Supporting IP/LEO Satellite Networks by Handover-Independent IP Mobility Management

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***Abstract*—Low earth orbit (LEO) satellite networks are capable of providing wireless connectivity to any part of the world while guaranteeing short propagation delays. There is a huge need for developing Internet protocol (IP) friendly networking technologies that aim to integrate emerging LEO satellite networks with the already existing terrestrial IP networks. LEO satellite networks are well characterized by frequent handover occurrences. These handovers largely affect mobility management in LEO satellite networks. Existing IP mobility management protocols, such as mobile IP, manage the location of mobile nodes on the basis of the network topology. Applying such mechanisms in LEO satellite networks will cause a binding update of mobile nodes upon every handover occurrence. Given the frequent occurrence of handovers in LEO satellite networks, a potentially large number of binding update requests will be generated and ultimately affects the scalability of mobility management. This paper argues a handover-independent mobility management scheme for LEO satellite networks. The proposed scheme purposes to exploit geographical location information to make the mobility management independent from handovers. This handover-independent management method reduces the number of update requests and eventually increases the system scalability. A detailed description of the actual implementation of the scheme is given. Through a mathematical analysis, the paper evaluates the required management cost and accordingly verifies the scalability of the proposed scheme.**

***Index Terms*—Binding update, geographical location, handover, Internet protocol/low earth orbit (IP/LEO) satellite networks, mobility management.**

I. Introduction

LOW EARTH ORBIT (LEO) satellite networks intend to provide connectivity to end users beyond time and space limitations. To provide global coverage, several studies have discussed the integration of LEO satellite systems into today's Internet protocol (IP) networks [1]. IP/LEO satellite networks are believed to provide a wide variety of IP-based applications, such as teleconferencing and tele-education. Being totally independent of terrestrial networks, LEO satellite networks have a unique ability of supporting certain emergency communication systems, such as I Am Alive (IAA) System [2]. To provide such applications, scalable mobility management and IP communication between end nodes are required.

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In terrestrial mobile networks, only end nodes are subject to motion while base stations remain fix. Whereas, in LEO satellite networks, both end systems and satellites (base stations) keep on moving. Furthermore, considering the fact that satellite networks cover wide areas and should consequently serve a potentially large number of end nodes, scalability becomes a major issue. This compels LEO satellite networks to operate under high-mobility conditions and makes them experience bursty handovers that do not occur in terrestrial networks.

In IP networks, the IP address of a node is decided from its logical location in the network. Upon a handover occurrence, a node is required to change its IP address and notifies the location directory of the new address. In such a manner, a "binding" between nodes' own unique name and their correspondent new addresses is maintained. One of the most important issues in mobility management is how to efficiently handle these binding updates.

Conventional IP mobility management protocols, typified by mobile IP [3] and location independent network architecture for IPv6 (LIN6) [4], require mobile nodes to send binding update requests to the location directory every time a handover occurs. Given the high-mobility of satellite networks, usage of these approaches will result in a large number of binding update requests and consequently affect the scalability of the mobility management schemes.

This paper proposes a handover-independent mobility management scheme specifically designed for IP/LEO satellite networks. The basic idea behind the scheme is to make IP addresses independent of logical locations and associated to only geographical location information. By so doing, the effect of handover occurrences on the binding update cost can be mitigated.

The rest of the paper is organized as follows. A brief explanation on IP/LEO satellite networks is given in Section II. Section III presents some important characteristics of LEO satellite networks and points out the bursty occurrence of handovers in LEO satellite networks. Section IV discusses the related work and describes how the bursty binding update requests, in LEO satellite networks, affects the scalability of the existing mobility management schemes. Section V presents the proposed scheme, scalable handover-independent mobility management. Discussion on implementation issues of the proposed method is given in Section VI. Section VII analyzes the cost of the proposed method. Section VIII shows evaluation result in terms of mobility management cost. Concluding remarks are in Section IX.

II. IP/LEO Satellite Networks

IP/LEO satellite networks are specifically designed to provide IP communication directly to mobile nodes. Throughout

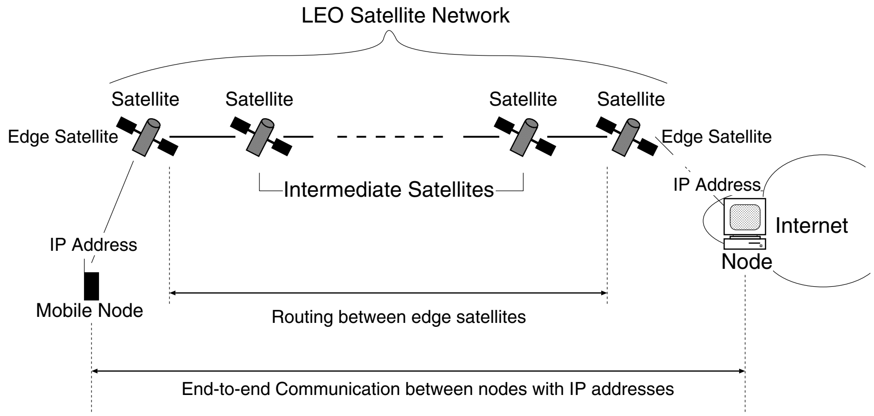

Fig. 1. IP/LEO satellite network.

