Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2010, Article ID 653838, 14 pages
doi:10.1155/2010/653838

Research Article

HH-MIP: An Enhancement of Mobile IP by Home Agent Handover

Jeng-Yueng Chen (EURASIP Member),[1] Chun-Chuan Yang,[2] and Li-Sheng Yu[2]

[1] *Department of Information Networking Technology, Hsiuping Institute of Technology, Taichung 41280, Taiwan*
[2] *Department of Computer Science and Information Engineering, National Chi Nan University, Nantou 54561, Taiwan*

Correspondence should be addressed to Jeng-Yueng Chen, s2321902@ncnu.edu.tw

Received 17 July 2009; Revised 28 February 2010; Accepted 13 March 2010

Academic Editor: Sudip Misra

We propose an enhancement of Mobile IP (MIP) called MIP with Home Agent Handover (HH-MIP) to enjoy most of the advantages of Route Optimization MIP (ROMIP) but with only a small increase of signaling overhead. In HH-MIP, the concept of Temporary HA (THA) is proposed and the mobile host (MH) registers the new CoA with its THA rather than its original HA. Since the THA of an MH is selected to be close to the current location of MH, HH-MIP reduces the handoff latency and shortens the signaling path of registration as well. Moreover, HH-MIP adopts an aggressive approach in selecting THA for an MH, that is, whenever an MH is moving away from its HA or previous THA, the MH triggers the handover of THA. Theoretical analysis demonstrates that the proposed scheme enjoys small handoff latency as well as routing efficiency, and the signaling cost of the proposed scheme is significantly less than that in ROMIP.

1. Introduction

Mobility management in the IP layer [1] is an essential component in wireless mobile networking. Mobile IP (MIP) [2, 3] was proposed to support global Internet mobility through the introduction of location directories and address translation agents. In MIP, a mobile host (MH) uses two IP addresses: a fixed home address and a care-of-address (CoA) that changes at each new point of attachment. A router called Home Agent (HA) on an MH's home network is responsible for maintaining the mapping (binding) of home address to the CoA. When an MH moves to a foreign network, the MH obtains a CoA from the Foreign Agent (FA) and registers the CoA with its HA. In this way, whenever an MH is not attached to its home network, the HA gets all packets destined for the MH and arranges to deliver to the MH's current point of attachment by tunneling packets to the MH's CoA. Some inefficiencies were identified in MIP: (1) triangular routing from the sender (called correspondent node (CN)) to the HA then to the MH leads to unnecessarily large end-to-end packet delay, (2) the HA is inevitably overloaded due to tunneling operations, and (3) when an MH is far away from its home network, the long signaling path for CoA registration leads to a long handoff latency resulting in a high packet loss [4, 5].

To remedy the problem of triangular routing and reduce the packet loss during handoff, Route Optimization MIP (ROMIP) [6, 7] was proposed. ROMIP allows every CN to cache and use binding copies. The original binding for an MH is kept in its HA, but ROMIP supports that a binding copy can be propagated to the requiring nodes. Local bindings in a CN enable most packets in a traffic session to be delivered by direct routing. Moreover, an MH also informs its previous FA about the new CoA, so that the packets tunneled to the old location (due to an out-of-date binding copy) can be forwarded to the current location. This forwarding mechanism in ROMIP reduces the handoff latency and thus reduces the packet loss during handoff. However, the improvement of ROMIP over MIP in terms of routing efficiency and smaller handoff latency is at the cost of significantly larger signaling overhead. One question arises: "is it possible to enjoy most of the advantages of ROMIP but with only a small increase of signaling overhead?" The answer to the question led to the research of this paper.

An interesting point of view about the reason of the disadvantages of MIP in routing and handoff latency is because the MH has the potential to move away from its home network and the HA. If somehow we can dynamically make the HA closer to the current location of MH, both routing and handoff efficiency can be achieved. Since the MH's home address is permanent, the MH's HA should not move. Therefore, the idea of Temporary HA (THA) emerges and the extension of MIP adopting the THA called HA Handover MIP (HH-MIP) is proposed in this paper. As will be shown in the analytical study, HH-MIP enjoys small handoff latency as well as routing efficiency, and signaling cost in HH-MIP is significantly less than that in ROMIP.

The rest of this paper is organized as follows. Some of the related work is briefly surveyed in Section 2. The proposed scheme of MIP with HA handover is presented in Section 3. Analytical studies for performance evaluation and comparison are presented in Section 4. Finally, Section 5 concludes this paper.

2. Related Work

Mobility management is the key to successfully enable seamless mobile services. It enables wireless or mobile networks to search and locate mobile devices for network communications and to maintain connections as the terminal device moves into a new service area. Basically, mobility management consists of two major components: location management and handoff management [4].

Location management enables the system to track the locations of MH between consecutive communications. It includes two major tasks. The first is location registration or location update, where the MH periodically informs the system to update relevant location databases with up-to-date location information. The second is call delivery, where the system determines the current location of MH based on the information available at the system databases when a communication for the MH is initiated.

Handoff management is the process by which an MH keeps its connection active when it moves from one access point to another. Handoff management research concerns issues such as minimizing signaling load on the network, optimizing the router for each connection, reducing packet loss during handoff, efficient use of network resources, and QoS guarantees during the handoff process.

Mobility management solutions can be divided into different layers. Network layer solutions provide mobility related features at the IP layer. They do not rely on or make any assumption about the underlying wireless access technologies [8]. In this paper, we will discuss about mobility management in network layer only. Network layer mobility management solutions can be broadly classified into two categories: macromobility and micromobility. The movement of mobile users between two different network domains is referred to as macro-mobility. As for micro-mobility, mobile users move between two subnets within one administrative domain. Mobile IP (MIP) [2] and Route Optimization (ROMIP) [6] are included into macro-mobility management protocols. Cellular IP (CIP) [9, 10], HAWAII [11], and Hierarchical MIP (HMIP) [12, 13] are some examples of micro-mobility management protocols.

In MIP, an HA is required to maintain the address mapping and packet forwarding for an MH. The MH sends its binding information to HA when its current CoA changes. HA forwards any packets destined for the MH through an IP tunnel to the MH. In this way the ongoing connections are maintained. However, MIP has several drawbacks [14]. A triangle route happens between the MH and CN. It causes extra transmission delay and may exacerbate the jitter in real-time applications. Moreover, HA becomes the traffic bottleneck and a single point of failure.

In order to remedy the problem of triangular routing and reduce packet loss during handoff, ROMIP is proposed. The basic idea of ROMIP is to use a direct route between the MH and its CN to bypass the HA. The CN maintains a binding cache of CoA of MH. Although ROMIP has some advantages over MIP in terms of route efficiency and packet loss latency, it still has shortcomings in term of large signaling overhead [7].

In Dynamic Hierarchical Mobile IP (DHMIP) [15], the location update messages to the HAs can be reduced by setting up hierarchy of FAs, where the level number of the hierarchy is dynamically adjusted based on each mobile user's up-to-date mobility and traffic load information. However the forwarding through multiple FAs will cause some service delivery delay, which may not be appropriate when there is delay restraint for some Internet applications such as video or voice services. In HH-MIP, the THA directly tunnels packets to the MH's current FA resulting in fewer tunneling operations.

In the mailbox-based approach [16], every MH is associated with a mailbox, which is a data structure residing at a mobility agent. If a sender wants to send a packet to an MH, it simply sends the packet to the receiver's mailbox no matter how the current location of the MH is. The mailbox acts as a relay and buffer station of MH. The mailbox forwards the buffered traffic to the MH based on the binding information maintained in it. Although HH-MIP and mailbox share a similar idea to some extent, there are some significant differences between them and will be discussed in Section 3.3.

3. Proposed HH-MIP Approach

3.1. Basic Idea and Data Delivery. As mentioned in Section 1, HH-MIP introduces the concept of Temporary HA (THA), and as in ROMIP each CN is required to maintain two addresses for an MH: the home address of MH and the THA address of MH. The HA of an MH maintains the binding of THA address for the MH. The handover of THA requires the MH to update the binding cache in its HA. The handoff of an MH to a new FA only triggers the registration of new CoA to THA (instead of the HA) when the THA of MH remains unchanged. Since the THA of an MH is selected to be close to the current location of MH, HH-MIP reduces the handoff latency and shortens the signaling path of registration as well.

