Hierarchical Location Management Scheme Based on Collaboration of Mobile Nodes

Takeru INOUE†[a], Noriyuki TAKAHASHI†, and Toshiaki MIYAZAKI†, Members

SUMMARY The exciting goals of ubiquitous computing and communication services can only be achieved if we can increase the efficiency with which the location of mobile terminals can be managed; current mobile infrastructures are not efficient since they treat all mobile terminals uniformly despite that fact that many mobiles often move together (i.e. passengers on the same train or a group of cars on a road). This paper presents a hierarchical location management scheme that handles such grouped mobiles collectively and so reduces the overhead costs of location management. In our scheme, mobiles that move together for long enough form a mobile network and make a hierarchy in the wireless access network. The scheme also adjusts the number of mobile networks to keep communication overhead low. We apply the scheme to Mobile IPv6 and evaluate the resulting performance improvement. Simulation results confirm that our hierarchical approach can greatly reduce the overhead costs of location management, and that it is very practical since it can flexibly develop suitable mobile networks.

key words: mobile IP, binding update, mobile network, network mobility, location management

1. Introduction

Mobile communications infrastructures such as the cellular phone have spread rapidly. Cellular phones are now seen as social necessities in many countries. Hot spot services, which provide high-speed access to the Internet using wireless LAN technologies, are available in airports, hotels, retail stores, coffee shops, and so forth. Also, sensor networks [1] and vehicle networks [2] are a more recent development. It is expected that the number and the variety of mobile terminals will continue to grow and eventually yield ubiquitous computing and communications services. It follows that the efficiency with which these services are provided must be enhanced.

The IP-based mobile communications architectures, such as Mobile IPv4 [3] and Mobile IPv6 [4], are considered to be the dominant trend in the next generation mobile infrastructures. Mobile IP is recognized to be a promising solution for mobile communications including cellular backbone [5], [6]. In Mobile IP, a mobile node is allowed to use the same IP address even when it is connected to a network other than its home network. In this mechanism, the home agent located in the home network manages the mobile’s location and forwards packets destined to the mobile in the visited network. Since the home agent is indispensable when communicating with the mobile, overloading the home agent causes packet loss.

In order to reduce the loads of the home agents, hierarchical location management techniques used in the core network are raised in references [7]–[10]. These techniques introduce local home agents which manage local mobility on behalf of home agents, and distribute the location management load among them. They can reduce the processing load of each agent, but the total load amount is not diminished. A fundamental solution that reduces the total load amount is required in the coming ubiquitous era where the number of mobiles is expected to grow as mentioned at the beginning.

Network mobility (NEMO) basic support protocol [11] is being investigated as an IETF standard. As described in reference [11], network mobility is transparent to the mobiles inside the mobile network. Hence the mobile in the mobile network never issues binding updates to the home agent even while the mobile network is traveling. This can be a fundamental solution that reduces the total number of binding updates. However, methods that yield stable mobile networks that suppress binding updates effectively, have not been proposed yet. In this paper, we suggest an efficient location management scheme using mobile networks. In the scheme, mobiles use a kind of log that records router connectivity in order to determine which mobile is moving together with the mobiles. Mobiles that move together for long enough form a mobile network, and make hierarchies in the wireless access network. Our scheme does not need any special hardware like a global positioning system, and is able to be applied to many types of mobile.

This paper is organized as follows. We first discuss related works in Sect. 2, and present the grouping method to form stable mobile networks in Sect. 3. An algorithm that can suppress the communication overhead is introduced in Sect. 4. Implementation issues are discussed in Sect. 5 and simulation results are given in Sect. 6.

2. Related Works

2.1 Mobile IPv6

The basic elements in Mobile IPv6 [4]† are mobile nodes, home agents, which manage a location database called binding cache, stationary routers, which advertise network prefixes, and correspondent nodes, which communicate with...

†Our discussion assumes the use of Mobile IPv6, however, Mobile IPv4 is also possible.
mobile nodes. A router sends router advertisements [12] periodically or when it is requested, in order to inform the mobile nodes in the connected network of its network prefix. The mobile node knows its point of attachment to the Internet by receiving the advertisement, and determines a care-of address, which is a temporary IPv6 address in the visited network. The mobile then sends a binding update including its care-of address to the correspondent home agent, which looks up the entry for the mobile in its binding cache and updates the care-of address. The binding cache is a database managed by home agents and correspondent nodes, in which care-of addresses are recorded. Whenever the mobile moves and changes its point of attachment, it determines its next care-of address and issues a binding update again.

