute cost of HMIPv6, an algorithm is proposed to choose the better alternative between MIPv6 and HMIPv6, as well as the best MAP and regional size in the case that HMIPv6 is better.

Finally, the performance of OCMM, HMIPv6, and MIPv6 are simulated under 1D and 2D mesh topologies. The results show that OCMM outperforms HMIPv6 and MIPv6 in terms of average registration and packet delivery costs.

The rest of the paper is organized as follows: Related work is presented in Section 2, while Section 3 analyzes the application scopes of MIPv6 and HMIPv6. Then, in Section 4, OCMM is proposed to determine whether and how to hierarchize a network. The simulation results are shown in Section 5. Finally, conclusions are offered in Section 6.

2 Related Work

In recent years, many micromobility management schemes [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13] have proposed to enhance the performance of MIP. In [3], a mailbox-based scheme is proposed, which is essentially a foreign agent (FA)-based hierarchical management solution. The trade-off between location update and packet tunneling costs in a regional MIP network is analyzed in [4], followed by a solution for the optimal regional size. Both [3], [4] require FAs to support mobility management function.

Das et al. [6] proposed a micromobility management architecture in cellular networks, where mobility agents (MAs) are distributed deployed. MNs select MAs according to their loads. Misra et al. proposed a fast handover mechanism [7] for intradomain mobility in 4 G mobile networks. Watanabe and Yabusaki [8] models an MIP network based on a cellular architecture, through which the optimal location area is solved to minimize the sum of location update and paging traffic. The methods of [6], [7], [8] are used in a personal communication system (PCS). A major difference between PCS and Internet is that the former is geographic-oriented while the latter is spatial-oriented [4].

HMIPv6 [2] is a standard for micromobility management. In an HMIPv6 network, more than one MAPs can be deployed in a domain. HMIPv6 suggests selecting the farthest MAP to avoid frequent registrations, which may make the farthest MAP becomes the communication bottleneck. In addition, since each MN has different mobility characteristics, the farthest MAP may not be suitable for MNs with low mobility rate.

To solve the above problem, an MAP selection algorithm is proposed in [9] that takes into account each MN's up-to-date velocity and distance to MAPs. However, this scheme requires MAPs to be organized as a tree structure. In [10], a high-level (respectively, low-level) MAP manages high-mobility (respectively, low-mobility) MNs to decentralize network load. In [11], MAPs are selected through estimating load transition with the exponential moving average method. Besides MAP selection, regional size is also critical to network performance. The optimal regional size utilizing the stochastic Petri net technique in light of MNs' mobility and service behaviors has been determined in [12].

As described above, existing schemes either propose new micromobility management methods or enhance existing micromobility management methods, such as HMIPv6 to shorten packet transmission delay or/and registration delay. Different from the existing schemes, our solution alternates between MIPv6 and HMIPv6 to reduce registration and packet delivery costs in IPv6 mobile Internet. Our reasons are: 1) MIPv6 and HMIPv6 are the most mature mobility management schemes in IPv6 mobile Internet. They have already become standards, which make our scheme easier to deploy in the industrial field. 2) MIPv6 and HMIPv6 have different application scopes, which lead to different performance in various scenarios. The complementary traits of MIPv6 and HMIPv6 can improve the performance of IPv6 mobility management.

In addition, existing literatures [14], [15], [16] study the impact of various network parameters on the performance of MIPv6 and HMIPv6, but do not point out their application scopes. In this paper, a model is developed to analyze the application scopes of MIPv6 and HMIPv6.

3 Application Scopes of MIPv6 and HMIPv6

This section analyzes the application scopes of MIPv6 and HMIPv6 according to the relative registration and packet delivery costs of HMIPv6 against MIPv6.

3.1 Relative Registration Cost

Definition 3.1 (Relative Registration Cost). *Relative registration cost (D_R) is defined as the average registration time saved by using HMIPv6 compared with MIPv6.*

Note that D_R may be positive or negative. $D_R > 0$ means the average registration delay of MIPv6 is shorter than that of HMIPv6, otherwise longer. Our analysis does not consider the periodic binding updates that an MN sends to its HA, CNs, or MAP for refreshing their binding records, because these binding updates do not affect handover latency.

