MOBILITY MANAGEMENT PROTOCOLS FOR NEXT-GENERATION ALL-IP SATELLITE NETWORKS

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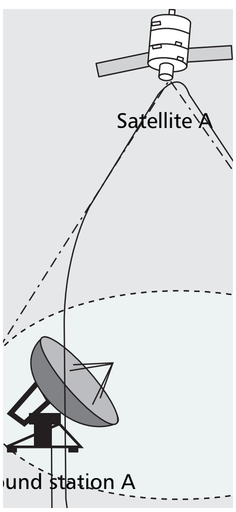

The authors provide a comprehensive summary and comparison of state-of-the-art research on mobility management schemes for satellite networks. The schemes are based on network and transport layer for managing host and network mobility.

ABSTRACT

To provide ubiquitous terrestrial Internet coverage mobility and Internet-based access to data generated by satellites, there is a strong desire to integrate the terrestrial Internet and satellite networks. This requires satellites that are based on IP for communications. Rotation of low Earth orbit satellites around the Earth results in communicating with different ground stations over time, and requires mobility management protocols for seamless communication between the Internet and satellite networks. In this article we provide a comprehensive summary and comparison of state-of-the-art research on mobility management schemes for satellite networks. The schemes are based on network and transport layers for managing host and network mobility. This article clearly indicates the aspects that need further research and which mobility management schemes are the best candidates for satellite networks.

INTRODUCTION

Satellites contain onboard equipment for sensing Earth and space, and communications links that transmit the data back to Earth for processing. Depending on altitude and movement, satellites are classified into three types: geosynchronous Earth orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO). LEO satellites have several advantages, such as low propagation delay and low power requirement over GEO/ MEO satellites. The advantages make LEO satellite constellations very suitable for ubiquitous access and enable seamless mobility on Earth. In the case of LEO satellites, data are downloaded when a satellite comes in contact with a ground station and are stored on a computer for further processing. Future satellite systems will consist of IP-enabled equipment that will allow direct download of data from the satellites by IP-based applications. Rotation of LEO satellites around the Earth, and the resulting disconnection and reconnection to ground stations give rise to mobility management and connection handover issues at the IP layer.

Constellations of IP-enabled satellites can be a part of the terrestrial IP network or be stand-alone satellite networks with satellites participating as sources, processors, and consumers of data. Due to the wide coverage area, satellite constellations are also expected to play a vital role as a carrier network in next-generation terrestrial IP networks requiring ubiquitous coverage and mobility. This has given rise to interest in treating satellite constellations like terrestrial networks to facilitate efficient data communication between them [1].

Data communication in terrestrial networks is predominantly carried over IP. In addition to low cost (as IP technology is mature and readily available) in implementing IP in future satellites, IP-based satellite networks will have good interoperability with the terrestrial IP network. The National Aeronautics and Space Administration (NASA) has been experimenting with the use of Internet protocols for satellite communications [2–5]. However, a number of issues have to be resolved before IP can be efficiently used in satellite networks. One of the major issues is maintaining connectivity between IP nodes on a satellite and the terrestrial network due to the orbiting of LEO satellites, which causes frequent handoffs. This gives rise to the need for handoff (mobility) management in future IP-based satellite networks.

The Internet Engineering Task Force (IETF) designed Mobile IP (MIP) [6] and Mobile IP version 6 (MIPv6) [7] to manage host mobility in terrestrial networks. MIP-based protocols are known to suffer from performance issues during handoff. An IP diversity-based host mobility scheme, called Seamless IP Diversity-Based General Mobility Architecture (SIGMA), has been developed to improve handover perfor-

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mance [8]. These protocols have subsequently been adapted to satellite networks [9, 10].

When a number of hosts, connected in a local area network (LAN), move together, network mobility (NEMO) [11] can be used to manage the mobility of the hosts. The IETF has designed NEMO Basic Support Protocol (BSP) to handle network mobility. NEMO BSP is based on and inherits all the performance limitations of MIPv6. To improve the performance of NEMO BSP, an IP diversity-based network mobility scheme called Seamless IP Diversity-Based Network Mobility Architecture (SINEMO) has been designed [12].

IP-enabled equipment on a satellite can be connected together to form an onboard LAN, the mobility of which can then be managed by NEMO BSP or SINEMO. Constellations of satellites can also be considered mobile networks of satellites. Research efforts have therefore focused on both types of mobility (host and network) architectures and protocols for satellite networks. Previous survey papers on handoff schemes for satellite networks have been limited to handoff management of a single piece of equipment on the satellite; the authors are not aware of any survey that includes application of NEMO to satellite networks. In this article our goal is to provide a comprehensive survey of the state of the art in mobility management protocols, including host and network mobility, for all-IP satellite networks, and their application to various satellite network scenarios. The main contributions of this article are as follows:

- Present the state of the art in mobility management schemes for all-IP satellite networks.
- Provide a comparison of the schemes and recommendations for implementation of the schemes in next-generation all-IP satellite networks.

The rest of the article is organized as follows. We present mobility scenarios in satellite constellations that need mobility management. Mobility characteristics of satellite networks related to mobility management are described. The state of the art in application of mobility management schemes to satellite networks is summarized, followed by a comparison of the schemes. We conclude the article and outline possible future research on mobility management of IP-enabled satellites.

Mobility In Satellite Networks

LEO satellites, connected together by intersatellite links (ISLs), communicate with different ground stations using ground-to-satellite links (GSLs) during rotation around the Earth. This rotation gives rise to the need for mobility management of onboard IP-enabled equipment. Mobility is also present in the integrated network formed by terrestrial and satellite networks, where both the satellites and terrestrial nodes are moving. If the above mobility causes the IP address of the peer hosts to change, mobility management is required for maintaining continuity of connections and reachability of the hosts. Like terrestrial networks, we can consider both host mobility [6] and network mobility [11] for satellite networks. In this section we present a comprehensive view of the mobility scenarios that arise in satellite networks. Application of mobility management schemes to mobility scenarios will be discussed later.

