IP Mobile Multicast over Next Generation Satellite Networks

Design and Evaluation of a Seamless Mobility Framework for IP Multicast
Communications over a Multi-beam Geostationary Satellite Network

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Submitted for the Degree of

Doctor of Philosophy

Faculty of Engineering and Informatics

University of Bradford

2016

# ABSTRACT

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**Title:**   IP Mobile Multicast over Next Generation Satellite Networks. Design and evaluation of a seamless mobility support framework for IP multicast communications over a multi-beam geostationary satellite network.

**Keywords:** DVB, gateway handover, satellite handover, mobility management, mobile multicast, IP multicast, PMIPv6, receiver mobility, source mobility.


The inherent broadcast nature of satellites, their global coverage and direct access to a large number of subscribers give satellites unrivalled advantages in supporting IP multicast applications. A new generation of satellite systems that support regenerative on-board processors and multiple spot beam technology have opened new possibilities of implementing IP multicast communication over satellites. These new features enable satellites to make efficient use of their allocated bandwidth resources and provide cost effective network services but equally, create new challenges for mobile satellite terminals. IP mobility support in general and IP mobile multicast support in particular on mobile satellite terminals like the ones mounted on continental flights, maritime vessels, etc., still remain big challenges that have received very little attention from the research community.

Up till now, there are no proposed mechanisms to support IP multicast for mobile receivers/sources in multi-beam satellite networks in open literature. This study explores the suitability of IP multicast mobility support schemes defined for terrestrial networks in a satellite environment and proposes novel schemes based on the concepts of Home and Remote subscription-based

approaches, multiple interface and PMIPv6 protocol. Detailed analysis and comparison of results obtained from the proposed schemes, Mobile IP (MIP) Home and Remote subscription-based approaches (for terrestrial networks) when implemented on a reference multi-beam satellite network are presented. From these results, the proposed schemes outperform the MIP Home and Remote subscription-based approaches in terms of gateway handover latency, number of multicast packets lost and signalling cost over the satellite air interface.

# ACKNOWLEDGEMENTS

First and foremost, I wish to thank my supervisors Dr Prashant Pillai and Prof Yim Fun Hu, for their advice, encouragement and support during the course of this research work.

Notably, I wish to express my deepest gratitude to my dear wife, Juliana for her constant love, encouragement and cooperation throughout the duration of my study. My special thanks go to my two lovely children, Jesse and Janella for their understanding and support over the past four years.

Also, I wish to express my gratitude to Dr Muhammad Ali for his assistance in the development and simulation of the M3U-based approach using NS3.

Last but not the least, I wish to thank all members of the FUN Lab for their support and cooperation in one way or another during the course of my study.

# DEDICATION

*In memory of my late father, Denis Tar Jaff*

*(15th April 1928 - 11th May 2011).*

*To my loving mother, Angelica Biy Jaff, who has been my*

*source of inspiration and strength.*

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| ATN | Aeronautical Telecommunication Network |
| BCE | Binding Cache Entry |
| BDMLSP | Base Deployment for Multicast Listener Support in Proxy Mobile IPv6 (PMIPv6) Domains |
| BS | Base solution for mobile source support in PMIPv6 networks |
| CMT | Correction Message Table |
| CNM | CUM Notification Message |
| CoA | Care-of-Address |
| CUM | Channel Update Message |
| DHCP | Dynamic Host Configuration Protocol |
| DR | Direct Routing |
| DVB-RCS | Digital Video Broadcasting - Return Channel via Satellite |
| DVMRP | Distance Vector Multicast Routing Protocol |
| FA | Foreign Agent |
| FL | Forward Link |
| GEO | Geostationary Earth Orbit |
| GWH | Gateway Handover |
| HA | Home Agent |
| HNP | Home Network Prefix |
| HS | Home Subscription |
| IGMP | Internet Group Management Protocol |
| IP | Internet Protocol |
| LLA | Link-Local Address |
| LMA | Local Mobility Anchor |
| M3U | Multicast Mobility Management Unit |
| MAG | Mobile Access Gateway |
| MI | Multiple Interface |
| MIP | Mobile IP |
| MLD | Multicast Listener Discovery |
| MMOFA | Mobile Multicast Support using Old Foreign Agent |
| MMPMSHN | Mobility Management Based on Proxy Mobile IPv6 for Multicast Services in Home Networks |
| MMROP | Multicast Mobility Routing Optimizations for Proxy Mobile IPv6 |
| MMT | Multicast Map Table |
| MOSPF | Multicast Extensions to Open Shortest Path First |
| MR | Multicast Router |
| mRCST | Mobile Return Channel Satellite Terminal |
| MS | Mobile Source |
| MSA | Mobility Support Agent |
| MSS | Mobile Satellite Services |
| MTMA | Multicast Tree Mobility Anchor |
| NCC | Network Control Centre |
| NMC | Network Management Centre |
| NS-3 | Network Simulator-3 |
| OBP | On-Board Processing/Processor |
| PID | Program Identifier |
| PIM-DM | Protocol Independent Multicast - Dense Mode |
| PIM-SM | Protocol Independent Multicast - Sparse Mode |

| PMIPv6 | Proxy Mobile IPv6 |
|--------|-------------------|
| RCST | Return Channel Satellite Terminal |
| RL | Return Link |
| RP | Rendezvous Point |
| RPF | Reverse Path Forwarding |
| RS | Remote Subscription |
| RSGW | Regenerative Satellite Gateway |
| SH | Satellite Handover |
| SHM | Source Handover Message |
| SHS | Satellite Home Subscription |
| SIUM | Service Interface Update Message |
| SI Table | Service Information Table |
| S-MAG | Satellite Mobile Access Gateway |
| SNMP | Simple Network Management Protocol |
| SRS | Satellite Remote Subscription |
| SSM | Source-Specific Multicast |
| TCP | Transmission Control Protocol |
| TIM | Terminal Information Message |
| Tx/Rx | Transmitter/Receiver |
| UDP | User Datagram Protocol |

# 1 INTRODUCTION

## 1.1 Satellite and multicast communications

Satellite communications is becoming a major player in the provision of mobile and ubiquitous communications especially in areas where terrestrial communication infrastructure is not present. Recent advancement in satellite technology has given birth to a new generation of satellite systems characterised by the support for multiple spot beams (frequency reuse), regenerative on-board processor (OBP) and the ability to utilise higher frequency bands (like the Ka-band, etc.). The presence of regenerative on-board packet processing implies that a full mesh, single-hop connectivity can be easily established between two or more satellite terminals/gateways compared to traditional 'bent pipe' satellite systems. Single-hop connectivity in mesh topology reduces the round trip delay by half compared to double-hop connectivity in star network topology. These new features are behind the huge increases in the satellite capacity, efficient utilisation of the allocated satellite bandwidth resources, support for high data rates and high-speed Internet access obtained in the new generation of satellite systems. While broadening the scope of satellite-based applications, these new features have also made satellite communications more competitive in the provision of services such as multimedia, integrated voice and data communications, etc., against other Internet-based communications technologies.

Considering the cost of satellite bandwidth resources, any technology that will efficiently utilize the available satellite bandwidth resources will be highly welcomed by both the satellite operators as well as satellite communication customers. This explains why IP multicasting which is a bandwidth saving technology is important to satellite networks. The unique ability of a satellite to

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reach millions of customers while eliminating large numbers of intermediate routing hops presents an unrivalled platform for global deployment of group communications i.e., global IP multicast.

Unlike in broadcast, where the traffic is flooded in the whole satellite footprint, in IP multicast, traffic is only sent to spot beams that have at least one interested receiver, thus saving bandwidth in those spot beams that have no receivers. IP multicast applications that could be applicable to Mobile Satellite Services (MSS) like in long haul flights, global maritime vessels, continental trains, etc., include: on-demand multimedia content delivery (e.g., IPTV), real-time financial data, software distribution and upgrade, important service information like weather conditions, ongoing disaster zones and information, route updates, etc. With all these sets of new applications, next generation satellite networks with their support for fast Internet broadband have a unique opportunity to attract new customers and generate new revenues by deploying these new IP-based services. The aeronautical industry which is one of the key customers for mobile satellite services has recently adopted IP as the future network protocol for the Aeronautical Telecommunication Network (ATN) [1]. This opens up new opportunities for satellite-based IP multicast applications on mobile platforms as real-time important service information could be cost-effectively disseminated using IP multicasting, to a group of airlines in mid-air operating in a particular region or route or from an airline to a group of ground offices/emergency services around the world. So, IP multicast support in stationary as well as mobile customers (airliners, trains, ships, etc.) could bring significant financial savings due to the efficient utilization of the allocated bandwidth resources. For satellite operators, the bandwidth resources saved in each satellite footprint

could be made available to satisfy the existing customers' demands or sell to new customers.

## 1.2  IP multicast

IP multicast is a network layer protocol which enables a sender to send a single copy of IP datagram simultaneously to a group of interested receivers which may be located at different destinations. Routers in the network layer play two key functions in IP multicasting:

• They ensure that only one copy of the same multicast traffic passes through any particular network link by replicating multicast packets only when necessary at network branches leading to interested receivers.

•  They use routing algorithms to figure out the optimal path to route packets through various links to the interested receivers.

The advantage of IP multicast over unicast is that it saves processing overhead at sender's network associated with sending duplicate copies to individual receivers and bandwidth overhead in the network since only one copy of the data traverses any network link leading to an interested receiver. Compared to broadcast in which the whole network is flooded with traffic, in IP multicast, traffic is sent to only network links that lead to an interested receiver. This reduces redundant traffic in the network, thus saving bandwidth resources compared to broadcast.

The fundamental concept of multicasting can be applied in three different layers of the Open System Interconnection (OSI) reference model namely: the Link layer, for Link Layer Multicast; Network Layer, for Network Layer  (or IP) Multicast and Application Layer, for Application layer  Multicast [2]. The Network Layer (or IP) Multicast is the most important amongst the three different

approaches of multicasting, as it consumes the least possible network bandwidth resources.

### 1.2.1 IP multicast addressing

IP Multicast has been assigned the class D address space i.e., 224.0.0.0 to 239.255.255.255 in IPv4 networks by the Internet Assigned Numbers Authority (IANA). In IPv6 networks, a set of binary 11111111 (0xFF) at the start of an IPv6 address identifies the address as an IPv6 multicast address. Any other value at the start of an IPv6 address identifies the address as a unicast address.

### 1.2.2 IP multicast protocols

IP Multicast Protocols can be classified into two main types: routing and group management protocols. There are mainly two types of multicast group membership protocols: Internet Group Management Protocol (IGMP) [3] and Multicast Listener Discovery (MLD) [4] for IPv4 and IPv6 networks respectively.

### *1.2.2.1 Group membership protocols*

Any IP node wishing to join a multicast group sends an IGMP/MLD to the neighbouring multicast router to register its interest in receiving multicast traffic from the multicast group specified in the IGMP/MLD. IGMPv3 and MLDv2 have the additional ability to support Source-Specific Multicast (SSM) [5] in IP multicasting where there may be many sources sending data to a single multicast group. In SSM, a group member of such a multicast group, G  may subscribe to a specific multicast channel (S, G) [5] i.e., to receive multicast packets only from some specific source addresses S, or from all but some specific source addresses S. SSM thus helps to reduce redundant traffic in the network by avoiding to forward multicast traffic from some specific sources to networks in which there are no interested receivers. This is contrary to Any-

Source Multicast (*, G) [5] where a group member registers to a multicast group and receives traffic from all sources with no option of choosing the sources it is interested in receiving multicast traffic from. Any-Source Multicast may lead to some group members receiving unwanted traffic from some sources, thus making it less efficient in bandwidth conservation compared to SSM.

### *1.2.2.2 Routing Protocols*

Multicast routing protocols make use of the information put together by group management protocols to route multicast traffic from the designated router in the source network to the designated routers in the receivers' networks. Multicast routing protocols therefore build distribution trees which enable the delivery of multicast traffic from the sources' networks to receivers' networks. There are basically five multicast routing protocols: Protocol Independent Multicast - Dense Mode (PIM-DM) [6], Protocol Independent Multicast - Sparse Mode (PIM-SM) [7], Multicast Extensions to Open Shortest Path First (MOSPF) [8], Distance Vector Multicast Routing Protocol (DVMRP) [9] and Core Based Tree (CBT) [10]. While the DVMRP and the PIM-DM use the broadcast and prune algorithm to route multicast traffic, the PIM-SM, MOSPF and CBT use the explicit-join/leave protocols to route traffic [2]. The explicit-join/leave protocols can either make use of a shared tree or a reverse shortest path. Multicast sources and receivers in the shared tree approach are linked together by the use of a core or a rendezvous point (RP) [2].

## 1.3 IP multicast over next generation satellite networks

In general, two types of IP multicast services are supported in satellite networks based on the two types of topologies [11]: Star IP multicast and Mesh IP multicast.

