Performance Analysis of Mobile IP Extended with Routing Agents *

Yu Wang  Weidong Chen  Joseph S.M. Ho
Department of Computer Science and Engineering  NORTEL Wireless Networks
Southern Methodist University  MS D0201
P.O. Box 750122  P.O. Box 833871
Dallas, TX 75275-0122  Richardson, TX 75083-3871
(214) 768-3097 (phone)  (972) 685-7260 (phone)
(214) 768-3085 (fax)  (972) 684-3744 (fax)
{wy,wchen}@seas.smu.edu  joeho@nortel.com

Abstract

Mobile IP is the proposed standard for IP mobility support. A mobile node registers its current location with its home agent when it moves across IP subnets in a foreign network. When a mobile node is far away from home, registration with its home agent can cause a long handoff delay. We have extended Mobile IP with routing agents. The routing agent of a mobile node serves as the current location of the mobile node at the home agent, and handles local movements of the mobile node directly through local registrations. Registrations with the home agent can change the routing agent of a mobile node but are performed much less frequently and do not involve changing the point of network attachment of a mobile node. This paper analyzes the performance of Mobile IP and the extension with routing agents in terms of registration cost, handoff delay, and packet tunneling cost. The results show that routing agents reduce the overall registration cost and the handoff delay significantly with a slight increase of the tunneling cost for each packet when a mobile node is not close to home. Both the handoff delay and the increase in tunneling cost are bounded, independent of the distance of a mobile node from its home agent. When a mobile node is close to home, Mobile IP is more efficient and is the special case where the routing agent coincides with the home agent.

*Supported in part by the National Science Foundation Grant NCR-9628126 and by the Texas Higher Education Coordinating Board, Advanced Technology Program Grant 003613-019.
1 Introduction

The growth in mobile and wireless communications has prompted research into mobility support in networking protocols. Mobile IP [11] is the proposed standard for IP mobility support by the Internet Engineering Task Force (IETF). It has three functional entities: mobile node, home agent and foreign agent. Each mobile node is assigned a long-term IP address on a home network called a home address. While away from home, the location of a mobile node is captured by a care-of address, which is either the IP address of a foreign agent with which the mobile node is registered or a temporary IP address acquired by the mobile node in the visited foreign network. The home agent of a mobile node maintains a mobility binding between the home address and the care-of address of the mobile node. All IP packets for a mobile node are routed using regular IP routing to its home agent, which then tunnels them to the care-of address of the mobile node.

The advantages of Mobile IP are its simplicity and its compatibility with wired networks since only mobility agents, namely home agents and foreign agents, and mobile nodes have to be modified. However, it also has several limitations. First, the triangular routing of IP packets to mobile nodes through home agents is not optimal. Second, the care-of address of a mobile node at the home agent changes whenever it moves from one IP subnet to another. This could lead to frequent registrations with the home agent. Third, registrations with the home agent may incur a long handoff delay when a mobile node is far away from home. This can cause significant packet drop and throughput reduction [9].

To avoid triangular routing, location caches are used at routers [15] or at correspondent hosts [8, 10] to maintain the mobility binding between the home address and the care-of address of a mobile node. When a mobile node moves, its mobility binding is propagated to correspondent hosts. An adaptive scheme is studied in [13] in which a mobile node determines dynamically a working set of hosts to which its mobility binding should be propagated.

To reduce registrations with the home agent, hierarchical approaches have been studied. In [7], a local region is defined for each mobile node by including those subnetworks among which the mobile node often moves. A hierarchy of redirection agents is used to intercept IP packets for mobile nodes within a region and send them directly to current locations of mobile nodes. Movements within a region will not cause registrations with home agents outside of the region. In [12], foreign agents are organized
into a hierarchy according to the regional topology. The home agent serves as the “universal root” and the current foreign agent is a leaf node in the hierarchy. Registration requests are sent to the foreign agent at the lowest level in the hierarchy that remains the same across a handoff. IP packets for a mobile node are sent to the home agent and then tunneled down through the hierarchy of foreign agents to the mobile node.

The hierarchical approaches reduce the average handoff delay since some registrations can be handled by foreign agents near the bottom of the hierarchy that are close to the current location of a mobile node. However, when a mobile node does cross regions at the top level of the hierarchy, registrations still involve home agents that may be far away, causing a long handoff delay. The fast handoff scheme in [5] handles only intra-subnet movement, which is orthogonal to the handling of inter-subnet movement.

In [6], Mobile IP is extended with a dynamic routing agent between the home agent and the current foreign agent of a mobile node to exploit locality of movement between IP subnets. The routing agent serves as the current location of a mobile node to the home agent. A distinctive feature is that registrations in Mobile IP are now separated into local and home registrations. A mobile node registers with its routing agent through local registrations when it moves from one cell to another, shielding frequent local movements from the home agent. Handoff delay is reduced by having the routing agent close, but not necessarily identical, to the current foreign agent of a mobile node. A mobile node registers with its home agent through home registrations to establish, renew or change its routing agent. More importantly, since home registrations do not involve the change of the point of network attachment, the maximum handoff delay is independent of the distance from a mobile node to its home agent and can be bounded. Mobile IP becomes the special case where the routing agent and the home agent coincide.

This paper presents a performance analysis of Mobile IP and the extension with routing agents in terms of registration cost, handoff delay and packet tunneling cost. When a mobile node is far away from home, the introduction of routing agents reduces the registration cost and handoff delay significantly with some extra packet tunneling cost. When a mobile node is near home, Mobile IP is more efficient and this can be achieved by having the home agent as the routing agent of the mobile node. The analysis shows that handoff delay is bounded given the transmission delay over a link and the processing delay at a mobility agent of local registration messages. Similarly the extra tunneling per IP packet is also bounded.