A packet destined to a mobile is routed to the home network of the mobile, and intercepted by the home agent. The home agent looks up the entry for the mobile in its binding cache, finds the care-of address, and then encapsulates the packet destined to the care-of address. The mobile receives the encapsulated packet and decapsulates it. The home agent has two main tasks, binding cache updating and packet encapsulation.

In order to reduce the encapsulation loads and transmission delay, a route optimization technique was standardized. When the mobile receives encapsulated packets, it sends a binding update to the correspondent node. The correspondent node records the care-of address of the mobile in its binding cache, and then sends a packet to the mobile directly without encapsulation. Whenever the mobile changes its point of attachment, it sends a binding update to the correspondent node as well as the home agent.

In this paper, we consider all access networks wireless links. A router broadcasts router advertisements within its radio zone, which is called the location area hereafter.

2.2 Existing Methods to Suppress Binding Updates

It is more difficult to ease the load of processing the binding updates than that of encapsulation. A hierarchical location management technique, an extension of Mobile IPv6, is proposed in reference [8]. This technique introduces mobility anchor points, namely local home agents, and a hierarchical structure rooted the mobility anchor point. Since the mobility anchor point aggregates binding updates forwarded by the connected routers, the home agent receives no binding update unless the mobile moves out of the hierarchy. This technique introduces hierarchies in the core network, and distributes the location management load among them, however, the total load amount is not diminished.

We note that Mobile IPv6 is unaware of, and thus does not utilize, the movement pattern of mobiles. However, several mobiles often move together for some duration. A good example is a group of cars running on the highway; hundreds of mobiles can move as one for several tens of minutes. Whenever the group passes a boundary between location areas, all mobiles in the cars issue binding updates simultaneously, and this places inordinately heavy loads on the home agent.

There are several techniques to ease these heavy loads based on the movement attributes of the mobiles. A mobile location area scheme was proposed in reference [13]. Stationary routers along the highway change the advertised information with time, and generate virtual location areas that move as rapidly as the cars on the highway. The mobiles in the cars keep receiving the same advertisement, and so do not issue binding updates. In this scheme, conventional stationary location areas overlap the new ones. Though mobiles in the overlap region should choose a location area that matches its movements, no algorithm was provided that could make this decision. Moreover, we have to match the velocities of the mobile location areas to the traffic.

Another scheme [14] utilizes the movement logs of the mobiles. A mobile enters information into the home agent such as when it passed a location area and which area it was. A mobile sends binding updates only when it makes an unexpected move; no binding updates are issued as long as its movement follows the anticipated route. When a packet is sent to the mobile, the home agent estimates the care-of address that is likely to suit the mobile by referring to the movement log. Though the scheme minimizes the binding updates from mobiles undergoing routine movement, it has several problems. Mobiles and home agents must maintain movement logs. In particular, the home agent has to track all movement logs of all mobiles', which requires large disk space. The home agent must also calculate the care-of address whenever it receives a packet destined to the mobile.

2.3 Network Mobility Basic Support Protocol

Network mobility (NEMO) basic support protocol [11] is being investigated as an IETF standard. The protocol introduces mobile routers whose definition extends that of the mobile node, by adding the capability of routing between its care-of address and a subnet which moves with the mobile router. We call such moving subnets mobile networks hereafter. In the protocol, we find the hierarchical relationship rooted at stationary router in the wireless access network, in contrast to reference [8] in which the hierarchy is found in the core network.

Figures 1, 2, and 3 overview NEMO basic support protocol. Figure 1 depicts the situation where the mobile router and the mobile node are at home. The home agents and the correspondent node have no binding cache. A packet destined to the mobile node is routed to it directly.