### 1.3.1 Star IP multicast

In a star IP multicast, multicast sources located on terrestrial networks forward their multicast flows to the Regenerative Satellite Gateway (RSGW) which then dynamically forwards the multicast traffic to the Return Channel Satellite Terminals (RCSTs).
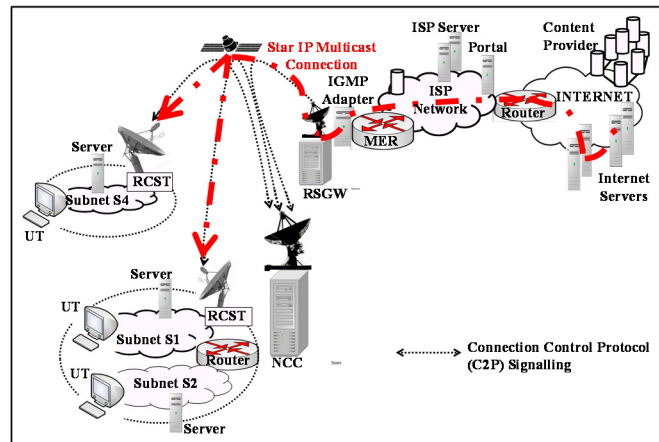


Figure 1.1 Star IP multicast topology [11]

If the RSGW is connected to the Internet, a star IP multicast service can provide worldwide IP multicasting through satellite networks. Dynamic multicast forwarding here means the RSGW will only forward multicast traffic for any particular multicast group to the uplink if at least one RCST has joined that group.

### 1.3.2 Mesh IP multicast
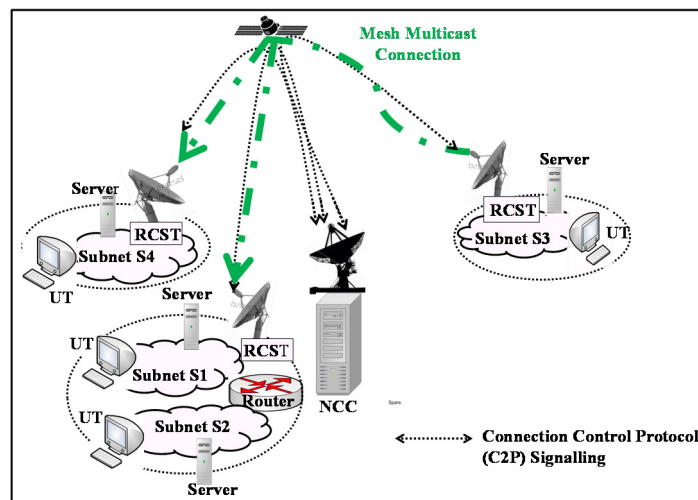


Figure 1.2 Mesh IP multicast topology [11]

A mesh IP multicast network provides multicast services between RCSTs of the same satellite Interactive network. Each RCST here may have one or more Local Area Networks (LANs) behind it with several user terminals. The multicast sources are on terrestrial LANs behind the RCSTs and they forward their multicast traffic to the source RCSTs for the onward uplink transmission.

### 1.3.3  IP multicast protocols over satellite air interface

The DVB, Satellite Earth stations and Systems (SES) [11] and Broadband Satellite Multimedia (BSM) [12] working group through the European Telecommunications Standards Institute (ETSI) have standardized many aspects of multicast transmission over satellite networks. Two multicast protocols have been adapted for use over satellites: Satellite IGMP (S-IGMP) [13] from standard IGMPv2 [14] and Satellite PIM (S-PIM) [15] from standard PIM-Sparse Mode (PIM-SM) [7].

#### *1.3.3.1      S-IGMP*

IGMP is used by IP hosts in IPv4 networks to establish or report their multicast group membership status to a multicast router in the LAN. IGMP is intended particularly for LANs with a shared (broadcast) medium, where every host can listen to IGMP reports sent by others, and where there is low delay. The use of IGMP over the satellite imposes several issues like IGMP flooding and latency [13].

##### *1.3.3.1.1 IGMP flooding*

In a dynamic IP multicast configuration over satellite, the multicast group can become very large and as a consequence, serious scalability issues can arise. This is particularly true of typical satellite configurations where, even with two-way communications, the broadcast property generally exists only in the

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forward link; terminals cannot listen to direct or retransmitted reports from other terminals to suppress redundant IGMP reports. Thus, IGMP Flooding occurs when many IGMP clients reply to a broadcast request from the IGMP querier at the same time, flooding it with report messages leading to a waste of bandwidth as well as high processing power demand at the querier.

*1.3.3.1.2 Latency*

This is the delay for stopping a multicast transmission after the last client leaves a multicast group. It is the delay of the querier becoming aware that the group is empty. This delay is a consequence of the anti-flooding mechanism introduced in hosts' reports to improve report suppression.

There is therefore a need to adapt IGMP to suit the satellite environment. IGMPv2 is the chosen version of the IGMP for adaptation in satellite networks for multicast group management by ETSI [13] despite the fact that IGMPv3 [3] is the latest version of the IGMP as defined by the IETF. The choice of IGMPv2 over IGMPv3 is due to the fact that [13]:

- IGMPv2 allows for Membership Report suppression thus making it more efficient in terms of signalling traffic as compared to IGMPv3.

- IGMPv2 needs minimal extensions in order to adapt for satellite networks as compared to IGMPv3 i.e., in IGMPv2, only the IGMP querier function (in the router) is modified unlike in IGMPv3 where the clients as well as queriers functions would require modification.

The S-IGMP applies primarily to the modification of the behaviour of the IGMP querier located in the local router. This querier function modifications consist of:

- introduction of a new state in the state diagram

- setting of specific timer values

- modified actions

- introduction of new actions in the state diagram

as detailed in [13].

For satisfactory adaptation performance in S-IGMP, [13] suggests that:

• The unsolicited report interval of the IGMP Client shall be configurable,

• In addition to the specified actions for the "join group" event, the IGMP client shall not send an unsolicited report if it receives a (retransmitted) report before the unsolicited report timer expires.

IGMPv3 allows reversion to IGMPv2 mode to permit interworking with earlier versions. The adaptation of IGMPv2 for satellites discussed here therefore can be considered as this mode of IGMPv3, which is identical to the original IGMPv2.

### *1.3.3.2    S-PIM*

Of the several versions of PIM, PIM-SM is the mode of PIM most widely considered in existing and proposed multicast routing applications today. PIM signalling over satellite mesh architectures introduces potential difficulties: all PIM messages (including Join, Prune, Hello, etc.,) are sent to the "ALL-PIM-ROUTERS" multicast address to neighbouring IP devices [16]. To reduce the unnecessary multiplication of redundant messages over satellite air interface, adapted PIM-over-Satellite (S-PIM) as detailed in [15] and [16] is necessary. S-PIM proposes:

- PIM Server (new entity) whose main function is to reduce the total number of PIM messages (for reasons of scalability), as well as to control the admission of multicast groups to the network

- A reduction of periodic PIM messages by configuring PIM-SM timers in such a way as to optimise performance over satellites. For example, a Hello message carries an option called Holdtime. Holdtime is the amount of time a receiver of the message should keep a neighbour "reachable" i.e. open to accept other subsequent PIM messages. S-PIM proposes that this Holdtime should be configured to be as large as possible or even to '0xffff' (i.e., the receiver never times-out the neighbour and so, avoids the need for periodic Hello messages).

## 1.4 Motivation and problem statement

Seamless and cost-effective mobility support is one of the main challenges facing satellite-based communications in a global multi-beam satellite network. To fully reap the benefits of IP multicast over satellite networks stated in Section 1.1 above in a global mobile satellite communication (e.g., satellite-based aeronautical, maritime, etc., communications), mobility support during beam, gateway and satellite handovers [17], must be given serious consideration. Bearing in mind the long propagation delays and the process of connection establishment in satellite networks, MIP protocol operations, IP multicast membership protocol implementation and multicast tree reconstruction or tunnelling through home network, current IP multicast mobility support schemes proposed for terrestrial networks might not be directly applicable in a satellite environment. The combination of these factors could lead to excessive handover signalling overhead, very long handover latency resulting in high

packets losses, break down of multicast delivery tree and consequently IP multicast communication (especially in real-time applications). Therefore, for the satellite operator to maintain connectivity and service level agreements at all times and also to provide cost effective satellite-based IP multicast services, the implementation of a suitable IP multicast mobility support scheme becomes imperative.

The IP multicast handover problem stems from the fact that the IP address of a mobile multicast receiver/source changes during a GW/satellite handover as it changes its point of attachment to the satellite network from one satellite GW to another.

Due to the IP address changes at GW/satellite handover in a mesh topology:

- A mobile receiver/source emerges from the handover as a completely new device as far as the IP layer is concerned [18, 19]. In IP multicast communication, multicast sources and receivers are identified by their IP addresses. The change in the IP address of a mobile multicast receiver/source during a GW/satellite handover means a change in its identity.

- The mobile receiver/source attachment to the multicast delivery tree is broken and therefore, the mobile receiver/source is cut-off from the delivery tree. In a multicast source mobility in SSM, traffic from the source cannot reach the receivers until they explicitly re-subscribe to the new multicast channel (CoA, G).

- A new multicast delivery tree (or branch) to mobile receiver/source needs to be established.

- The link or multicast delivery tree breakage at GW/satellite handover implies multicast packets loss.

Multicast source mobility in SSM, where receivers subscribe to a multicast channel (S, G) i.e., requesting to receive traffic from only some specific sources S, is even a more acute problem when the source IP address changes during a GW/satellite handover. In SSM, a change in source IP address during a gateway handover (GWH) or satellite handover (SH) implies a change in the source identity thereby invalidating the old source-specific delivery tree (S, G). This results in breakdown of communication as the mobile source can no longer reach any of the multicast group members. In terrestrial networks, IP multicast communication between the mobile source at foreign network and all group members in SSM can be restored in main ways:

- IP tunnelling: The mobile source at foreign network could tunnel multicast traffic to its home network for the home agent (HA) to deliver it to the existing source-specific delivery tree.
- Re-subscription: If the Interested group members know the mobile source care-of address (CoA) in the foreign network, then they will have to explicitly re-subscribe to the new channel (CoA, G). This will result in a multicast tree reconstruction of the new source-specific tree (CoA, G).

Research is needed to assess the suitability of these methods and their cost-effective in a satellite environment, and to address the IP mobile multicast receiver/source problems in satellite networks.

## 1.5  Aims and objectives

The main aim of this work is to design a cost-effective and reliable IP mobile multicast support scheme for a mobile multicast receiver and source in a multi-

beam satellite network during a GW/satellite handover. The following objectives have been set to meet the defined aim of this study:

- Review current satellite network architectures, mobility/handover support in satellite networks, IP mobile multicast support schemes in terrestrial networks with the intention of assessing their applicability to the satellite environment and the latest proposals for IP multicast over satellite networks.

- Carry out performance evaluation of some existing IP mobile multicast support schemes for terrestrial network (identified as good candidate schemes for adaptation in a multi-beam satellite environment) over a reference satellite network.

- Propose and design a cost-effective IP multicast mobility support scheme for a mobile multicast receiver over a multi-beam satellite network during a GW/satellite handover.

- Carry out performance evaluation of the schemes that will be proposed and analyse the results.

- Write up thesis.

## 1.6  Contribution of the Thesis

The main contributions of this thesis include:

- Introducing a new mechanism to support multicast source mobility within a multi-beam satellite network in SSM-based applications. A new device called Multicast  Mobility Management Unit (M3U) is responsible for the source mobility support during GW/satellite handover in a mesh multi-beam satellite network topology with receivers both within the satellite network and in the Internet. Up till now Remote Subscription (RS)-based approaches have been used to support source mobility only in any source multicast (*, G). The

introduction of the M3U to support RS –based approach for SSM in satellites is quite a novel idea. The functioning of the M3U ensures that all listening satellite terminals are re-subscribed to the new multicast channel (CoA, G) after GW/satellite handover without any IGMP join report being issued over the satellite air interface.

- Adapting the Proxy Mobile IPv6 (PMIPv6)-based approaches defined for IP multicast receiver mobility support in terrestrial networks, to design a novel IP multicast receiver mobility support scheme in a multi-beam satellite network during GW/satellite handover. This study is the first to use PMIPv6 protocol to support IP-based mobility within a multi-beam satellite network. The functioning of the PMIPv6 main architectural entities like the Local Mobility Anchor (LMA) and Mobile Access Gateway (MAG) [20] are slightly modified here to suit the satellite network architecture.

- Comparing IP multicast receiver/source mobility support techniques designed for terrestrial networks in terms of their applicability to satellite networks. The description of how the most suitable techniques are adapted to support IP multicast receiver/source mobility in a mesh multi-beam satellite network topology is given.

- This study is the first in open literature to propose solutions to the problems of IP mobile multicast receiver/source in a multi-beam satellite network during handover when the attachment to satellite network changes from one satellite GW to another.

In the course of this PhD programme, the publications listed below have been made. These publications form the core contributions of this thesis.

**International Journal Papers**

- **E.K. Jaff**, P. Pillai, and Y. F. Hu, "IP Multicast Receiver Mobility Support Using PMIPv6 in A Global Satellite Network," Communications Magazine, IEEE, vol. 53, pp. 30-37, March 2015.