this paper, mobile nodes are assumed to be directly connected to LEO satellite networks. Due to the dynamic properties of LEO satellite networks, certain aspects of IP communication, such as routing and multicasting, are likely to encounter some difficulties [5]–[9]. Therefore, the key issue of the realization of IP/LEO satellite networks consists in the affinity between IP protocols and satellite networks as layer-2 media. Especially, to exploit satellites' abilities of broadcasting, a cooperative design with IP broadcasting is required [10]. The main idea behind the design is to match the coverage area of satellites with IP broadcast domain. Satellites are, therefore, modeled as access routers (ARs) [11] and are assigned a given IP broadcast domain.

Fig. 1 depicts the underlying model.

An IP communication path consists of three components, namely mobile nodes, edge satellites, and intermediate satellites. Each mobile node is assigned a particular IP address. Along a given path, edge satellites are given a certain number of addresses and play the role of ARs. Intermediate satellites are limited to only transmitting IP packets between edge satellites.

This paper aims to integrate IP protocols with LEO satellite networks, while focusing on the interactions between mobile nodes and edge satellites. To make LEO satellite networks entirely independent of terrestrial networks, terrestrial stations are assumed not to be involved in the management of LEO satellite networks.

III. Characteristics of LEO Satellite Networks

This section describes certain characteristics of LEO satellite networks. The spotlight is mainly directed on the inherent nature of handover occurrences in LEO satellite networks.

A. Difference From Terrestrial Networks

Table I summarizes the main differences between terrestrial and LEO satellite networks. In LEO satellite networks, the size of coverage is larger than that in terrestrial networks and, thus, the number of nodes in the coverage area is likely to be large. LEO satellites (ARs) move faster than mobile nodes resulting in the movement of the network itself. Consequently, handovers occur due to satellite movements, and mobile nodes seem to be always moving (relatively to the network) even if they are indeed steady in the same geographical position. Additionally, relative movements of mobile nodes are more considerably global than that in terrestrial networks. Given the possible high number of end users, this compels LEO satellite networks to work under high-mobility conditions.

TABLE I
Comparison of Network Characteristics

	Terrestrial Networks	LEO Satellite Networks
Size of Coverage	small	large
Number of Nodes in a Coverage	small	large
Velocity of AR	0 (fix)	fast
Velocity of Node	slow	slow
Total Mobility	low-mobility	high-mobility

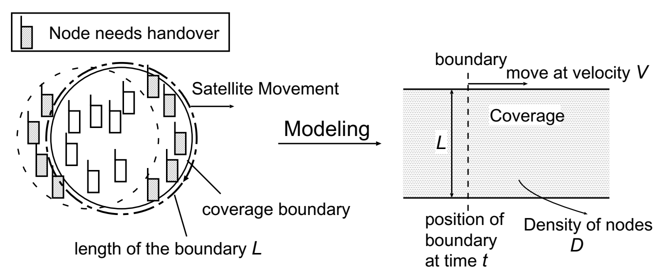

Fig. 2. Model of boundary crossing.

B. Characteristics of Handover Occurrence

Handovers are of significant importance in mobility management. Their occurrence takes place when a mobile node crosses over the coverage boundary. To evaluate the characteristics of handover occurrence, this boundary crossing event is modeled as shown in Fig. 2. For the sake of simplicity, a coverage boundary is assumed to be a straight line and locations of mobile nodes are presumed to follow a uniform distribution. In Fig. 2, mobile nodes are located in fixed positions. A coverage boundary of length L moves with velocity V from left to right during a period of time Δt. According to this model, nodes that belong to the area with surface $L \cdot V$ will be required to perform handover during the time Δt.

Denoting the area density of nodes as D, the rate of boundary crossing event R can be expressed as

$$R = V \cdot L \cdot D. \tag{1}$$

Considering the fact that handovers are mainly due to satellites movement, V can be approximated to the ground speed of satellites. Let $D_L(V_{\text{sat}} \cdot t)$ denote the linear density of nodes on the coverage boundary at time t. The rate of handover occurrence $R_{\text{HO}}(t)$ is

$$R_{\text{HO}}(t) = V_{\text{sat}} \cdot L_{\text{sat}} \cdot \int_{V_{\text{sat}} \cdot (t-\Delta t)}^{V_{\text{sat}} \cdot t} D_L(V_{\text{sat}} \cdot t)\, dt \tag{2}$$

where V_{sat} and L_{sat} denote the ground speed of satellite and the coverage boundary length, respectively.