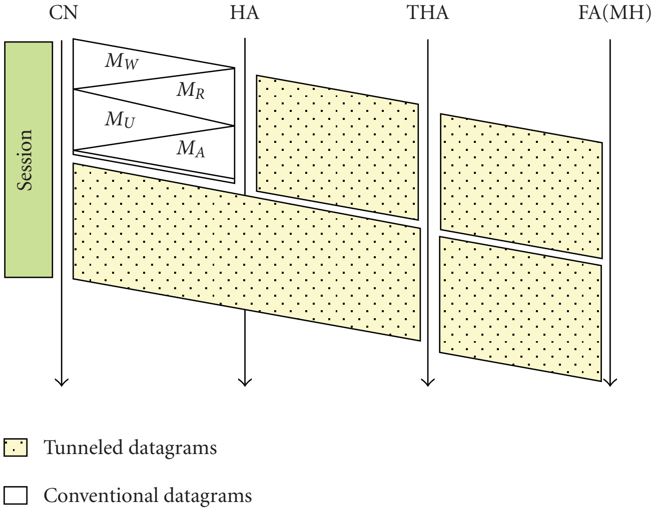


Figure 1: Flow diagram for data delivery in HH-MIP.

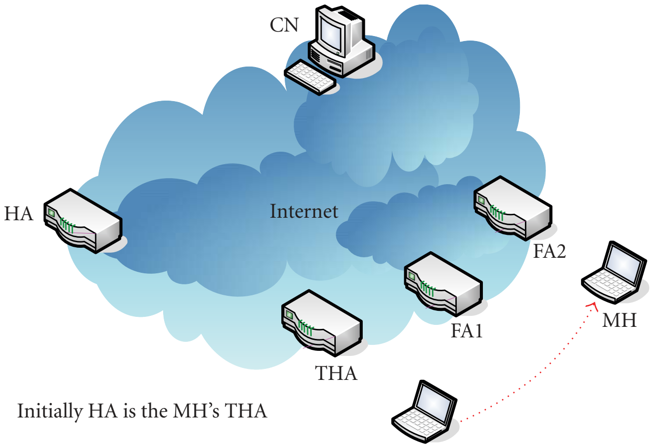


Figure 2: Selection of THA in HH-MIP.

The data delivery in HH-MIP is similar to that in ROMIP as explained in the following. Initially the CN sends packets to the home address of destined MH, the HA intercepts and sends the packets to the THA by tunneling, and the THA tunnels the packets to the current location (FA) of MH. Meanwhile, a binding copy of the MH's THA is sent by the HA to CN so that later packets can be directly delivered to the THA, and the THA tunnels the packets to the current location (FA) of MH. Therefore, regular data delivery in HH-MIP requires the packets sent by the CN to be tunneled twice before they reach the destined MH.

Four messages are used for binding update of THA as in ROMIP: (1) Binding Warning Message (M_W), (2) Binding Request Message (M_R), (3) Binding Update Message (M_U), and (4) Acknowledgment Message (M_A). The HA just after having tunneled the first packet sends an M_W back to the CN informing that the MH is not in the home network. In response to the received M_W, the CN sends an M_R to the HA asking for binding update. The HA replies with an M_U containing the requested CoA (i.e., THA's address). Finally, the CN sends an M_A to the HA acknowledging the successful binding update. Figure 1 illustrates the process of data delivery in HH-MIP.

3.2. THA Handover.

Initially, an MH will select its HA as the THA. HH-MIP adopts an aggressive approach in selecting the THA for an MH: whenever an MH is moving away from the HA or the previous THA, the MH triggers the handover of THA. As illustrated in Figure 2, if the distance (hop count) from FA2 (MH's current location) to THA is longer than the distance from FA1 to THA implying that the MH is moving away from THA, FA2 is selected as the new THA, and the MH notifies its HA of the new THA. On the other hand, if HA is closer to FA2 than THA implying that the MH is moving back to HA, HA should be selected as the new THA (see Algorithm 1).

Once a new FA is selected as the new THA by an MH, the MH sends the Binding Update Message (M_U) to its HA as well as the previous THA. Before the CN gets the

```
if Distance (FA2, HA) < Distance (FA2, THA) then
/*** MH is moving closer to its HA ***/
  HA is selected as the new THA
else if Distance (FA2, THA) > Distance (FA1, THA)
  /*** MH is moving away from its previous THA ***/
    FA2 is selected as its new THA
else
    MH's THA remains the same
```

Algorithm 1

address of new THA (according to the M_U sent by the HA), packets are still tunneled to the previous THA (packets loss in this period), and the previous THA tunnels (forwards) the packets to the current FA (i.e., the new THA) which is similar to the forwarding mechanism in ROMIP. When the binding update of the new THA is complete in the CN, packets are sent directly to the new THA. Flow diagram for the handover of THA is illustrated in Figure 3.

In order to support HH-MIP, each FA or HA must be equipped with the functions of THA. The functions of THA include (1) maintaining a Temporary Children List (TCL) and dealing with the registration of new CoA for every MH in the TCL, and (2) a previous THA for an MH is responsible for forwarding packets to the new THA after the MH performs THA handover.

3.3. Discussion. As mentioned in Section 2, Cao et al. [16] published a similar idea namely mailbox in the IEEE INFOCOM 2004 conference. In the mailbox approach, every MH is associated with a mailbox. If a CN wants to send a packet to an MH, it simply sends the packet to the MH's mailbox no matter how the current location of the MH is. The mailbox acts as a relay and buffer station of the MH. The mailbox forwards the buffered traffic to the MH based on the binding information maintained in it. Although HH-MIP and mailbox share a similar idea to some extent, there are some differences between them as explained as follows.

(i) The decision of mailbox handover is made by the mobile agent which maintains the current mailbox for the MH. As mentioned previously, the decision of THA handover is made by the MH. In general, it is easier for the MH to get information about its communicating sessions and can make more accurately decisions. Moreover, the decision is made based on a pair of thresholds (d; n) in the mailbox approach: if either the distance exceeds d or the communication traffic exceeds n, the mailbox will hand over to the new FA. Nevertheless, the THA handover is made according to a single parameter: distance. When an MH is moving away from its previous THA, the MH triggers the handover of THA. Technologically, HH-MIP is comparatively simple.

(ii) The mailbox approach presented a probability-based analysis in which the two parameters (for distance and traffic as mentioned above) make the analysis complicated. In this paper, a Markovian analysis is proposed for performance evaluation of HH-MIP, which presents more extensive results over the mailbox paper as follows.

   1. The mailbox approach assumed that the size of the network is infinite (i.e., without boundary), but the analysis for HH-MIP considers different network sizes with boundary, which is more realistic.
   2. More performance criteria are analyzed in this paper, including routing efficiency, the handoff latency, and the signaling cost. Routing efficiency and the signaling cost were evaluated in the mailbox paper.
   3. More contrasts for performance comparison are considered in this paper, including MIP and ROMIP. Only ROMIP was considered in the mailbox paper.
   4. Theoretical gain of HH-MIP over MIP and ROMIP in terms of the three performance criteria is calculated, which demonstrates the theoretical potential of the proposed HH-MIP scheme.

4. Performance Evaluation

In this section, we present the theoretical analysis and comparisons between our proposed HH-MIP approach and other protocols such as MIP and ROMIP. Although HH-MIP and mailbox [16] share a similar idea to some extent, there are some fundamental differences between them as mentioned in Section 3.3. Thus, we do not perform the performance comparison against mailbox approach. Criteria for performance evaluation and comparison include (1) routing efficiency (number of hops used in data delivery sent by the CN), (2) handoff latency (number of hops used by a binding update message), and (3) signaling cost (number of hops used by a handoff signaling message).

4.1. Markovian Model. The network topology for the analytical model is a $2n-1 \times 2n-1$ mesh network. Each node in the mesh represents an FA in foreign network. The initial location of MH is randomly selected in the mesh. In order to simplify the complexity of the analytical model, the locations of HA and CN are $(1,1)$ and (n,n), respectively. The MH stays or randomly moves among the mesh network for a period of time. Figure 4 shows the network topology used in the analytical model.

Let $P_{\mathrm{MH}}(i,j)$ denote the probability that the MH is at location (i,j), and let p denote the probability that the MH leaves its current network. As shown in Figure 5, the value of $P_{\mathrm{MH}}(i,j)$ will be the probability that MH stays at location (i,j) plus the probability that the MH moves in from neighbor networks. Thus, the value of $P_{\mathrm{MH}}(1,1)$ can be found as follow:

$$\begin{aligned} P_{\mathrm{MH}}(1,1) &= P_{\mathrm{MH}}(1,1)\times(1-p)+P_{\mathrm{MH}}(1,2)\times\frac{p}{3} \\ &\quad + P_{\mathrm{MH}}(2,1)\times\frac{p}{3} \\ &= \frac{P_{\mathrm{MH}}(1,2)}{3}+\frac{P_{\mathrm{MH}}(2,1)}{3}. \end{aligned} \tag{1}$$

$P_{\mathrm{MH}}(1,2), P_{\mathrm{MH}}(1,3),\ldots,$ and so forth, can also be expressed by similar equations:

$$\begin{aligned} P_{\mathrm{MH}}(1,2) &= \frac{P_{\mathrm{MH}}(1,1)}{2}+\frac{P_{\mathrm{MH}}(1,3)}{3}+\frac{P_{\mathrm{MH}}(2,2)}{3}, \\ P_{\mathrm{MH}}(1,3) &= \frac{P_{\mathrm{MH}}(1,2)}{3}+\frac{P_{\mathrm{MH}}(1,4)}{3}+\frac{P_{\mathrm{MH}}(2,3)}{4},\ldots, \end{aligned} \tag{2}$$

and $\sum_{i=1}^{2n-1}\sum_{j=1}^{2n-1} P_{\mathrm{MH}}(i,j)=1$.