The rest of this paper is organized as follows. Section 2 reviews the basic framework of Mobile IP
and the extension with routing agents [6]. Section 3 presents a performance analysis of Mobile IP and the extension with routing agents. We conclude with a brief discussion of related work and some issues for future work.

2 Mobile IP and the Extension with Routing Agents


2.1 Mobile IP

The architecture of Mobile IP [11] has three functional entities: mobile nodes, home agents, and foreign agents. Figure 1 indicates the triangular routing when a correspondent node $S$ sends IP packets to a mobile node $M$ that is away from home, where $A_h$ is the home agent and $A_f$ is the current foreign agent for $M$. An IP packet to $M$ has the home address of $M$ as the destination and is routed using regular IP routing to the home network. The home agent $A_h$ intercepts the IP packet and realizes that $M$ is away from home. It encapsulates the IP packet and tunnels the IP packet (indicated by the dashed path) to the care-of address. If the care-of address is the address of the foreign agent $A_f$, $A_f$ decapsulates the IP packet and sends it to $M$ over the air interface. If the care-of address is a temporary IP address acquired by the mobile node in the visited foreign network, then the mobile node receives the encapsulated IP packet directly and decapsulates the packet itself. (Since these two types of care-of addresses do not affect our analysis results in any major way, we assume, for simplicity, a foreign agent care-of address when discussing registration messages in the rest of this paper.) Notice that IP packets from $M$ to the correspondent node $S$ follow regular IP routing.

Mobile IP supports two services: agent discovery and registration. Agent discovery allows a mobile node to determine if it is at home or in a foreign network, to detect when it moves from one IP subnet to another, and to find out the foreign agent care-of addresses. Registration allows a mobile node to communicate its location information to its home agent. This leads to the creation or modification of a mobility binding at the home agent that associates the home address with a care-of address along with the remaining lifetime of that association.
A mobile node registers with its home agent, through a foreign agent if necessary, when it

- visits a foreign network and requests forwarding services, or
- renews a registration that is about to expire, or
- de-registers upon returning home.

\[ \mathcal{A}_h \xleftrightarrow{\frac{2}{3}} \mathcal{A}_f \xleftrightarrow{\frac{1}{4}} \mathcal{M} \]

Figure 2: Registration message flow in Mobile IP

Figure 2 shows the message flow when a mobile node registers with its home agent via a foreign agent:

1. A mobile node sends a registration request to its foreign agent, containing, among other information, the home address, the address of its home agent, a care-of address, and a registration lifetime.

2. The foreign agent forwards the registration request to the home agent.

3. The home agent sends back a registration reply containing the home address, the address of the home agent, and a possibly modified registration lifetime.

4. The foreign agent relays the registration reply back to the mobile node.

Registration requests and replies are sent as UDP packets to port 434. They must be authenticated with the Mobile-Home Authentication Extension. The default algorithm is keyed MD5 used in “pre-
fix+suffix" mode with a key size of 128 bits [14]. Besides a home address and a network mask, a mobile
node must be configured with a mobility security association for each home agent.

2.2 Extension of Mobile IP with Routing Agents

In Mobile IP, the routing of IP packets requires that a mobile node register with its home agent whenever
it moves across IP subnets. In [6], we extended Mobile IP with a new mobility agent, called routing
agent, in order to handle frequent local movements locally independent of the home agent. Figure 3
shows the IP packet routing with a routing agent $A_r$ for a mobile node $M$.

![Figure 3: IP packet routing in the extension of Mobile IP with routing agents](image)

The home agent maintains a mobility binding between the home address and the routing agent
address of a mobile node. The routing agent maintains a mobility binding between the home address
and the care-of address of a mobile node. The local movements of a mobile node are shielded from
its home agent since a mobile node changes its point of attachment to the wired network, i.e., foreign
agent, without changing its routing agent. The change of the foreign agent is called a local handoff and
the change of the routing agent is called a routing handoff. Mobile IP becomes the special case in which
the routing agent and the home agent of a mobile node coincide. This paper assumes that every home
agent or foreign agent can serve as a routing agent.

Registration in Mobile IP is now divided into two types of registrations, which we call home regis-
tration and local registration. A mobile node initiates home registration

- to communicate its current location to its home agent, and, as an option,
to establish or renew its routing agent at the current foreign agent.

If a mobile node chooses to establish its routing agent, a key is also established during home registration, which will be used later for local registrations of the mobile node with the routing agent. Any of the mechanisms in [8] can be used for setting up the local registration key.

\[ A_h \overset{3}{\underset{4}{\leftarrow}} A_r \overset{2}{\rightarrow} A_f \overset{1}{\leftarrow} M \]
\[ A_r \overset{2}{\rightarrow} A_f \overset{1}{\leftarrow} M \]

(a) Home registration  (b) Local registration

Figure 4: Registration message flow in the extension of Mobile IP with routing agents

The message flow for home registration by a mobile node is as follows (see Figure 4(a)):

1. The mobile node sends a home registration request to its foreign agent with a flag for renewing its current routing agent or establishing a new routing agent at the foreign agent. The home registration request contains the home address of the mobile node, the home agent address, the current routing agent address (whose default is the home agent address), and the foreign agent care-of address. If the flag is set for establishing a new routing agent at the foreign agent, the home registration must have an appropriate extension for key request.

2. The foreign agent forwards the home registration request to the current routing agent.

3. The current routing agent forwards the home registration request to the home agent.

4. The home agent grants or denies the home registration request and sends a home registration reply to the current routing agent.

5. The current routing agent forwards the home registration reply to the foreign agent (which may become the new routing agent for the mobile node).

6. The foreign agent forwards the home registration reply back to the mobile node.

Having home registration requests and replies pass through the current routing agent allows it to update or expire the lifetime of the mobility binding that it maintains for the mobile node.