Since satellites are assumed to cover wide areas and move fast, V_{sat} and L_{sat} are large. From (2), it becomes evident that $R_{\text{HO}}(t)$ takes large values even for small values of Δt. Furthermore, this rate of handovers is likely to become even larger in a very populated area [large values of $D_L(V_{\text{sat}} \cdot t)$].

IV. Mobility Management in IP/LEO Satellite Networks

A. Outline of General Mobility Management

Mobility management is a core issue in IP/LEO satellite networks. Mobility management purposes to locate mobile nodes and to guarantee a seamless data transmission upon change in nodes position. Mobility management mainly consists of two procedures, namely binding update and data delivery.

The binding update operation aims to associate Reachability Identity (Reach.ID) and Routing Identity (Route.ID) of each node [12]. The former indicates a unique name of the node and is not subject to change, whereas the latter specifies the position of the node in the network and changes in response to node movement. When a mobile node changes its position, the Route.ID changes as well and the old binding is no longer valid. To update the binding, mobile nodes are requested to send their new Route.ID to the location directory [13].

Problems related to the binding update have been discussed in many previous studies. Considering the possibility of location directory to be geographically too far from mobile nodes, the cost of binding update can become expensive, mainly in a high-mobility environment such as satellite networks [14]. Recall that a handover is a local process that concerns only the mobile node, the old AR and the new AR, whereas a binding update is a global process that may affect other network elements in addition to the three adjacent entities.

When Route.ID precisely indicates the position of mobile nodes, data transmission can be seamlessly done with no further operations. However, this precise location of mobile nodes requires frequent update of nodes registration even upon a slight movement of the node. The required update cost can be extremely huge.

On the other hand, when Route.ID roughly indicates the position of nodes, additional procedures, such as paging, are required for precise location of the node. Rough location management will reduce the binding update frequency, but on the price of some overhead due to paging. Note that this overhead can be significant in case of wide paging areas.

To conclude, Route.ID has a decisive influence on the management cost. More attention should be, thus, paid to the choice of the Route.ID type that suites best mobility management in the underlying network.

B. Mobility Management in IP Networks

The major problem of mobility management in IP networks is the fact that IP addresses, that are originally designed for Route.IDs, are also used as Reach.IDs in higher layers [13]. This means that a mobile node cannot be identified in the higher layers if its IP address changes at handover occurrence time.

To tackle this problem, mobile IP, the most dominant protocol among existing mobility management protocols, proposes two different IP addresses for the two identities of mobile nodes. One is referred to as home address and serves as a Reach.ID, and the other is dubbed care of address (CoA) and functions as Route.ID. Home agent plays the role of location directory in mobile IP. Upon a handover occurrence, nodes are assigned different CoAs according to the connected AR. Recall that new CoAs shall be notified to the home agent for binding maintenance. LIN6, a recently proposed mobility management protocol, uses LIN6 addresses to refer to the Route.ID of mobile nodes. Similarly to CoA of mobile IP, LIN6 addresses are decided according to the AR to which mobile nodes are connected. In these protocols, locations of nodes are precisely managed thanks to binding update upon every handover occurrence.

As previously mentioned, a precise location management necessitates a binding update every time the node changes its position and ensures every node ready to communicate all the time. However, not all of nodes are communicating, such a precise location management is required for only active nodes. Therefore, a loose location management is sufficient for idle nodes. When an idle node becomes active, paging is usually used for locating the node. Paging is widely used in cellular systems to locate idle nodes prior to calls establishment. By introducing a loose location management of idle nodes and applying paging to locate idle nodes, binding update frequency can be mitigated.

The most representative of mobility management protocols that introduced a loose location management of idle nodes are paging mobile IP (P-MIP) [15] and cellular IP [16]. In these protocols, the coverage area of a certain number of ARs is considered as a single paging area. When a packet data destined for an idle node arrives at one of the ARs in a paging area, the AR broadcasts a paging request to all the other ARs that sequentially send paging messages within their own coverage areas. Upon receipt of the paging message, the idle node in question responsively becomes active. In such a case, the idle node is not required to perform binding updates within the whole paging area. The node should update its binding only when it crosses the paging area boundary. By so doing, binding update frequency can be reduced.

In the remainder of this section, we further investigate the advantages and downfalls of both precise and loose management schemes, and accordingly decide the most appropriate scheme for IP/LEO satellite networks.