Host Mobility

We consider below two host mobility scenarios where a node in a satellite network requires network layer handoff [8].

Satellite as a Router — A satellite with onboard IP routing devices can act as a router in the satellite network. A terrestrial host, connected to the satellite, is handed over from one satellite to another as the host comes under the footprint of different satellites due to the rotation of LEO satellites. The terrestrial host needs to maintain a continuous transport layer connection with the correspondent node (CN) while it is handed over between satellites. As shown in Fig. 2 (which is described in detail later), the terrestrial host (mobile host ([MH])/foreign host ([FH]) maintains a continuous transport layer connection with the CN using satellites A and B as routers during handoff. Different satellites, or even different spotbeams within a satellite, can be assigned different IP subnet addresses. In such a case the IP address of the terrestrial host changes during handoffs, thereby requiring a network layer handoff. For highly dense service areas, a spotbeam handoff may also require a network layer handoff.

Satellite as a Host — When a satellite has onboard IP-enabled equipment (such as Earth and space observing equipment) that generates and sends data to Earth, or the satellite receives control signals from Earth, nodes on the satellite act as endpoints of communication. As shown in Fig. 3, a CN on Earth sends control signals to MH in the satellite, and then MH sends data to the CN after receiving the signal. Since ground stations belong to different IP subnets, nodes on a satellite change IP addresses as they hand off between ground stations, and therefore require mobility management to maintain continuous connection with terrestrial nodes.

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Network Mobility

When several nodes move together, it is advantageous to manage the aggregate movement using NEMO [11]. LEO satellites are continuously on the move and sometimes move harmoniously. NEMO can thus be used to manage the:

- Mobility of onboard nodes by connecting them together in a LAN
- Mobility of the satellite constellations

The above two network mobility scenarios in satellite networks are described below.

Network of IP-Enabled Devices on a Satellite — If the onboard IP-enabled equipment is connected to a LAN on the satellite, the mobility of the equipment can be managed in an aggregated fashion by considering the LAN as a mobile network and managing the mobility of the LAN (in contrast to individual equipment) by NEMO [12]. The onboard LAN can be connected by ISL or

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GSL to a ground station on Earth or to another satellite in space.

Mobile Network of Satellite Constellation —A constellation of satellites can be considered as a unit consisting of one or more IP subnets. This unit is connected to the terrestrial IP network as a mobile subnetwork through one or more mobile satellite routers. Changing the attachment to the ground station of the mobile subnetwork is managed transparent to the satellites inside the mobile subnetwork. This mobile subnetwork of satellites can be directly mapped to and managed by NEMO BSP.

CHARACTERISTICS OF MOBILITY IN SATELLITE NETWORKS

LEO satellites are mobile by nature. We describe below the characteristics of mobility in satellite networks [13].

Dynamic Nature of Satellite Topology — Satellites within line of sight are interconnected via ISL. The length of the ISLs between different planes changes depending on the movement of satellites. This affects the mobility management of satellite constellations.

High Handover — Due to the high velocity of satellites, mobility management protocols for satellite networks should be able to carry out fast handoff with minimum handover latency.

Dynamic and Non-Homogenous Traffic — The volume of satellite traffic varies with the geographical location of the Earth's surface. In cities satellite traffic is higher than in the ocean. Hence, mobility management protocols cannot afford high handover latency or signaling overhead in high traffic load.

Deterministic Mobility Pattern — Due to the deterministic paths of satellites, the location of satellites over time can be predicted quite accurately. Mobility management protocols for satellites can take advantage of this pattern to reduce signaling by storing routing information for mobile hosts and sending information for reachability a priori.

MOBILITY MANAGEMENT PROTOCOLS FOR SATELLITE NETWORKS

To maintain continuity of ongoing connections at higher layers and ensure reachability of the satellite hosts, mobility in satellite networks, requiring changes of IP address, can be managed at the network or transport layer. Mobility management involves two steps: location management (for reachability) and handoff management (for continuity). Both steps require exchange of signaling messages among entities involved in mobility management. The key challenges in handling mobility of satellites are:
- High mobility rate of satellites
- Long propagation delay GSLs

In this section we focus on mobility management schemes for satellite networks.

MOBILE IP IN SATELLITE NETWORKS

MIP [6] was designed to permit mobile nodes to move randomly through the Internet while still receiving datagrams at a fixed address. A moving IP-enabled satellite, connecting first to one ground station and then to another, fits the definition of a mobile host. It is natural, then, to apply MIP to mobility management of IP-enabled satellites.

Basics of Mobile IP — Before demonstrating how MIP fits in satellite networks, let us look at the basic elements of MIP. There are three basic elements: the home agent (HA), foreign agent (FA), and MH. The HA is a router on an MH's home network that tunnels datagrams for delivery to the MH when it is away from home and maintains the current location information for the MH. The FA is a router on an MH's visited network that provides routing services to the MH while it is away from home. The FA detunnels and delivers datagrams to the MH. For datagrams sent by an MH, the FA may serve as a default router for registered MHs.

The key steps of MIP operation are as follows:
- An MH first determines whether it is attached to its home network or a foreign network by using Internet Control Message Protocol (ICMP) router discovery messages.
- If attached to a foreign network, the MH determines if an FA is available. The MH registers with the FA if available.
- The FA notifies the HA that it has a visitor, and a unidirectional IP tunnel is established from the HA to the FA.
- The HA now encapsulates all packets destined for the MH and tunnels them to the MH.
- The FA de-encapsulates the packets and forwards them to the MH.
- Standard IP routing is used to deliver datagrams sent by the MH, with the FA as the MH's default router.