A mobile node may initiate local registration with its routing agent when it
• moves from one IP subnet to another in a foreign network, or

• renews a local registration that is about to expire.

The lifetime in a local registration should be less than or equal to the minimum of the remaining lifetime of the home registration and the lifetime in an agent advertisement message from the foreign agent. This allows the home agent to control service authorization for mobile nodes.

The message flow for a local registration by a mobile node is as follows (see Figure 4(b)):

1. The mobile node sends a local registration request to its foreign agent.

2. The foreign agent forwards the local registration request to the routing agent.

3. The routing agent grants or denies the request and sends a local registration reply to the foreign agent.

4. The foreign agent forwards the local registration reply to the mobile node.

We have assumed that all home and foreign agents can serve as routing agents. In general, if a foreign agent cannot act as a routing agent, it indicates that in its Agent Advertisement. A mobile node visiting this foreign agent may keep using its current routing agent until it moves to another subnetwork, or change its routing agent to its home agent.

3 Performance Analysis

From the network perspective, IP mobility support incurs additional overhead, including:

• registration: A mobile node must register its location with its home agent so that the home agent can tunnel IP packets to the mobile node;

• packet tunneling: The home agent must intercept IP packets destined to its mobile nodes and tunnel them to the current locations of mobile nodes.

From a mobile user point of view, there are two important quality of service criteria:

• handoff delay: A mobile node is temporarily detached from the network during a handoff, causing packet drop and throughput reduction;
• packet tunneling: Packet tunneling requires extra processing and increases the length of the route from the source to the destination. This results in increased end-to-end delay for packet delivery.

This section analyzes registration cost, handoff delay, and packet tunneling cost under Mobile IP and the extension with routing agents. This analysis allows the identification of the strengths and weaknesses of the two approaches in terms of various cost factors. The flexibility of the routing agents allows to combine advantages of both approaches depending upon different cost criteria. (For convenience, a glossary of symbols used throughout this analysis is given in Appendix A.)

3.1 Simulation Model

We assume that the coverage area of the Mobile Network is partitioned into cells. A cell is defined as the coverage area of a mobility agent that has the capability to exchange packets with mobile nodes directly through the air interface. A mobility agent serves only one cell. Cells do not overlap each other.

A movement of a mobile node is defined as a cell boundary crossing by the mobile node. A movement occurs when a mobile node moves from the residing cell to one of its neighboring cells. We consider a movement-based scheme for routing handoff with a threshold of $d$. A mobile node moves $d$ times, performing $d$ local registrations, and initiates a home registration for routing handoff.

The distance between any two cells in the networks is measured by the minimum number of cell boundary crossings that is required for a mobile node to travel from one cell to the other. If we assume that a mobility agent is a router in a cell that can communicate directly through wired line with other mobility agents in neighboring cells, the distance between two agents can also be considered as the distance between their cells.

We consider a grid configuration for a Mobile Network composed of equal-sized, non-overlapping, rectangular cells. Figure 5 shows a Mobile Network coverage area with $7 \times 7$ cells. In this grid configuration, each cell has four neighboring cells. The distance between two cells with coordinates $(x_1, y_1)$ and $(x_2, y_2)$ is $|x_2 - x_1| + |y_2 - y_1|$. In Figure 5, the numerical label associated with each cell represents the distance of that cell from the cell with the label 0.

We compute the average registration cost, handoff delay and packet tunneling cost for a single mobile node between two routing handoffs under the movement-based routing handoff scheme with threshold $d$ in Mobile IP with routing agent. The initial position of the current foreign agent is in the same cell of the routing agent after the first routing handoff. For Mobile IP, we compute the these parameters in
the same period, i.e. the the same $d$ movements starting from the same initial foreign agent.

### 3.1.1 Sizing Up a Triangle

The following distances are important parameters in evaluating the performance of Mobile IP and the extension with routing agents: between the home agent and the routing agent, between the routing agent and the foreign agent, and between the home agent and the foreign agent.

Let $k$ be the distance between the home agent and the routing agent after the first routing handoff. To determine the distance between the routing agent and the current foreign agent, we use a technique described in [1]. Consider the cell of the current routing agent of a mobile node as the center. A distance-$i$ cell of a mobile node is a cell that of distance $i$ away from the center. Notice that the center (or the cell of the current routing agent) is the distance-0 cell.

Define $P_d^n(1 \leq n \leq d)$ as a $(d + 1) \times (d + 1)$ transition matrix, where $d$ is the movement threshold. Each element $p_{i,j}^n(0 \leq i, j \leq d)$ in the matrix represents the probability of a mobile node moving from a distance-$i$ cell to a distance-$j$ cell in exactly $n$ movements. When $n = 1$,

$$
P_d^1 = \begin{pmatrix}
  a_{0,0} & a_{0,1} & a_{0,2} & \cdots & a_{0,d} \\
  a_{1,0} & a_{1,1} & a_{1,2} & \cdots & a_{1,d} \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  a_{d-1,0} & a_{d-1,1} & a_{d-1,2} & \cdots & a_{d-1,d} \\
  0 & 0 & 0 & \cdots & 1
\end{pmatrix}
$$

(1)

where $a_{i,j}(i = 0, 1, \ldots, j = 0, 1, \ldots)$ is the probability of moving from a distance-$i$ cell to a distance-$j$ cell in one movement. We assume that $P_d^1$ is constant. That is, the $a_{i,j}$’s do not change with time and
the location of a mobile node. (This can be true when we observe the mobile user in a short period of time.) Then for $1 < n \leq d$, the matrix $P^n_d$ can be obtained by

$$P^n_d = P^1_d \times P^{n-1}_d$$

(2)

An element of the form $p^n_{0,j}$ in $P^n_d$ indicates the probability that the distance between the routing agent and the current foreign agent is $j$ after $n$ movements.