C. Mobility Management Issues in LEO Satellite Networks

Usage of mobile IP is one of the solutions for mobility management over IP/LEO satellite networks. However, applying mobile IP to LEO satellite networks will result in a precise management of mobile nodes location and, consequently, an invocation of binding update upon each handover occurrence. Given the high frequency of handover occurrences in LEO satellite networks, as explained in Section III-B, a large number of binding update requests is likely to be generated, all, in a single burst. To process such bursts of binding update requests, a massive amount of network bandwidth and computational load are required. This is intuitively a critical issue for scalability of mobility management in IP/LEO satellite networks.

To reduce binding update frequency, hybrid solution that introduced a loose location management, such as P-MIP, is a good alternative. However, since paging areas, formed from coverage areas of a certain number of satellites, are constantly moving, bursty binding updates may occur as well when mobile nodes cross the paging area boundary. As a conclusion, existing loose location management schemes are not appropriate enough for LEO satellite networks.

Since it is all but impossible to avoid the bursty occurrence of handovers in LEO satellite networks, mitigation of binding update frequency can be done by only developments of new mobility management protocols.

V. Handover-Independent Mobility Management

This section gives a detailed description of the proposed method. The core idea behind the proposal is to make binding updates independent of handovers and, thus, increase the mobility management scalability under high-mobility environments in LEO satellite networks.

A. Description of the Proposal Method

In IP/LEO satellite networks, mobile nodes constantly change their ARs leading to a high-mobility network. As the handover and the resulting binding update requests frequency become critical, binding updates should be independent of handovers.

To achieve such an objective, Route.IDs are associated with only geographical location information and are independent of logical locations. This operation eventually leads to a more loose management of mobile nodes locations. In the proposed method, the earth surface is divided into a number of cells, and mobile nodes' Route.IDs are associated with the cell where mobile nodes reside. Mobile nodes are assumed to be equipped with a global positioning system (GPS) receiver for finding their location. A Route.ID changes and the corresponding binding update occurs only when a mobile node moves to the neighboring cell. Recall that location directory is necessary to maintain bindings.

It is emphasized that geographical locations are independent of satellite positions and this fact makes the considered Route.ID entirely independent of handovers.

B. Handover-Independent Binding Update

To more readily explain the merits of the proposed concept, the proposed method is compared with mobile IP as indicated in Fig. 3. In mobile IP, upon crossing satellite coverage boundaries, mobile nodes are requested to update their bindings. In the proposed method, however, binding updates are performed only when nodes cross a cells boundary. The proposed method accordingly eliminates the effect of satellite handovers and gives an illusion of a low mobility characteristic to IP/LEO satellite networks.

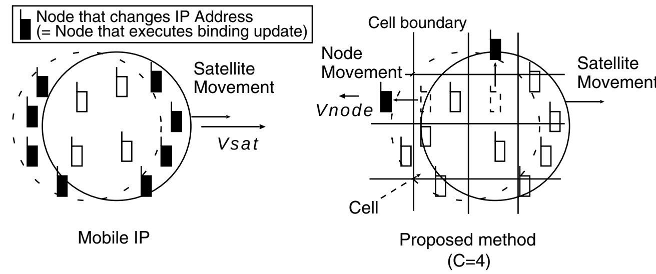

Fig. 3. Comparison of mobile IP and the proposed method.

Dividing a satellite coverage area into C cells, the total rate of binding update occurrence, denoted as $R_{\mathrm{CC}}(t)$, can be approximated to the sum of the rate of cell crossing event of the C cells. On the other hand, for each cell, the rate of cell crossing event can be derived from (1). $R_{\mathrm{CC}}(t)$ can be, thus, expressed as

$$R_{\mathrm{CC}}(t) = C \cdot V_{\mathrm{node}} \cdot L_{\mathrm{cell}} \cdot \int_{V_{\mathrm{node}}(t-\Delta t)}^{V_{\mathrm{node}} t} D_n(V_{\mathrm{node}} \cdot t)\, dt \tag{3}$$

where V_{node} and L_{cell} denote the velocity of nodes and the cell boundary length, respectively. $D_L(V_{\mathrm{node}} \cdot t)$ denotes the linear density of nodes in a boundary at time t.

V_{sat} and V_{node} are in the order of 10 000 km/h and 10 km/h, respectively. Comparing (2) with (3), it becomes clear that the proposed method can remarkably mitigate the bursty occurrence of binding updates and result in a scalable mobility management.

Another credit of the proposed method is in the reduction of dropped packets. Generally, packets may be dropped due to delays in binding update process. This issue becomes even more critical in the case of large-delay links environments, such as satellite networks. However, since the proposed method reduces the binding update frequency per node, the total packet drops that can be inevitable due to delays in binding update process, can be avoided thanks to the proposed method.

VI. Proposed Method Implementation Issues

To realize the proposed method in practice, the following issues should be taken into account:

1) geographical location mapping to Route.ID;
2) cells distribution in a satellite coverage;
3) connection setup and maintenance.