- **E.K. Jaff**, P. Pillai, and Y. F. Hu, "Multicast Source Mobility Support for Regenerative Satellite Networks," International Journal on Advances in Internet Technology, vol. 7 no 1 & 2, pp. 148-160, July 2014.

**International Conference Papers**

- **E.K. Jaff**, M. Susanto, M. Ali, P. Pillai and Y.F. Hu, "Network coding for Multicast Communications over Satellite Networks", 7th EAI International Conference on Wireless and Satellite Systems, Bradford, UK, July 2015.

- G. Giambene, M. Muhammad, D. K. Luong, M. Bacco, A. Gotta, N. Celandroni, **E. K. Jaff**, M. Susanto, Y. F. Hu, P. Pillai, M. Ali, T. de Cola, "Network Coding Applications to High Bit-Rate Satellite Networks", 7th EAI International Conference on Wireless and Satellite Systems, Bradford, UK, July 2015.

- **E.K. Jaff**, M. Ali, P. Pillai, and Y.F Hu, "Satellite Mobile Multicast for Aeronautical Communication," International Conference on Wireless Communications and Signal Processing (WCSP), Hefei, China, IEEE, October 2014, pp. 1-6.

- **E.K. Jaff**, P. Pillai, and Y.F. Hu, "PMIPv6-Based IP Mobility Management Over Regenerative Satellite Mesh Networks", 7th Advanced Satellite Multimedia Systems Conference and 13th Signal Processing for Space

Communications Workshop (ASMS/SPSC), Livorno, Italy, IEEE, September 2014, pp. 1-8.

- **E.K. Jaff**, P. Pillai, and Y. F. Hu, "Source Mobility support for source specific multicast in satellite networks", 3rd International Conference on Mobile Services, Resources and Users (MOBILITY 2013), Lisbon, Portugal, IARIA, November 2013, pp. 69-74.

- **E.K. Jaff**, P. Pillai, and Y. F. Hu, "IP Multicast receiver mobility using multi-homing in a multi-beam satellite network", 3rd International Conference on Mobile Services, Resources and Users (MOBILITY 2013), Lisbon, Portugal, IARIA, November 2013, pp. 108-113.

- **E.K. Jaff**, P. Pillai, and Y. F. Hu, "Performance analysis of IP mobile multicast mechanisms during handovers in next generation satellite networks", 7th International working conference on Performance and Security modelling & Evaluation of Cooperative Heterogeneous Networks (IFIP HET-NETs 2013), Ilkley, Bradford, UK, November 2013, pp. P09-1 – P09-10.

## 1.7  Organisation of the Thesis

This thesis is organised into 8 chapters. Chapter 1, gives a brief introduction of the research topic, stating clearly the aims and objectives of the work and also highlighting the problems faced by mobile multicast receivers/sources during a GW/satellite handover scenario. Chapter 2 presents a brief account of a DVB-RCS satellite network architecture with explanations of the main architectural entities, mobile scenarios envisaged and different types of handovers in satellite networks. In Chapter 3, the problems faced by IP mobile multicast receiver/source in terrestrial networks are given. The existing IP multicast mobility support schemes in terrestrial networks are compared against some

defined parameters to determine which ones could be adapted for a satellite environment. Based on this comparison, a detailed account of each scheme identified as a good candidate scheme for the satellite environment is given. Chapter 4 evaluates the performance of the Home Subscription (HS)-based and Remote Subscription (RS)-based approaches defined for terrestrial networks and identified as good candidate schemes for adaptation in a satellite network if implemented over a reference multi-beam satellite network. Results obtained here are analysed and conclusions on their suitability in the current form in a satellite environment drawn. Chapter 5 presents detailed accounts of the new proposed schemes to support IP multicast receiver mobility in a multi-beam satellite network. Chapter 6 gives a comprehensive account of the proposed source mobility support scheme in SSM over a multi-beam satellite network i.e., the Multicast Mobility Management Unit (M3U)-based scheme and also, describes the simulation scenario of the M3U-based scheme using NS-3. Chapter 7 gives a comprehensive result and analysis of each of the proposed schemes in Chapters 5 and 6. A comparison of the results from the proposed schemes and those of the HS and RS-based approaches obtained in Chapter 4 are also given in this chapter. Chapter 8 concludes the thesis and highlights some areas for future work.

# 2  SATELLITE NETWORK ARCHITECTURE

In this chapter, the discussion on the satellite network architecture will be limited only to that of the Digital Video Broadcasting - Return Channel via satellite (DVB-RCS/RCS2) [12, 21]. The DVB-RCS/RCS2 network architecture which is an open standard that defines the complete air interface specification for two-way satellite broadband scheme is the most popular satellite network architecture in the world today. Its popularity is partly because at the moment it is the only multi-vendor VSAT standard [22], and also, the fact that it is an open standard. The popularity and vendor independence of DVB-RCS/RCS2 compliant equipment have given them more flexibility in the choice of satellite operators and service providers to choose from, thus making the equipment and operational costs cheaper [23] compared to proprietary ones.

## 2.1  The DVB-RCS/RCS2 network architecture

The DVB-RCS/RCS2 network architecture is based on well-defined set of factors such as number of spot beams (single-beam/multi-beam), network topology (star/mesh) and satellite payload architecture (transparent/regenerative) [12]. Based on the above mentioned factors, the following DVB-RCS/RCS2 network scenarios can be identified [12]:

- single-beam/multi-beam, star transparent

- single-beam/multi-beam, mesh transparent

- single-beam/multi-beam, star/mesh regenerative

Whereas  a star topology here, represents one in which a satellite connection is established between a gateway and one or more RCSTs, a mesh topology is one in which a satellite connection is established between two or more user

RCSTs without passing through the gateway [11, 12]. In DVB-RCS/RCS2 satellite networks, the following architectural entities and satellite system operator roles are defined [12, 21]:

- Return Channel Satellite Terminal (RCST): Network device that provides the interface between the satellite system and external users [12].

- Gateway (GW): Network device that provides accounting functions for RCSTs, interactive services and/or connections to external networks for traffic sent using star connection [12].

- On-Board Processor (OBP): This could be a multiplexer or switch or router on-board the satellite that can separate the uplink and downlink air interface formats (modulation, coding, framing, etc.) [12].

- Transparent satellite payload (bent pipe): On-board multiplexer that provides connectivity between uplink and downlink of the same or different beams at the physical layer i.e., physical layer switching. Here, there is no demodulation or decoding of the received signal [12].

- Regenerative satellite payload: OBP which is capable of providing demodulation/modulation and decoding/coding functions to the received signal on-board the satellite as well as providing connectivity between uplink and downlink of the same or different beams at higher layers (network and data link layers) [12].

- Network Control Centre (NCC): Network element that provides control and monitoring functions (session control, connection control, routing, RCST access control to satellite resources, etc.) [12].

- Network Management Centre (NMC): Network device responsible for the NCC, RCST, GWs and OBP management functions [12].

- Satellite Operator (SO) [21]: The SO Manages the whole satellite and sells capacity at transponder level to one or several Satellite Network Operators (SNOs). The SO is identified by the Original Network ID (ONID) [21].

- Satellite Network Operator (SNO) [21]: A SNO owns one or more satellite transponders. Each SNO owns one or more NCC and Network Management Centre. The SNO configures the time/frequency plan. Each SNO is responsible for one Interactive Network, IN (identified by the Network ID) corresponding to one DVB network and controls its own capacity. The SNO may divide the IN into Operator Virtual Networks (OVN) and shares its own physical and logical resources among OVNs. Each OVN is managed by a Satellite Virtual Network Operator (SVNO).

- Satellite Virtual Network Operator (SVNO) - also called Service Provider [21]: Each SVNO manages one or more OVNs. Each OVN is an independently managed higher layer network. An active RCST can only be a member of one OVN assigned at logon to the DVB-RCS2. Each OVN is given a pool of Satellite Virtual Network (SVN) [21] numbers from which it can allocate SVN-MAC addresses to RCSTs. SVN concept is used to logically divide the addressing space controlled by SNO. SVNOs sell connectivity services to subscribers which are RCSTs. End-users connected to a RCST LAN interface are the final actors enjoying the satellite services. In Regenerative satellite systems, the SVNO manages one or more Regenerative Satellite Gateway (RSGWs)

The above defined satellite system operator roles which are summarised in Figure 2.1, are mostly associated with DVB-RCS2 networks.
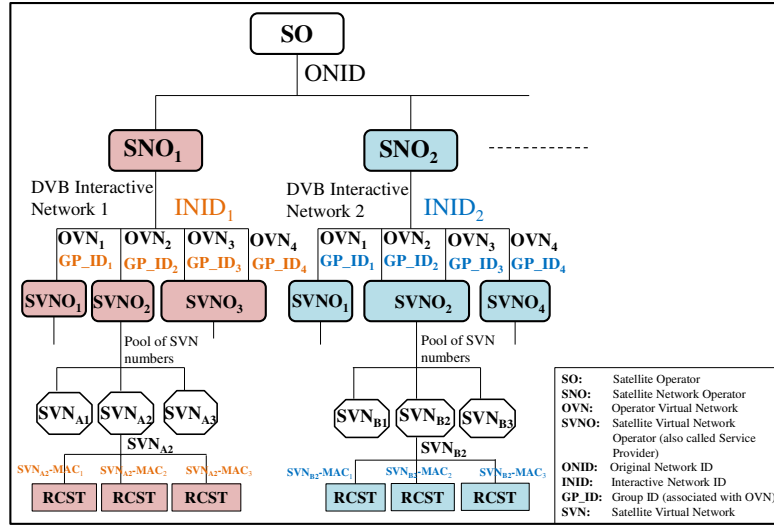


Figure 2.1 Satellite system operator roles

Traditionally, satellites have been usually treated as a transparent pipe that carries data between a gateway and the satellite receivers. Nowadays, advances in satellite technology which have seen the above defined architectural entities introduced in satellite systems like the DVB-RCS/RCS2, have transformed satellite communications. One of the most significant improvements in satellite technology is the increase in the overall satellite capacity.  This capacity increase is brought about mainly by the support for spot beam technology in new generation of satellite systems. Spot beam technology enables a satellite footprint to be divided into multiple beams. Dividing the satellite footprint into multiple spot beams enables the satellite to focus its power over a relatively small area resulting in high power density. High power density supports high data rate, thus increasing the satellite capacity. Also, dividing the satellite footprint into multiple spot beams allows frequency reuse across different spot beams. Reusing the allocated frequency band also increases the overall satellite capacity.

## 2.2 Interactive Satellite Network for Mobile Scenarios

Mobile scenarios envisaged in satellite networks as stipulated in [17] can be classified into two main categories; Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) scenarios.

LOS scenario is further categorized into:

• Maritime scenario: comprises mainly of passenger transportation ships (ferries and cruises), commercial ships (cargos and tankers), and private transportation ships (sailing boats).

• Aeronautical scenario: comprises mainly of passenger aircrafts (including wide-body and single aisle aircrafts) and private aircrafts (executive jets).

The LOS scenarios correspond to low-fading scenarios, which are almost always in LOS or close to LOS conditions since the satellite signal is not expected to be blocked or shadowed by any obstacle in normal operation conditions. The only channel impairments affecting the satellite signal are those linked to the narrowband fast fading (due to multipath propagation), Doppler shift and Doppler rate (due to the terminal speed). Channel conditions encountered in LOS scenarios generally show that the channel can be modelled as pure Ricean with high Rice factor; which is very close to an AWGN channel [17, 24] . LOS scenarios are considered as global coverage scenarios as well as regional.

 NLOS scenarios correspond to land-based moving platforms and are also further classified into:

• Railway scenario: mainly comprises the high-speed long-distance trains.

• Vehicular scenario: consists of passenger vehicles (buses); commercial vehicles (trucks); and private vehicles (cars).

NLOS scenarios suffer from mobility effects, such as multipath, shadowing and blockage due to the presence of adjacent buildings, vegetation, bridges, power arches (only in railways) and tunnels, resulting in sporadic severe fading. Despite the fact that NLOS scenarios are characterised by short blockages and shadowing, it should be noted that the railroad and the land-vehicular road satellite channels are in LOS state most of the time. NLOS scenarios are generally considered as regional coverage scenarios since trains and land-vehicles remain within one continent [17, 24] .

## 2.3 Handovers in satellite networks

Three main types of handovers do take place within a global multi-beam satellite network, namely, the Beam, Gateway and Satellite handovers [17].

### 2.3.1 Beam handover

Beam handover (BH)) occurs when a RCST moves from one beam into another in a multi-beam satellite network. BH essentially a transponder handover is considered a lower-layer handover in which the NCC coordinates the handover procedure. No higher layer involvement is required in the implementation since it does not result in a change of the IP address. Therefore, BH is mainly a layer two handover where satellite resources in the current beam are released and new set of resources in the target beam are acquired. BH entails both forward link (FL) and return link (RL) handover.