Application of Mobile IP to Satellite Networks — Application of Internet technology and MIP to satellite networks was presented by Israel *et al.* [9]. Leung *et al.* [10] also presented the application of MIP in space and aeronautical networks. The general idea of applying MIP to satellite networks is demonstrated in Fig. 1. Consider the satellite an MH; the HA and FA are collocated with ground stations A and B, respectively, and the control center is the CN. When in the home network, datagrams between the satellite and the control center are exchanged through the old data path (i.e., through HA to ground station A). Whenever the satellite comes in contact with ground station B in a foreign network, the procedure for obtaining a care-of address (CoA) is initiated. After obtaining the CoA, the HA (collocated with ground station A) in the home network is informed of the CoA. Thus, an IP encapsulation tunnel from the HA to the FA (collocated with ground station B) is established, and data delivery begins through ground station B.

When the control center sends a datagram to the satellite's address, the packet goes to the HA, which encapsulates and tunnels the packet to the FA, which forwards the packet to the satellite through ground station B. When packets are sent from the satellite to the control center, the ground station simply uses the destination address to forward the packets using standard Internet routing protocols. The difference in the forward and reverse routing paths between the CN and MH results in triangular routing. One possible exception to triangular routing is if the foreign ground station has additional routing rules (e.g., ingress filtering) for security reasons that prevent it from forwarding packets whose source address is not within the foreign subnet. In such cases reverse tunneling is used to encapsulate the packets for delivery through their home subnet to the control center.

It is important to note that some features of satellite networks can be utilized when deploying MIP for mobility management in satellite networks. Since MIP cannot predict the movement of mobile agents in terrestrial network, the protocol specifies several mechanisms (i.e., obtaining a CoA, sending a binding update, BU) to associate an MH with a mobility agent (e.g., FA or HA). Satellites, however, do not move randomly. Contacts between satellites and ground stations are scheduled a priori. This a priori knowledge of contact period can be used by the ground station to act as a proxy for the MH, preregister with the HA, and set up the tunnel. This will free satellite link resources during the initial contact period.

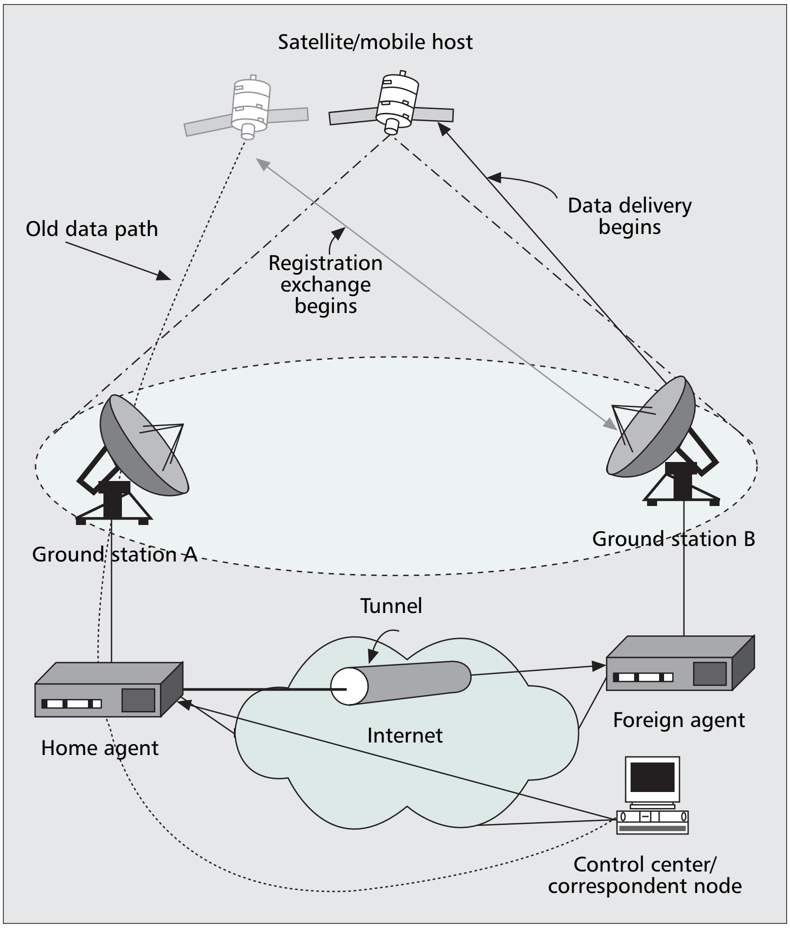


Figure 1. *Application of MIP in satellite networks.*

MOBILE IP VERSION 6 (MIPV6)

MIPv6 [14] is an IPv6-based mobility protocol from IETF. This section delineates the basics of MIPv6 and its application to satellite networks.

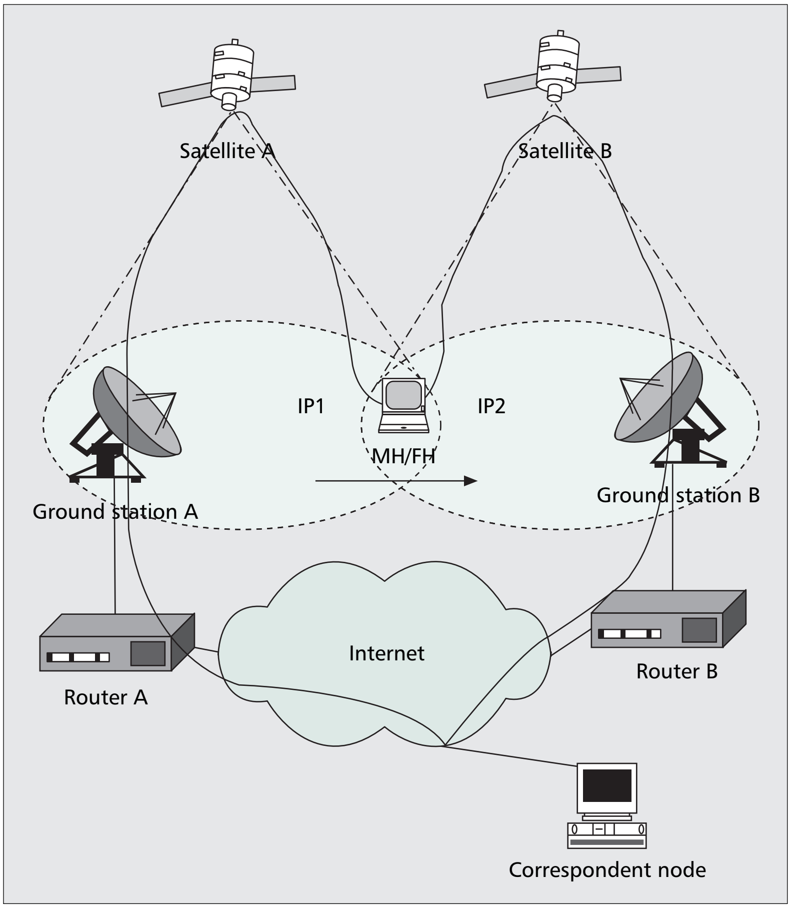
Basics of MIPv6 — MIPv6, developed to adapt IPv6 to basic MIP, basically follows the design for MIP. The MH now has an ensured capability to obtain a CoA and inform the HA of the CoA by sending a BU. Thus, FAs have been eliminated from MIPv6. Moreover, to resolve the triangular routing problem in MIPv4, MIPv6 integrates route optimization.