To determine the distance between the home agent and the current foreign agent, we define a different matrix $L^n$ where each element $L^n_{i,j}$ is the probability of the current foreign agent located in the cell corresponding to the index $(i, j)$ after $n$ movements. In the grid configuration, the size of $L^n$ is $(2d + 1) \times (2d + 1)$, where $0 \leq n \leq d$, and the index $(d, d)$ corresponds to the location of the routing agent. Let the indices be the coordinates of the corresponding locations in the grid configuration. Since the home agent is of distance $k$ away from the current routing agent, the possible coordinates of the home agent are $(d+s, d+k-s), (d+k-s, d-s), (d-s, d-k+s), (d-k+s, d+s)$ for $s = 0, \cdots, k - 1$, the total number of which is $4k$. Thus the distance between the home agent and the current foreign agent after $n$ movements can be computed whose location corresponds to any non-zero element in $L^n$.

### 3.1.2 Walk Models of a Mobile Node

The computation of the matrices $P^n_d$ and $L^n$ depends upon the walk model of a mobile node. Two walk models are considered, namely the random walk model and a directional walk model.

In the random walk model, a mobile node moves to one of its four neighboring cells with equal probability of $1/4$. Thus the probability $a_{i,j}$ of moving from a distance-$i$ cell to a distance-$j$ cell in one movement in equation (1) is as follows:

$$a_{i,j} = \begin{cases} 
1 & i = 0, j = 1 \\
\frac{2s+1}{4} & i > 0, j = i + 1 \\
\frac{2s-1}{4} & i > 0, j = i - 1 \\
0 & otherwise
\end{cases}$$

(3)

For the probability matrix $L^n$ of possible locations of the current foreign agent after $n$ movements, the size of $L^n$ is $(2d + 1) \times (2d + 1)$ in the grid configuration, where $0 \leq n \leq d$. Since a mobile node moves to one of its four neighbors with equal probability $1/4$, we compute $L^{n+1}$ from $L^n$ by adding $L^n_{i,j}/4$ to elements $L^{n+1}_{i-1,j}, L^{n+1}_{i,j+1}, L^{n+1}_{i+1,j},$ and $L^{n+1}_{i,j-1}$ of $L^{n+1}$ for each non-zero element $L^n_{i,j}$ in $L^n$. Let
$L^0$ be the matrix of the initial foreign agent (after 0 movement). The only non-zero element of $L^0$ is $L_{d,d}^0 = 1$. We start with $L^0$ and end with $L^d$, where $d$ is movement threshold for routing handoff.

The random walk model may be appropriate for pedestrian mobile users. For mobile vehicle users, a directional walk model is more suitable. We assume that a mobile node moves towards only one direction in our analysis period. A mobile node moves to the next cell on the moving direction with a probability of 1. Thus the probability $a_{i,j}$ of moving from a distance-$i$ cell to a distance-$j$ cell in one movement becomes

$$a_{i,j} = \begin{cases} 1 & \text{if } i + 1 = j \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

For the probability matrix $L^n$ of all the possible locations of the current foreign agent after $n$ movements, we compute $L^{n+1}$ from $L^n$ by adding $L^n_{i,j}$ to element $L^{n+1}_{i-1,j}$ of $L^{n+1}$ for each non-zero element $L^n_{i,j}$ of $L^n$. As in the random walk model, we start from $L^0$ in which the only non-zero element is $L^0_{d,d} = 1$ and end at $L^d$.

3.2 Registration Cost

3.2.1 Registration Cost in the Extension of Mobile IP with Routing Agents

The registration cost includes the processing cost of registration messages at mobility agents and the transmission cost of registration messages among mobility agents. For simplicity, the processing costs at different mobility agents are assumed to be the same and is denoted by $C_A$. The transmission cost is assumed to be proportional to the distance between the source and the destination mobility agents. The proportionality constant is denoted by $\delta_T$. Let

- $C_{hr}$ be the transmission cost between the home agent and the routing agent,
- $C_{rf}$ be the transmission cost between the routing agent and the foreign agent, and
- $C_{fm}$ be the transmission cost over the wireless link between the foreign agent and the mobile node.

Figure 4(b) shows the message flow for a local registration when the current foreign agent is in a different cell of the routing agent. When the current foreign agent is the same as the routing agent, local registration messages can be exchanged directly between the routing agent and the mobile node,
and the home registration messages can be exchanged directly between the home agent and the serving foreign agent. So the cost for a local registration under Mobile IP with routing agents is

\[
\begin{cases}
C_A + 2C_{fm} & \text{when the foreign agent is the same as the routing agent} \\
2C_{rf} + 3C_A + 2C_{fm} & \text{otherwise}
\end{cases}
\]  

(5)

Let \( j \) be the distance between the routing agent and the foreign agent. Then \( C_{rf} = j\delta_T \). The transmission cost of the wireless link is generally higher than that of the wired link. Suppose that the transmission cost over the wireless link is \( m \) times higher than the unit distance wired link transmission cost, \( \delta_T \). The transmission cost between the foreign agent and the mobile node can be written as \( C_{fm} = m\delta_T \). Therefore the cost for a local registration at a location which is distance \( j \) away from the routing agent can be expressed as

\[
\begin{cases}
2m\delta_T + C_A & \text{when the foreign agent is the same as the routing agent} \\
2(j + m)\delta_T + 3C_A & \text{otherwise}
\end{cases}
\]  

(6)

Similarly according to the message flow for a home registration in Figure 4(a), the cost for a home registration under Mobile IP with routing agents is

\[
\begin{cases}
2C_{hr} + 3C_A + 2C_{fm} & \text{when the foreign agent is the same as the routing agent} \\
2C_{hr} + 2C_{rf} + 5C_A + 2C_{fm} & \text{otherwise}
\end{cases}
\]  