### 2.3.2 Gateway handover

A GWH is when a BH takes place between two beams associated with different gateways. GWH always entails BH. The GWH is coordinated by the NCC which has a database that includes all beams, gateways and satellites profiles. Figure 2.2 shows the step-by-step DVB-S/RCS signalling messages between all

entities involved in a gateway handover [17]. Most often, a GWH involves a layer three handover, especially if the GWs are connected to the Internet or terrestrial networks. In such a scenario, a GWH will entail a layer 3 (IP Layer) handover since the IP address of the mobile satellite terminal will have to change.
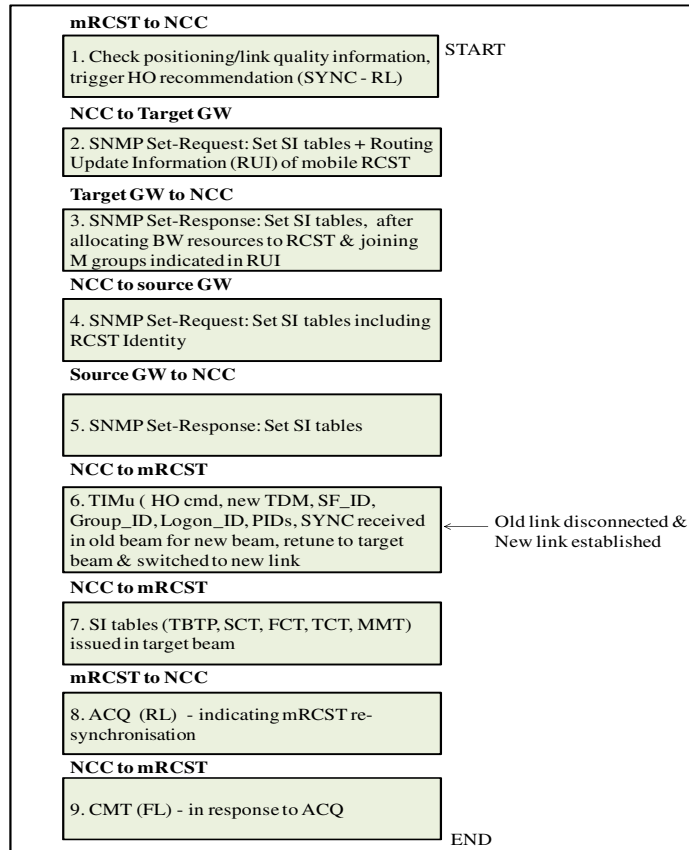


Figure 2.2  Gateway handover signalling sequence

### 2.3.3  Satellite handover

A satellite handover (SH) takes place when a RCST moves from one beam into another one which belongs to a different satellite. SH always entails a BH and GWH. SH is coordinated by the NCC if the satellites belong to the same interactive network [21] and by the NMC if the satellites belong to different interactive networks of the same satellite operator.  Since SH entails GWH, it means that SH requires handover at the IP layer.

## 2.4  Summary

In this chapter, an overview of the satellite network architecture (from the point of view of a DVB-RCS) is given. The key communication entities in satellite networks have been given and defined.  This chapter also introduces the mobile scenarios envisaged in satellite networks. These are broadly classified into Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) scenarios. The three common types of handovers in satellite networks have been stated and explained.

After studying the satellite network architecture in this chapter, the next chapter examines the current IP mobile multicast support schemes in terrestrial networks in order to assess their suitability for adaptation in a multi-beam satellite network.

# 3 IP MOBILE MULTICAST SUPPORT SCHEMES AND ADAPTATION TO THE SATELLITE ENVIRONMENT

This chapter explores the mobile multicast receiver/source issues and the current proposed solutions to these problems in terrestrial networks. It also compares the current IP mobile multicast solutions with the view of establishing which ones could be suitable for adaptation in a multi-beam satellite network. Based on some defined parameters relevant to handover scenarios in a multi-beam satellite network, some of the terrestrial IP mobile multicast support schemes are considered to be good candidate schemes for adaptation in a satellite environment.

## 3.1 IP mobile multicast problems

In terrestrial networks, mobile multicast receivers/sources face similar problems like the ones explained in Section 1.4, due to changes in their IP addresses as they undergo layer 3 handover from one IP network to another.

### 3.1.1 Mobile receiver problems

The problems faced by mobile multicast receivers include:

- **Multicast latency:** - Due to handover procedures from one network to another (e.g., link-switching delay, mobile IP protocol operations), membership protocol implementation, multicast tree reconstruction and increased propagation delays to new locations, mobile receivers experience extra delays in receiving multicast data. This could pose serious problems especially for time delay sensitive applications (e.g., voice, video conferencing, etc.).

- **Packet loss:** - This occurs mostly during handover period when the mobile receiver is switching from one network point of attachment to another. During this period, the mobile receiver is unreachable i.e., cannot receive or send traffic and so the multicast traffic sent during this time frame is lost.

- **Packets out of order:** - Due to delays and handover procedures, a mobile node (MN) may receive some packets out of order.

- **Packet duplication:** - This occurs when a MN is receiving multicast packets from different routers or base station as a consequence of its movement from one subnet to another.

- **Leave latency:** - A MN may not have enough time to unsubscribe to the multicast groups it was previously subscribed to before losing connection to the previous network. This is particularly important if the MN was the last member of a multicast group in the subnet as multicast data will still continue to be forwarded to the subnet despite the fact that no member of the group is still left in the subnet.

### 3.1.2  Mobile source problems

Whereas the problem of a mobile receiver has a local and single impact on the receiver only, that of a mobile source (MS) is more important as it could affect the entire multicast group. During a handover procedure, the MS cannot send traffic when switching links from one IP network to another. For an ongoing multicast session, this could result in long multicast latency to the entire multicast group causing serious problems especially to real-time applications. The problems of mobile multicast sources are very serious particularly in SSM, where a receiver subscribes to a multicast channel (S, G) i.e., to receive traffic from a specified source identified by its IP address S. The mobile multicast sources problems in terrestrial networks are similar to the ones for satellite

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networks described in Section 1.4. Due to these problems, the multicast traffic from the MS might not reach the group members.

## 3.2 Current solutions to IP mobile multicast problems

Many IP mobile multicast support schemes have been proposed to solve the problems of mobile multicast receivers/sources in terrestrial networks. In [25], a brief description of most of the proposed IP mobile multicast support techniques for terrestrial networks available today in open literature has been given. The IP mobile multicast support schemes proposed so far can be classified into four main categories; Home subscription (HS)-based approach, Remote subscription (RS)-based approach, Hybrid-based approach and Unicast/ Explicit (Xcast)-based approach [25].

In this section, the IP mobile multicast support schemes in each category will be compared to see which ones could be suitable for adaptation in supporting mobile multicast receivers/sources within a multi-beam satellite network. For any of these terrestrial schemes to be adapted for a satellite environment, they need to at least possess the following characteristics: short multicast disruption time; less overall signalling traffic and less signalling traffic over the wireless domain during handover; simple with explicit procedures/steps for supporting mobility (i.e., less complexity and no ambiguity); clear indication of how the newly defined multicast protocols (architectural entities) interoperate with the existing multicast protocols; etc. The following parameters in any given IP mobile multicast support scheme can give an indication of some of these characteristics:

- Number of mobility entities: The number of network entities required to support multicast communications during handover from one IP network to

another can give an indication of the amount of signalling traffic, handover latency (disruption time) and level of complexity that could be encountered during a handover process. A higher number of mobility entities would suggest a larger amount of signalling traffic and a longer handover latency compared to one with a small number of mobility entities as these entities will have to communicate with each other during a handover process. Also, a mobile multicast support scheme with a higher number of mobility entities would suggest a more complex system compared to one with a small number of mobility entities. Coordination and integration of a larger number of mobility entities into a satellite system to support IP multicast mobility during handover will present a more challenging task compared to dealing with a mobility scheme with fewer number of mobility entities. So, it is imperative that the number of mobility entities involved in any handover process should be as few as possible in any scheme for it to be considered a good candidate for adaptation in a satellite environment.

- Level of involvement of the MN in the handover process. If the mobile receiver has to make several contacts (too involved) with mobility entities during a handover process, this may suggest that the amount of signalling traffic over wireless domain at handover is high. Fewer contacts will therefore mean low amount of signalling traffic over wireless domain at handover. In a satellite network, a lot of signalling messages is not good as they consume scarce and expensive satellite bandwidth resources. This implies that any terrestrial scheme with high level of signalling messages in the wireless domain will not be suitable for the satellite environment as these signalling message plus the standard handover/control messages in satellite

networks could consume significant amount of the satellite bandwidth resources.

- Level of complexities: Some of the proposed schemes have a lot of complexities and ambiguities like no clear mechanisms used by MNs in discovering newly introduced multicast mobility entities, how the new membership control messages interoperate with the existing multicast membership protocols, introduction of new complex addressing systems and data structures, etc. The complexities and ambiguities in some of these proposed schemes make them extremely unsuitable for adaptation in a satellite environment which requires precision in signalling procedure.

- Level of suitability for satellite environment. This parameter takes into account how the basic concept of a scheme fits into a satellite network scenario, the amount of signalling messages generated during handover (especially those over the wireless domain) and the level of complexity in the scheme. Therefore, this parameter will give an indication of how suitable each of the current terrestrial IP mobile multicast techniques could be adapted during a GWH or SH for a satellite network. Here, if the level of suitability of any scheme is moderate/high then, that scheme is considered good candidate for adaptation in a satellite environment but if level of suitability is low or very/extremely low, that scheme is considered not good enough for satellite environment.

All these parameters amongst others, will be key in identifying which of the current proposed terrestrial multicast mobility support schemes could be adapted for the satellite environment.

## 3.2.1  Multicast receiver mobility support schemes
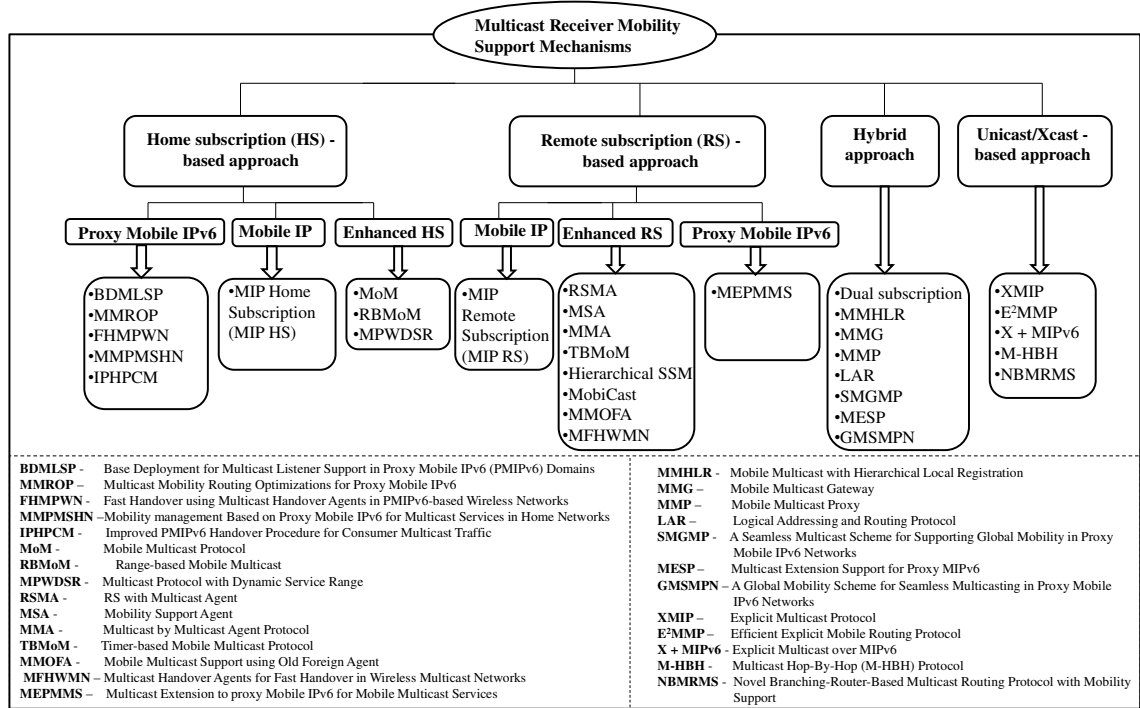


Figure 3.1 Multicast receiver mobility support schemes [20, 25, 26]

Figure 3.1 shows a catalogue of the current proposed terrestrial multicast receiver mobility support mechanisms. Details of each of these schemes can be found in [20, 25, 26].

### *3.2.1.1      HS-based approaches*

One common feature that all HS-based approaches have is that the mobile receiver while away from its home network still uses its home network infrastructures to receive multicast traffic and to join/leave a multicast group. This is made possible through either a MIP bi-directional tunnel [25] established between the mobile receiver in IPv6 networks  or Foreign Agent (FA) in IPv4 networks, serving the mobile receiver in a foreign network and the mobile receiver's HA at its home network or a PMIPv6 bi-directional tunnel between the mobile receiver's LMA and the MAG where the mobile receiver is currently attached.