Enhancements of MIPv6 — In MIPv6 (as in MIP), data transmission is suspended during the handoff period (called handoff latency). This latency comprises the time required for movement detection, new address configuration, and location update processes. Packets sent to the MH during the handover period are lost. To reduce this loss, IETF proposed Fast MIPv6 (FMIPv6) (RFC 4068), which enables fast and lossless handovers of an MH from its previous access router (PAR) to the new one, by carrying out address configuration of the MH prior to handover. Hierarchical Mobile IPv6 (HMIPv6) is another enhancement of MIPv6 proposed by IETF (see RFC 4140) to reduce the amount of signaling required and improve handoff speed for mobile connections.

Application of MIPv6 to Satellite Networks — It might be fair to consider the same model used above for MIPv4 to illustrate the application of MIPv6 to satellite networks. Let us assume satellites as MHs, ground stations as simple routers, the and control center as the CN. Whenever the satellite is in contact with a ground station, it obtains a CoA and establishes a virtual tunnel between the satellite and HA (which might be another ground station). When the control center sends a datagram to the satellite, the packet goes to the HA using standard Internet routing. The HA notices that there is a tunnel to the satellite; packets are thus sent through the tunnel to the satellite. The satellite finally decapsulates and receives the packet.

On the contrary, when packets are sent from the satellite to the control center, reverse tunneling can be used. However, since packets in both directions always pass through an HA, this communication requires additional network resources, and incurs delays compared to direct communication between the satellite and the control center. To avoid this, satellites may utilize route optimization by sending BU messages to the control center. The control center updates its binding cache and sends packets directly to the satellite's CoA instead of using the home address. Ground stations simply act as default routers for the satellite.

Although not studied in the literature, application of FMIPv6 to satellite networks is straightforward. As in FMIPV6, when a satellite hands off from one ground station to another, the previous ground station can establish a tunnel with the new one. This tunneling of packets can reduce packet losses during handoff in satellite networks. Due to the large access coverage of



■ **Figure 2.** *SIGMA in space when satellites are used as routers.*

satellites (compared to terrestrial hosts), ground stations are not deployed densely on Earth. The movement of a satellite between ground stations can therefore be considered global mobility that cannot take advantage of HMIPv6.

SIGMA IN SATELLITE NETWORKS

Base MIP (and MIPv6) suffers from a number of performance problems, the most important being high handover latency, high packet loss rate, and low throughput. To develop an alternative to MIP, researchers at the University of Oklahoma and NASA Glenn Research Center have developed a transport layer-based end-to-end mobility management scheme called SIGMA [8]. Being an end-to-end mobility management scheme, SIGMA does not require any change in the Internet infrastructure. SIGMA can be used for both satellite and terrestrial networks, thereby allowing easy integration between the two types of networks.

Basic Operation — SIGMA is an end-to-end mobility management scheme that can be used with any transport layer protocol that supports IP diversity. In this scheme there is no concept of home and foreign agents or networks. When an MH approaches the overlapping coverage area of two access routers while in data communication with a CN, it obtains a new IP address from the new access router. During the process of obtaining a new IP address, data communication with CN is kept alive using the old IP address which is the primary IP address. When the received signal from the old access router falls below a certain threshold, MH changes the new IP address to its primary IP address. Keeping the connection alive through the old IP address while obtaining the new IP address has the advantage of smaller handoff delay for SIGMA than that of MIP/ MIPv6-based schemes. Moreover, for location management, SIGMA deploys a location manager (LM) that maintains a database of the correspondence between MHs' identities and their current primary IP addresses. An MH always updates the LM whenever it obtains a new address and changes this new address to its primary address. When a CN wants to start communication with an MH, it simply queries the LM with the MH's identity (home address, domain name, public key, etc.), and the LM replies to the CN with the primary IP address of the MH obtained from the database. The CN can then initiate communication with the MH in its new location. As mentioned earlier, SIGMA [15] can be adapted to manage mobility in satellite networks.

Application of SIGMA to Satellite Networks — Figure 2 shows the application of SIGMA to mobility management of a satellite network when the *satellite acts as a router*. In this case the MH/ FH obtains an IP address from satellite A and communicates through satellite A. Due to the rotations of satellites (or movement of the MH), the MH/FH comes under the footprint of both satellites A and B, and obtains an IP address from satellite B. A host can predict the movement of satellites A and B quite accurately; this a priori information is used to decide on the time to perform the setting of the primary address to the new IP address and delete the old IP address. This is much easier than in cellular networks, where user mobility is hard to predict.