According to RFC3775 [1] and RFC4140 [2], MIPv6 includes only a home registration during a handover. However, HMIPv6 includes a regional registration when an MN roams within a region, as well as a home registration when it roams across regions.

In actual scenario, each MN may access any AR and visit the same AR several times. Let $m \geq 1$ be the number of handovers needed by an MN to move out of a region. In other words, an MN will enter a new region at its mth handover. So the total average delay (D_{IT}) that an MN spends for m handovers in HMIPv6 is

$$D_{IT} = (m-1)D_{intra} + D_{inter}, \tag{1}$$

where D_{intra} and D_{inter} are, respectively, the average registration delays during an intraregion handover and an interregion handover. Without the concept of region, the total average registration delay (D_{AT}) that an MN spends for m handovers in MIPv6 is

$$D_{AT} = m \cdot D_{RM}, \tag{2}$$

where D_{RM} is the average registration delay of MIPv6 in one handover.

According to Definition 3.1, the relative registration cost can be calculated by (3), where T is the average time that an MN resides in an AR. T reflects an MN's mobility rate. The smaller T is, the faster the MN moves, and vice versa. Thus, mT represents the average time that the MN spends in an MAP region.

$$D_R = ((m-1)D_{intra} + D_{inter} - m \cdot D_{RM})/(m \cdot T). \tag{3}$$

To compute D_R, we use D_{intra}, D_{inter}, and D_{RM} as input parameters like [13], which can be estimated by statistical data. Only when $D_R < 0$, HMIPv6 can gain the average registration revenue. To make $D_R < 0$, m needs to satisfy the following inequality:

$$m > (D_{inter} - D_{intra})/(D_{RM} - D_{intra}). \tag{4}$$

In fact, m lies on regional size. To further analyze the relative registration cost, let us analyze the relationship between m and regional size.

3.2 Relationship between m and Regional Size

To analyze the relationship between m and regional size, we study the mobility of an MN using the Markov chain, where the state represents an AR that the MN accesses and the transition probability is the MN's movement direction probability. When regional size is K, no matter which direction the MN moves toward, the MN leaves the region once the number of different ARs it has visited exceeds K. Hence, we introduce the absorbing state "O" to represent the ARs outside the region. According to the property of absorbing state, once entered, it cannot be left. In other words, there is a self-transition to this state with a probability of one.

Even though starting from the same AR, an MN may visit different sets of ARs under different movement routes, hence leading to visiting different regions. Given regional size K, let Ψ be the set of regions that an MN may reach before the number of different ARs that it has visited from the starting point beyond K. And also let N_Ψ be cardinality of Ψ. In 1D topology, N_Ψ is 2. While in 2D mesh topology, N_Ψ can be calculated by

$$N_\Psi = \begin{cases} 1, & K = 1, \\ 4 \times 3^{K-2}, & K \geq 2. \end{cases} \tag{5}$$

We use the idea of [17] to analyze the average intraregion handover times of an MN before it moves out of a region with size K. Assuming that $b_{i,j}$ be the number that an MN visits state j before moving out of the region when it starts from state i. Let B be the matrix with elements $b_{i,j}$. If state i is not equal to state j, there are two cases: 1) the MN starts from i, after one handover, it arrives at another state k. In this case, the number of visiting state j is $b_{k,j}$; and 2) the MN starts from i, after one handover, it goes into the absorbing state. In this case, the number of visiting state j is zero. Thus, if state i is not equal to state j, $b_{i,j}$ can be calculated by (6), where $P_{i,k}$ is the transition probability from state i to state k and s_i is the ith ($i \in \Psi$) MAP region.

$$b_{i,j} = \sum_{k \in s_i} P_{i,k} \cdot b_{k,j} \quad i \neq j. \tag{6}$$

If state i is equal to state j, $b_{i,j}$ means the total number that an MN visits state i before moving out of the region when it starts from state i. In this case, the number of visiting state i should be counted once when the MN initially visits state i. Thus, $b_{i,j}$ can be calculated by

$$b_{i,j} = 1 + \sum_{k \in s_i} P_{i,k} \cdot b_{k,j} \quad i = j. \tag{7}$$

According to (6) and (7), matrix B can be solved by (8), where P is the transition probability matrix of inner states.