(7)

Assuming that the distance between the home agent and the routing agent is \( k \), we have \( C_{hr} = k\delta_T \). With the same assumption in the computation of local registration cost, the registration cost for a home registration in Mobile IP with routing agents is

\[
\begin{cases}
2(k + m)\delta_T + 3C_A & \text{when the foreign agent is the same as the routing agent} \\
2(k + j + m)\delta_T + 5C_A & \text{otherwise}
\end{cases}
\]  

(8)

We compute the average registration cost between two routing handoffs. Each element \( p_{0,j}^n \), \( 0 \leq j \leq n \), in \( P_d^n \) (see equation 2) is the probability that the current foreign agent is of distance \( j \) away from the current routing agent. Let \( \text{Cost}_n \) denote the average local registration cost for the \( n \)-th movement. Then

\[
\text{Cost}_n = p_{0,0}^n (C_A + 2m\delta_T) + \sum_{j=1}^{n} p_{0,j}^n [2(j + m)\delta_T + 3C_A]
\]  

(9)

Under the movement-based routing handoff scheme with threshold \( d \), a home registration is performed after \( d \) movements to change the routing agent. The average distance between the current
routing agent and the foreign agent after \( d \) movements is

\[
D_d = \sum_{j=0}^{d} p_{0,j} \]

(10)

Given that the distance between the home agent and the current routing agent is \( k \) and that the transmission cost is proportional to the distance with proportionality constant \( \delta_T \), the cost of the home registration is

\[
2(k + m + D_d) \delta_T + 5 C_A - 2p_{0,0}^d C_A
\]

(11)

The last term of the above equation accounts for the reduction in processing cost when the mobile node is located in the same cell as the current routing agent and the current foreign agent is the same as the routing agent, in which case there is no extra processing at the routing agent.

Since there is exactly one local registration per movement of the mobile node and one home registration every \( d \) movements, the average registration cost per movement between routing handoffs is

\[
[2(k + m + D_d) \delta_T + 5 C_A - 2p_{0,0}^d C_A + \sum_{n=1}^{d} Cost_n]/d
\]

(12)

### 3.2.2 Registration Cost in Mobile IP

Let \( C_{hf} \) be the transmission cost between the home agent and the foreign agent. According to the message flow for registration under Mobile IP in Figure 2, the registration cost per movement under Mobile IP is

\[
\begin{cases}
C_A + 2C_{fm} & \text{when the mobile node returns home} \\
2C_{hf} + 3C_A + 2C_{fm} & \text{otherwise}
\end{cases}
\]

(13)

In order to compare with the extension with routing agents, we compute the average registration cost in Mobile IP in a similar period, i.e. \( d \) movements starting from an initial foreign agent that is of distance \( k \) away from the home agent. Each element \( L^{n}_{i,j} \) in the matrix \( L^n \) (see Section 3.1.1) is the probability that the current foreign agent after \( n \) movements is located in a cell indexed by \((i,j)\). Let \( d_{i,j}^k \) denote the distance between the home agent and the foreign agent in a cell indexed by \((i,j)\). When a mobile node registers with its home agent from the cell indexed by \((i,j)\), the cost is

\[
C_{i,j,h} = \begin{cases}
2m\delta_T + C_A & d_{i,j}^k = 0 \\
2(d_{i,j}^k + m)\delta_T + 3C_A & d_{i,j}^k \neq 0
\end{cases}
\]

(14)
The average registration cost in Mobile IP for $d$ movements can be obtained as

$$\frac{1}{d} \sum_{n=1}^{d} \sum_{i,j} L_{i,j}^n C_{i,j,h}$$  \hfill (15)

Since the home agent can be in any cell that is of distance $k$ away from the initial foreign agent (after 0 movement), we compute the average among all possible locations for the home agent for comparison with the registration cost in the extension with routing agents.

### 3.2.3 Comparison of Registration Cost

A selected set of values for the parameters $\delta_T$, $C_A$ and $m$ is used in the comparison of registration cost. As it is generally difficult to select parameter values which reflect the characteristics of all existing networks, we focus on comparing the registration cost at different movement threshold values when either the processing cost or the transmission cost of registration messages dominates.

![Graphs showing the ratio of average registration costs for different values of $k$](image)

(a) $\delta_T = 0.01$ and $C_A = 0.001$  \hspace{1cm} (b) $\delta_T = 0.001$ and $C_A = 0.01$

**Figure 6:** Ratio of average registration costs for random walk model

Figure 6 shows the ratio of the average registration cost in the extension with routing agents against that in Mobile IP for the random walk model where $m = 2$. A ratio less than 1 means that Mobile IP has a higher registration cost that the extension with routing agents.

Figure 6(a) assumes $\delta_T = 0.01$ and $C_A = 0.001$, which means that the transmission cost of registration messages dominates and the processing cost at mobility agents is small. When a mobile node is close to home, e.g., $k < 4$, or if the movement threshold $d$ is very small, Mobile IP performs better in
registration cost. The highest average registration cost in the extension with routing agents occurs at 
\( d = 1 \), where a routing handoff is performed for every movement after the corresponding local handoff. 
As the distance \( k \) between the home agent and the current routing agent increases, however, the average 
registration cost for the extension with routing agents is much lower than that for Mobile IP. This 
indicates that based upon the registration cost, we should choose a threshold value bigger than 1 and 
when a mobile node is close to home, we should switch back to Mobile IP by having the routing agent 
coincide with the home agent.