Figure 2 illustrates binding update, where the mobile router and the mobile node move together for some time. At first, the mobile node is attached to the mobile router which visits network 7::: The home agents have binding caches, as shown in Fig. 2(a). As the mobiles travel, the mobile network is likely to visit many networks one after another. However, the mobile nodes in the mobile network keeps receiving router advertisements from the mobile router and so do not issue binding updates, only the mobile router issues
such updates, as illustrated in Fig. 2(b).

Figure 3 shows communication between the correspondent node and the mobile node. NEMO basic support protocol offers no route optimization, and the routing solution described in reference [11] requires setting up a bidirectional tunnel between the mobile router and its home agent, as shown in Fig. 3(b). However, route optimization in NEMO basic support protocol is possible as our proposal in Sect. 5.2 shows; the proposal reduces the encapsulating loads of home agents.

2.4 Mobile Network Formation Issues in NEMO Basic Support Protocol

As shown in Fig. 2, network mobility is transparent to the mobiles inside the mobile network, and the mobiles never issue binding updates to the home agents. Most binding updates are expected to be issued by high speed mobiles, which are often moving together because there are only a few modes of travel available to the public such as by train or car. Hence, stable mobile networks, which can suppress the binding updates from such co-moving mobiles, provide an efficient solution.

The assumption made by reference [11] is that the formation of the mobile network is already known or can be obtained. Methods for forming mobile networks, which can ease the loads of the home agent, have not proposed yet.
In order to form such mobile networks, we have to address three issues.

The first issue is movement attributes (direction and velocity). The simplest way to form a mobile network is to use spatial proximity. Proximity can be obtained in several ways such as signal intensity or global positioning system information. However, the nearest router may be moving in the opposite direction, which would lead to unstable mobile networks. The movement of each mobile should be taken into account, as shown in Fig. 4.

Second, the size of the mobile network is another important factor determining the number of binding updates. Large mobile networks as (β) in Fig. 5 greatly reduce the number of binding updates.

Finally, mobile networks increase the processing cost of encapsulation, while decreasing that of binding updates. As illustrated in Fig. 3, the more deeply mobile networks are nested, the more encapsulations have to be performed. There is a trade-off between the processing cost of binding updates and that of encapsulation.

3. Grouping Method to Form Mobile Networks Based on Movement Attributes

This section proposes a grouping method to form stable mobile networks. The method is not aimed at distributing the location management cost, but at reducing the total cost, namely, the summation of processing cost that all home agents perform. Hereafter, cost should be taken to mean total cost.

Our proposal is performed by a mobile that becomes not to receive advertisements from the router to which the mobile attaches itself. The method proceeds as follows. Each mobile estimates, by itself, movement attributes based on the connectivity logs, and calculates the cost of surrounding stationary/mobile routers. Finally, the lowest cost router is chosen and attached to by the mobile. This process creates mobile networks that offer the lowest total cost.

We define the hierarchy in Sect. 3.1 and discuss cost estimation in Sect. 3.2. A heuristic that estimates the movement attributes is proposed in Sect. 3.3. Section 3.4 discusses the routers that can be candidates for attachment.

3.1 Hierarchy in Mobile Network

In NEMO basic support protocol, we find the hierarchical relationship rooted at stationary router in the wireless access network. In Fig. 3, the mobile node attaches to the mobile router and the mobile router attaches to the stationary router. This relationship can be expressed as a tree, see Fig. 6. When a mobile leaves the location area of its parent, the edge linking the mobile to the parent is broken. The mobile attaches to another router as its new parent, and the tree structure changes accordingly.

3.2 Processing Cost of Home Agents

We start by discussing the processing cost of home agents as performed in basic Mobile IPv6, and then focus on the cost in NEMO basic support protocol. Reference [15] evaluates the processing cost of binding updates. Home agent has, however, two main tasks: packet encapsulation and updating of binding cache. Therefore, we evaluate the effectiveness of the method in terms of the combined processing cost.