Table 3.1  Comparison of the HS-based approaches

| | IP mobility | Join latency | Tunnel Convergence | Architectural Mobility entities | MN software change required | Number of Mobility entities | Level of Complexity | Level of involvement of the MN in handover process | Level of suitability for satellite environment |
|---|---|---|---|---|---|---|---|---|---|
| **MIP HS** | IPv4 and IPv6 | Long | One tunnel per MN | HA | Yes | 1 | Very Low | Low | High |
| **MoM** | IPv4 | Long | One tunnel for all MNs | HA, FA, DMSP | Yes | 3 | Low | High | Low |
| **RBoM** | IPv4 | Short | One tunnel for all MNs | HA, FA, MHA, DMSP | Yes | 4 | High | High | Extremely Low |
| **MPWDSR** | IPv6 | Short | One tunnel for all MNs | HA, MHA, BFA | Yes | 3 | Very High | High | Extremely Low |
| **BDMLSP** | IPv6 | Long | One tunnel per MN | LMA, MAG | No | 2 | Low | Low | Moderate |
| **MMROP** | IPv6 | Long | One tunnel for all MNs | MTMA, LMA, MAG | No | 3 | Low | Low | Moderate |
| **FHMPWN** | IPv6 | Short | One tunnel for all MNs | LMA, MAG MHA | No | 3 | High | Low | Low |
| **MMPMSHN** | IPv6 | Long | One tunnel for all MNs | LMA, MAG | No | 2 | Low | Low | Moderate |
| **IPHPCM** | IPv6 | Short | One tunnel per MN | LMA, MAG | No | 2 | Moderate | Low | Low |

**HA** – Home Agent; **FA** – Foreign Agent; **DMSP** – Designated Multicast Service Provider; **MHA** – Multicast Home Agent; **BFA** – Boundary Foreign Agent; **LMA** – Local Mobility Anchor; **MAG** – Mobility Access Gateway; **MTMA** – Multicast Tree Mobility Anchor.

From the descriptions of the HS-based approaches detailed in [20, 25-39] and the comparison in Table 3.1, MIP HS, BDMLSP, MMROP and MMPMSHN are good candidates in this category for IP multicast receiver mobility support adaptation in satellite networks. The MIP HS-based approach and the three PMIPv6-based approaches (BDMLSP, MMROP and MMPMSHN) will now be described in details.

### 3.2.1.1.1 MIP HS-based approach

MIP HS-based approach is based on MIP protocol.  A MIP bi-directional tunnel established between the MN's home network and the foreign network where the MN is currently located is the basic functional unit upon which all other HS-based approaches which rely on MIP for mobility support are built.  When the MN moves away from its home network to a foreign network (FN1) as illustrated in Figure 3.2, it first acquires a Care-of-address (CoA) from this foreign network. Through the process called binding update, the MN registers this CoA with its HA in its home network. After receiving the CoA, the HA creates a binding cache entry that maps the permanent IP address, the multicast group address

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and the CoA of the MN and then sends a binding acknowledge to indicate that the forwarding to the MN is set. Once the binding process is completed, a unicast bi-directional tunnel [27] is established between the MN (or FA) and its HA.
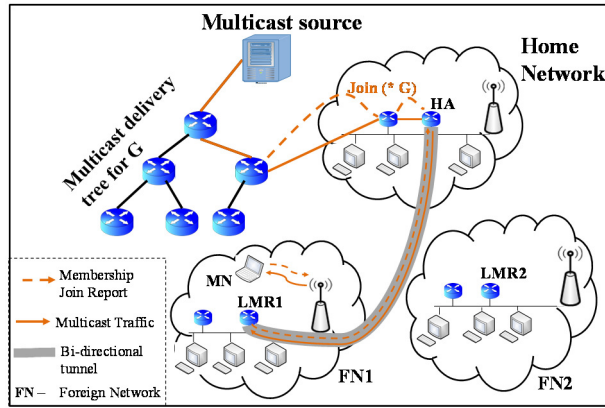


Figure 3.2 MN joins group G via its HA in foreign network (FN1) – HS

To join a multicast group G say, the MN through the established bi-directional tunnel sends an IGMP/MLD report message to its HA as a request to join the particular multicast group. When the IGMP/MLD report message from the MN is received by the HA, on behalf of the MN it then joins the multicast group. This results in the creation of a new branch of the multicast tree through the home network as shown in Figure 3.2. If a member of this group was already existing in the MN's home network, there will be no need for the HA to explicitly join the group.
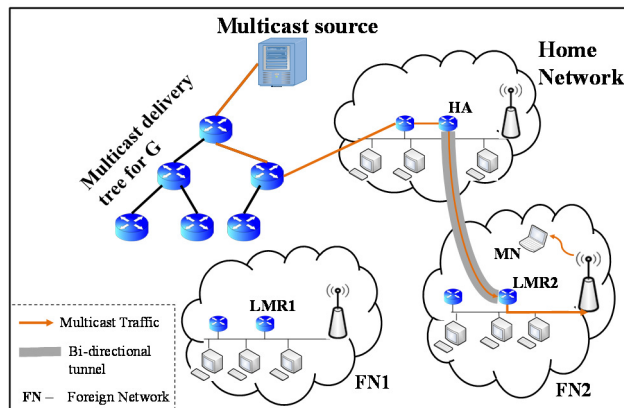


Figure 3.3 MN in FN2 continues to receive multicast traffic via HA – HS

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When the MN moves into another foreign network say foreign network 2 (FN2) as shown in Figure 3.3, it acquires a new CoA and through binding update, it registers this new CoA with its HA. This results in a MIP bi-directional tunnel being created to the MN in its new location and the old tunnel is torn down. The MN in this way always remains connected and will therefore continue to receive multicast data.

The HA here is assumed to be a multicast router, but in situations where it is not, the so-called proxy MLD functionality must be implemented as follows:

- A multicast subscription table must be kept by the HA for each MIP tunnel it handles (i.e., for each MN)

- A global synthesis of the multicast subscriptions of all the multicast groups that the attached MNs want to join must be kept by the HA to make it possible for the MN to join them [28].

*Advantages of this method are:*

- MN does not need to re-join the multicast group when it moves from one foreign network to another

- No reconstruction of the distribution tree is required whenever the MN (receiver or source) changes its location.

- MIP HS-based approach natively benefits from MIPv6 extensions for advanced support such as fast handover with Fast MIPv6 or per-flow handover to tackle handover delay problems [28].

- MIP HS-based approach supports source mobility.

*Disadvantages of this method are:*

- Suffers from Triangular routing problems across the home network which may end up increasing the join latency. Triangular routing problem in mobile IP refers to an un-optimised method of routing packets between the MN and the correspondent node (CN). Here, packets are first routed to the MN's HA (at home network) which then forwards the packets to the MN at its current location. Packets from the MN away from its home network are however, sent straight to their destinations without necessarily passing through the MN's home network (or HA) [40].

- All the traffic passes through the HA which then represents a single point failure.

- Suffers from multicast tunnel convergence problem. Multicast tunnel convergence problem is a scenario where multiple IP tunnels from different HA all carrying identical multicast packets terminate at a particular foreign network [30]. This occurs when MNs from different networks belonging to the same multicast group happens to be located at same foreign network. Due to the fact that the FA (in foreign network) delivers every multicast packet received natively to the interested mobile hosts, the problem of duplicate multicast packets to the MNs is created. Multiple tunnels carrying identical packets and the delivery of duplicate packets waste network resources.

- MIP HS-based approach cannot handle per flow handover of multicast sessions. This because the equipping of a MN with many active network interfaces is not supported by MIPv6 and also the fact that only one primary CoA can be registered by a MN to its HA. The handling of many multicast

sessions simultaneously therefore is extremely difficult to achieve in MIP HS-based approach [28].

*3.2.1.1.2 Base deployment for multicast listener support in PMIPv6 domains (BDMLSP)*

The fundamental idea of PMIPv6 protocol is that during handover of the MN from one point of attachment to another in an IP network, the MN is not involved in any network layer mobility related signalling. PMIPv6 protocol was conceptually designed for unicast communication. However, in [39] the authors have given options for deploying multicast listener functions in PMIPv6 domains without modifying mobility and multicast protocol standards.
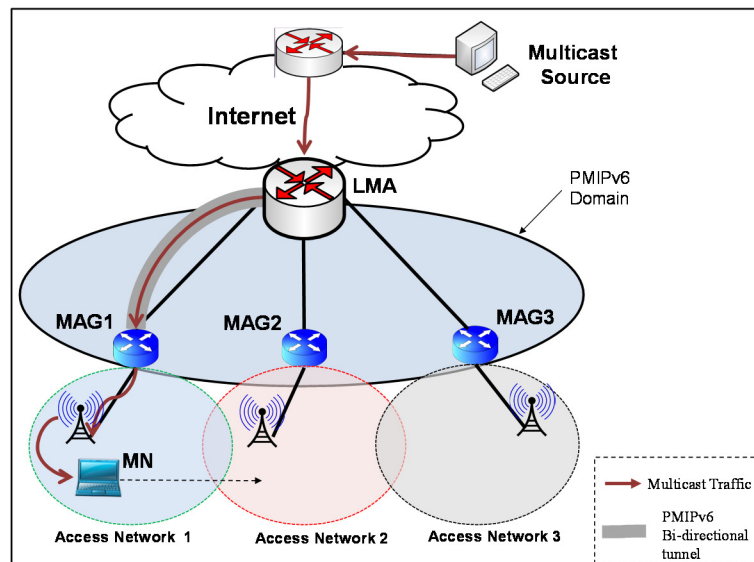


Figure 3.4 IP multicast deployment in PMIPv6

In the BDMLSP, the LMA serves as a designated multicast router and also acts as an MLD querier within the PMIPv6 domain [39]. An MLD proxy is configured on each MAG [39]. According to the provisions of the PMIPv6 protocol, when a visiting MN enters a PMIPv6 domain it attaches itself to an access network through the link provided by the MAG as shown in Figure 3.4. After signalling between the MN, MAG and the MN'S LMA, a PMIPv6 bi-directional is

established between the MAG on which the MN is attached and the MN's LMA [20]. Through this tunnel, the MN can receive multicast traffic, join or leave a multicast group.

The following steps are executed during handover to support IP multicast communication in an IP mobility unaware MN as it moves from access network 1 to 2 as illustrated in Figure 3.4 [39]:

- MAG 2 discovers the new MN in its access network as the MN attaches itself to the link (MAG2-MN) provided by MAG2.

- MAG2 determines the MN's LMA and then performs the unicast configuration and PMIPv6 binding which eventually results in the establishment of a bi-directional tunnel between MAG2 and LMA (MN's LMA).

- Acting as the MLD proxy, MAG2 following the IPv6 address configuration, issues an early MLD General Query to the newly established downstream link (MAG2-MN) to learn of the multicast membership status of the MN.

- MAG2 then adds the new downstream link (MAG-MN) to the MLD proxy instance with the uplink to the MN's LMA. The corresponding proxy instance triggers an MLD General Query on the new downstream link.

- Membership Reports from the MN arrive at MAG2 in response to the either an earlier query or the query sent by the proxy instant.

- MAG2 processes the MLD Report received from MN, update its downstream forwarding states and reports upstream if necessary.

These steps are performed each time a MN moves from one access network to another and ensure that the multicast traffic from source reaches the MN no matter the IP network it is currently located within the PMIPv6 domain.

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*Advantages of this method are:*

- No additional software modifications or complex security configurations are required in the MNs i.e. MNs remain IP mobility unaware nodes just like the fixed standard IP nodes.

- Reduced cost in mobile subscriber equipment and mobile network management.

- Efficient utilization of the wireless network resources since the MN not does not participate in layer 3 signalling during handover.

- Easier extension of mobility support to other technologies. Since IP mobility support is implemented only at the wired portion of the network, it is easier to extend this support to any type of wireless link technology.

- Security enhancement. Security threats such as identity theft faced by other schemes where the MN is required to register its CoA with its home network is completely eliminated in PMIPv6 schemes.

- Handover performance improvement (signalling is between fixed network entities).

These advantages are not only limited to the BDMLSP but apply to all PMIPv6-based approaches.

*Disadvantages of this method are:*

- Suffers from multicast tunnel convergence problem.

- Triangular routing problem. This occurs when a mobile multicast receiver and source, all having different LMAs are attached to the same MAG. Instead of the mobile receiver receiving multicast traffic on a shortest path, multicast streams from the source flow up to the LMA of the mobile source, then are transmitted to the LMA of the mobile listener and tunnelled

downwards to the same MAG hosting the mobile source and receiver for delivery.