Figure 3 depicts the application of SIGMA when the *satellite acts as a mobile host*; the satellite and access routers A/B are mapped to the MH and access routers, respectively. In order to apply SIGMA, there is no special requirement on the access routers; this eases the deployment of SIGMA by not requiring any change to the current Internet infrastructure. Here, the procedure of applying SIGMA to satellite networks is similar to the previous case (where the satellite acts as a router) if the FH/MH is replaced by the satellite, in addition to replacing satellites A/B by access routers A/B. Since a satellite's path is deterministic, it can contact ground station B while still connected to ground station A. There may be multiple new ground stations from which to choose due to the large footprint of satellites. The strategy for choosing a ground station can be influenced by several factors such as highest signal strength, lowest traffic load, and longest remaining visibility period.

NEMO BASIC SUPPORT PROTOCOL IN SATELLITE NETWORKS

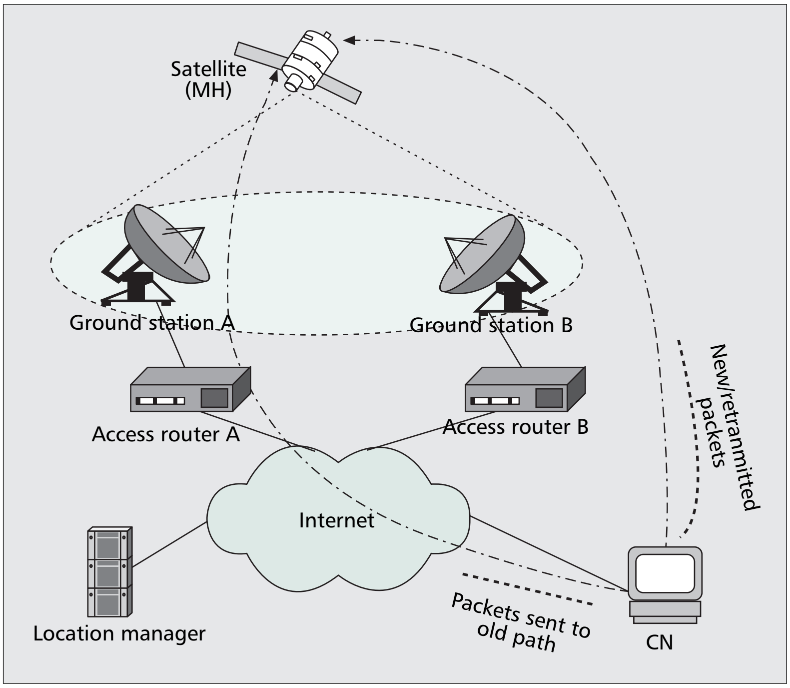
IETF designed NEMO BSP to manage network mobility [11]. NEMO BSP is an extension of the MIPv6 protocol. Figure 4 shows the general architecture of NEMO. One or more routers, called mobile routers (MRs), serve as gateways for different types of nodes in a mobile network. Different types of nodes include the local fixed node (LFN), local mobile node (LMN), and visiting mobile node (VMN). All nodes in a mobile network reach the Internet through the MRs managing mobility. When the point of attachment to the Internet changes during movement, MRs perform handoff; the mobility is thus transparent to the nodes in the mobile network.

Basics of NEMO BSP — The point of attachment of a mobile network to the Internet is called the home network. An MR is registered with a router, called the HA, in its home network and has a home address (HoA) through which it is reachable when in its home network. MRs are delegated one or more address prefixes for use inside its network. When the MR moves out of its home network to a foreign network, the MR obtains a CoA from the foreign network and sends a BU to its HA informing it of the CoA. MR indicates that it is acting as a router by setting a bit in the BU message along with sending the prefixes of the mobile network. In reply, the HA sends a binding acknowledgment (BA) to the MR, and a bidirectional tunnel is established between the HA and the MR. When a CN sends a packet to a node in the mobile network, the packet is forwarded to the HA (as the HA advertises the prefix of the MR in the home network). The HA encapsulates the packet and tunnels it to the MR. The MR decapsulates and forwards the packet to the destination node. Packets in the reverse direction also follow the same path.

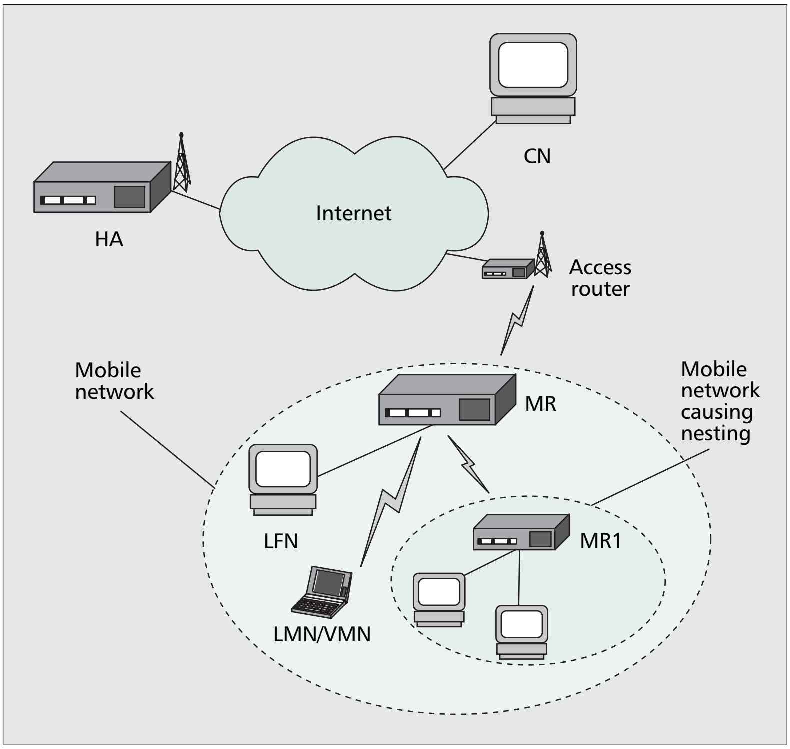
Application of NEMO BSP to Satellite Networks — Figure 5 shows the application of NEMO to satellite networks. The satellite contains IP-enabled devices that form an onboard LAN. One of the devices act as a MR that connects to a ground station using GSL. Since the satellite is on the move, the onboard network can be considered a mobile network where the onboard MR acts as a gateway to the terrestrial network (accessed through ground stations) [12]. The onboard mobile network has a terrestrial home network with an HA collocated with a ground station (e.g., ground station A); other ground stations (e.g., ground station B) act as access routers. The MR manages the connection migration between ground stations. Like MIP and SIGMA, the advantage of deterministic movement of the satellites can be used to adapt NEMO BSP to a satellite network.