$$B = I + PB. \tag{8}$$

According to (8), $B = (I - P)^{-1}$. Because the intrahandover number before an MN goes out of a region is the sum of its visiting all inner states starting from the origin, when the region is s_i with size K, the average number of intraregion handovers is

$$m_K(s_i) = \sum_{j \in s_i} b_{0,j}. \tag{9}$$

Thus, the expected number of handovers required by an MN to move out of a region with size K is

$$m_K = \sum_{i=1}^{N_\Psi} P(s_i(K)) \cdot m_K(s_i), \tag{10}$$

where $P(s_i(K))$ is the probability that the MN visits the ith region with K different ARs. To solve $P(s_i(K))$, we use the

TABLE 1
Boundary Conditions

Topo.	Boundary conditions
1-D	$P(1/0) = P_{0,1}, P(-1/0) = P_{0,-1}$
2-D	$P((0,1)/(0,0)) = P_{(0,0),(0,1)}, P((0,-1)/(0,0)) = P_{(0,0),(0,-1)}$ $P((1,0)/(0,0)) = P_{(0,0),(1,0)}, P((-1,0)/(0,0)) = P_{(0,0),(-1,0)}$

following method. Let $s_i(j)$ be the set of the first different j ARs that the MN visits within s_i. Then, $P(s_i(K))$ can be obtained by

$$P(s_i(K)) = P(s_i(K-1)) \cdot P(s_i(K)/s_i(K-1)), \tag{11}$$

where $P(s_i(K)/s_i(K-1))$ is the probability that the MN visits K different ARs within $s_i(K)$ under the condition that it has visited $(K-1)$ different ARs within $s_i(K-1)$. It is equal to the probability that the MN visits the Kth AR after it have visited the first $(K-1)$ different ARs within s_i. $P(s_i(K)/s_i(K-1))$ can be calculated by

$$\begin{aligned} P(s_i(K)/s_i(K-1)) &= P_{(K-1),K} + P_{(K-1),(K-2)} \\ &\cdot P(s_i(K-1)/s_i(K-2)) \cdot P(s_i(K)/s_i(K-1)). \end{aligned} \tag{12}$$

In (12), $P_{(K-1),K}$ is the probability that the MN visits the Kth AR directly from the $(K-1)$th AR. However, the MN can reach the Kth AR through another route. Specifically, the MN may directly move to the $(K-2)$th AR from the $(K-1)$th AR with probability $P_{(K-1),(K-2)}$, from which the MN may visit other ARs and then go back to the $(K-1)$th AR with probability $P(s_i(K-1)/s_i(K-2))$, and finally the MN may visit the Kth AR with probability $P(s_i(K)/s_i(K-1))$. According to (12), we have

$$\begin{aligned} &P(s_i(K)/s_i(K-1)) \\ &= \frac{P_{(K-1),K}}{1 - P_{(K-1),(K-2)} \cdot P(s_i(K-1)/s_i(K-2))}. \end{aligned} \tag{13}$$

Given the MN's movement direction probability, according to the boundary conditions shown in Table 1, $P(s_i(K)/s_i(K-1))$ can be obtained by recursion, through which $P(s_i(K))$ can be calculated.

3.3 Relative Packet Delivery Cost

Definition 3.2 (Relative Packet Delivery Cost). *Relative packet delivery cost (D_P) is defined as the average time wasted by using HMIPv6 instead of MIPv6 to forward packets.*

When an MAP is also a gateway of a region, the main difference between HMIPv6 and MIPv6 in terms of packet delivery is packet processing latency of MAP. As a result, the relative packet delivery cost can be formulated as

$$D_P = \alpha \cdot L \cdot K. \tag{14}$$

In (14), α is the average packet arrival rate. $L > 0$ is a coefficient. $L \cdot K$ is the processing latency per packet, which is proportional to the number of different ARs managed by the MAP, i.e., K. Equation (14) shows $D_P > 0$, which means the average packet delivery delay of HMIPv6 is longer than that of MIPv6. This is because in HMIPv6, the packet processing delay of MAP prolongs the whole packet delivery time.