Curves in Figure 6(a) for different \( k \)'s have similar shapes but they reach the minimum point at 
different threshold values. The average registration cost increases slowly as the movement threshold 
increases beyond its optimal value. This is because when the movement threshold increases, the average 
distance between the routing agent and the foreign agent increases, and hence the local registration 
cost. This suggests that in order to minimize the registration cost, a dynamic scheme should be used 
to determine the best movement threshold \( d \) according to the distance between the home agent and the 
foreign agent.

Figure 6(b) shows the results for \( \delta T = 0.001 \) and \( C_A = 0.01 \), where the processing cost of registration 
messages at mobility agents dominates and the transmission cost is small. Under this situation, the 
average registration cost depends less on the distance between the mobility agents, so Mobile IP with 
routing agents is less beneficial. In Figure 6(b), our scheme becomes beneficial when \( k \geq 10 \) and \( d > 4 \). 
In fact, if transmission cost is neglected and only processing cost is considered, the average registration 
cost in Mobile IP with routing agents will be always larger than that in Mobile IP.

Figure 7 shows the results for the directional walk model, which are similar to those for the random 
walk model in Figure 6. The main difference is that in Figure 7(a) where the transmission cost dominates, 
the registration cost increases more rapidly as the threshold increases beyond its optimal value. The 
reason is that the distance between the routing agent and the current foreign agent increases more 
rapidly in the directional walk model.

3.3 Handoff Delay

The handoff delay consists of two main components, namely the agent discovery delay and registration 
delay. Agent discovery is the operation by which a mobile node detects that it has traveled to another 
cell. The delay for agent discovery depends on a number of factors which include the degree of over-
lacking between the current and the previous cells, the broadcast interval of agent advertisements, the movement detection strategy employed by the mobile node, and the type of mobility support provided by the link layer. Since the same agent discovery procedure can be used under both Mobile IP and the extension with routing agents, we will not consider the agent discovery delay in our analysis.

Registration delay consists of the processing delay of registration messages at mobility agents and the transmission delay of registration messages among mobility agents. We assume that transmission delay is proportional to the number of links the registration request and reply messages travel, and the processing delay is the same at every mobility agent. Therefore the analysis of registration delay is similar to that of registration cost in Section 3.2, except that \( C_A \) now represents the processing delay of a registration message at each mobility agent and \( \delta_T \) is the proportionality constant for transmission delay.

Under Mobile IP, a mobile node is temporarily detached from the network when it tries to register with the home agent. During this period, all data packets transmitted to the mobile node are tunneled to the old foreign agent and may not reach the mobile node. The average registration delay in Mobile IP is computed following equation (15) under the new interpretation of \( C_A \) and \( \delta_T \) as processing and transmission delay.

In Mobile IP with routing agents, there exist two types of registrations, i.e., local registration and home registration. During local registration after a movement, a mobile node is temporarily detached
from the network. This is similar to registration in Mobile IP. In contrast, the mobile node is connected to the wired networks through its foreign agent while home registration is being performed. The mobile node will continue to receive data packets tunneled from the home agent. Therefore home registration delay is not included in the handoff delay. The average local registration delay per movement is

\[
\frac{1}{d} \sum_{n=1}^{d} Cost_n
\]  

where \( C_A \) now represents the processing delay of a registration message at a mobility agent and \( \delta_T \) is now the proportionality constant for transmission delay. Notice that it is independent of the distance between the home agent and the current foreign agent of a mobile node. Even if a mobile node is far away from home, the local registration delay, during which a mobile node is temporarily disconnected, is still bounded depending upon the threshold \( d \) and parameters \( C_A \) and \( \delta_T \) for processing and transmission delay.

![Figure 8: Ratio of registration delays in random walk model](image)

**Figure 8:** Ratio of registration delays in random walk model

Figure 8(a) shows the ratios of the local registration delay in Mobile IP with routing agents against the registration delay in Mobile IP when the transmission delay dominates. The local registration delay is much smaller than the registration delay especially when a mobile node is not close to home. It increases with the movement threshold \( d \) under Mobile IP with routing agents. The minimum value occurs at the smallest movement threshold \( d = 1 \). This corresponds to the case where a routing handoff is performed immediately after each local handoff and, the routing agent is always changed to the current foreign agent. As the movement threshold increases, the average distance between the routing agent
and the foreign agent increases slowly. As a result, the local registration delay increases slightly. It is demonstrated in Figure 6 that the overall registration cost is very high when the movement threshold is 1. Therefore, a movement threshold value higher than 1 may be more desirable even though the local registration delay is slightly increased.

From equation (16) we know that the local registration delay is independent of the distance between the home agent and the routing agent in Mobile IP with routing agents and can be controlled by adjusting the movement threshold. In contrast, the registration delay in Mobile IP increases with the distance between the home agent and the current foreign agent.

Figure 8(b) shows the ratios of the registration delays when the processing delay dominates. The trends are similar to those in Figure 8(a). The spikes of the curves are caused by the grid configuration. A mobile node always moves to one of its neighboring cells. Since a mobile node is initially in the distance-0 cell, the possible locations of a mobile node after an odd number of movements are all distance-$i$ cells where $i$ is odd, and those after an even number of movements are all distance-$j$ cells where $j$ is even. The latter include the distance-0 cell where the processing delay is the smallest compared to other cells. When the processing delay dominates the registration delay, this leads to the fluctuation of the delay ratios. When $k = 1$ and $d = 1$, the delay in Mobile IP is smaller than that in the extension with routing agents. The fluctuation in registration delays decreases when the number of movements increases.

An interesting observation is that the handoff delays of the two schemes are not necessarily the same even if we neglect the transmission delay (i.e. $\delta_T = 0$). This is because when a mobile node is far away from home, it is more probable to return to the cell associated with its routing agent than to its home network. When the foreign agent is the same as the routing agent, local registration is processed by only one mobility agent and the total processing delay is reduced.