Therefore, those simultaneous equations can be solved as follows:

$$\begin{aligned} P_{\mathrm{MH}}(1,1) &= P_{\mathrm{MH}}(1,2n-1) = P_{\mathrm{MH}}(2n-1,1) \\ &= P_{\mathrm{MH}}(2n-1,2n-1) = \frac{1}{2}\times\frac{1}{4n^2-6n+2}, \\ P_{\mathrm{MH}}(1,a) &= P_{\mathrm{MH}}(2n-1,a) = P_{\mathrm{MH}}(a,1) \\ &= P_{\mathrm{MH}}(a,2n-1) = \frac{3}{4}\times\frac{1}{4n^2-6n+2}, \\ P_{\mathrm{MH}}(a,b) &= \frac{1}{4n^2-6n+2}, \end{aligned} \tag{3}$$

where $a,b\in\{2,3,\ldots,2n\}$.

Let $P_{\mathrm{THA}}(i,j)$ denotes the probability that the THA is at location (i,j). As mentioned in Section 3, the THA of an MH is selected to be close to the current location of MH. In HH-MIP, the THA will remain the same if the MH leaves the current THA one hop away since the MH has a chance to move back to the current THA. The THA will hand over to new FA of MH if MH leaves the current THA two hops away. Therefore, $P_{\mathrm{THA}}(i,j)=0$ if $i+j$ is odd.

As marked in Figure 5, $P_{\mathrm{THA}}(1,1)$ includes (a) the probability that the MH stays in $(1,1)$, (b) probabilities that the MH moves into $(1,2)$ or $(2,1)$ from $(1,1)$, (c) probabilities that the MH stays in $(1,2)$ or $(2,1)$, and (d) probabilities that the MH moves into $(1,1)$ from $(1,2)$ or $(2,1)$:

$$\begin{aligned} P_{\mathrm{THA}}(1,1) &= P_{\mathrm{MH}}(1,1)+P_{\mathrm{MH}}(1,2)\times\frac{p}{3}+P_{\mathrm{MH}}(1,2) \\ &\quad\times\frac{1-p}{3}+P_{\mathrm{MH}}(2,1)\times\frac{p}{3}+P_{\mathrm{MH}}(2,1) \\ &\quad\times\frac{1-p}{3} \\ &= P_{\mathrm{MH}}(1,1)+\frac{P_{\mathrm{MH}}(1,2)}{3}+\frac{P_{\mathrm{MH}}(2,1)}{3} \\ &= \frac{1}{4n^2-6n+2}. \end{aligned} \tag{4}$$

Similar to the derivation of P_{MH}, we can find the probability of P_{THA}:

$$\begin{aligned} P_{\mathrm{THA}}(i,j) &= 0 \quad \text{if } i+j \text{ is odd}, \\ P_{\mathrm{THA}}(1,1) &= P_{\mathrm{THA}}(1,2n-1) = P_{\mathrm{THA}}(2n-1,1) \\ &= P_{\mathrm{THA}}(2n-1,2n-1) = \frac{1}{4n^2-6n+2}, \\ P_{\mathrm{THA}}(1,c) &= P_{\mathrm{THA}}(2n-1,c) = P_{\mathrm{THA}}(c,1) = P_{\mathrm{THA}}(c,2n-1) \\ &= \frac{3}{2}\times\frac{1}{4n^2-6n+2}, \\ &\quad \text{where } c=3,5,7,\ldots,2n-3, \\ P_{\mathrm{THA}}(a,b) &= \frac{2}{4n^2-6n+2}, \\ &\quad \text{where } a,b\in\{2,3,\ldots,2n\},\ a+b \text{ is even}. \end{aligned} \tag{5}$$

We use a simulation program written by C to verify the value of $P_{\mathrm{MH}}(i,j)$ and $P_{\mathrm{THA}}(i,j)$. In order to model the mobility of the MH, time is slotted and the parameter called *Movement Probability* (*MoveProb*) [17] is used during the simulation. *MoveProb* represents the probability that an MH will leave its current network in the next slot time. The *MoveProb* is setting to 1 in the simulation program, that is, the MH will always handoff to neighbor FA at each slot time. The initial location of MH is randomly selected for 1 000 times. The total run time of the simulation for each selected MH is 100 000 000 slot times. The mesh network size used in our simulation includes 21 × 21, 41 × 41, 61 × 61, 81 × 81, and 101 × 101 nodes. The simulation program shows that the theoretical results are well matched with the simulation results. The difference between simulation and theoretical value of $P_{\mathrm{MH}}(i,j)$ or $P_{\mathrm{THA}}(i,j)$ is less than 10^{-5} in average.

4.2. Routing Efficiency. We use the average routing path length (in hop counts) for end-to-end data delivery to evaluate routing efficiency. Protocol with large end-to-end delay is not suitable for real-time applications. Because packets issued by the MH destined to the CN are transmitted via normal IP routing. Therefore, we only analyze the routing path through which the CN sends packets to the HA.

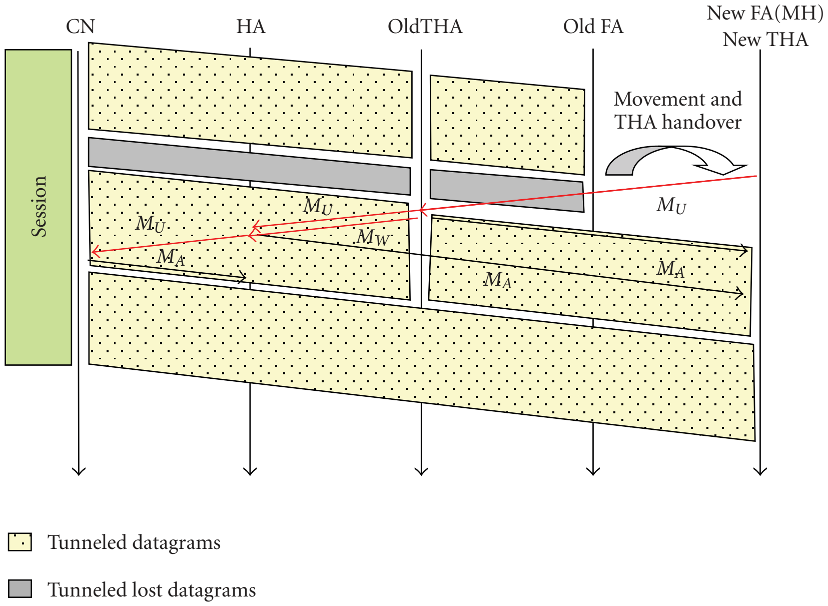


Figure 3: Flow diagram for THA handover.

Figure 4: Network topology of the analytical model.