A. Geographical Location Mapping to Route.ID

In order to support a large number of mobile nodes, usage of IPv6 [17] is seem to be very appropriate for IP/LEO satellite networks. To include geographical location information in nodes'

IP addresses, the following basic address structure is considered throughout this paper:

$$\text{IP Address} = \text{Prefix} + \text{NodeID}.$$

Basically, the prefix indicates the location of the node. In the proposed method, the prefix represents the cell where the node is located. Inclusion of geographical information, such as latitude and longitude, in the prefix has been considered in recent routing related work [18], [19]. Application of such methods is envisioned in the rest of this paper to represent cells. Note that the predictable characteristic of satellite movements can help to develop some efficient routing schemes based on this geographical information [6]. Usage of these routing schemes guarantees a seamless delivery of packets to cells through satellites. NodeID is used to identify a node in a cell. In order to avoid changing the NodeID when a node moves into a neighboring cell, NodeID should be globally unique.

While it is impractical to approximate the whole coverage area of a satellite to the IP broadcast domain, the proposed method matches the IP broadcast domain to a cell. Since the considered prefix contains geographical information and is, thus, different from the prefix of standard IP addresses, routers may be required to have the ability of handling the two types of prefixes. Since geographical location of user terminals can be considered as private information and can be used to track down user locations [20], techniques to prevent a third party from having access to this private information should be taken into account.

B. Cell Distribution in a Satellite Coverage

As shown in Fig. 3, satellite coverage areas consist of several cells in the proposed method. When a cell covers the entire coverage area of a satellite, the implementation of the proposed method can be simpler. Adversely, when cell sizes take small values, the number of cells per a coverage becomes larger and binding updates occur frequently. This makes the mobility management cost higher. The effect of the cell size on the mobility management is evaluated in Section VIII.

C. Connection Setup and Maintenance

In the proposed method, the location of mobile nodes is loosely managed. Hence, there is a need for more careful handling of connections when a handover takes place. Another challenge is in the initiation of new connections, i.e., when idle nodes become active. This section describes a local forwarding scheme and a paging scheme for connection maintenance and setup, respectively.

1) Local Forwarding Scheme: When a handover occurs, the path between two communicating nodes changes resulting in a possible disconnection of the nodes. To maintain a seamless communication, certain modifications in routing mechanisms are required. Intuitively, these modifications are likely to incur some overhead due to the high frequency of handover occurrences in LEO satellite networks.

We consider the following modifications. An active mobile node notifies its new AR of its old AR at handover occurrence time. Upon receipt of such notification, the new AR informs the old AR that the mobile node has indeed performed a handover. In response to that, the old AR forwards the packets that are destined for the node to the new AR. Recall that unlike the binding update process, this forwarding mechanism generates some control messages among only the three adjacent entities (the mobile node, the new AR, and the old AR). The required overhead for this local forwarding is, thus, smaller than the cost of the binding update. The performance evaluation takes into account this cost.

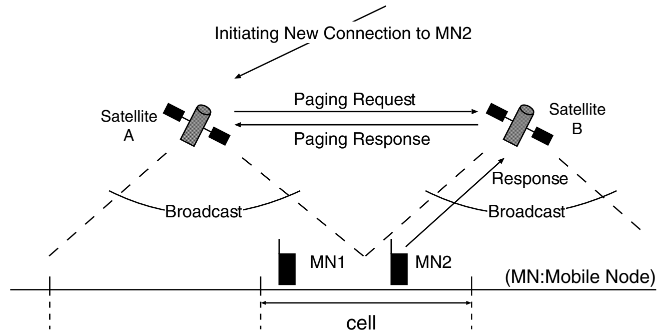

Fig. 4. Description of the considered paging scheme.

2) Paging Scheme: As explained in Section IV-C, it is difficult to mitigate the bursty updates by only setting paging areas to a certain number of satellite coverage areas (similarly to P-MIP). In the proposed method, satellites that cover a single cell broadcast paging messages. While satellites broadcast paging messages in their coverages, only mobile nodes in the cell indicated by the prefix of an idle node's IP address check paging messages. The proposed method, thus, considers each cell as a single paging area.

Fig. 4 illustrates the functioning of the considered paging scheme. A cell is covered by satellites A and B. Two mobile nodes, MN1 and MN2, reside in the cell. All satellites are assumed to have a list of active nodes they are serving. In Fig. 4, MN2 is an idle node and a new connection for MN2 is depicted arrived at Satellite A. Being unaware of whether MN2 resides in its coverage, Satellite A broadcasts a paging message within the coverage. Simultaneously, Satellite A issues a paging request asking Satellite B to broadcast as well a paging message within its coverage. Upon receipt of the paging message, MN2 changes its state to active. Satellite B receives the response from MN2 and accordingly sends a paging response to Satellite A indicating that MN2 is within its coverage. After this operation, Satellite A forward data packets toward MN2 through Satellite B.