In basic Mobile IPv6, the processing cost of binding updates and encapsulation in time period $\Delta t$ is given by

$$C(\Delta t) = \sum_{i=1}^{N} \left\{ CuE[u_i(\Delta t)] + CpE[p_i(\Delta t)] \right\},$$

where $N$ is the number of mobiles in the network, $Cu$ is the cost to process a single binding update operation and $Cp$ is the cost to process a single encapsulation, $E[u_i(\Delta t)]$ is the expected number of binding updates issued by $MN_i$ in $\Delta t$, $E[p_i(\Delta t)]$ is similarly the expected number of packets destined to $MN_i$ routed through the home agent in $\Delta t$. $MN_i$ estimates $E[p_i(\Delta t)]$ from its communication record, which logs information such as when a session starts. We present a method to estimate $E[u_i(\Delta t)]$ in Sect. 3.3.
In Eq. (1), only term $i = n$ changes when MN$_n$ issues a binding update; the other terms are independent of MN$_n$’s binding update. The difference in cost when MN$_n$ chooses SR$_p$ as its new attached router, which is denoted as $\Delta C_{n,p}$, is as follows.

$$\Delta C_{n,p}(\Delta t) = CuE[u_n(\Delta t)] + CpE[p_n(\Delta t)].$$ (2)

Let us introduce a method to estimate the processing cost of home agents in NEMO basic support protocol. Sections 3.2 to 3.4 consider the situation shown in Fig. 7. MR$_n$ leaves the location area of its parent SR$_{p_{\text{prev}}}$ and receives no advertisement from SR$_{p_{\text{prev}}}$ thereafter. MR$_n$ tries to estimate the cost for MR$_p$. Let $D_n$ and $D_p$ denote the sets of descendants of MR$_n$ and MR$_p$, respectively. SR$_{p_{\text{eq}}}$ is the parent of MR$_p$.

In NEMO basic support protocol, the number of encapsulations for a mobile implicitly depends on the number of its ancestors, the third issue in Sect. 2.4. Ancestors are upper level nodes of the mobile in the hierarchy. When $l$ is the path length of MR$_n$, the cost to process a single encapsulation operation is a function of $l$, which we denote as $Cp(l)$. When a mobile router changes its level in the hierarchy, the encapsulation costs for its descendants, as well as itself, change. Therefore, the change in encapsulation cost for MN$_d$ has to be added to Eq. (2). The total change in cost is, accordingly, revised to

$$\Delta C_{n,p}(\Delta t) = CuE[u_n(\Delta t)] + CpE[p_n(\Delta t)] + \sum_{d=1}^{D_p} \Delta CpE[p_d(\Delta t)],$$ (3)

where $\Delta Cp = Cp(l_{d_{\text{new}}}^d) - Cp(l_{d_{\text{prev}}}^d)$, and the third term is the change in encapsulating cost for $D_p$; $|D_n|$ is the number of elements in set $D_n$.

The packet destined to the mobile is routed to the home agents of its ancestors, that is, the mobile uses the binding caches of the ancestors to receive the packet. Henceforth, we divide the cost, incurred to process a single binding update issued by a mobile router, among its descendants and itself. Equation (3) is accordingly revised to

$$\Delta C_{n,p}(\Delta t) = \frac{1}{1 + |D_n|} CuE[u_n(\Delta t)]$$
$$+ \frac{1}{1 + |D_p| + 1 + |D_n|} CuE[u_p(\Delta t)]$$
$$+ \sum_{d=1}^{D_p} \Delta CpE[p_d(\Delta t)].$$ (4)

where the cost for MR$_n$’s update is divided among MR$_n$ and its descendants $D_n$, and the cost for MR$_p$’s update is also divided among MR$_p$ and its descendants ($D_p$, $D_n$ and MR$_n$).

The first and second terms in Eq. (4) are small if the router has many descendants. Mobiles are likely to choose such a router and attach to it. This increases the number of mobiles in the network as illustrated in Fig. 5 ($\beta$), and greatly reduces binding update frequency. This solves the second issue in Sect. 2.4.

### 3.3 Movement Attribute Estimation Based on Connectivity Logs

In this section, we discuss the mobiles’ movement attributes (direction and velocity), and present a heuristic that estimates $E[u(\Delta t)]$, the expected number of binding updates.