### 3.2.1.1.3 Multicast mobility routing optimizations for Proxy Mobile IPv6 (MMROP)

MMROP was proposed to solve the tunnel convergence problem between the LMA and MAGs that exist in BDMLSP [39]. The authors in [26] proposed two operational modes; Multicast Tree Mobility Anchor (MTMA) and Direct Routing (DR) for IP multicast provision within the PMIPv6 domain. In this proposal, the IP multicast traffic to or from the domain is separated from the unicast traffic. The unicast traffic passes through the LMA as defined in [20] and multicast traffic through the MTMA in the MTMA mode or the Multicast Router (MR) in the DR mode. The difference between the two operational modes is that in the MTMA, a bi-directional tunnel is established between the MTMA and the MAGs which have MNs with multicast group membership, while in the DR mode, native multicast routing takes place between the MR and MAGs. In both the modes, the MAGs support MLD proxy function where the MNs are connected to the downstream interface and the upstream interface of the MLD proxy configured to point towards the internal interface of the MTMA or MR.

Figures 3.5 and 3.6 show the MTMA and DR operational modes respectively in PMIPv6 domain. The MN in Access Network 1 (AN1) is engaged in both unicast and multicast communication.

**MTMA mode:** When the MN moves from AN1 to AN2, it attaches to the new MAG (MAG2) and a PMIPv6 tunnel for unicast traffic is first established between the MAG2 and the MN's LMA following the procedures described in

[26]. In a similar way to the unicast tunnel establishment, a multicast tunnel is established between the MAG2 and MTMA.
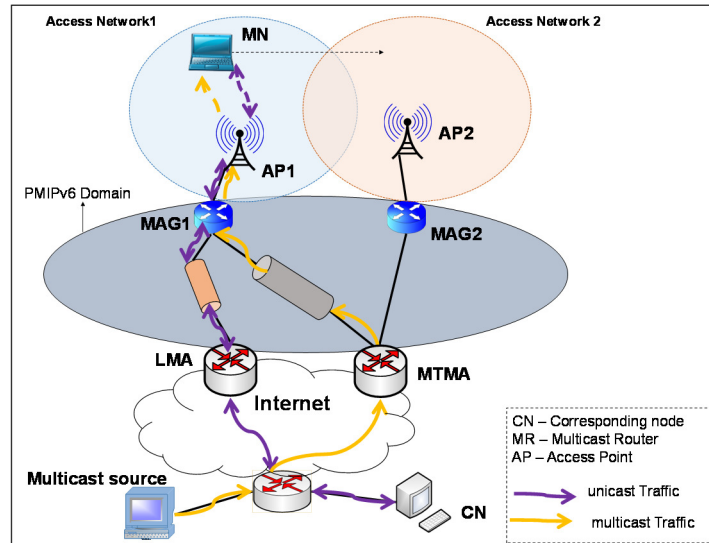


Figure 3.5 MTMA mode architecture for IP multicast receiver mobility support

MAG2 then issues an MLD Query to the MN. When MAG2 receives the MLD Report from the MN which contains the multicast group information, an aggregate MLD Report is issued to the MTMA, if a new multicast group which MAG2 is not already a member of is requested by the MN. A branch of the delivery tree for the new group leading to MAG2 is created by the MTMA. When MTMA receives multicast traffic from the source, it encapsulates and tunnels it to all MAGs that are members of the multicast group in question. The MN will then subsequently receive multicast traffic through MAG2. The MTMA and the MAGs acting as the MLD querier and MLD proxy querier respectively, periodically sends general and group specific queries to all MAGs and MNs respectively to find out their multicast subscription status.

**Direct Routing (DR) mode:** Here, there is direct connectivity between MAGs and the local MR. Once the MAG2 in Figure 3.6 detects the attachment of the MN, it will send a MLD query towards the MN. Upon reception of the MLD Report from the MN by MAG2, MAG2 checks its MLD proxy instance

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associated with the downstream interface to see if the requested multicast group already exists.
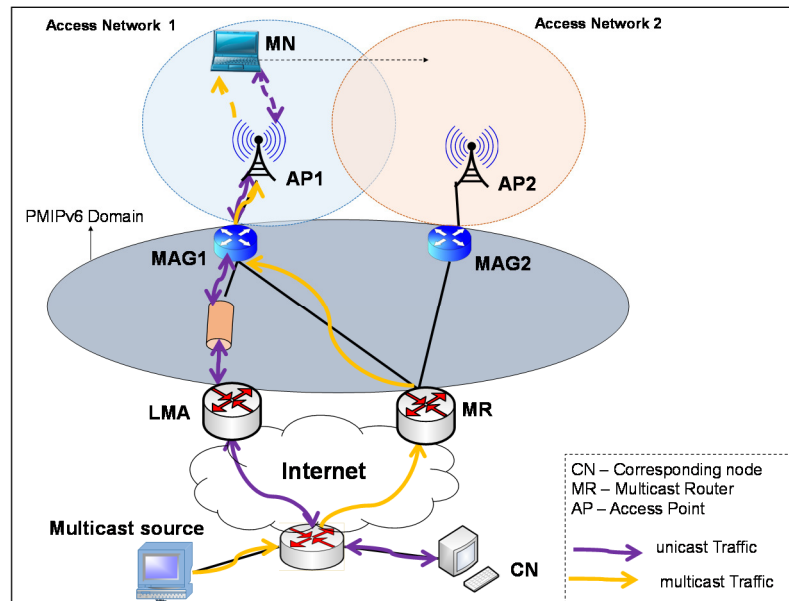


Figure 3.6 DR mode architecture for IP multicast receiver mobility support

If not, an aggregate MLD report will be sent to the local MR. Multicast data received by the local MR for the request group is then natively routed down to MAG2 which finally delivers it to the MN.

*Advantages of this method are:*

- Eliminates the multicast tunnel convergence problem suffered by BDMLSP

- DR provides optimised multicast routing and does not use IP tunnels.

*Disadvantages of this method are:*

- DR mode may suffer from multicast delivery tree reconstruction if some multicast groups contained in the MN's MLD report are new to the new MAG.

- MTMA mode still uses IP tunnels to serve MNs away from home network.

### 3.2.1.1.4 Mobility management based on Proxy Mobile IPv6 for multicast services in home networks (MMPMSHN)

This scheme, proposed in [37] is identical to the DR mode [26] of MMROP described above.

### 3.2.1.2    RS – based approaches

Table 3.2 Comparison of the RS-based approaches

| | IP mobility | Join latency | Tunnel Convergence | Architectural Mobility entities | MN software change required | Number of Mobility entities | Level of Complexity | Level of involvement of the MN in handover process | Level of suitability for satellite environment |
|---|---|---|---|---|---|---|---|---|---|
| **MIP RS** | IPv4 and IPv6 | Short | Does not use IP tunnel | FA, LMR | Yes | 1 | Very Low | Low | High |
| **RSMA** | IPv4 | Short | One tunnel between FA and MA | FA, MA | Yes | 2 | High | High | Low |
| **MSA** | IPv4 | Very Short since pre-registration is used | Does not use IP tunnel | MSA | Yes | 1 | Low | Low | High |
| **MMA** | IPv4 | Very short | One tunnel between MA and MF | MA, MF | Yes | 2 | High | High | Low |
| **TBMoM** | IPv4 | Short | Does not use IP tunnel | FA, FMA, DMSP | Yes | 3 | High | High | Low |
| **Hierarchical SSM** | IPv4 | Short | One tunnel between multicast source and BGR | FA, BGR | Yes | 2 | High | High | Low |
| **MoBiCast** | IPv4 | Very Short since buffering is used | Does not use IP tunnel | DFA | Yes | 1 | High | Low | Low |
| **MMOFA** | IPv4 | Short | Does not use IP tunnel | FA | Yes | 1 | Moderate | Low | Moderate |
| **MFHWMN** | IPv4 | Short | Does not use IP tunnel | MHA_old, MHA_new | Yes | 2 | High | Very Low | Low |
| **MEPMMS** | IPv6 | Short | Does not use IP tunnel | oMAG, nMAG | Yes | 2 | High | High | Low |

**FA** – Foreign Agent; **LMR** – Local Multicast Router; **MHA** – Multicast Handover Agent, **MSA** – Mobility Support Agent; **MF** – Multicast Forwarder; **FMA** - Foreign Multicast Agent; **DMSP** – Designated Multicast Service Provider; **DFA** – Domain Foreign Agent; o**MAG/nMAG** – Old/new Mobility Access Gateway

The common feature in the RS-based approaches is the fact that MNs in foreign networks join a multicast group and receive multicast traffic through a local entity in the foreign network just like any other fixed node in this foreign network will do.

From the different RS-based approaches described in [25, 26, 28, 41-49] and the comparison in Table 3.2, only the MIP RS, MSA and MMOFA approaches possess a good number of the characteristics required for the satellite environment and are therefore chosen for full description.

## 3.2.1.2.1 MIP-RS-based approach

The MN in a foreign network simply sends its report messages to the Local Multicast Router (LMR) and performs any multicast related tasks through the LMR similar to any fixed node in the visited network. Upon reception of the report messages, the LMR will join the multicast group requested by the MN. This will result in a new branch of the multicast tree being created [25, 28].
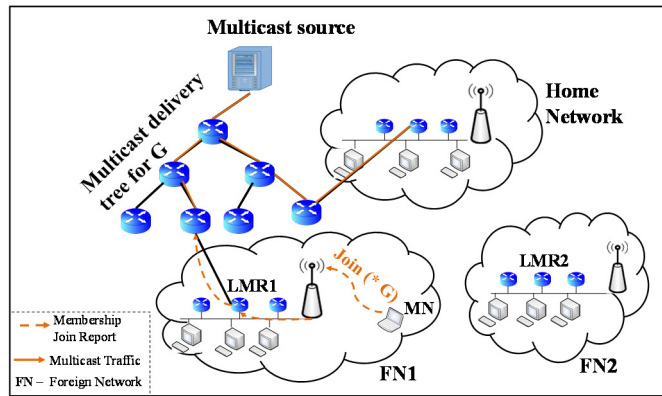


Figure 3.7 MN joins multicast group G via LMR1 in FN1 – RS
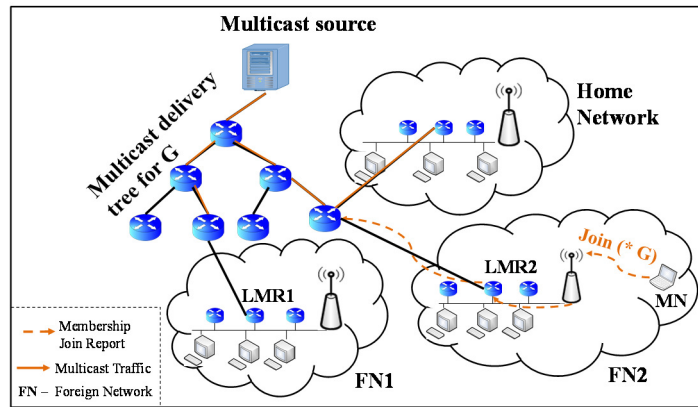


Figure 3.8 MN re-subscribes to multicast group G via LMR2 in FN2

Similarly, when the MN moves into FN2, it joins the multicast group G through the new local multicast router LMR2 similar to any fixed node in FN2. A new branch of multicast group G delivery tree is then created to the MN's new location as illustrated in Figure 3.8.

*Advantages of this method are:*

• Multicast avalanche (tunnel convergence) problem does not exist in MIP-RS

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- Multicast traffic is routed from source to various recipients through the shortest possible path, thus route is optimized

- MIPv6 or any unicast mobility protocol is not required to sustain active multicast communications when a MN is moving from one IPv6 subnet to another

  *Disadvantages of this method are:*

- MIP-RS introduces additional latency due to the multicast delivery tree reconstruction, re-subscription to the multicast group whenever a MN moves from one network to another.

*3.2.1.2.2 Mobility support agent (MSA)*

This approach is very similar to the MIP RS-based approach. The only difference between the two is that in MSA, pre-registration of multicast group before handover completion is supported while in MIP RS-based approach, there is no support for pre-registration. In MSA scheme, a new network entity called Mobility Support Agent (MSA) [41] is introduced. This MSA is a router located at foreign network and dedicated to multicast pre-registration procedure. During handover, MN triggers pre-registration procedure immediately by sending a membership report message to the MSA in the foreign network. Upon reception, the MSA send IGMP join message to local multicast router. This therefore ensures that the multicast packet delivery to MN starts immediately after handover is completed.

  *Advantages of this method are:*

- The use of pre-registration mechanism prior to handover reduces multicast packet loss and join latency

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- Pre-registration is simple and is built over UDP

- Could potentially benefit from seamless (fast Mobile IP)

  *Disadvantages of this method are:*

- Movement detection and prediction are two major concerns here

- MSAs of old and new networks need substantial co-ordination

*3.2.1.2.3 Mobile multicast support using old foreign agent (MMOFA)*

MMOFA [47] which makes use of the old foreign agent (oFA) to route by tunnelling, multicast packets destined for the MN during the handover period in a neighbouring network is derived from MIP-RS. When the MN moves into a foreign network, it registers with the new FA (nFA). The MN then sends its join messages to this nFA to join any multicast group the MN is interested in, on behalf of the MN. The MN is then added on the list of members for the group(s) in the nFA. If the MN is the first member of this group in this foreign network, then the nFA will send an IGMP-join message for the group to all neighbouring multicast routers. Due to join and graft latencies, the MN is most likely to lose some multicast data. To minimise any chances of losing multicast data, the MN's oFA is requested by means of a handover message from nFA to forward by tunnelling all the multicast traffic destined for the MN to the nFA. No delay is experienced by the MN in receiving multicast traffic through the nFA if at least a member of the group had already been in the nFA's network and in this situation, a leave message will then be sent to the MN's oFA by the nFA. The oFA removes the MN from its membership list once it receives the handover message from the nFA and add it to the tunnelling list in the entry of the group, thus a tunnel toward a nFA is created. Once the oFA receives multicast packets destined for the MN, it is tunnelled to the nFA which will then forward it to the

MN in its affiliated subnet. Once the MN's multicast tree-joining request is completed and it starts receiving traffic directly, the tunnel to the oFA will cease to exist [47].