Figure 9 shows the ratios of registration delays using the directional walk model. The trends are similar to those in the random walk model. However the distance between the routing agent and the current foreign agent increases more rapidly with the increasing movement threshold in the directional walk model than in the random walk model. Consequently the curves are also increasing faster. When $k = 1$ and the processing delay dominates, the registration delay in Mobile IP is smaller than that in Mobile IP with routing agents. This again suggests that our scheme should switch back to Mobile IP when $k$ is small.
3.4 Packet Tunneling Cost

We consider the average tunneling cost per IP packet during $d$ movements between two consecutive routing handoffs. The packet tunneling cost consists of the transmission cost and the processing cost of data packets from the home agent to the current foreign agent. We assume that the transmission cost is proportional to the number of links the data packets travel with the proportional constant $\delta_{T,p}$, and the processing cost is proportional to the number of mobility agents that tunnel data packets with the proportional constant $C_{A,p}$.

Under Mobile IP, every IP packet destined for a mobile node is intercepted by the home agent and is tunneled directly to the care-of address of the mobile node. Let $d_{i,j}^h$ denote the distance between the home agent and the current foreign agent located in a cell indexed by $(i, j)$. The cost of tunneling a packet to the foreign agent is

$$CT_{i,j,h} = \begin{cases} 
C_{A,p} + d_{i,j}^h \times \delta_{T,p}, & d_{i,j}^h \neq 0 \\
0, & d_{i,j}^h = 0
\end{cases} \quad (17)$$

Following the same analysis for the registration cost in Mobile IP in Section 3.2.2, the average tunneling cost per packet in $d$ movements in Mobile IP is

$$\frac{1}{d} \sum_{n=0}^{d-1} \sum_{i,j} L_{i,j}^n CT_{i,j,h} \quad (18)$$

Since the home agent could be in any cell that is of distance $k$ away from the initial foreign agent (after
0 movement), we compute the average among all possible locations for the home agent.

Under Mobile IP with routing agents, a packet for a mobile node is routed through an intermediate routing agent to arrive at the foreign agent as shown in Figure 3. When a mobile node is residing in a distance-$i$ cell that $i \neq 0$, data packets have to travel through 2 mobility agents and $(k + i)$ links to arrive at the foreign agent. Let $P_i$ be the probability of a mobile node residing in a distance-$i$ cell during the $d$ movements between routing handoffs. Then

$$P_i = \begin{cases} \frac{1}{d}(1 + \sum_{n=1}^{d-1} p^0_{0,i}) & i = 0 \\ \frac{1}{d} \sum_{n=1}^{d-1} p^0_{0,i} & 1 \leq i \leq d - 1 \end{cases}$$

and the tunneling cost for a packet arrived when a mobile node is in a distance-$i$ cell is

$$\begin{cases} C_{A,p} + k \delta_{T,p}, & i = 0 \\ 2C_{A,p} + (k + i)\delta_{T,p}, & i > 0 \end{cases}$$

The average tunneling cost of a data packet in $d$ movements between two routing handoffs in Mobile IP with routing agents is

$$R_0(C_{A,p} + k \delta_{T,p}) + \sum_{i=1}^{d-1} P_i[2C_{A,p} + (k + i)\delta_{T,p}]$$

![Graph](image.png)

(a) $\delta_{T,p} = 0.01$ and $C_{A,p} = 0.001$

(b) $\delta_{T,p} = 0.001$ and $C_{A,p} = 0.01$

Figure 10: Ratio of tunneling cost per packet in random walk model

For the random walk model, Figure 10(a) shows the ratios of tunneling cost per packet in Mobile IP with routing agent to that in Mobile IP when the transmission cost is high compared to the processing cost. The tunneling cost of Mobile IP with routing agents is always higher than that of Mobile IP. The
curve of $k = 1$ increases with the movement threshold $d$ initially to reach a maximum value, and then drops down. This is because when $d$ is much larger than $k$, the difference between the two tunneling costs becomes less significant. The same trend is expected for other $k$ values.

Before the ratio of the two tunneling costs reaches its maximum value, the curves are more level as $k$ increases. The reason is that for any specific movement threshold $d$, the extra tunneling cost due to routing agents does not grow with the distance $k$ between the home agent and the routing agent. Instead it is bounded and determined by the average distance between the routing agent and the foreign agent that are in turn determined the movement threshold $d$ and walk models.

Figure 10(b) shows the ratios of tunneling cost per packet when the processing cost is high compared to the transmission cost. The ratios are bigger because there are two mobility agents involved in tunneling, the routing agent and the foreign agent, instead of one. Nevertheless, the extra tunneling cost per packet is still independent of $k$ and determined by the average distance between the routing agent and the foreign agent.

\begin{center}
\begin{tabular}{ll}
(a) $\delta_T, p = 0.01$ and $C_{A,p} = 0.001$ & (b) $\delta_T, p = 0.001$ and $C_{A,p} = 0.01$
\end{tabular}
\end{center}

Figure 11: Ratio of tunneling cost per data packet in directional walk model

For the directional walk model, Figure 11 shows the ratios of tunneling cost per packet in Mobile IP with routing agent against that in Mobile IP. The results are similar. One difference is that the ratio of tunneling cost reaches the maximum earlier, because the average distance between the routing agent and the foreign agent increases more rapidly (linearly) than that in the random walk model. However, the extra tunneling cost per packet is still independent of the distance between the home agent and the
foreign agent.

4 Discussion

We have analyzed an extension of Mobile IP with routing agents in terms of registration cost, handoff delay, and packet tunneling. A routing agent is introduced to handle movements locally for mobile nodes that are not close to home, shielding them from the home agent. It exploits the individual locality of user mobility in a dynamic two-level hierarchical architecture. For mobile nodes that are not close to home, it reduces both the registration cost and handoff delay with a slight increase in packet tunneling.