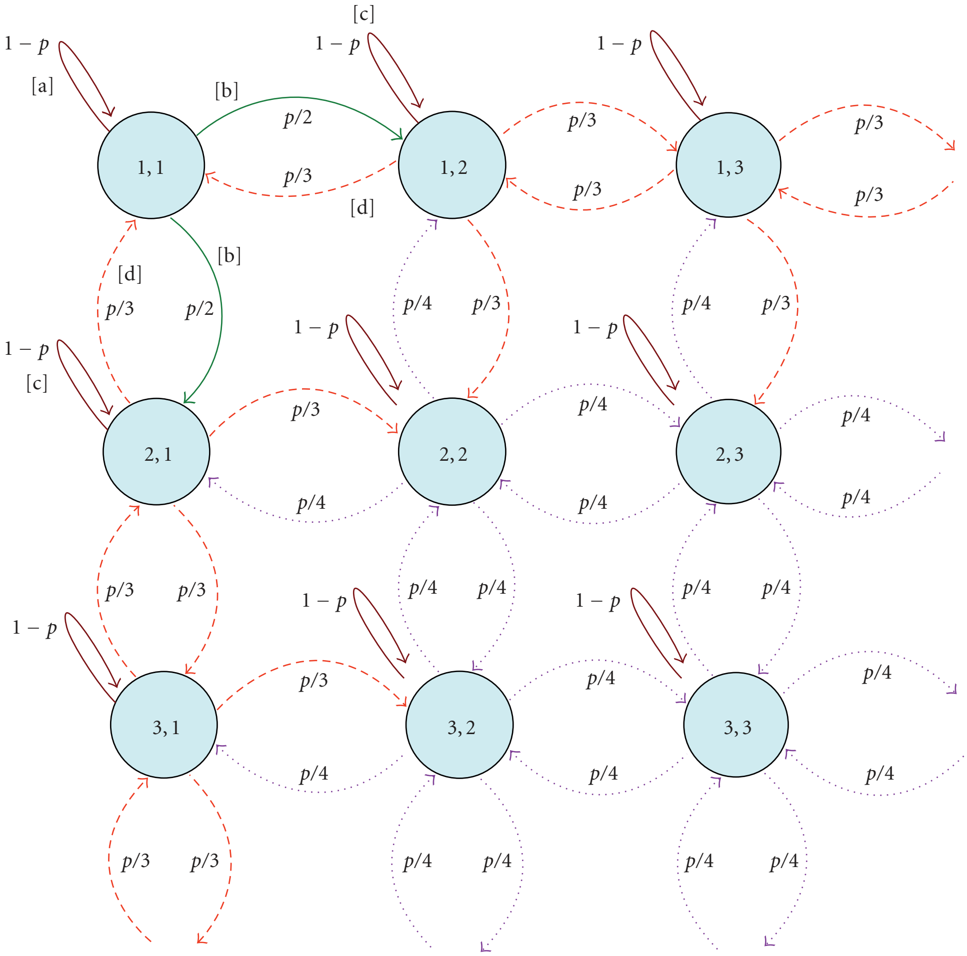


Figure 5: State transition diagram (partial) of the Markovian model.

In HH-MIP, the CN sends packets to the THA of MH, and then the THA forwards those packets to the MH's current location by tunneling. Thus, the routing path from the CN to MH is

$$\text{RoutingPath}_{\text{CN}\to\text{MH}} = \text{Distance}_{\text{CN}\to\text{THA}} + \text{Distance}_{\text{THA}\to\text{MH}}. \tag{6}$$

The distance between the THA and MH is 0 hop if current FA is also the THA of MH. In other case, the distance between THA and MH is 1 hop because the MH will only leave the current THA one hop away.

Since the CN is located in the center and the network topology is symmetric in the analytical model, the average routing path can be calculated by four quadrants which will have the same calculated value.

When the current location of THA is in region A, as shown in Figure 6, the routing distance between the THA and MH is $2n - 2$ hops. If the current location of the THA is $(1, 1)$, then the potential locations of MH are $(1, 1)$, $(1, 2)$, and $(2, 1)$. The probabilities for the MH staying at those locations are $(1/2) \times (1/(4n^2 - 6n + 2))$, $(3/4) \times (1/(4n^2 - 6n + 2))$, and $(3/4) \times (1/(4n^2 - 6n + 2))$, respectively. The distance between the THA and MH is 0 hops if current location of the MH is $(1, 1)$ while the distance is 1 hop if current location of the MH is $(1, 2)$ or $(2, 1)$. Therefore, the average distance between the MH and THA is 3/4 hop. Thus, if the current location of THA is in region A, the average routing path length will be

$$\begin{aligned}&\text{Probability}_{\text{THA}} * (\text{Distance}_{\text{CN}\to\text{THA}} + \text{Distance}_{\text{THA}\to\text{MH}})\\&\quad = 4 \times \left(\frac{1}{4n^2 - 6n + 2}\right) \times \left[(2n - 2) + \frac{3}{4}\right] = \frac{8n - 5}{4n^2 - 6n + 2}.\end{aligned} \tag{7}$$

When the current location of THA is in region B, as shown in Figure 6, the routing distance between the THA and CN is $(n - 1) + |n - i|$ hops if the location of THA is $(1, i)$, $i = 3, 5, 7, \ldots, 2n - 3$. If the current location of the THA is $(1, 3)$, then the potential locations of MH are $(1, 2)$, $(1, 3)$, $(1, 4)$, and $(2, 3)$. The probabilities for the MH staying at those locations are $(3/4) \times (1/(4n^2 - 6n + 2))$, $(3/4) \times (1/(4n^2 - 6n + 2))$, $(3/4) \times (1/(4n^2 - 6n + 2))$, and $1/(4n^2 - 6n + 2)$, respectively. The distance between the THA and MH is 0 hops if current location of the MH is $(1, 3)$ while the distance is 1 hop if current location of the MH is $(1, 2)$, $(1, 4)$, or $(2, 3)$. Therefore, the average distance between the

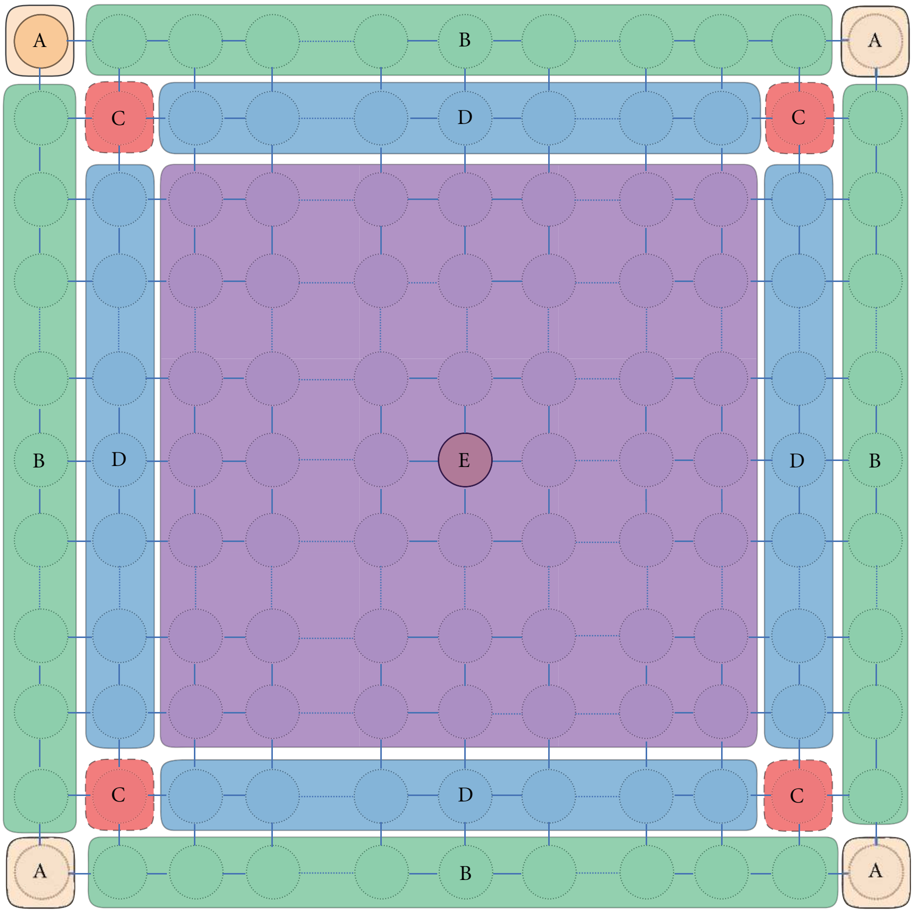


Figure 6: Different location cases used for routing path analysis in HH-MIP.

MH and THA is 10/13 hop. Thus, if the current location of THA is in region B, the average routing path length will be

$$\text{Probability}_{\text{THA}} * (\text{Distance}_{\text{CN}\rightarrow\text{THA}} + \text{Distance}_{\text{THA}\rightarrow\text{MH}})$$

$$= 4 \times \sum_i \left(\frac{3}{2} \times \frac{1}{4n^2 - 6n + 2}\right) \times \left[\left((n-1) + |n-i|\right) + \frac{10}{13}\right], \quad \text{where } i = 3, 5, 7, \ldots, 2n-3$$

$$= \frac{117n^2 - 330n + 153}{13 \times (4n^2 - 6n + 2)}. \tag{8}$$

Using similar method, we can calculate the average routing distances for different cases as shown in Table 1.