As mentioned in Sect. 2.4, we often move together because of the limited forms of transportation available. That is, we consider that mobiles that have moved together up to now are very likely to continue to move together. Let $\tau_{n,p}$ be the time period for which MR$_n$ receives advertisements from MR$_p$ (that is, the time period in which MR$_n$ can connect to MR$_p$). We assume that MR$_n$ continues to attach to MR$_p$ in the following $\tau_{n,p}$ period with probability of $1/2$, as illustrated in Fig. 8. When MR$_n$ leaves the location area of SR$_{p_{\text{prev}}}$, MR$_n$ issues a binding update immediately. MR$_n$ leaves the location area of MLP$_p$ in the successive period $\tau_{n,p}$ with probability $1/2$, and issues next binding update. Consequently, we get $E[u_{n_p}(\tau_{n,p})] = 1 + 1/2$.

Each mobile maintains a record of $\tau$ for the routers from which the mobile has received advertisements. We call this record the connectivity log.

We normalize Eq. (4) to compare routers as follows.

$$\Delta C(1) = \frac{1}{1 + |D_n|} Cu\left(1 + \frac{1}{2}\right) \frac{1}{\tau_{n,p}}$$
$$+ \frac{1 + |D_n|}{1 + |D_p| + 1 + |D_n|} Cu\left[1 - \frac{1}{2}\frac{1}{\tau_{p,pp}}\right]$$
$$+ \sum_{d=1}^{D_p} \Delta CpE[p_d(1)].$$ (5)

Note that, when MR$_n$ and MR$_p$ move together, $\tau_{n,p}$ is large and the first term in Eq. (5) is small. This is the first issue in Sect. 2.4. Since the three issues raised in Sect. 2.4 are
Finally, we correct $\tau$ for a stationary router. When a mobile passes the boundary of a location area of a stationary router, $\tau$ for the new stationary router starts at a relatively small value. This suggests that a mobile, which is carried by a walking user near the boundary, may choose a faster mobile router passing through the mobile by accident rather than a stationary router. Movement attributes of the previous stationary router can be applied to the new stationary router, because all stationary routers have the same movement attributes (stationary, of course). A mobile adds one half of $\tau$ of the previous stationary router to $\tau$ of the new stationary router.

3.4 Selection Method for Candidate Routers

In NEMO basic support protocol, a mobile router can attach to another router as well as being attached to by other mobiles. If a mobile router attaches to one of its descendants, the hierarchy that contains the mobile router will develop a loop. The loop makes the home agents encapsulate a packet without end. We discuss a set of routers which can be candidates for attachment.

In order to avoid making loops, $MR_n$ must remove its descendants $D_n$ from a set of routers from which $MR_n$ receives advertisements. Let $V_n$ denote the set of valid candidate routers of $MR_n$, and $A_N$ denote a set of routers from which $MR_n$ receives advertisements, $V_n = A_n - (A_n \cap D_n)$.

In estimating the cost change $\Delta C_{p,n}$, $MR_n$ also estimates $\Delta C_{p,n}$. If $\Delta C_{p,n} < \Delta C_{n,p}$, $MR_n$ removes $MR_p$ from the valid candidate routers to keep itself as one of the candidate routers of $MR_p$. Finally, the set of valid candidates of $MR_n$ is given by

$$V_n = A_n - (A_n \cap D_n) - B_n,$$

where $B_n = \{ p | \Delta C_{p,n} < \Delta C_{n,p} \}.$

4. Dynamic Role Change Algorithm between Mobile Routers and Mobile Nodes

Mobile routers as well as stationary routers send advertisements periodically, which consumes the radio link bandwidth. To minimize radio link bandwidth consumption, it is desirable to keep the number of mobile routers low. We present an algorithm that adjusts the ratio of mobile routers to all mobiles so as to reduce the communication overhead. We consider an example in which $MN_n$ and $MN_m$ move together at high speed. In the example, $MN_n$ compares the costs of being and not being a mobile router. At first, they work as mobile nodes, i.e. send no advertisements and have no children. When $MN_n$ attaches to a stationary router, the cost change derived from Eq. (5) is given by

$$\Delta C_{m,SR}(1) = Cu \left[ 1 + \frac{1}{2} \right] \frac{1}{\tau_{m,SR}}$$

$$+ \frac{1}{1 + |D_{SR}|} \frac{Cu E[u_{SR}(1)]}{1 + \frac{1}{2} \tau_{m,SR}}$$

$$+ C_p \left( \frac{E[p_n(1)]}{1 + \frac{1}{2} \tau_{m,SR}} \right).$$

(7)

where we let $E[u_{SR}(1)]$ equal zero because stationary routers never issue binding updates.