3.4 Relative Cost

As the above sections shown, HMIPv6 outperforms MIPv6 in terms of registration in some scenarios, whereas MIPv6 outperforms HMIPv6 in terms of packet delivery in all scenarios. Thus, different performance metrics lead to different application scopes of MIPv6 and HMIPv6. To analyze their application scopes, we define the relative cost function as follows:

Definition 3.3 (Relative Cost). *Relative cost (D_T) formulates the overall performance of HMIPv6 against MIPv6 in terms of registration and packet delivery costs.*

$$D_T = n_1 \cdot D_R + n_2 \cdot D_P, \tag{15}$$

where $n_1 > 0$ and $n_2 > 0$ are the coefficients.

The reason for choosing D_R and D_P as the components of D_T is that the former affects handover latency, while the latter affects packet delivery latency. Both D_R and D_P are critical to an MN's communication quality. n_1 and n_2 are, respectively, weights of D_R and D_P. They are set according to the preference of users. If a user thinks handover latency is more important than packet delivery latency, he can set $n_1 > n_2$, and vice versa. If a user has no preference for them, he can set $n_1 = n_2$.

4 Description of OCMM

4.1 Optimal Solution for K

As described above, the value of D_T largely depends on the regional size K of an MAP. If K increases, D_R decreases while D_P increases, and vice versa. The value of K that minimizes D_T is the optimal K, denoted as K_{opt}. In another word, $K_{opt} = argmin(D_T(K))$. Through K_{opt}, HMIPv6 can achieve the optimal relative performance.

Since K_{opt} can only be an integer and the relative cost is not a continuous function of K, we adopt the following method which detects the minimum D_T step by step to find K_{opt}. Let us first define the following functions:

$$\triangle(K) = \begin{cases} 1, & if\ D_T(K) > D_T(K-1), \\ 0, & if\ D_T(K) \le D_T(K-1), \end{cases} \tag{16}$$

$$\varphi(x) = \begin{cases} 0, & if\ x \neq 0, \\ 1, & otherwise. \end{cases} \tag{17}$$

Equations (16) and (17) lead to the following minimization function [18]:

$$\varphi(\triangle(K)) = \begin{cases} 0, & if\ D_T(K) > D_T(K-1), \\ 1, & otherwise. \end{cases} \tag{18}$$

According to the minimization function [18], K_{opt} can be calculated using (19). In fact, when K satisfies the condition $D_T(K) - D_T(K-1) > 0$, the computation of K_{opt} is completed. Therefore, the number of iterations for solving the optimal K is $K_{opt} + 1$.

$$K_{opt} = \sum_{K=1}^{\infty} \varphi(\triangle(K)). \tag{19}$$

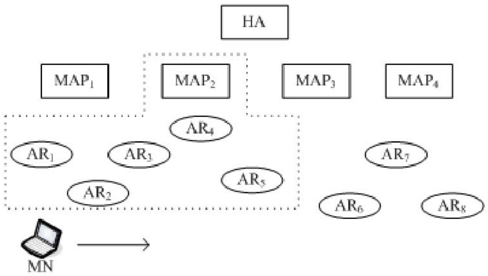


Fig. 2. Example of OCMM.

4.2 OCMM

Actually, K not only influences the relative performance of HMIPv6 against MIPv6, but also the absolute performance of HMIPv6. We define a cost function C_{HMIPv6} to formulate the absolute performance of HMIPv6 in terms of registration and packet delivery costs. It is given by

$$C_{HMIPv6} = n_1 \cdot \frac{(m-1) \cdot D_{intra} + D_{inter}}{m \cdot T} + n_2 \cdot \alpha \cdot (\mu \cdot (l_{HM} + l_{MA} + \eta) + L \cdot K). \tag{20}$$

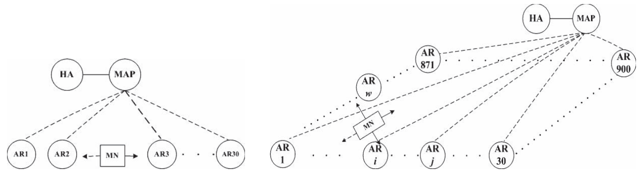
In (20), the first part is the average registration delay while the second part is the average delay that delivers packets from HA to the MN's AR through MAP. Here, we assume that packets are delivered by way of HA. However, this assumption does not affect our following analysis. In other words, if packets are transmitted directly from CN to MAP, our conclusion is also correct. In (20), l_{HM} and l_{MA} are the average distance between HA and MAP, as well as MAP and AR, respectively, μ is the unit distance wired delivery delay. $\mu \cdot \eta$ is the unit wireless delivery delay, where $\eta > 1$ because wireless bandwidth is usually small. The meanings of other parameters are the same as those in (3), (14), and (15).