Therefore, we can conclude the average routing path length for HH-MIP:

AvgPathLength of HH-MIP:

$$\frac{44460n^3 - 64467n^2 + 10350n - 8402}{11115 \times (4n^2 - 6n + 2)}. \tag{9}$$

Using the similar analysis method, we can also find the equations of average routing path length for MIP and ROMIP

AvgPathLength of MIP

$$\sum_{i=1}^{2n-1} \sum_{j=1}^{2n-1} P_{\text{MH}}(i, j) \times (2n + i + j - 4) = \frac{16n^3 - 40n^2 + 32n - 8}{4n^2 - 6n + 2} \tag{10}$$

AvgPathLength of ROMIP:

$$\sum_{i=1}^{2n-1} \sum_{j=1}^{2n-1} P_{\text{MH}}(i, j) \times (|n-i| + |n-j|) = \frac{4n^3 - 9n^2 + 6n - 1}{4n^2 - 6n + 2}. \tag{11}$$

4.3. Handoff Latency. In case of handoff, the MH will send an update message and wait for the first packet to arrive. Before the binding update message arrives the previous FA/THA (ROMIP/HH-MIP) or HA (MIP), packets will be sent to the previous location of the MH and will be lost. The longer

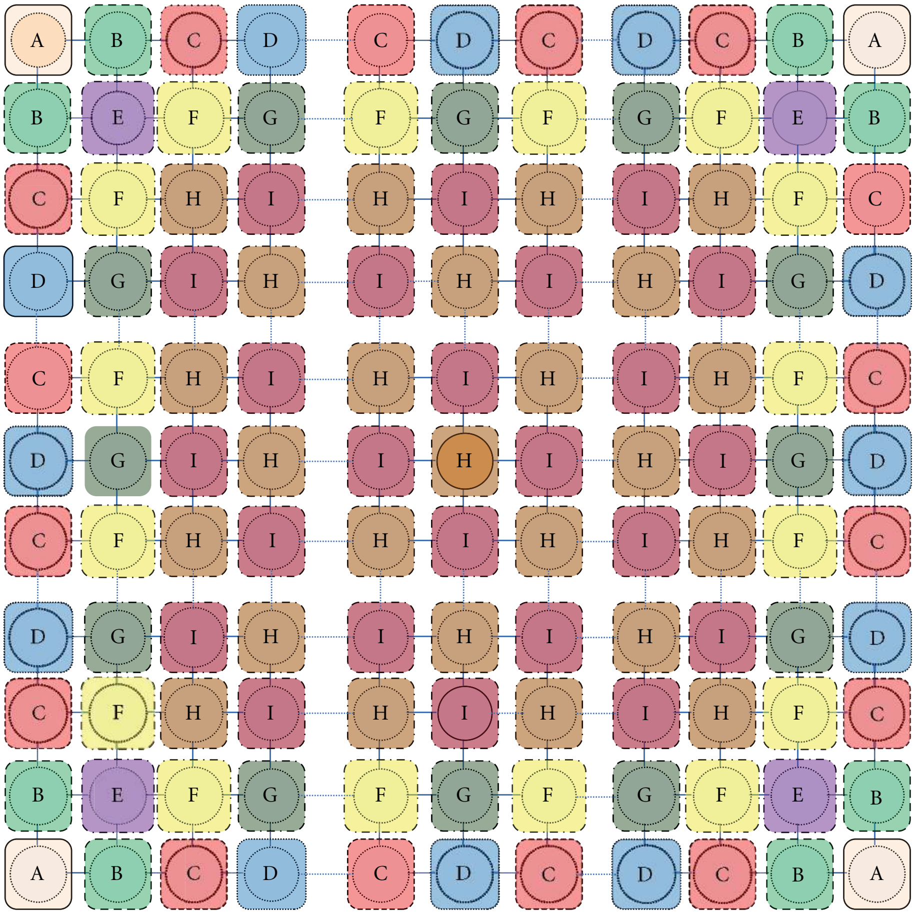


Figure 7: Different cases used for handoff latency analysis in HH-MIP.

the path that update messages need to travel, the larger the handoff latency resulting in more packet loss. Therefore, we measure the delivery distance of binding message as the handoff latency.

The HH-MIP approach adopts the forwarding mechanism that the MH notifies its previous THA of the new CoA after handoff. Because the probability of MH or THA staying in a specific location has different values, we use 9 different cases, as shown in Figure 7, to construct the equation of handoff latency for HH-MIP.

When the previous location of the MH is in region A, as shown in Figure 7, the FA will also serve as THA. After the MH handoff to a neighbor FA, it sends a binding update message to its previous THA without THA handoff. Because the MH only has two moving directions in this case, the average handoff latency will be

$$\frac{1}{2\times(4n^2-6n+2)}\times\left(\frac{p}{2}\times 2\right)\times 4=\frac{2p}{4n^2-6n+2}. \tag{12}$$

If the previous location of the MH is in region B of Figure 7, the FA will not serve as THA. For example, if the current location of the MH is $(1,2)$, then the potential locations of THA are $(1,1)$, $(1,3)$, and $(2,2)$. After the MH handoff to a neighbor FA, the handoff latency will be 0 hops if the new location of MH is also its previous THA. In such a case, the THA does not hand over. However, the handoff latency will be 2 hops when the THA handover occurs. The MH has three different handoff directions with the same probability $p/3$. Thus, the average handoff latency for this case will be

$$\begin{aligned}&\frac{3}{4\times(4n^2-6n+2)}\times\left[\frac{p}{3}\times 2\times\left(\frac{6}{10}+\frac{7}{10}+\frac{7}{10}\right)\right]\times 4\\&\quad=\frac{4p}{4n^2-6n+2}.\end{aligned} \tag{13}$$

Using similar method, we can calculate the average handoff latency for different cases as shown in Table 2.

Therefore, we can calculate the average handoff latency for HH-MIP:

$$\text{AvgHandoffLatency of HH-MIP: }\frac{(5n^2-8n-6)\times p}{4n^2-6n+2}. \tag{14}$$

Table 1: Average routing distances derived by the regions where the THA is located.

Region	Average routing distance
A	$4 \times (1/(4n^2 - 6n + 2)) \times [(2n - 2) + 3/4] = (8n - 5)/(4n^2 - 6n + 2)$
B	$= 4 \times \sum_i((3/2) \times (1/(4n^2 - 6n + 2))) \times [(n - 1) + \lvert n - i\rvert) + 10/13]$ where $i = 3, 5, 7, \ldots, 2n- 3 = (117n^2 - 330n + 153)/(13 \times (4n^2 - 6n + 2))$
C	$4 \times (2/(4n^2 - 6n + 2)) \times [(2n - 4) + (7/9)] = (144n - 232)/(9 \times (4n^2 - 6n + 2))$
D	$4 \times \sum_i(2/(4n^2 - 6n + 2)) \times [(n - 2) + \lvert n - i\rvert + (15/19)]$ where $i = 4, 6, 8, \ldots, 2n - 4 = (228n^2 - 1096n + 1236)/(19 \times (4n^2 - 6n + 2))$
E	$4 \times \sum_i \sum_j(2/(4n^2 - 6n + 2)) \times [(2n - j - i) + 4/5]$ where $i = 3, 4, 5, \ldots, n$ $j = 3, 4, 5, \ldots, n - 1$ and $i + j$ is even $= (20n^3 - 134n^2 + 300n - 234)/(5 \times (4n^2 - 6n + 2))$

Table 2: Average handoff latency derived by the regions where the THA located.

Region	Average handoff latency
A	$1/(2\times(4n^2-6n+2))\times((p/2)\times 2)\times 4 = 2p/(4n^2-6n+2)$
B	$3/(4 \times (4n^2 - 6n + 2)) \times [(p/3) \times 2 \times (6/10 + 7/10 + 7/10)] \times 4 = 4p/(4n^2 - 6n + 2)$
C	$3/(4 \times (4n^2 - 6n + 2)) \times p \times (n - 2) \times 4 = ((3n - 6) \times p)/(4n^2 - 6n + 2)$
D	$3/(4 \times (4n^2 - 6n + 2)) \times ((p/3) \times 2 \times 2) \times (4n - 12) = ((4n - 12) \times p)/(4n^2 - 6n + 2)$
E	$1/(4n^2 - 6n + 2) \times ((p/4) \times 4) \times 4 = 4p/(4n^2 - 6n + 2)$
F	$((6n - 12) \times p)/(4n^2 - 6n + 2)$
G	$((4n - 12) \times p)/(4n^2 - 6n + 2)$
H	$((2n^2 - 10n + 12) \times p)/(4n^2 - 6n + 2)$
I	$((3n^2 - 15n + 18) \times p)/(4n^2 - 6n + 2)$

Similarly, we can also find the equations of average handoff latency for MIP and ROMIP.

AvgHandoffLatency of MIP:

$$\begin{aligned} &\sum_{i=1}^{2n-1} \sum_{j=1}^{2n-1} P_{\mathrm{MH}}(i, j) \times (i + j - 2) \times p \\ &\quad = \frac{(8n^3 - 20n^2 + 16n - 4) \times p}{4n^2 - 6n + 2}, \end{aligned} \tag{15}$$

AvgHandoffLatency of ROMIP: p.