VII. Analysis of Mobility Management Cost

This section evaluates the cost of the proposed method and compares it with that of mobile IP and P-MIP.

A. Management Cost Elements

As discussed in Section IV-A, the mobility management cost consists mainly of the cost of the binding update and data delivery. The tradeoff between the two costs depends on how precisely nodes' location are managed. A precise management of a nodes location leads to a large value of binding update cost, while a loose management method decreases the update cost.

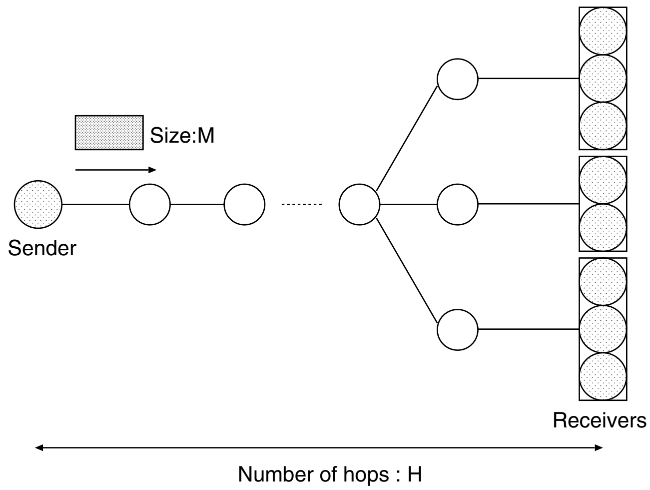

Fig. 5. Definition of the management cost.

On the other hand, since additional procedures such as local forwarding and paging are envisioned, data delivery cost may increase.

B. Management Cost Definition

In [15], the management cost is computed as the product of the generated control message size M and the number of hops H required to deliver the message. Applying such definition to the paging cost, the cost should be in proportion with the number of receivers. Taking into account the broadcasting capabilities of satellites, however, the cost is also simply a product of the message size and the number of traveled hops.

Equation (4) and Fig. 5 indicate the definition of the cost in this evaluation.

$$\text{Cost} = M \cdot H. \tag{4}$$

C. Binding Update, Local Forwarding, and Paging Cost

The following defines the cost required for each mobility management event; binding update, local forwarding, and paging.

For ease of exposition in mind, control messages of the three events are assumed to be equally sized (M). The number of control messages that are generated upon a handover occurrence between mobile nodes and the corresponding ARs, is assumed to be the same for mobile IP, P-MIP, and the proposed method. We, thus, neglect this number of control messages in the cost evaluation.

1) Binding Update Cost: Let $H_{\text{MN,LD}}$ denote the number of hops between a mobile node and the location directory. The cost for binding update procedure can be expressed as

$$M \cdot H_{\text{MN,LD}}. \tag{5}$$

2) Local Forwarding Cost: Denoting the number of hops between two adjacent satellites as $H_{\text{AR,AR}}$, the local forwarding cost is shown as follows:

$$M \cdot H_{\text{AR,AR}}. \tag{6}$$

3) Paging Cost: S denotes the number of single-beam satellites that cover a single paging area. Since a satellite is required to issue a paging request to its $S-1$ neighboring satellites upon a paging initiation, the cost of sending these paging requests between satellites is

$$M \cdot H_{\text{AR,AR}} \cdot (S-1). \tag{7}$$

Considering the paging messages broadcast by the S satellites to mobile nodes within their coverage areas, the broadcasting cost is expressed as the product of message size and the number of single-beam satellites

$$M \cdot 1 \cdot S. \tag{8}$$

Summing (7) and (8), the total paging cost becomes

$$M \cdot H_{\text{AR,AR}} \cdot (S-1) + M \cdot 1 \cdot S. \tag{9}$$

D. Management Cost of Mobile IP, P-MIP, and the Proposed Method

The cost of mobile IP, P-MIP, and the proposed method are defined as follows.

1) Mobile IP: In mobile IP, the binding update cost is the product of (5) and the rate of handover occurrence, whereas the paging cost is zero. Using (4) and (5), the mobile IP management cost $C_{\text{MIP}}(t)$ can be expressed as

$$C_{\text{MIP}}(t) = M \cdot H_{\text{MN,LD}} \cdot R_{\text{HO}}(t). \tag{10}$$

2) Paging Mobile IP: In P-MIP, active nodes update their bindings upon handover occurrence. However, idle nodes perform binding update only when they cross the paging area boundary.

Using (1), the rate at which nodes cross the paging area boundary at time t, $R_{p\_\text{area}}(t)$, is as follows:

$$R_{p\_\text{area}}(t) = V_{\text{sat}} \cdot L_{p\_\text{area}} \cdot \int_{V_{\text{sat}}\cdot(t-\Delta t)}^{V_{\text{sat}}\cdot t} D_L(V_{\text{sat}} \cdot t)\, dt \tag{11}$$

where L_{p_area} denotes the boundary length of the paging area.