*Advantages of this method are:*

- High routing efficiency

- Mobility agents (HA and FA) serve as a proxy of multicast services to MNs in addition to their mobility management responsibility.

*Disadvantages of this method are:*

- No additional drawbacks than those experienced in MIP-RS

### 3.2.2  Hybrid - based approaches

Table 3.3 Comparison of the hybrid-based approaches

| | IP mobility | Join latency | Tunnel Convergence | Architectural Mobility entities | MN software change Required | Number of Mobility entities | Level of Complexity | Level of involvement of the MN in handover process | Level of suitability for satellite environment |
|---|---|---|---|---|---|---|---|---|---|
| **Dual Subscription** | IPv6 | Short if RS is used | One tunnel between HA and MN | HA, LMR | Yes | 2 | High | Very High | Low |
| **MMHLR** | IPv4 | Very Short | Does not use IP tunnels | HA, FA, Root FA, HA_MSP | Yes | 4 | Very High | Extremely High | Low |
| **MMG** | IPv4 | Very short if MMG is already added to multicast tree | One tunnel between MMG and MN | HA, FA, MMG | Yes | 3 | Very High | High | Extremely Low |
| **MMP** | IPv4 and IPv6 | Short if RMP and FMP have already joined to multicast tree | One tunnel between a Multicast Proxy and MN | HMP, RMP, FMP | Yes | 3 | Very High | Very High | Extremely Low |
| **LAR** | IPv6 | Short | Does not use IP tunnels | LAR Router, LAR Manager, DNS Server | Yes | 3 | Extremely High | Very High | Extremely Low |
| **SMGMP** | IPv6 | Short | One tunnel for all MNs | LMA, MAG, RP, PS | Yes | 4 | Extremely High | Very High for global Mobility | Very Low |
| **MESP** | IPv6 | Long | One tunnel per MN in LMA_Based, One tunnel per PMIPv6 domain in inter-domain handover | LMA, MAG, HA | Yes | 3 | High | Very High for global Mobility | Very Low |
| **GMSMPN** | IPv6 | Long | One tunnel for all MNs | LMA, MAG, RP, PS | Yes | 4 | Extremely High | Very High | Very Low |

**HA** – Home Agent; **LMR** – Local Multicast Router; **FA** – Foreign Agent; **HA_MSP** – Home Agent Multicast Service Provider; **MMG** – Mobile Multicast Gateway; **HMP** – Home Multicast Proxy; **RMP** – Remote Multicast Proxy; **FMP** – Foreign Multicast Proxy; **LAR** – Local Addressing and Routing; **DNS** - Domain Name System, **LMA** – Local Mobility Anchor; **MAG** – Mobility Access Gateway, **RP** – Rendezvous Point, **PS** – Policy Server

Hybrid approaches combine different multicast approaches and architectural entities to benefit from their advantages, avoid packet loss during handover and

minimise join latency. Amongst the hybrid-based approaches described in [25, 50-54] and their comparison in Table 3.3, none of the approaches possesses the stated characteristics for a good candidate for adaptation in satellite networks. In each of the techniques in this category, the levels of complexity, involvement of the MN in handover process and difficulty in adaptation for satellite network as shown in Table 3.3 ranges from high to extremely high. These amongst others (Table 3.3) explain why no scheme from this category is deemed suitable for adaptation in a mobile satellite scenario.

### 3.2.3  Unicast /explicit multicast (Xcast)–based approaches

The general characteristics of the IP multicast receiver mobility support schemes under this category are that they employ [25, 55-58]:

- Techniques that do not use IP multicast protocols

- Explicit multicast (Xcast) and recursive unicast techniques

- New or modified membership protocols different from IGMP and MLD.

The five mobile multicast techniques described in [25, 55-58] all have different sets of weaknesses. The general weakness within this category is the scalability issue since the multicast source or intermediate router needs to keep record of all the receivers or their HAs. The general scalability issue in this category implies that these schemes might not be suitable for a satellite network which could have thousands of potential IP mobile multicast receivers within a gateway or regional beam.  This coupled with the fact that all the schemes under this category do not use the standard IP multicast protocols, make the Unicast /Explicit Multicast (Xcast)–Based Approaches very unattractive for consideration in the satellite environment.

### 3.2.4 Multicast source mobility support schemes
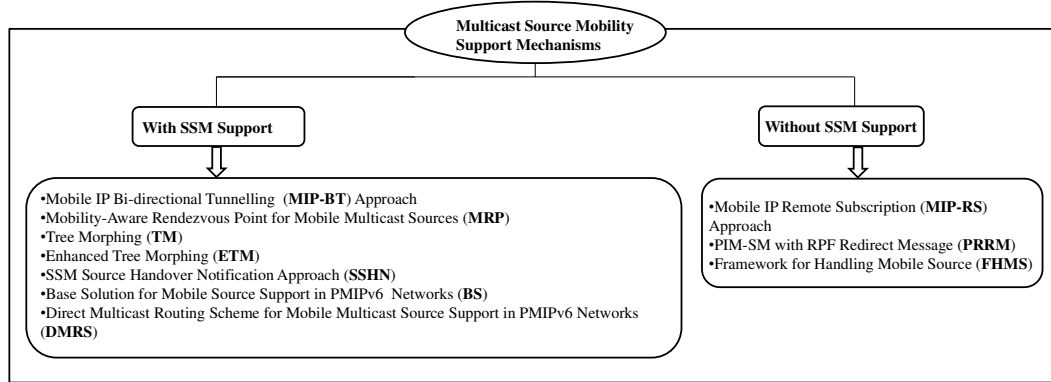


Figure 3.9 Current multicast source mobility support schemes

Figure 3.9 shows the multicast source mobility support techniques in terrestrial networks available today in open literature. From the details of these schemes contained in [25, 59-65], they can be classified into two main categories as shown in Figure 3.9, i.e., those that support SSM and those that do not.

Table 3.4 Comparison of IP multicast source mobility support schemes

|  | IP mobility | Tunnel Convergence | Architectural Mobility entities | MS software change required | Number of Mobility entities | Level of Complexity | Level of involvement of the MS in handover process | Level of suitability for satellite environment |
|---|---|---|---|---|---|---|---|---|
| **MIP-BT** | IPv4 and IPv6 | One tunnel per MS | HA (and FA in IPv4) | Yes | 1 | Very Low | High | High |
| **MRP** | IPv6 | One tunnel per MS | MRP | Yes | 1 | High | High | Very Low |
| **TM** | IPv6 | Does not use IP tunnels | MS, HA, nDR, pDR | Yes | 4 | Very High | Extremely High | Extremely Low |
| **SSHN** | IPv6 | Does not use IP tunnels | MS, Receivers, oAR | Yes | 3 | Very High | Extremely High | Low |
| **ETM** | IPv6 | Does not use IP tunnels | MS, HA, nDR, pDR | Yes | 4 | Very High | Extremely High | Extremely Low |
| **BS** | IPv6 | One tunnel per MS | LMA, MAG | No | 2 | High | Low | Moderate |
| **DMRS** | IPv6 | One tunnel per MS | LMA, MAG, RP | No | 3 | Very High | Low | Low |
| **MIP-RS** | IPv4 and IPv6 | Does not use IP tunnels | LMR | Yes | 1 | Very Low | High | High |
| **PRRM** | IPv4 and IPv6 | One tunnel per MS | RP, RPF Crossover Routers | Yes | 2 | Very High | High | Low |
| **FHMS** | IPv4 | One tunnel per MS | HA, FA | Yes | 2 | High | High | Low |

**MS** – Mobile Source; **HA** – Home Agent; **FA** – Foreign Agent; M**RP** – Mobility-Aware Rendezvous Point; **RP** - Rendezvous Point; **pDR/nDR** – previous/new Designated Router; **oAR –** old Access Router; **LMA** – Local Mobility Anchor; **MAG** – Mobility Access Gateway; **LMR** – Local Multicast Router; **RPF** – Reverse Path Forwarding

From the comparison of the IP multicast source mobility support schemes in Table 3.4 and their detailed description in [25, 59-65], it can be seen that the

MIP HS, BS and MIP-RS are the only approaches that meet most of the criteria set for terrestrial schemes to be adapted for satellite environment.

### 3.2.4.1    MIP HS-based approach

A MS away from home network uses its CoA to tunnel multicast packets to its HA at home network. The enclosed data contains the MS home address as the source address and the multicast group address as the destination address. Upon reception, the HA decapsulates the tunnelled packets and forwards them to multicast delivery tree. To send packets to a given multicast group, the MS does not need to join that multicast group. MIP HS-based approach is applicable to both mobile IPv4 and IPv6 protocol. MIP HS-based approach supports both any source multicast and SSM.

*Advantages of this method are:*

- Preserves  the transparency of  the handover of the mobile sources

- The source-specific tree is always built with reference to the home address and not the CoA. This implies the entire multicast delivery tree will always be rooted in the source's home network and therefore there is no need for tree reconstruction whenever the handover of  the source occurs

*Disadvantages of this method are:*

- No optimal routing as it suffers from triangular routing across the home network

- Inefficient in multicast packet delivery and waste resources of the HA entity

- Suffers from long delays

- Single point of failure at HA, since all the multicast traffic from the MS away from home network has to be first tunnelled to the MN's HA.

### 3.2.4.2    Base solution for mobile source support in PMIPv6 networks (BS)
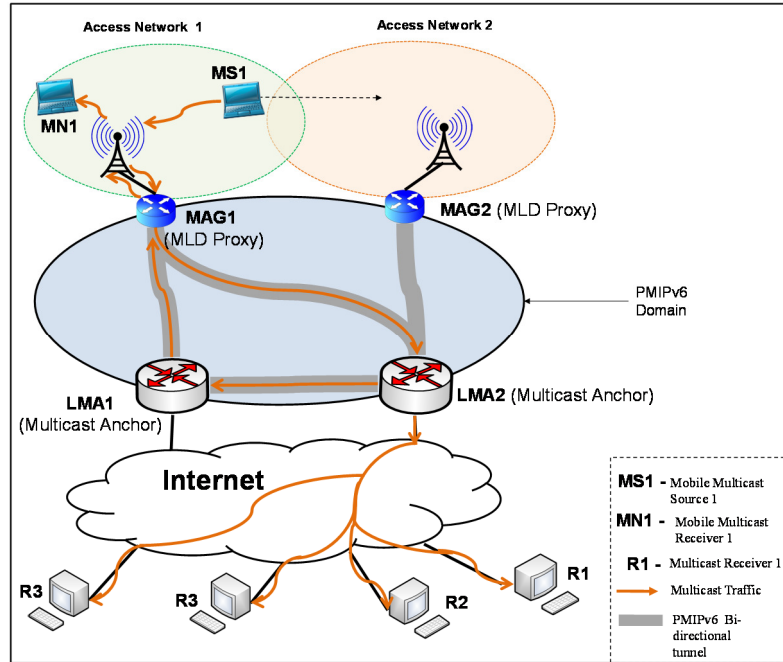


Figure 3.10 Base solution architecture for multicast source mobility support in PMIPv6 networks

The authors in [63, 64] proposed the BS which is based on the PMIPv6 protocol. Figure 3.10 shows the BS architecture for multicast source mobility support in PMIPv6 networks. MS1 is the mobile multicast source, MN1 is the mobile multicast receiver and the R1, R2, R3 and R4 are fixed multicast receivers in the Internet. MS1 and MN1 are authorised for the network-based mobility management services (including mobile multicast services) within the PMIPv6 domain. LMA1 is the corresponding LMA for MN1 while LMA2 is that for MS1. Here, the LMAs serve as multicast anchor points and the MAGs as MLD proxy with their interfaces to the LMA configured as the upstream interfaces and those to the MS1 and MN as downstream interfaces. As stated in [66], multicast traffic received at a downstream interface of an MLD proxy will be

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forwarded to the upstream interface and to all but the incoming downstream interfaces that have appropriate forwarding states for this group. This implies that when the multicast traffic originating from a MS is received by MAG1 which is currently serving MS1, it is forwarded through its upstream interface to LMA2 and through its downstream interfaces to all receivers with matching subscriptions. LMA2 functioning as the designated multicast router or an additional MLD proxy then forwards the traffic to the fixed Internet or to other LMA/MAG whenever forwarding states are maintained by multicast routing. In a situation where LMA2 is acting as another MLD proxy, the received multicast traffic is forwarded to its upstream interface and downstream interfaces with matching subscriptions.