4.4. Signaling Cost. Signaling cost is measured in terms of the delivery distance (in hops) by which the control packets are transmitted when the MH is performing handoff to other foreign networks.

In HH-MIP, it enjoys local registration when the THA of MH does not hand over. In such a case, the MH sends a binding update message to inform the THA of its new CoA. The THA replies with a binding acknowledgment message to the MH completing the handoff procedure. However, if the THA hands over into a new FA of MH, the signaling is similar to the ROMIP. In such a case, the MH sends a binding update messages to its HA and previous THA for THA handoff. The HA and previous FA will also reply with a binding acknowledgment message to the MH. After updating binding information, the previous THA sends a binding warning message to inform the HA of the address of the CN. The HA sends a binding update message to the CN and then the CN replies with a binding acknowledgment message. Therefore, the signaling cost in HH-MIP will be

$$\begin{aligned} &\text{SignalingCost}_{\text{THAremain}} \\ &\quad = \text{BindingUpdate}_{\text{MHnew} \to \text{THA}} \quad (0 \text{ or } 1 \text{ hop}) \\ &\qquad + \text{BindingACK}_{\text{THA} \to \text{MHnew}} \quad (0 \text{ or } 1 \text{ hop}), \\ &\text{SignalingCost}_{\text{THAhandover}} \\ &\quad = \text{BindingUpdate}_{\text{MHnew} \to \text{THAold}} \quad (2 \text{ hops}) \\ &\qquad + \text{BindingACK}_{\text{THAold} \to \text{MHnew}} \quad (2 \text{ hops}) \\ &\qquad + \text{BindingUpdate}_{\text{MHnew} \to \text{HA}} \\ &\qquad + \text{BindingACK}_{\text{HA} \to \text{MHnew}} \\ &\qquad + \text{BindingWarning}_{\text{THAold} \to \text{HA}} \\ &\qquad + \text{BindingUpdate}_{\text{HA} \to \text{CN}} \quad (2n - 2 \text{ hops}) \\ &\qquad + \text{BindingACK}_{\text{CN} \to \text{HA}} \quad (2n - 2 \text{ hops}). \end{aligned} \tag{16}$$

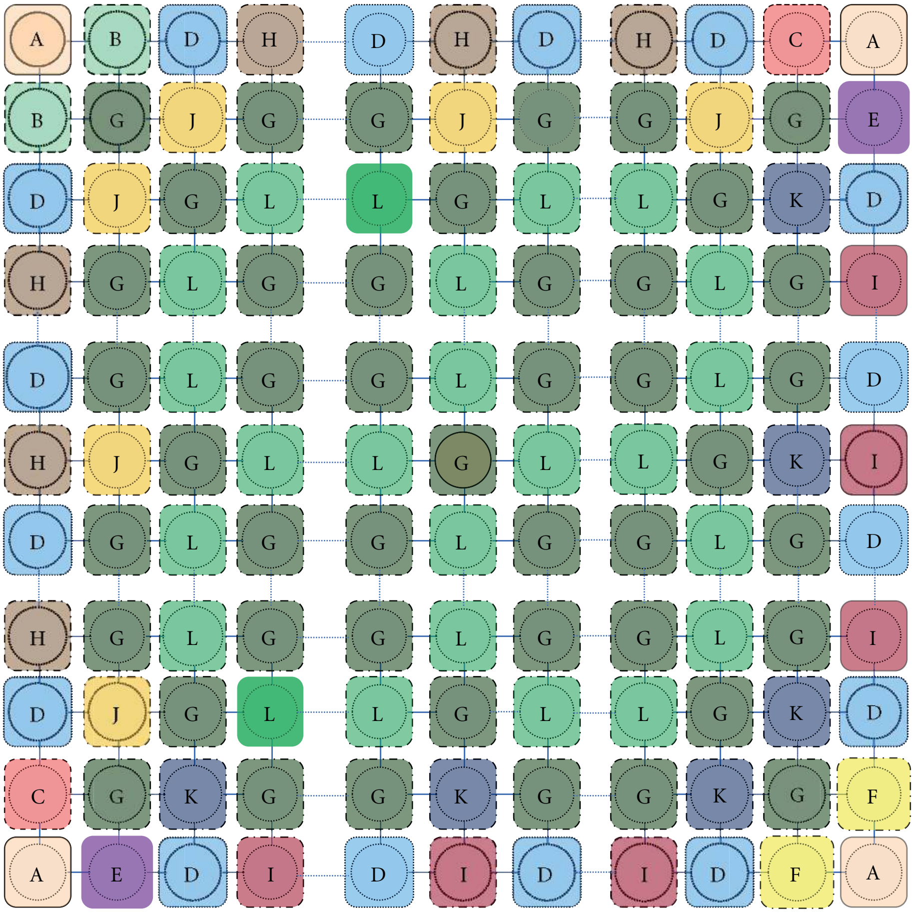
There are 12 different cases, as shown in Figure 8, to construct the equation of signaling cost for HH-MIP. If the previous location of the MH is in region A of Figure 8 and then hands off into a neighbor FA, it only needs to send a binding update message to its previous location where its THA is located. The THA then replies with a binding acknowledgment message to it. Thus, the average signaling cost for this case will be $4 \times p/(4n^2 - 6n + 2)$.

If the previous location of the MH is in region B (e.g., $(1, 2)$) of Figure 8 and then hands off into a neighbor FA, there are three possible THA locations for the MH (e.g., $(1, 1)$, $(1, 3)$, $(2, 2)$). The probability is 1/3 that the MH moves back to its THA (e.g., $(1,1)$). On the other hand, the probability is 2/3 that the MH moves 2 hops away from its THA, resulting in signaling for THA handoff. Thus, the average signaling cost for this case will be $(4n + 4) \times p/(4n^2 - 6n + 2)$. Using similar method, we can calculate the average signaling cost for different cases as shown in Table 3.

Therefore, we can conclude the average signaling cost for HH-MIP as

AvgSignalingCost of HH-MIP:

$$\frac{(1350n^3 - 3195n^2 + 4329n + 1168) \times p}{90 \times (4n^2 - 6n + 2)}. \tag{17}$$



A	B	D	H	D	H	D	H	D	C	A
B	G	J	G	G	J	G	G	J	G	E
D	J	G	L	L	G	L	L	G	K	D
H	G	L	G	G	L	G	G	L	G	I
D	G	L	G	G	L	G	G	L	G	D
H	J	G	L	L	G	L	L	G	K	I
D	G	L	G	G	L	G	G	L	G	D
H	G	L	G	G	L	G	G	L	G	I
D	J	G	L	L	G	L	L	G	K	D
C	G	K	G	G	K	G	G	K	G	F
A	E	D	I	D	I	D	I	D	F	A

FIGURE 8: Different cases used for signaling cost analysis of HH-MIP.

In the same way, we can also find average signaling cost for MIP and ROMIP

AvgSignalingCost of MIP:

$$\sum_{i=1}^{2n-1}\sum_{j=1}^{2n-1} P_{\mathrm{MH}}(i,j)\times(2i+2j-4)$$
$$=\frac{(16n^3-40n^2+32n-8)\times p}{4n^2-6n+2}, \qquad (18)$$

AvgSignalingCost of ROMIP:

$$\frac{(40n^3-92n^2+67n-16)\times p}{4n^2-6n+2}.$$

4.5. Verification and Comparison. Simulation studies are conducted for verification of the theoretical analysis. Figure 9 shows that the average length of data path, both numerical (theoretical) and simulated, for HH-MIP, MIP, and ROMIP. Well match of the numerical and simulated results in Figure 9 (also in Figures 10 and 11) has demonstrated the correctness of the Markovian analysis. Figure 9 also shows the average data path length of HH-MIP is very close to that of ROMIP, indicating routing efficiency of HH-MIP.

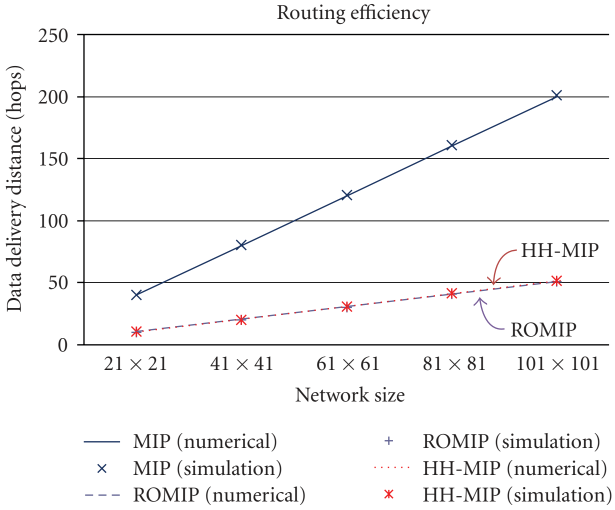


FIGURE 9: Comparison of routing efficiency between different approaches.