As a result, the P-MIP management cost $C_{\text{P}-\text{MIP}}(t)$ is derived from the following equation:

$$\begin{aligned} C_{\text{P}-\text{MIP}}(t) = {} & M \cdot H_{\text{MN,LD}} \cdot R_{p\_\text{area}}(t) + M \cdot H_{\text{MN,LD}} \\ & \cdot \{R_{\text{HO}}(t) - R_{p\_\text{area}}(t)\} \cdot \alpha \\ & + \{M \cdot H_{AR,AR} \cdot (S-1) + M \cdot S\} \\ & \cdot n(t) \cdot (1-\alpha) \cdot \lambda \end{aligned} \tag{12}$$

where $n(t)$ and α denote the total number of nodes per a coverage area at time t and the ratio of active mobile nodes to the total number of nodes, respectively. The rate of newly coming connections to a mobile node is denoted as λ. The first and second terms indicate the binding update cost, whereas the third term refers to the paging cost. Observe that $n(t) \cdot (1-\alpha) \cdot \lambda$ indicates paging the occurrence rate.

3) Proposed Method: In the proposed method, the local forwarding and paging schemes incur some additional cost as discussed in Section VI-C. Using (5), (6), and (9), the total cost is

$$\begin{aligned} C_p(t) = {} & M \cdot H_{\text{MN,LD}} \cdot R_{\text{CC}}(t) \\ & + M \cdot H_{\text{AR,AR}} \cdot R_{\text{HO}}(t) \cdot \alpha \\ & + \{M \cdot H_{\text{AR,AR}} \cdot (S-1) + M \cdot S\} \\ & \cdot n(t) \cdot (1-\alpha) \cdot \lambda. \end{aligned} \tag{13}$$

The first term in (13) indicates the binding update cost. The second and third terms represent the local forwarding and paging cost, respectively.

VIII. Performance Evaluation

A. Comparison of Mobility Management Cost

Dividing (10)–(13) by $M \cdot H_{\mathrm{MN,LD}}$, the following equations are obtained:

$$C'_{\mathrm{MIP}}(t) = R_{\mathrm{HO}}(t), \tag{14}$$

$$C'_{\mathrm{P-MIP}}(t) = R_{p\_\mathrm{area}}(t) \cdot (1-\alpha) + R_{\mathrm{HO}} \cdot \alpha + \frac{1}{H_{\mathrm{MN,LD}}} \cdot \{(2S-1) \cdot n(t) \cdot (1-\alpha) \cdot \lambda\} \tag{15}$$

$$C'_{p}(t) = R_{\mathrm{CC}}(t) + \frac{1}{H_{\mathrm{MN,LD}}} \cdot R_{\mathrm{HO}}(t) \cdot \alpha + \frac{1}{H_{\mathrm{MN,LD}}} \cdot \{(2S-1) \cdot n(t) \cdot (1-\alpha) \cdot \lambda\}. \tag{16}$$

While the number of hops between two ARs $H_{\mathrm{AR,AR}}$ depends on the network topology and may take values larger than one, $H_{\mathrm{AR,AR}}$ is set to one.[1] From these equations, it is evident that the proposed method and P-MIP can reduce the management cost as $H_{\mathrm{MN,LD}}$ increases. This means that both methods decrease global communication for the binding update by reducing the number of binding update requests. In the remainder of this section, performance evaluation is based on the mobility management cost derived from (14)–(16).

B. Effectiveness of the Proposed Method

In all analyses, a satellite's coverage radius and satellites ground speed are set to 700 km and 7 km/s,[2] respectively. Mobile nodes are assumed to move at velocity 17 m/s (60 km/h). Similarly to [15], 95% of all nodes are assumed to be idle and idle nodes become active on an average of three times per hour α and λ are, thus, set to 5% and 0.0008, respectively. The mobility management cost is evaluated every second ($\Delta t = 1$ s).

Satellite coverage areas are assumed to be square-shaped and their surfaces are equal to that of a circle with a radius 700 km. A node's density is calculated as the ratio of the total number of nodes to the coverage area surface. For the sake of simplicity, effects of cell shapes on the management cost are ignored and cells are assumed to be square shaped.

In this evaluation, 1 000 000 nodes are assumed to reside in a coverage area and the effect of cell sizes is investigated by considering various cell sizes. While the proposed method is believed to exhibit better performance in the case of a larger number of hops between mobile nodes and location directory, $H_{\mathrm{MN,LD}}$ is deliberately set to two to investigate the performance of the proposed method in the worst case where mobile nodes reside geographically close to the location directory.