An entire constellation of satellites can also be considered as a mobile satellite network as depicted in Fig. 6 [16]. A satellite that is a border router acting as a gateway between a mobile satellite network and terrestrial networks is called a satellite mobile router (SMR). A satellite access router (SAR) provides Internet access service to visiting MHs or mobile networks in the constellation. A terrestrial access gateway station (TAGS) acts like the access router of NEMO BSP discussed in this section. A satellite home aagent (SHA) is the HA of a mobile satellite network residing in the terrestrial network. An SMR sends a BU to an SHA, which creates a binding cache entry to forward encapsulated packets to the satellite mobile network. The SHA intercepts packets destined to the home address of the host inside the satellite mobile network, encapsulates them, and tunnels them to the SMR's registered CoA.

The user segment network (terrestrial) is composed of visiting mobile networks or MHs, similar to a mobile network in terrestrial networks. The user segment network (space) is a



■ **Figure 3.** *SIGMA in space when a satellite is an MH.*



■ **Figure 4.** *Architecture of NEMO.*

mobile network of satellites. User segment networks can get access to both terrestrial and satellite networks. A space segment network (mobile satellite network) is a constellation of satellites. All satellite nodes in the constellation have the same network prefix, and can establish connection with the terrestrial network through one or more SMRs. The mobile satellite network is the space segment of the satellite constellation network that provides the backbone communication network for the user segment networks.

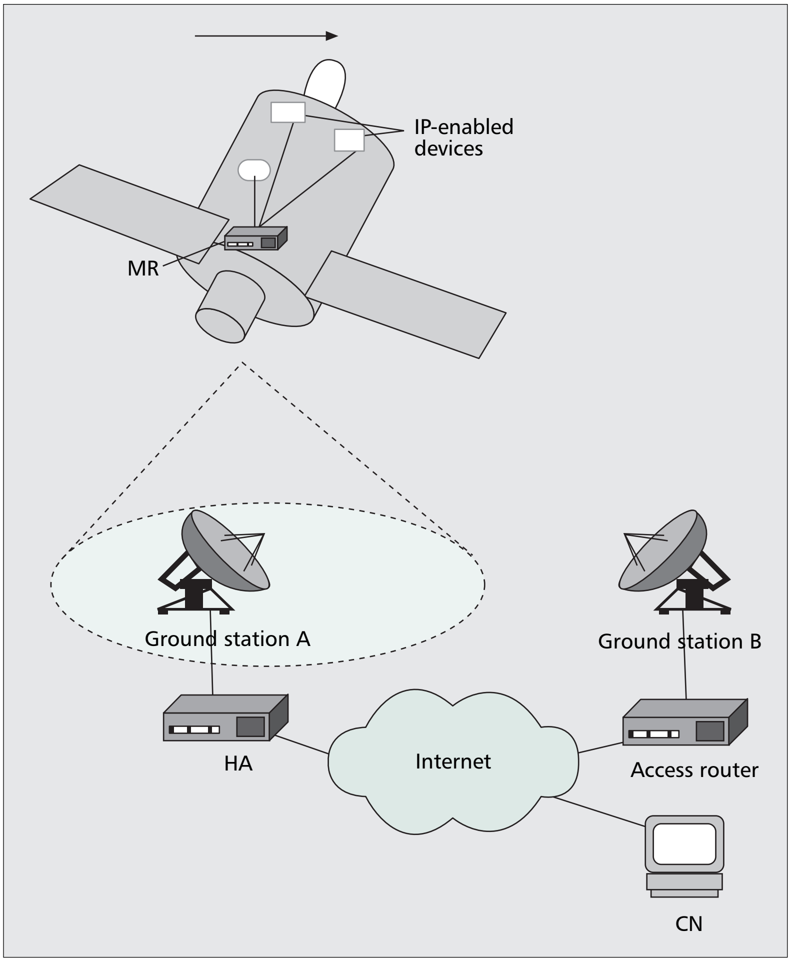


Figure 5. *A mobile network onboard a satellite.*

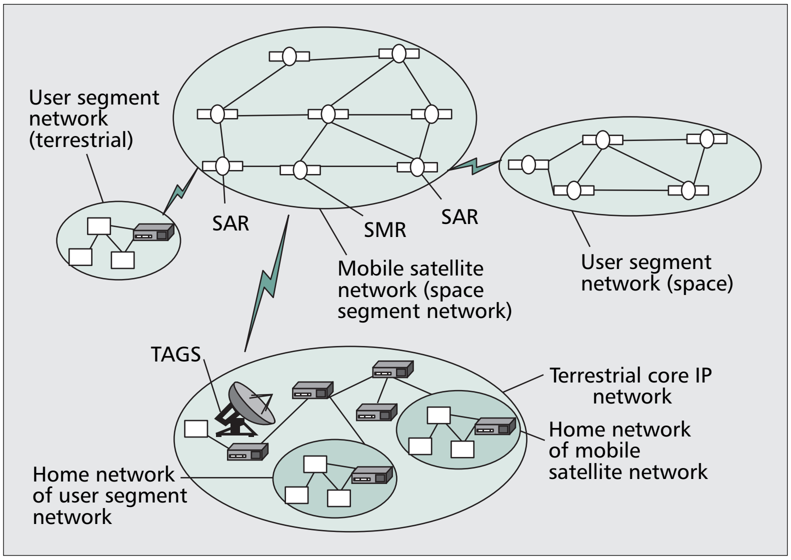


Figure 6. *A mobile network consisting of a constellation of satellites [15].*

SINEMO in Satellite Networks

NEMO BSP inherits the drawbacks of MIPv6 and also suffers from the problem of inefficient routing due to nested tunneling [11]. To overcome the limitations of NEMO BSP, a new network mobility scheme called SINEMO has been proposed in the literature [12].