Next, we consider that $MN_n$ becomes the mobile router $MR_n$, and $MN_m$ attaches to $MR_n$. At this time, the cost change is given by

$$\Delta C_{m,n}(1) = Cu E[u_{m}(1)] + \left. \frac{1}{1 + \frac{1}{2} \tau_{m,SR}} \right|_{\tau \approx 1}$$

$$+ C \left( \frac{E[p_m(1)]}{1 + \frac{1}{2} \tau_{m,SR}} \right)$$

$$\simeq \frac{1}{1 + \frac{1}{2} \tau_{m,SR}} \frac{Cu}{2} + C \left( \frac{E[p_m(1)]}{1 + \frac{1}{2} \tau_{m,SR}} \right),$$

(8)

where $E[u_{m}(1)] = \frac{3}{2} \frac{1}{\tau_{m,n}} \ll \frac{1}{2} \frac{1}{\tau_{m,SR}}$, and $\tau_{m,n} \gg \tau_{m,SR}$ because $MR_n$ and $MN_m$ move together at high speed.

When $\Delta C_{m,n}(1)$ is smaller than $\Delta C_{m,SR}(1)$, $MN_n$ becomes a mobile router, which decreases the processing cost of the home agents. This inequality reduces to

$$\Delta C_{m,n}(1) < \Delta C_{m,SR}(1)$$

$$\frac{1}{1 + \frac{1}{2} \tau_{m,SR}} \left. \frac{Cu}{2} \right|_{\tau \approx 1} + C \left( \frac{E[p_m(1)]}{1 + \frac{1}{2} \tau_{m,SR}} \right)$$

$$< \frac{Cu}{2} \left( \frac{1}{1 + \frac{1}{2} \tau_{m,SR}} \right) + C \left( \frac{E[p_m(1)]}{1 + \frac{1}{2} \tau_{m,SR}} \right),$$

then,

$$\frac{1}{\tau_{m,SR}} > \frac{4}{5} \frac{C \left( \frac{E[p_m(1)]}{1 + \frac{1}{2} \tau_{m,SR}} \right)}{Cu E[p_m(1)]}.$$ 

(9)

where $\tau_{m,n} \gg \tau_{m,SR}$ because we assume that $MN_n$ and $MN_m$ move together. If $MN_n$ cannot obtain $E[p_m(1)]$, it uses $E[p_m(1)]$ or the general value instead. When the inequality (9) is satisfied, $MN_n$ becomes a mobile router. Intuitively, the inequality (9) is satisfied when the processing cost of binding updates is greater than the processing cost of encapsulation; i.e., when $MN_n$ moves at high speed. If the inequality (9) fails and $MR_n$ has no children at that time, $MR_n$ stops advertising and turns back into a mobile node.

Finally, we modify $\tau$ to suit a mobile router. When $MN_n$ becomes a mobile router and begins advertising, $\tau_{m,n}$ starts at zero. However, $MR_n$ and $MN_m$ have moved together before, so the estimated value of $\tau_{m,n}$ is too small. We present an algorithm that estimates a reasonable value of $\tau$ from a comparison of connectivity logs, see Fig. 9. This algorithm is based on the idea that mobiles moving with the same set of mobiles also move together. $MR_n$ appends its connectivity log to the first advertisement and broadcasts it. $MN_n$ receives the advertisement containing the connectivity log. As the first step, $MN_n$ compares the connectivity log of $MR_n$ with that of $MN_m$, and $\tau' = \min(\tau_{m,n}, \tau_{n,m})$ for each router $x$. As the second step, $MN_n$ obtains the offset value for $\tau_{m,n}$. $\tau_{offset}$ for $MN_n = \max(\tau_{m,n}, \tau_{n,m})$. Finally, $MN_n$ adds $\tau_{offset}$ to the original $\tau_{m,n}$ and gets the reasonable value of $\tau_{m,n}$.
5. Implementation in Network Mobility Basic Support Protocol

This section focuses on implementing the proposed scheme. The grouping method proposed in Sect. 3 should be implemented in all mobile nodes and mobile routers. Mobiles that can be mobile routers may perform the dynamic role change algorithm described in Sect. 4. We have to append extra information to router advertisements broadcasted by the mobile routers as shown in Sect. 5.1. Other nodes and messages need no modification.