Figure 10 shows the comparison of handoff latency between different approaches. The mobility probability p is

TABLE 3: Average signaling cost derived by the regions where the THA is located.

Region	Average signaling cost
A	$4 \times p/(4n^2 - 6n + 2)$
B	$(4n + 4) \times p/(4n^2 - 6n + 2)$
C	$(18n + 8) \times p/(3 \times (4n^2 - 6n + 2))$
D	$(3/(2 \times (4n^2 - 6n + 2))) \times (n - 2) \times 4 \times p = (6n - 12) \times p/(4n^2 - 6n + 2)$
E	$(18n - 4) \times p/(3 \times (4n^2 - 6n + 2))$
F	$(72n - 50) \times p/(9 \times (4n^2 - 6n + 2))$
G	$(4n^2 - 12n + 10) \times p/(4n^2 - 6n + 2)$
H	$2 \times \sum_i((10n + 5i - 3) \times p/(20 \times (4n^2 - 6n + 2))) = (15n^2 - 48n + 9) \times p/(10 \times (4n^2 - 6n + 2))\ i = 4, 6, 8, \ldots, 2n - 4$
I	$2 \times \sum_i((100n + 30i - 101) \times p/(20 \times (4n^2 - 6n + 2))) = (130n^2 - 491n + 303) \times p/(10 \times (4n^2 - 6n + 2))\ i = 4, 6, 8, \ldots, 2n - 4$
J	$2 \times \sum_i((180n + 135i + 1) \times p/(60 \times (4n^2 - 6n + 2))) = (315n^2 - 629n - 2) \times p/(30 \times (4n^2 - 6n + 2))\ i = 3, 5, 7, \ldots, 2n - 3$
K	$2 \times \sum_i((450n + 135i - 541) \times p/(60 \times (4n^2 - 6n + 2))) = (585n^2 - 1711n + 1082) \times p/(30 \times (4n^2 - 6n + 2))\ i = 3, 5, 7, \ldots, 2n - 3$
L	$\sum_i \sum_j((12n + 9i + 9j - 18) \times p/(4 \times (4n^2 - 6n + 2))) = (15n^3 - 84n^2 + 162n - 54) \times p/(4n^2 - 6n + 2)$ $(i = 3, 5, 7, \ldots, 2n - 3$ and $j = 4, 6, 8, \ldots, 2n - 4)$ or $(i = 4, 6, 8, \ldots, 2n - 4$ and $j = 3, 5, 7, \ldots, 2n - 3)$

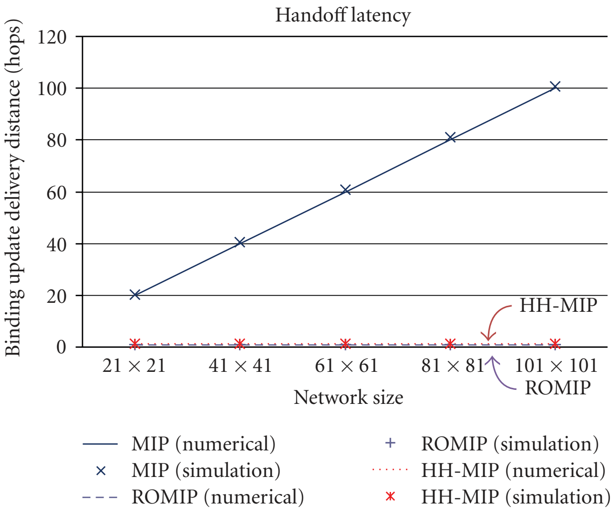


FIGURE 10: Comparison of handoff latency between different approaches.

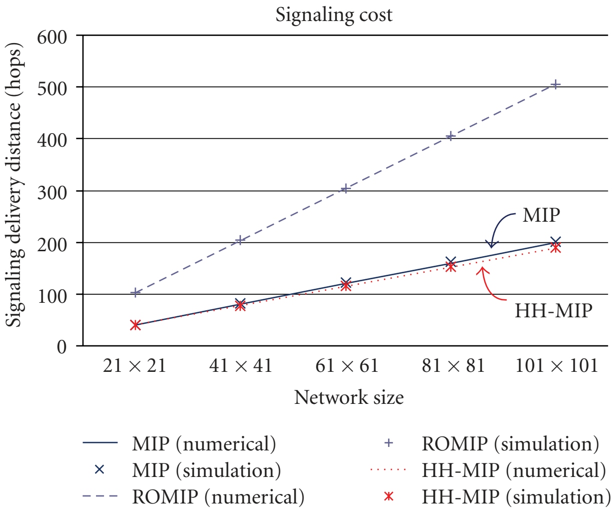


FIGURE 11: Comparison of signaling cost between different approaches.

set to 1 (always handoff at each slot time). The simulation program shows that the handoff latency of HH-MIP is very close to the ROMIP.

In MIP, the MH sends a binding update message to its HA after handover into another FA. The handoff latency becomes larger as network size increases because the potential distance between the HA and FA increases. However, both of the HH-MIP and ROMIP approaches adopt the forwarding mechanism resulting in low handoff latency. In HH-MIP, the THA will hand over into another FA only when the MH leaves previous THA two hops away, since the MH has 4 different movement directions with equal probability on average. Thus, HH-MIP has 1.25 hops of handoff latency on average while the ROMIP has 1 hop of handoff latency.

Figure 11 shows the comparison of signaling cost between different approaches. The mobility probability p is also set to 1 (always move at each slot time). The simulation program also shows that the theoretical results are very close to the simulation results.

Interestingly, the average signaling cost of HH-MIP approach is smaller than MIP or ROMIP. In MIP and ROMIP, the MH and FAs send a lot of binding messages to related devices after handover into a new FA. The average signaling cost becomes larger as network size increases. The HH-MIP approach adopts local registration to reduce the numbers of signaling results in smaller signaling cost. the number of related binding messages and signaling delivery distance is larger than MIP when the THA handover occurs. However, the THA handover does not occur frequently. Moreover, the MH has opportunities that handoff returns to its THA without further signaling cost. Thus, the signaling cost of HH-MIP is smaller than MIP in average.

Since simulation confirms the correctness of theoretical analysis, we can easily obtain the protocol gains against other

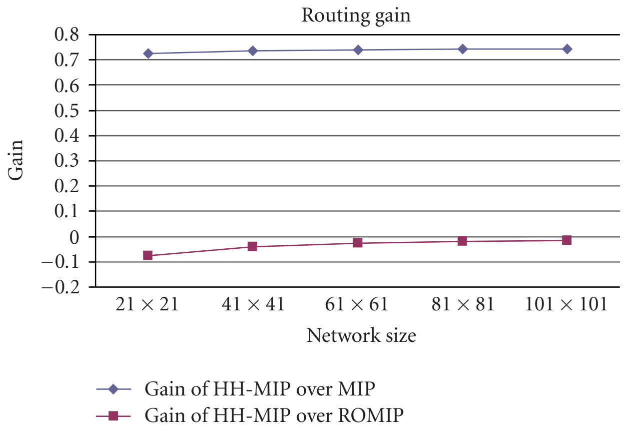


Figure 12: Comparison of routing gains.

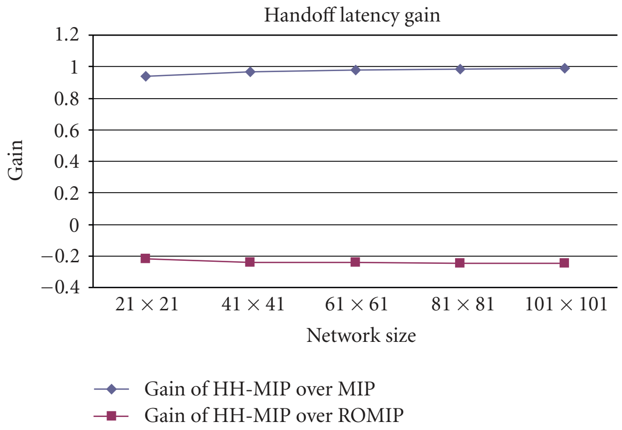


Figure 13: Comparison of handoff latency gains.

approaches. The routing gain of HH-MIP over MIP/ROMIP can be derived from (9), (10), and (11) as follows:

Routing Gain of HH-MIP over MIP is

$$\frac{133380n^3 - 380133n^2 + 345330n - 80518}{177840n^3 - 444600n^2 + 355680n - 88920}, \tag{19}$$

Routing Gain of HH-MIP over ROMIP is

$$\frac{-35568n^2 + 56340n - 2713}{177840n^3 - 444600n^2 + 355680n - 88920}. \tag{20}$$

Figure 12 shows the comparison of routing gains between different approaches. It shows that HH-MIP can reduce more than 70% of routing distance over MIP at network size larger than 21 × 21. Since the THA of an MH is selected to be close to the current location of MH, the routing distance of HH-MIP is very close to the ROMIP.