Compared with the related work, the extension of Mobile IP with routing agents is orthogonal to techniques for route optimization [8, 10, 13, 15], fast intra-subnet handoff [5], and improving TCP performance in wireless networks [3, 4, 9]. In fact it can be combined with these techniques for a better overall support for mobility.

Although the extension of Mobile IP with routing agents can be viewed as a dynamic two-level hierarchical architecture, it is different from other hierarchical schemes such as [7, 12]. Unlike redirection agents in [7], routing agents do not have to be strategically located in order to intercept traffic for mobile nodes since the home agent maintains the routing agent address as the care-of address of a mobile node. The two-level hierarchy with routing agents is dynamic and can be specific to each mobile node, while the hierarchy of foreign agents in [12] is the same for all mobile nodes according to the regional topology. Perhaps the most distinctive feature of the extension of Mobile IP with routing agents is that the (maximum) handoff delay no longer depends upon the distance between a mobile node and its home agent. Instead it can be controlled and bounded based upon the movement threshold and the underlying mobility models. This is especially useful when a mobile node is far away from home and cannot tolerate handoff delays over a certain level.

There has been extensive work on location management in personal communications service networks [2]. Most of the work is concerned with optimizing the cost of location update and paging based upon the incoming call-to-mobility ratio of a mobile user. The main difference in Mobile IP is that it is connectionless and the home agent has to maintain the care-of address of a mobile node in order to tunnel IP packets correctly for ongoing communications to mobile nodes. Besides registration cost, minimizing the handoff delay is of paramount importance since IP packets to a mobile node may be
dropped during handoff.

Although our analysis is limited to a simple grid configuration of a mobile network and two simple mobility models, namely random walk and directional walk, there is reason to believe that the results are applicable to more general network topologies and mobility models. Whenever a mobile node moves, it can only move into one of the neighboring cells. The fundamental assumption in our analysis is that the geographical locality among cells implies network locality among the corresponding mobility agents. Therefore when a mobile node is not close to home, the distance between the routing agent and the mobile node can be kept shorter than the distance between the home agent and the mobile node. Most networks use some hierarchy to make routing more scalable and our assumption holds in such networks except for neighboring cells that belong to different areas in network routing.

Mobile IP with routing agent is a flexible scheme. A variety of parameter selections can be made according to various design criteria. One variation of this scheme is to make the routing agent coincide with the home agent such that the movement threshold for routing handoff is infinite. In this case, the proposed scheme is reduced to Mobile IP. Another variation is to use the movement threshold of 1. This is a kind of forwarding scheme which has a maximum registration cost, a minimum local registration delay and a minimum packet tunneling cost. A dynamic variation of the proposed scheme is also possible to set the movement threshold adaptively to minimize the overall registration cost.

The functions of the routing agent are not restricted to routing and mobile registration only. It can play a more active role in the mobile network management and upper level functionality. The potential of the routing agents and their impact on the network deserve further research.

References


Appendix

A Glossary of Symbols

\( \mathcal{S} \) A network host which sends data packets to a mobile node

\( \mathcal{M} \) A mobile node

\( \mathcal{A}_h \) The home agent of a mobile node

\( \mathcal{A}_f \) The foreign agent serving a mobile node away from home

\( \mathcal{A}_r \) The routing agent serving a mobile node away from home

\( a_{i,j} \) The probability that a mobile node moves from a distance-\( i \) cell to a distance-\( j \) cell after a movement

\( C_A \) Processing cost of a registration message at a mobility agent

\( \delta_T \) Proportionality constant of the transmission cost of a registration message

\( d \) Movement threshold for performing routing handoff

\( C_{hf} \) The transmission cost between the home agent and the serving foreign agent

\( C_{hr} \) The transmission cost between the home agent and the current routing agent

\( C_{rf} \) The transmission cost between the serving routing agent and the serving foreign agent

\( C_{fm} \) The transmission cost over the wireless link between the serving foreign agent and the mobile node

\( k \) The average distance between the home agent and the new serving foreign agent

\( m \) The proportionality constant of the transmission cost of a registration message over the wireless link

\( Cost_n \) The average local registration cost for the \( n \)-th movement since the last routing handoff

\( P_d^n \) A \( (d+1) \times (d+1) \) transition matrix for the random walk model when the movement threshold for routing handoff is \( d \)

\( p_{i,j}^n \) The probability of moving from a distance-\( i \) cell to a distance-\( j \) in exactly \( n \) movements
$\overline{D}_n$ The average distance between the serving routing agent and the serving foreign agent when the mobile node is at its $n$th movement.

$L^n$ The probability matrix of every possible location of foreign agent at the $n$th movement.

$L^n_{i,j}$ The probability of locating at point $(i, j)$ at the $n$th movement of a mobile node.

$d^h_{i,j}$ The distance between the home agent and the current foreign agent when the home agent is at one of its possible locations $h$ which is of distance $k$ away from the initial foreign agent, and the current foreign agent is at location $(i, j)$.

$N$ The number of all possible locations of the home agent.

$C_{i,j,h}$ The registration cost in Mobile IP when the home agent is at one of its possible locations $h$ which is distance $k$ away from the initial foreign agent, and the current foreign agent is at location $(i, j)$.

$CT_{i,j,h}$ The tunneling cost of data packet in Mobile IP when the home agent is at one of its possible locations $h$ which is distance $k$ away from the initial foreign agent, and the current foreign agent is at location $(i, j)$.

$C_A,p$ The processing cost of a tunneled packet incurred at each mobility agent.

$\delta_T,p$ The proportionality constant of the transmission cost of a tunneled packet between the sending and the receiving mobility agents.

$P_i$ The probability of a mobile node residing in a distance-$i$ cell.