Basic Architecture and Operation — SINEMO is an extension of SIGMA for mobility management of mobile networks. Figure 7 shows the basic architecture and operation of SINEMO. In SINEMO the MR is multihomed and connected to two wireless networks through access routers while in the overlapping coverage area of two access routers. A central LM (CLM) maintains the IP addresses of MRs of a mobile network. A local LM (LLM), collocated with the MR, maintains the IP addresses of the nodes inside the mobile network. An MR acts as a gateway between the nodes in the mobile network and the Internet.

The MR provides each node inside the mobile network a private IP address from a predefined private IP address space, and also maps those private IP addresses to public IP addresses. The nodes are not aware of their public IP addresses; they use only the private IP addresses for connectivity. When an MH moves into the mobile network, it sends a registration message to the MR, and the LLM is updated with the new public address of the MH. The MR also updates the CLM with the new public address of the MH.

When the mobile network moves into the overlapping coverage area of two access routers, the MR obtains a public IP address from the new access point. An MR is also delegated one or more public address prefixes to allocate IP addresses for nodes inside the mobile network. During handoff of the mobile network, only the public addresses are changed in the address mapping at the MR; the private IP addresses of the nodes remain unchanged. The MR thus hides mobility from the nodes inside the mobile network. Network Address Translation (NAT) is used to translate between the node's private and public (globally reachable) IP addresses. The MR intercepts data packets, translates the IP addresses, and forwards the packets to and from nodes.

Providing nodes with private IP addresses and mapping with public IP address results in efficient routing support and, most important, has the advantage of reducing signaling across the air interface as the nodes will not generate any dynamic updates or BUs when the mobile network moves. The MR updates the CLM with the IP address of the LLM, and updates the LLM with IP addresses of MHs. As the LLM is collocated with the MR, an MR does not generate any signaling; location update is done locally. On the other hand, when an MH moves across MRs within a mobile network, the MH changes its IP address and updates the LLM. Thus, the LLM always has the most recent addresses of MHs. When a CN wants to send data to a host inside the MN, it queries the CLM; the query is forwarded to the LLM, which responds with the public IP address of the MH directly to the CN.

Although NAT hides the private addresses of the nodes inside the mobile network, in SINEMO a CN, being outside the mobile network, can get the corresponding public address of any node inside the mobile network by querying the CLM and thus can establish connection with that node successfully.

Application of SINEMO to Satellite Networks — SINEMO can be used for mobility management for the two mobility scenarios described earlier. To adapt SINEMO for the first scenario, the MR in the satellite needs to be multihomed with a collocated LLM. SINEMO can also be applied to the second case by making the SMR multihomed with a collocated LLM. In both cases the access routers are ground stations, and the CLM is a fixed host in the terrestrial network.

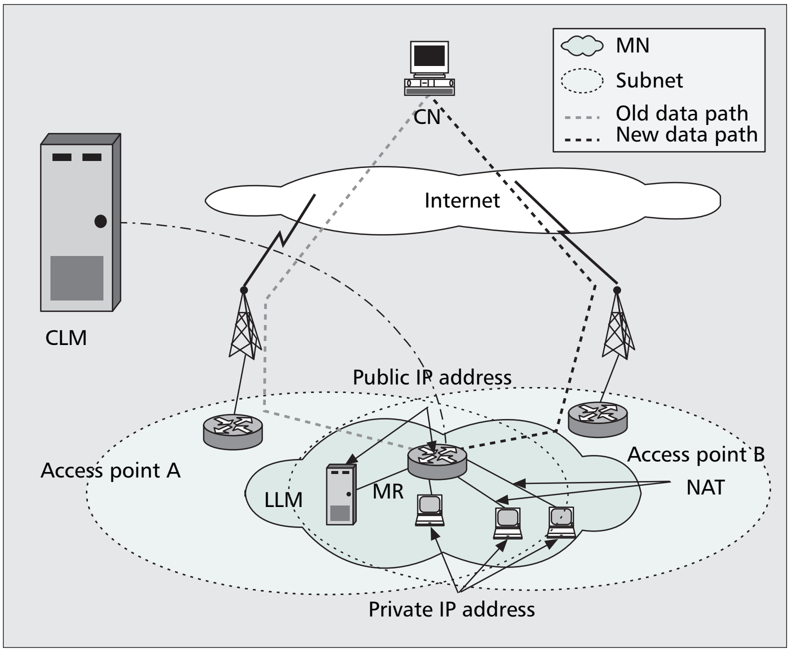


Figure 7. *SINEMO architecture.*

Comparison of Mobility Management Schemes for Satellite Networks

A comparison of the mobility management schemes presented earlier is shown in Table 1. MIP-based protocols suffer from handoff latency and packet drop during handoff. Increased handoff latency, and hence increased packet loss, is due to the fact that data communication does not continue while the new address is being configured. FMIPv6 and HMIPv6 partly reduce the handoff latency by using packet forwarding from the previous access routers, and differentiating between movement types respectively. Inefficient routing is also a problem in MIP-based protocols, as every packet must go through the home network, although the mobile host is not in the home network. The problem of inefficient routing can be avoided if the protocols operate in route optimization mode. Operating in route optimization mode has the restriction that the peer node (mobile or fixed) must also run the mobility protocols. In addition, all the MIP-based protocols forward packets toward the mobile hosts using encapsulation when the host is not in its home network. This encapsulation of packets introduces overhead, as an extra header is added to the packet. Header overhead is worse in NEMO BSP as a packet is encapsulated multiple times when the mobile network is nested. Moreover, MIP-based mobility management schemes require changes in the existing Internet infrastructure. Changes in the infrastructure are required due to the installation of mobility entities such as the HA and FA in the existing network.