Handoff latency gain of HH-MIP over MIP/ROMIP can be derived from (14) and (15) as follows:

Handoff Latency Gain of HH-MIP over MIP is

$$\frac{8n^3 - 25n^2 + 24n + 2}{8n^3 - 20n^2 + 16n - 4}, \tag{21}$$

Handoff Latency Gain of HH-MIP over ROMIP is

$$\frac{-n^2 + 2n + 8}{4n^2 - 6n + 2}. \tag{22}$$

Figure 13 shows the comparison of handoff latency gains between different approaches. It shows that HH-MIP can almost reduce up to 90% of handoff latency over MIP at network size larger than 21 × 21. In MIP, the MH sends a binding update message to its HA after handover into another FA. On the contrary, HH-MIP adopts the forwarding mechanism that the MH notifies its previous THA of the new CoA after the MH handoff. The THA is away from the MH no more than 2 hops. The ROMIP also adopts the forwarding mechanism with 1-hop latency. The handoff latency of HH-MIP increases 0.25 hop in average comparing to ROMIP since there are only 25% of possibilities that the MH leaves its THA 2 hops away and then triggers THA handover.

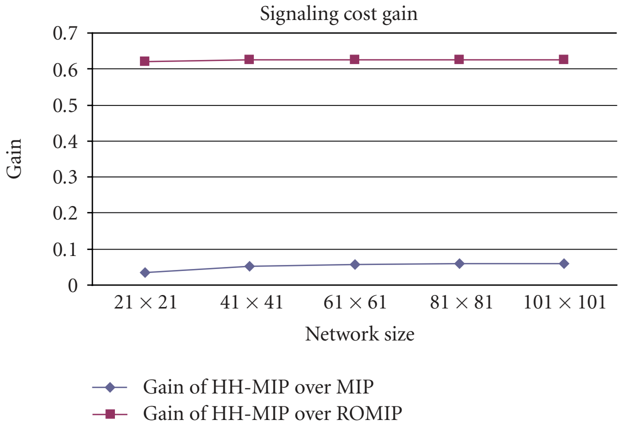


Figure 14: Comparison of signaling cost gains.

The singaling cost gain of HH-MIP over MIP/ROMIP can also be derived from (17) and (18) as follows:

Singaling Cost Gain of HH-MIP over MIP is

$$\frac{90n^3 - 405n^2 - 1449n - 1888}{1440n^3 - 3600n^2 + 2880n - 720}, \tag{23}$$

Singaling Cost Gain of HH-MIP over ROMIP is

$$\frac{2250n^3 - 5085n^2 + 1701n - 2608}{3600n^3 - 8280n^2 + 6030n - 1440}. \tag{24}$$

Figure 14 shows the comparison of signaling cost gains between different approaches. Since the THA of an MH is selected to be close to the current location of MH and the THA handover does not occur frequently, HH-MIP benefits from localized registration. Therefore, HH-MIP can reduce more than 6% and 60% of average signaling cost of MIP and ROMIP, respectively, at network size larger than 41 × 41.

In summary, the gains of HH-MIP over the other two schemes demonstrate that the proposed HH-MIP scheme enjoys small handoff latency as well as routing efficiency, and the signaling cost of proposed scheme is significantly less than that in the ROMIP.

5. Conclusion

Development of wireless networking has made mobility management more important. Although Mobile IP that was introduced by IETF can provide global mobility capability, it still has some shortcomings. Triangular routing and large handoff latency are some of the shortcomings. Route Optimization as an enhancement of MIP resolves the shortcomings in MIP but it introducing larger signaling cost. In this paper, we propose a mobility management protocol called HH-MIP. HH-MIP reduces Mobile IP shortcomings without introduces large signaling cost. The main idea of HH-MIP is introducing THA concept that can move dynamically near MH's current position. Performance criteria are analyzed in this paper including routing efficiency, the handoff latency, and the signaling cost. The theoretical analysis and simulation results show that HH-MIP has better performance in routing efficiency and handoff latency than the MIP. HH-MIP also reduces signaling cost during the MH handoff. Theoretical gain of HH-MIP over MIP and ROMIP in terms of the three performance criteria is calculated, which demonstrates the theoretical potential of the proposed HH-MIP scheme. We use a simplified analytical model to evaluate the performance of the proposed scheme. Although this makes the analytical model not so realistic, the analytical study becomes much easier. We will try to use different analytical parameters such as different network topology, mobility pattern, traffic characteristics, and so forth in the future works of this research.

Acknowledgments

This work was supported in part by the National Science Council, Taiwan, under Grant NSC95-2219-E-260-004. A preliminary version of the research in the paper has been published in proceedings of the 62nd Semiannual Vehicular Technology Conference (VTC-2005Fall), 2005.

References

[1] I. F. Akyildiz, J. Xie, and S. Mohanty, "A survey of mobility management in next-generation all-IP-based wireless systems," *IEEE Wireless Communications*, vol. 11, no. 4, pp. 16–28, 2004.

[2] C. E. Perkins, "IP Mobility Support for IPv4," RFC 3344, 2002.

[3] D. Johnson, C. E. Perkins, and J. Arkko, "Mobility support in IPv6," RFC 3775, 2004.

[4] Y.-H. Huang, J.-Y. Chen, C.-C. Yang, H.-T. Chu, and W.-S. Chen, "A comparison between SIP and network layer mobility management protocols in IP-based wireless networks," in *Proceedings of the 5th IEE International Conference on 3G Mobile Communication Technologies*, pp. 317–321, 2004.

[5] A. T. Campbell, J. Gomez, S. Kim, Z. R. Turányi, A. G. Valkó, and C.-Y. Wan, "Internet micromobility," *Journal of High Speed Networks*, vol. 11, no. 3-4, pp. 177–198, 2002.

[6] C. E. Perkins and D. B. Johnson, "Route Optimization in Mobile IP," draft-ietf-mobileipoptim-11.txt, 2001.

[7] M. Dell'Abate, M. De Marco, and V. Trecordi, "Performance evaluation of mobile IP protocols in a wireless environment," in *Proceedings of the IEEE International Conference on Communications*, vol. 3, pp. 1810–1816, 1998.

[8] A. Misra, S. Das, A. Dutta, A. McAuley, and S. K. Das, "IDMP-based fast handoffs and paging in IP-based 4G mobile networks," *IEEE Communications Magazine*, vol. 40, no. 3, pp. 138–145, 2002.

[9] A. T. Campbell and J. Gomez-Castellanos, "IP micro-mobility protocols," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 4, no. 4, pp. 45–53, 2001.

[10] A. G. Valko, "Cellular IP: a new approach to internet host mobility," *ACM Computer Communication Review*, vol. 29, no. 1, pp. 50–64, 1999.

[11] R. Ramjee, K. Varadhan, L. Salgarelli, S. R. Thuel, S.-Y. Wang, and T. La Porta, "HAWAII: a domain-based approach for supporting mobility in wide-area wireless networks," *IEEE/ACM Transactions on Networking*, vol. 10, no. 3, pp. 396–410, 2002.

[12] E. Gustafsson, A. Jonsson, and C. E. Perkins, "Mobile IPv4 Regional Registration," RFC 4857, 2007.

[13] H. Soliman, et al., "Hierarchical Mobile IPv6 Mobility Management (HMIPv6)," RFC 4140, 2005.

[14] I.-W. Wu, W.-S. Chen, H.-E. Liao, and F. F. Young, "A seamless handoff approach of mobile IP protocol for mobile wireless data networks," *IEEE Transactions on Consumer Electronics*, vol. 48, no. 2, pp. 335–344, 2002.

[15] W. Ma and Y. Fang, "Dynamic hierarchical mobility management strategy for mobile IP networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 4, pp. 664–676, 2004.

[16] J. Cao, L. Zhang, H. Chan, and S. K. Das, "Design and performance evaluation of an improved mobile IP protocol," in *Proceedings of the 23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '04)*, vol. 1, pp. 7–11, 2004.

[17] C.-C. Yang and K.-Y. Lin, "Distributed mobile tracking: a novel location management scheme for routing improvement in cellular IP networks," *Journal of Computer Networks*, vol. 43, no. 2, pp. 147–161, 2003.