Theorem 4.1. *The K_{opt} that minimizes D_T also minimizes C_{HMIPv6}, thus making HMIPv6 achieve the optimal relative performance as well as the absolute performance.*

Proof. According to (3), (14), (15), and (20), it can be deduced that $C_{HMIPv6} = D_T + n_1 \cdot D_{RM}/T + n_2 \cdot \alpha \cdot \mu \cdot (l_{HM} + l_{MA} + \eta)$. Since the second and third parts are independent of K, the K_{opt} that minimizes D_T also minimizes C_{HMIPv6}. □

According to the above theorem, K_{opt} can optimize the performance of HMIPv6. However, $D_T(K_{opt}) > 0$ implies that the optimal performance of HMIPv6 is still worse than that of MIPv6. Therefore, the value of $D_T(K_{opt})$ can be used to determine whether to hierarchize the network. Specifically, if $D_T(K_{opt}) > 0$, it is better not to hierarchize the network and thus MIPv6 is an optimal alternative. Otherwise, HMIPv6 is better, and then the question becomes how to hierarchize the network, i.e., which MAP is the best and how many ARs managed by it are optimal. Because C_{HMIPv6} formulates the absolute performance of HMIPv6 and the K_{opt} that minimizes $D_T(K_{opt})$ also minimizes C_{HMIPv6}, the MAP with minimum $D_T(K_{opt})$ value should be chosen as the regional mobility management entity.

Based on the above analysis, we propose OCMM. The operations of an MN in OCMM are shown in Algorithm 1,



(a) 1-D topology (b) 2-D mesh topology

Fig. 3. Simulation topology.

where M is the number of MAPs that the MN hears from the router advertisement messages. We give an example to illustrate OCMM. As shown in Fig. 2, we assume that an MN currently accesses AR_1 and there are four MAPs in the domain, i.e., MAP_1-MAP_4. If the MN leaves its old MAP region, it needs to compute $D_T[i]$ and $K_{opt}[i]$ of MAP_i before it performs the home registration. We assume the results are: $D_T[1] = -0.005$, $K_{opt}[1] = 4$; $D_T[2] = -0.025$, $K_{opt}[2] = 5$; $D_T[3] = 0.01$, $K_{opt}[3] = 5$; $D_T[4] = -0.015$, $K_{opt}[4] = 3$. Because $D_T[2]$ is minimal and negative, the MN adopts HMIPv6 and chooses MAP_2 as the regional mobility management entity. Since $K_{opt}[2] = 5$, the MN considers that the optimal regional size of MAP_2 is 5. As a result, AR_1-AR_5 form a region for the MN.

Algorithm 1. Operation of an MN in OCMM

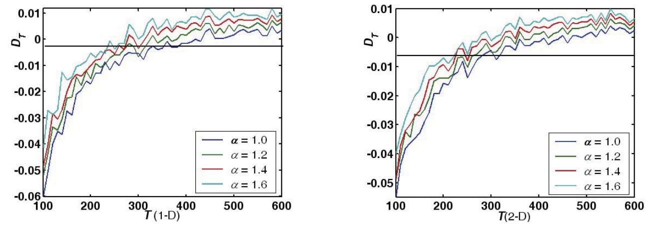
```
IF (MN wants to perform the home registration)
    MN computes the K_opt[i] and D_T[i] of MAP
    i(∈ (1, 2, ..., M));
    OD = min(D_T[i]|i ∈ (1, 2, ..., M));
    OK_opt = arg min(D_T[i]|i ∈ (1, 2, ..., M));
    IF (OD ≥ 0)
        MN adpots MIPv6 as the mobility
        management solution;
    ELSE        //OD < 0
        MN adpots HMIPv6 as the mobility
        management solution;
        MN chooses the MAP whose sequence number
        os OM;
        The chosen Map's regional size is OK_opt;
    ENDIF
ENDIF
```

To compute $D_T[i]$ and $K_{opt}[i]$ of MAP_i, the average dwell time T that an MN stays in an AR, and the average packet arrival rate α should be obtained beforehand. Actually, T can be calculated using the method introduced in [9], [19], while the algorithms for estimating α can be found in [8], [19]. Such parameters can be periodically collected by each MN using statistical data. The period of collecting these parameters lies on experiential data, and how to obtain it is not discussed in the paper due to length limitation.