In P-MIP, a paging area is constructed by the coverage areas of five satellites that are a certain satellite and its four neighboring satellites (i.e., $S = 5$). Each neighboring satellite is in the same orbit and both adjacent orbits. On the other hands, in the proposed method, S depends on a cell size.

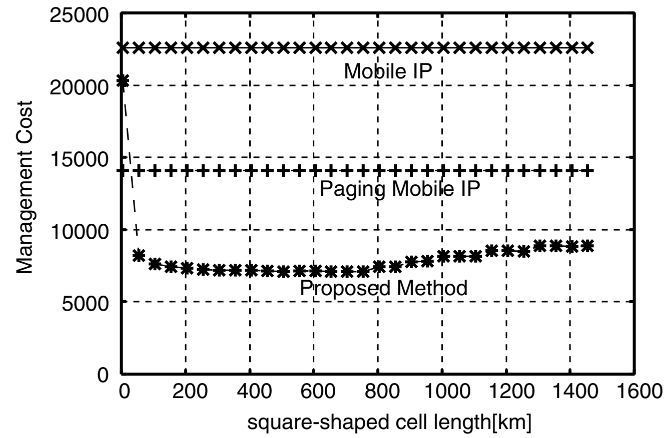

Fig. 6. Performance evaluation in terms of management cost.

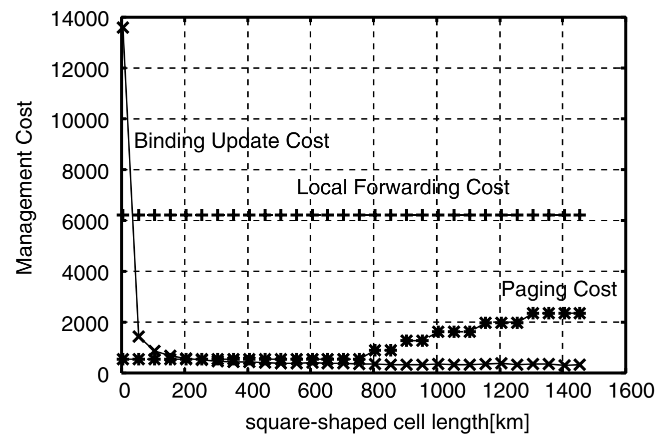

Fig. 7. Breakdown of the proposed method cost.

Fig. 6 presents the evaluation results. The figure demonstrates that the proposed method significantly outperforms mobile IP and P-MIP in terms of the management cost. Observe also that P-MIP exhibits better performance than mobile IP. It is noted that the proposed method incurs higher management cost for smaller values of square-shaped cell length. This is mainly due to the frequent binding updates that can be caused when a large number of mobile nodes cross the cell boundary. The management cost remains, however, significantly small for wider cells.

Fig. 7 illustrates the breakdown of management cost required for the proposed method. As cell length becomes large, the binding update cost decreases and the paging cost increases. The local forwarding cost remains constant because occurrences of the local forwarding process are independent of cell length. Although the local forwarding cost dominates the mobility management cost, the local forwarding messages affect only three adjacent entities unlike the binding update messages. As discussed in Section IV-A, while a handover is inherently a local process, binding updates upon handover occurrence affect global portion in the network. From this point of view, the proposed method can realize the localization of the effect of handover occurrence. The paging cost can be huge for extremely large cells and, thus, the total cost can overwhelm

[1]Case of handover between two neighboring ARs.

[2]These values are based on Teledesic system.

the cost required for mobile IP and P-MIP. However, the paging cost is relatively small when the cell length is smaller than about 1500 km. Consequently, we conclude that the proposed method is efficient for mobility management in IP/LEO satellite networks in the case of appropriate cell sizes.

IX. Conclusion

In this paper, we proposed a handover-independent mobility management scheme specifically designed to support mobile connectivity in IP/LEO satellite networks. A simple mathematical analysis was developed to verify the high frequency of handover occurrence in LEO satellite networks. Given this high mobility characteristic, existing mobility management schemes, such as mobile IP and paging mobile IP, are likely to run into difficulty. An explanation of how these schemes incur higher binding update costs and, thus, lead to an unscalable-to-operate system was given.

To enhance mobility management scalability over LEO satellite networks, a new method was developed. The proposed method exploits geographical location information to make the binding update process entirely independent of handovers. In the proposed method, binding updates are issued only when a node crosses the cell boundary and the rate of binding updates is accordingly reduced.

Comparison of the proposed method performance to that of mobile IP and paging mobile IP was made through a mathematical analysis. Performance evaluation results demonstrated the efficiency of the proposed method in reducing the management cost.

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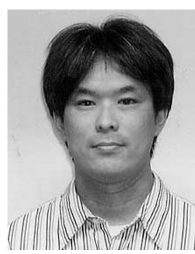

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