5.1 Router Advertisements

The advertisements issued by the routers must provide the information that allows the mobiles to estimate cost change $\Delta C$ given by Eq. (5).

The mobile router $MR_n$ advertises the following information which is appended to a normal router advertisement,

- path length to $MR_n$ from the root in the hierarchy,
- list of IPv6 addresses of $MR_n$’s ancestors,
- the number of descendants of $MR_n$,
- $\sum_d E[p_d]$, the total packet rate of $MR_n$’s descendants, where $d$ represents a descendant of $MR_n$,
- $\tau_{n,p}$, expected time period to be able to connect to the current attached router (parent), where $p$ represents the parent of $MR_n$.

The total packet rate of the descendants is used to calculate the fourth term of Eq. (5). Since we define $C_p(l) = l$ in Sect. 6, $\sum_d \Delta C_p E[p_d] = \Delta C_p \sum_d E[p_d]$.

A mobile router also broadcasts advertisements when it issues a binding update to the home agent or is attached to by other mobiles, because the information in the advertisement is altered at that time. The interval of broadcasting advertisements should have some small random variation to avoid successive collisions. In order to reduce battery consumption, a mobile router may extend the advertisement lifetime and lengthen the interval between advertisements.

Let us consider router advertisements that are broadcasted by stationary routers. The path length of a stationary router must be zero and they have no ancestor. The number of descendants and the total packet rate are used by ancestors, and so stationary routers do not need to append this information.

$\tau_{SR,x}$, the expected stay period of a stationary location pointer, is assumed to be infinity, because stationary routers never issue binding updates. Hence router advertisements of stationary routers do not carry any extra information.

5.2 Route Optimization in NEMO Basic Support Protocol

In basic Mobile IPv6, a packet destined to a mobile in the mobile network is routed through the home agent of the mobile router, as illustrated in Fig. 3(b). Though the route optimization in NEMO basic support protocol has several
problems such as security issues, it can be realized in terms of the mechanism and is expected to be standardized in the near future. We propose an example of route optimization in NEMO basic support protocol and utilize it in the simulation in Sect. 6.

Figure 10 shows the same situation as Fig. 3 and how route optimization works in NEMO basic support protocol. When the mobile router receives an encapsulated packet, it sends a binding update to the original source address, namely, the correspondent node. The correspondent node updates its binding cache, and sets the two mobiles’ care-of addresses in the routing header. The packet sent by the correspondent node is routed not through any home agent to the destination mobile. In this route optimization protocol, home agents have to encapsulate only the first few packets in the session.

6. Performance Evaluation

6.1 Simulation Scenarios

We simulated the proposed scheme in software to evaluate its effectiveness. The software reproduces the movement and behavior of several mobiles, the routers, and the home agents.

First, we discuss the processing cost of binding updates and encapsulation. The processing cost incurred by a home agent depends on the implementation, operation, and network design. For convenience, we consider that the cost to process a single binding update equals to the cost to encapsulate a single packet. This is because both operations consist of a table search in the binding cache, packet processing, and security-related operations. Also, the cost is expected in proportion to the number of binding updates and encapsulations. We use the number as the performance evaluation measure, and call it the total location management cost.

Home agents perform a binding update when a mobile changes its location area, and also encapsulate a few packets when a correspondent node tries establishing a session to a mobile. It is unpredictable how many packets are routed till the correspondent node receives a binding update from the mobile. We assume that the home agent encapsulates only the first packet. In the simulation, sessions are initiated uniformly randomly and the average rate is 2 times per hour. The movement of each mobile is described later.

In our scheme, not only stationary routers but also mobile routers issue router advertisements. We also evaluated the communication overhead of the advertisements. The advertisement size of a stationary router is 88 bytes, while that of a mobile router is $96 + 16 \times l$ bytes (both sizes include the IPv6 header). The first advertisement of a mobile router contains the connectivity log. The advertisement intervals of stationary routers and mobile routers are 1 second and 10 seconds, respectively. We assume that the intervals of mobile routers are smaller than stationary routers’ so as to let mobile routers save on their power.