5 Simulation Results

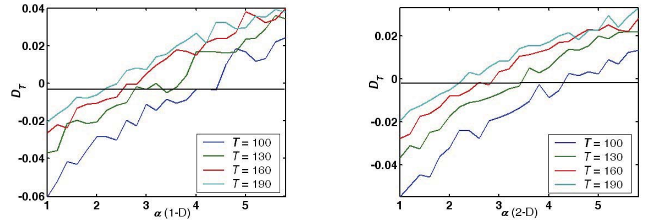
In this section, a C++-based simulator is developed to observe the impact of key parameters on OCMM, and the performance of OCMM, HMIPv6, and MIPv6 in 1D and 2D mesh topologies as shown in Figs. 3a and 3b.

In our simulation, the distance (measured by hops) between the MAP and the HA (respectively, the MAP and



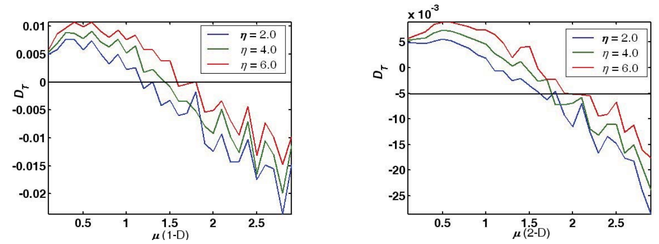
(a) (b)

Fig. 4. Impact of T on D_T.



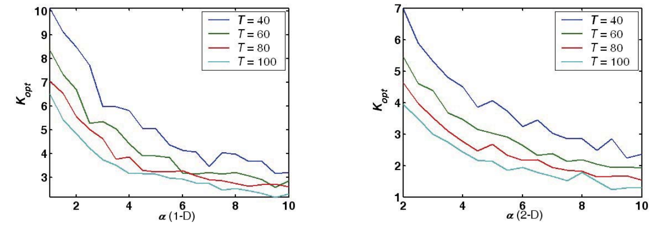
(a) (b)

Fig. 5. Impact of α on D_T.



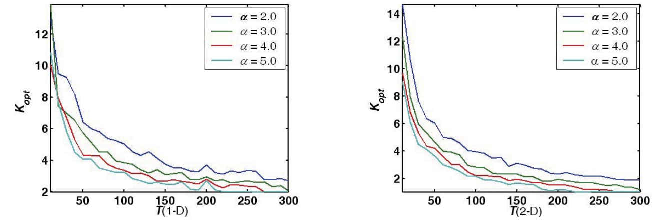
(a) (b)

Fig. 6. Impact of wired/wireless delivery delay on D_T.



(a) (b)

Fig. 7. Impact of α on the average value of K_{opt}.



(a) (b)

Fig. 8. Impact of T on the average value of K_{opt}.

the AR) follows a normal distribution with mean 6 (respectively, 4) and variance 0 (respectively, 0). When simulating MIPv6, the MAP acts as the gateway. The MN can move from the current AR to one of the adjacent ARs with arbitrary probabilities. The average signaling/packet delivery delay of the wired link is proportional to the distance that signals/packets travel. The unit distance wired delivery delay is μ and the wireless delivery delay is $\mu \cdot \eta$. The simulation lasted 8,000 unit time, following which the statistics are collected. In this simulation, the coefficients of n_1, n_2, and L are set to 1, 1, and 0.005, respectively.

5.1 Impact of Key Parameters on OCMM

5.1.1 *Impact of Key Parameters on* D_T

Figs. 4a and 4b, respectively, show the impact of T on D_T in 1D and 2D topologies when $\mu = 1$ and $\eta = 2$. We can see that D_T increases as T increases. This is because T reflects an MN's mobility rate. The increase of T means the MN slows down. When the MN moves slowly, the average registration revenue of HMIPv6 against MIPv6 is small. However, in this scenario, the average packet delivery cost of HMIPv6 is not reduced, resulting in the increase of D_T.