SIGMA-based schemes overcome the limitations of MIP-based protocols. In SIGMA-based protocols data transfer continues through the old connection while registering with the new access router during handoff. This results in SIGMA-based protocols having lower handoff latency and packet loss than MIP-based protocols. In SIGMA packets are always sent directly to the new address of the mobile host, eliminating the prob-

Scheme	Layer for handling mobility	Mobility type handled	Handover latency	Routing	Header overhead due to encapsulation	Infrastructure change required
MIP and MIPv6	Network layer	Host	High	Efficient in optimized mode	Yes	Yes
FMIPv6	Network layer	Host	Medium	Efficient in optimized mode	Yes	Yes
HMIPv6	Network layer	Host	Medium	Efficient in optimized mode	Yes	Yes
NEMO BSP	Network layer	Network	High	Inefficient	Yes	Yes
SIGMA	Transport layer	Host	Low	Efficient	No	No
SINEMO	Transport layer	Network	Low	Efficient	No	No

Table 1. *Comparison of different mobility management schemes.*

The concept of network mobility and associated protocols are still at their early stages of development. Application of network mobility for satellites containing many IP-enabled devices connected to an on-board LAN is an interesting future research issue.

lem of inefficient routing and requiring no encapsulation. The problem of header overhead is also not present in SIGMA-based protocols, as there is no encapsulation of packets. Moreover, SIGMA-based protocols can easily be deployed in the existing infrastructure, as there is no distinction between home and foreign networks.

The frequency of handoff and the long-delay GSL links of satellite networks have significant impact on the performance of mobility management schemes. Frequent handoffs will result in increased packet loss in satellite networks if handoff latency is not reduced. Also, header overhead results in wasted bandwidth over resource-constrained GSLs in satellite networks. Coupled with the long delay in GSL links, inefficient routing of packets will make the end-to-end delay even worse.

Conclusion

In this article we summarize the mobility protocols (both host and network mobility) suitable for managing the mobility of IP-enabled LEO satellites. Application of host and network mobility to satellite networks has also been described. The concept of network mobility and the associated protocols are still in their early stages of development. Application of network mobility for satellites containing many IP-enabled devices connected to an onboard LAN is an interesting future research issue. A comparison of the suitability of the mobility protocols for satellite networks has been presented. This will help network designers choose the best mobility management scheme for satellite networks.

References

[1] K. Bhasin and J. L. Hayden, "Space Internet Architectures and Technologies for NASA Enterprises," *IEEE Aerospace Conf.*, Big Sky, MT, Mar. 10–17, 2001, pp. 2/931–41.

[2] W. Ivancic *et al.*, "Secure, Network-Centric Operations of a Space-Based Asset–An Abridged Report," *Earth-Sun Sys. Tech. Conf.*, College Park, MD, June 28–30, 2005.

[3] K. Bhasin and J. L. Hayden, "Space Internet Architectures and Technologies for NASA Enterprises," *Int'l. J. Sat. Commun.*, vol. 20, no. 5, Sept. 2002, pp. 311–32.

[4] J. Rash, K. Hogie, and R. Casasanta, "Internet Data Delivery for Future Space Missions," Space Internet Wksp., Cleveland, OH, June 4–5, 2003.

[5] R. Parise *et al.*, "Internet Technology on Spacecraft," *AAS/AIAA Space Flight Mechanics Mtg.*, Clearwater, FL, Sept. 21, 2000.

[6] C. Perkins, "IP Mobility Support for IPv4," RFC 3220, Jan. 2002.

[7] S. Deering and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification," Internet draft, Dec. 1998.

[8] S. Fu *et al.*, "Performance of SIGMA: A Seamless Handover Scheme for Data Networks," *Wireless Commun. and Mobile Comp.*, vol. 5, no. 7, Nov. 2005, pp. 825–45.

[9] D. Israel *et al.*, "Space Communication Demonstration Using Internet Technology," http://ipinspace.gsfc.nasa.gov/documents/ITC02-CANDOS.doc, 2002.

[10] K. Leung *et al.*, "Application of Mobile-IP to Space and Aeronautical Networks," *IEEE Aerospace and Elect. Sys.*, vol. 16, no. 12, 2001, pp. 13–18.

[11] E. Perera, V. Sivaraman, and A. Seneviratne, "Survey on Network Mobility Support," *ACM SIGMOBILE Mobile Comp. and Commun. Rev.*, vol. 8, no. 2, April 2004, pp. 7–19.

[12] P. K. Chowdhury, M. Atiquzzaman, and W. Ivancic, "SINEMO: An IP-Diversity Based Approach for Network Mobility in Space," *2nd Int'l. Conf. Space Mission Challenges for Info. Tech.*, Pasadena, CA, July 17–21, 2006.

[13] F. Alagz, O. Korak, and A. Jamalipour, "Exploring the Routing Strategies in Next-Generaion Satellite Networks," *IEEE Wireless Commun.*, vol. 14, no. 3, June 2007, pp. 79–88.

[14] D. B. Johnson, C. E. Parkins, and J. Arkko, "Mobility Support in IPv6," Internet draft, June 2003.

[15] S. Fu and M. Atiquzzaman, "SIGMA: A Transport Layer Handover Protocol for Mobile Terrestrial and Space Networks," *e-Business and Telecommunincation Networks*, J. Ascenso, L. Vasiu, and C. Belo, Eds. Springer, 2006, pp. 41–52.

[16] D. Shi and C. Tang, "The Handoff Study on Satellite Networks Based on Mobility Network," *6th Int'l. Conf. ITS Telecommun.*, Chengdu, China, June 21–23, 2006, pp. 1029–32.

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