Location area of each stationary router is a circle with diameter of 4.1 km. In current mobile infrastructures, location areas overlap each other in order to keep mobiles in the boundary region from alternately registering in both location areas. In our simulation, we also overlap the location areas, as illustrated in Fig. 11. Mobile routers broadcast advertisements over 600 meter diameter circles, which are smaller than stationary routers’ because of the limitation of antenna. The simulations examined three situations as follows; the simulation period for each was 5,000 seconds.

- **Situation A: Highway 1**
  We assume the double-loop highway depicted in Fig. 12. The entire highway is covered by the location areas of eight stationary routers. 1,000 cars, each of which carries a mobile, are running on the highway. Considering actual roads, there are several situations in which child nodes are separated from their parent nodes. For example, the road has intersections, or the car speeds are different. The first situation is duplicated by the junction in the road. Upon arriving at the junction, each car goes right or left with equal probability (0.5). Each car changes its speed; the changes follow a normal distribution $N(90, 5)$—a mean speed of 90 km/h and a standard deviation of 5 km/h. In this situation, 95.4% of all cars run at 80–100 km/h.

- **Situation B: Highway 2**
  We assume a highway carrying fewer cars than situation A. 500 cars run on the highway of Fig. 12. Each car has a velocity distribution of $N(100, 10)$. In this situation, 95.4% of all cars run at 80–120 km/h. Other conditions are the same as in situation A.

- **Situation C: Downtown**
  We assume a downtown region in which 1,000 mobile users walk at random within a 5 km square. The square is covered by six stationary routers. A mobile user de-
cides its velocity and destination randomly, and leaves for the destination. Arriving at the destination, the user stops there for a while. The user then decides its next velocity and destination and starts moving again. The velocity is set uniformly randomly within the range of 2 to 4 km/h. The stop time varies from 0 to 30 minutes uniformly randomly.

6.2 Simulation Results

The first simulations did not use the dynamic role change algorithm presented in Sect. 4. Figures 13, 14, and 15 depict the location management cost and the communication overhead versus the ratio of mobile routers in each situation. When there is no mobile router, the proposed scheme is equivalent to basic Mobile IPv6. Next, we changed mobile roles dynamically, and observed the ratio of mobile routers among all mobiles. The average ratios of mobile routers are also shown in the figures. The simulation results with the dynamic role change algorithm are slightly different from those without it at the same mobile router ratio. However, the difference is within 0.5% so we ignore the difference here and present just the results without the algorithm.

Figure 13 demonstrates that the location management cost decreases by 63.7% in situation A. Figure 14 shows a 58.7% improvement in situation B. In both situations, the location management cost is greatly reduced by the grouping method presented in Sect. 3.

In the situation where few mobiles move together, the proposed scheme cannot create stable mobile networks. If mobiles were forced to create mobile networks, location management cost would actually be increased. Our scheme, however, changes its behavior according to the situation, and so the grouping method is inactive in unmatched situations. Figure 15 shows that the location management cost of the proposed scheme is not worse than that of basic Mobile IPv6.

The location management cost decreases as the ratio of mobile routers increases in situations A and B, while the communication overhead increases with the ratio of mobile routers in all situations. Figures 13, 14, and 15 demonstrate that the proposed algorithms yield low management cost with low communication overhead. The communication overhead is greater than is true in basic Mobile IPv6 by 105 bps, 101 bps, and 0 bps in the three situations. In situation C, all mobiles remain just mobile nodes, so no increase in communication overhead is observed.

7. Conclusion

This paper has proposed a unique hierarchical location management scheme for Mobile IPv6. We noted that mobiles in mobile networks never issue binding updates, and developed a grouping method that forms mobiles that move together into a mobile network. As a result, hierarchies are found in the wireless access network and mobiles can be managed collectively. The proposed scheme also adjusts the number of mobile networks to reduce communication overhead. Simulation results show that our approach greatly reduces the overhead costs of location management. They also demonstrate that mobile routers incur only a slight penalty in terms of communication overhead. Future works are to
verify the scheme’s feasibility and elucidate security issues.

References