Figs. 5a and 5b, respectively, show the impact of α on D_T in 1D and 2D mesh topologies when $\mu = 1$ and $\eta = 2$. According to these figures, D_T increases with the increase of α. This is due to the fact that the average packet processing delay of MAP in HMIPv6 will increase as α increases, thus leading to the increase of D_T.

Figs. 6a and 6b, respectively, show the impact of μ and η on D_T in 1D and 2D mesh topologies when $T = 500$ and $\alpha = 1.0$. It can be observed that D_T decreases as μ increases. This is because when μ increases, the relative registration profit of HMIPv6 increases, decreasing D_T. On the other hand, from the figures, when μ is unchanged, D_T increases with the increase of η. This is because when an MN performs an interregion handover, it must register the MAP as well as the HA, and hence the registration signals must be transmitted on the wireless link twice. In the case that μ is unchanged and η increases, the relative registration cost of HMIPv6 increases, thus increasing D_T.

In Figs. 4, 5, and 6, no matter how D_T changes, as long as $D_T < 0$, HMIPv6 is the better alternative. Otherwise, it is better for the MN to use MIPv6 as the mobility management solution.

5.1.2 *Impact of Key Parameters on* K_{opt}

Figs. 7a and 7b, respectively, show the impact of α on the average value of K_{opt} in 1D and 2D mesh topologies when $\mu = 1$ and $\eta = 2$. We can observe that the average value of K_{opt} decreases with the increase of α. This is because the larger α is, the heavier is the traffic needed to process by the MAP. In this scenario, decreasing K_{opt} is beneficial to alleviate the processing cost of MAP, further reducing D_T.

Figs. 8a and 8b, respectively, show the impact of T on the average value of K_{opt} in 1D and 2D mesh topologies when $\mu = 1$ and $\eta = 2$. These figures reveal that the average value of K_{opt} increases with decreasing T. This is because the smaller T is, the faster the MN moves, which leads to the higher handover probability and registration frequency. In this scenario, increasing K_{opt} is beneficial to reduce the number of interregion handovers, hence reducing D_T.

Figs. 9a and 9b, respectively, show the impact of μ and η on the average value of K_{opt} in 1D and 2D mesh topologies when $T = 100$ and $\alpha = 2.0$. It can be observed that the average value of K_{opt} increases with the increase of μ and η. The reason behind this fact is the increase of μ and η makes

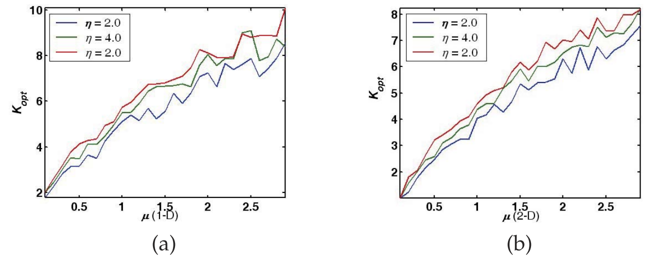


Fig. 9. Impact of wired/wireless delivery delay on the average value of K_{opt}.

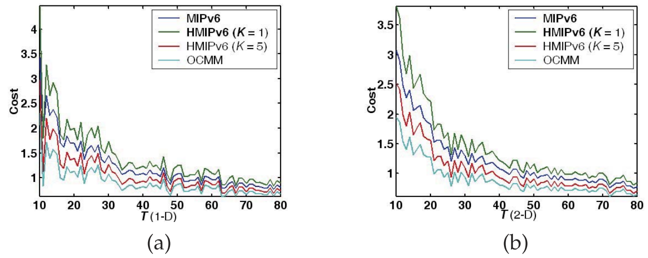


Fig. 10. T versus cost.

the relative registration cost increase. In this case, increasing K_{opt} is beneficial to reduce the frequency of HA registration, thus reducing the relative registration cost and D_T.

5.2 Comparison among MIPv6, HMIPv6, and OCMM

In this section, we compare the performance of MIPv6, HMIPv6, and OCMM in terms of the cost that includes the average registration and packet delivery costs. The cost of HMIPv6 can be calculated by (19) while those of MIPv6 (C_{MIP}) and OCMM (C_{OCMM}) can be calculated as follows:

$$C_{MIP} = n_1 \cdot D_{RM}/T + n_2 \cdot \alpha \cdot (\mu \cdot l_{HA} + \eta), \qquad (21)$$

$$C_{OCMM} = \begin{cases} C_{MIP}, & \text{if } D_T(K_{opt}) > 0, \\ C_{HMIP}(K_{opt}), & \text{otherwise.} \end{cases} \qquad (22)$$

Figs. 10a and 10b, respectively, show how the cost of three schemes in 1D and 2D mesh topologies changes with T when $\mu = 1$, $\eta = 2$, and $\alpha = 0.05$. According to these figures, the cost of each scheme reduces as T increases. This is because the increase of T will reduce average registration delay, further reducing the cost of each scheme.

Figs. 11a and 11b, respectively, show how the cost of three schemes in 1D and 2D mesh topologies changes with α when $\mu = 1$, $\eta = 2$, and $T = 50$. We can observe that the cost of each scheme increases with the increase of α . This is because the increase of α will increase packet delivery delay, further increasing the cost of each scheme.

Figs. 12a and 12b, respectively, show how the cost of three schemes in 1D and 2D mesh topologies changes with μ when $\eta = 2$, $T = 50$, and $\alpha = 0.1$. It can be observed that the cost of each scheme increases with the increase of μ. This is because the increase of μ will increase the registration and packet delivery delay of each scheme, further increasing the cost of each scheme.

All figures including Figs. 10, 11, and 12 show the cost of OCMM is the smallest, which means OCMM outperforms HMIPv6 and MIPv6. This is because OCMM chooses the better alternative between HMIPv6 and MIPv6 for an MN

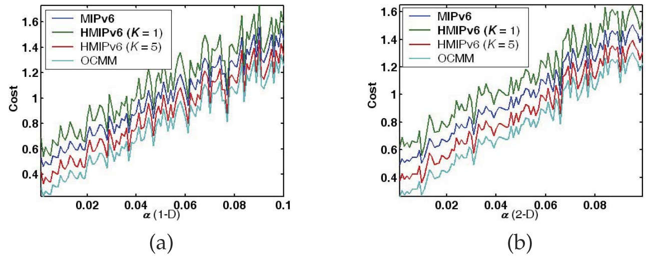


Fig. 11. α versus cost.

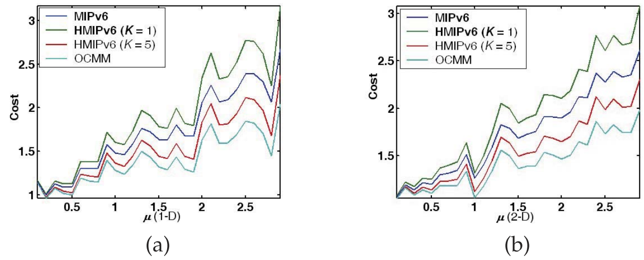


Fig. 12. Wired delivery delay versus cost.

according to its mobility and service characteristics. And when HMIPv6 is chosen, the best MAP and regional size are selected.

6 Conclusion

Both MIPv6 and HMIPv6 are standards of mobility management for IPv6 internet. Although HMIPv6 is an extension of MIPv6, it does not outperform MIPv6 in all scenarios. In this paper, we propose an analytical model to formulate the relative registration and packet delivery costs of HMIPv6 against MIPv6 to analyze their application scopes. Based on the analytical model, a scheme called OCMM is proposed for an MN to choose the better alternative between MIPv6 and HMIPv6. When HMIPv6 is adopted, OCMM decides which MAP is the best and how many ARs managed by it are optimal. Simulation results exhibit the impact of the average packet arrival rate, the average AR dwell time, and the unit wired/wireless delivery delay on the application scopes of MIPv6 and HMIPv6, as well as the optimal regional size of HMIPv6. Finally, it is demonstrated that OCMM outperforms MIPv6 and HMIPv6 in terms of the total cost including the average registration and packet delivery costs.

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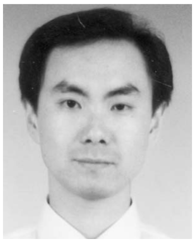

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