As illustrated in Figure 3.10, it is important to note that MN1 that is attached to the same MAG1 as MS1 (mobile source), but has a different LMA cannot receive multicast traffic on a shortest path. In such a situation, MAG1 has to tunnel the multicast traffic upstream to LMA2 (corresponding LMA of MS1), which will forward the traffic to LMA1 (corresponding LMA of MN1) which then tunnels the traffic back to the same MAG1 for delivery to MN1, resulting in redundant flows in MAG1 and Access Network 1. This phenomenon is known as triangular routing problem.

During handover of the MS1 from MAG1 to MAG2, MAG2 has to identify MS1, determine the IPv6 unicast address configuration of MS1, MS1 corresponding LMA and if MS1 is authorised for the network-based mobility management services. As soon as all these processes are completed and the network connectivity is reconfigured, the MS1 (unaware of IP mobility) can continue to send multicast packets. The multicast traffic received at this stage by the MAG2

is either discarded or buffered until the MAG2 has completed the following steps [64]:

- MAG2 has determined that the MN is admissible to multicast services.

- MAG2 has added the new downstream link to the MLD proxy instance with up-link to the corresponding LMA2.
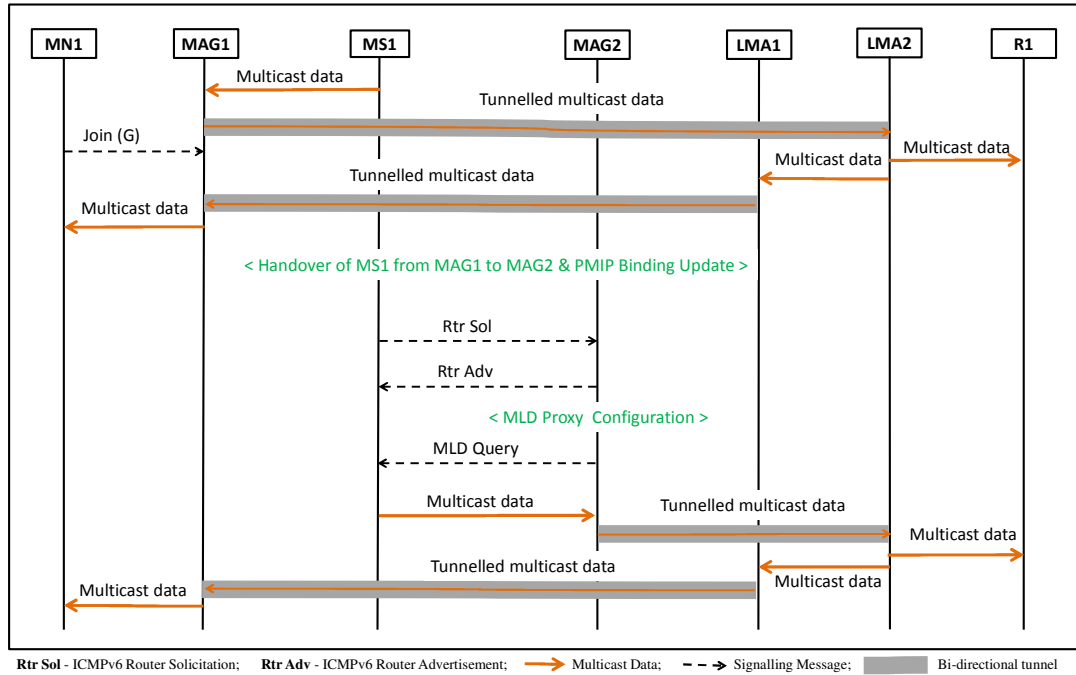


Figure 3.11 Base solution call flow for multicast communication during MS1 handover in PMIPv6 domain [64]

As shown in Figure 3.11, multicast packets originating from MS1 are forwarded to the LMA2 and eventually to all receivers as soon as the MS1's uplink is associated with the corresponding MLD proxy instance.

*Advantages of this method are:*

- No upgrade or change of the MS's software is required as the MS remains an IP mobility unaware node.

- Minimal signalling traffic within the wireless domain.

*Disadvantages of this method are:*

• Routing within the PMIPv6 domain can be inefficient due to the triangular routing problem.

### 3.2.4.3 MIP-RS-based approach

As shown in Figure 3.9, this approach was designed for ASM and consequently, does not offer source mobility support for SSM. The mobile source in the foreign network simply uses its CoA as the source address to send multicast packets to the local multicast router [25]. Since the receivers are subscribed to receive multicast traffic from the group without any particular attention to the source(s) sending the traffic, the mobile source changing its source address as it moves from one foreign network to another does not create any problems. The multicast delivery tree here is built with routing states that use the CoA and not the home address [25].

*Advantages of this method are:*

• Optimised routing. Multicast traffic is delivered through the shortest path possible i.e., no triangular routing across home network

*Disadvantages of this method are:*

• Difficulties for multicast routers and receivers to interpret multicast traffic coming from a new CoA as coming from the same multicast source.

• Suffers from multicast delivery tree reconstruction each time the source moves into a new foreign network

## 3.3 Summary

Chapter 3 highlights the problems of mobile multicast receivers and sources. From these problems, it can be deduced that the mobile receiver problems have a single impact on that particular receiver only. However, those of a mobile source may affect the entire multicast group, thereby making it a more critical issue. In this chapter, after some comparison of the current proposed solutions for mobile multicast receiver/source problems in terrestrial networks (Internet), some IP mobile multicast schemes have been identified as good candidate schemes for adaptation in a satellite environment. A more detailed account of each solution considered suitable for adaptation in a satellite network is given.

Although in this chapter some IP mobile multicast support schemes for terrestrial networks have been identified as good candidate schemes for adaptation in a satellite environment, no evaluation of them over a satellite network has been performed to test their suitability. In the next chapter, analytical mobility modelling for some of the IP mobile multicast support schemes for terrestrial networks identified as suitable for adaptation in a satellite environment are developed and performance evaluation carried out.

# 4 EVALUATION OF EXISTING IP MOBILE MULTICAST MECHANISMS OVER A MULTI-BEAM SATELLITE NETWORK

In Chapter 3, some IP mobile multicast schemes for terrestrial networks have been identified as good candidate schemes for adaptation in a satellite environment. Due to the long latency, the process of connection establishment and architectural nature of satellite networks, these terrestrial network schemes may not be directly applicable to a multi-beam satellite network with many GWs. To implement these schemes over a multi-beam satellite network, some modifications to their current form may be required. In this chapter, analytical mobility modelling for some of the IP mobile multicast schemes for terrestrial networks identified as good candidate schemes for adaptation in a satellite environment are developed and implemented on a reference satellite network architecture. Results obtained from the analytical mobility models developed here are used to assess the performance of these terrestrial network schemes over the reference satellite network architecture.

## 4.1 Good candidate schemes suitable for satellite environment

Although some of the IP multicast mobility support schemes for terrestrial networks have been identified as good candidate schemes for adaptation in a multi-beam satellite environment, significant modifications to their current form may be required for them to be applicable in a satellite network. For example, to adapt the PMIPv6-based approaches in a global multi-beam satellite network with many satellite GWs (which provide interconnections between satellite and terrestrial networks), it is not clear how the concept of the LMA being the topological anchor for all traffic to/from the PMIPv6 domain will fit in such a

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satellite network. Also, the questions of: what portion of the global multi-beam satellite network constitutes a PMIPv6 domain, where will the LMA and MAG be configured, etc., need to be answered taking cognisance of the nature of the global multi-beam satellite network architecture.

Amongst the IP multicast mobility support schemes for terrestrial networks considered as good candidate schemes for adaptation in a satellite environment, the MIP HS/RS-based approaches are the only schemes which could be implemented directly in such a satellite environment with very little modification. Consequently in this chapter, analytical mobility modelling for MIP HS/RS-based approaches defined for terrestrial networks are implemented on the reference satellite network architecture shown in Figure 4.1. Results obtained from the analytical mobility modelling in terms of: gateway handover (GWH) latency, satellite handover (SH) latency, signalling cost at GWH/SH, number of packets lost due to GWH/SH and packet delivery cost before and after GWH will be used to assess the performance of these terrestrial network schemes on a satellite environment.

## 4.2  The reference satellite network architecture

The following assumptions regarding the reference satellite network are made:

- All aircrafts, maritime vessels, etc., are each equipped with an mRCST, GPS (or Galileo) receiver and the global satellite network map. The GPS (or Galileo) receiver and the global satellite network map enable the aircrafts (or maritime vessels) to perform the analysis of their position information and then signal handover recommendation whenever necessary with a specified target beam to be used in the handover decision process by the NCC.

- A handover detection/recommendation technique adopted here is the position based distributed approach [17] which is the recommended approach in the DVB-RCS specification [17]. In this approach, the aircraft knows its location at any time and therefore the target GW whenever it enters the overlapping area of any two beams belonging to different GWs.

Since the satellite GWs, NCC and the NMC are all connected by terrestrial private networks and the global terrestrial Internet, communication between any of them is done through terrestrial networks. The satellite link (network) is only used for connection to a remote RCST or mRCST which of course has no access to terrestrial networks.
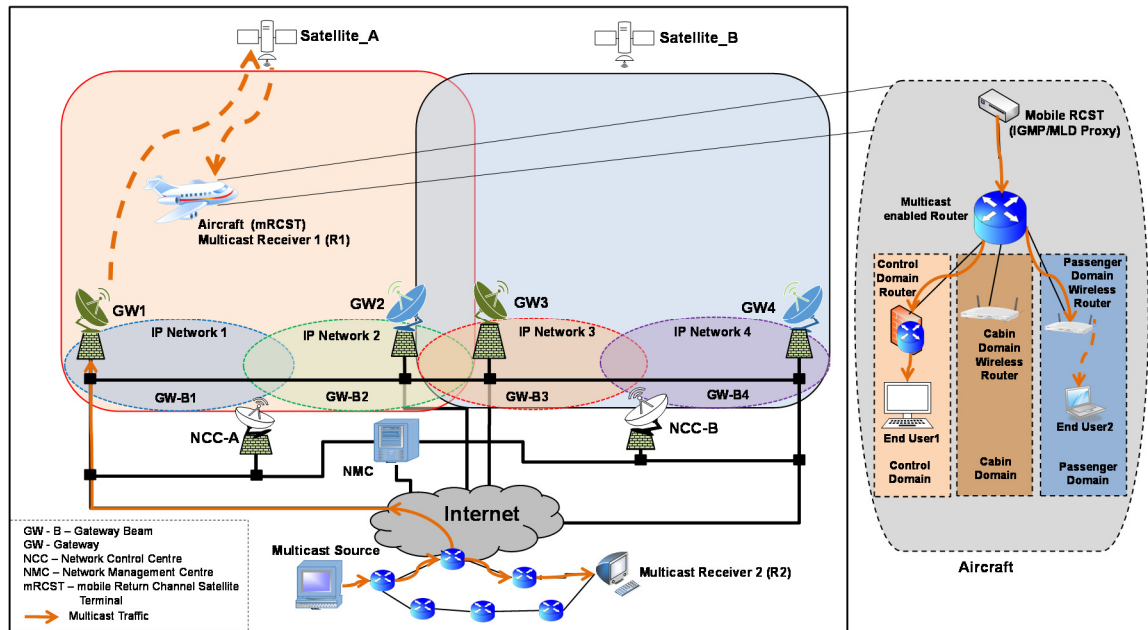


Figure 4.1 Reference network architecture for IP multicast mobility support over satellites

Figure 4.1 shows the reference satellite network architecture adopted for IP multicast mobility support. While a minimum of three GEO satellites are required to provide global coverage, for simplicity the reference network architecture only shows two satellites. In order to cover various possible

aspects of IP mobile multicast in a global GEO multi-beam satellite network, the reference network architecture is designed as follows:

- Considering the fact that the new generation of High-Throughput Satellites have capacities in excess of 100 Gbps per satellite [67], one GW per satellite footprint may not be able to efficiently handle the high density traffic. So, for maximum spectrum usage and high-throughput in the system, each of the GEO satellites in this network is designed to have two GW Beams, each representing a separate IP network. A GW Beam is a wide beam or regional beam which normally has a GW that interconnects the satellite network to terrestrial networks. Each GW Beam shown in Figure 4.1 is sub-divided into multiple spot beams in order to further enhance the overall satellite capacity and to support higher data rate as explained in Chapter 2.

- Satellites A and B are controlled by NCC-A and NCC-B respectively, providing real-time control and monitoring functions e.g., session control, connection control, terminal access control to satellite resources, routing, etc. The NMC is in charge of the whole global satellite network.

- The multicast source is located on the terrestrial network and the receivers are both on terrestrial network and satellite network (i.e. in the aircraft). The aircraft is currently located at GW-B1 (i.e. IP network 1) which is its home network.

- The mRCST on board the aircraft is configured to support IGMP/MLD proxy with the upstream interface towards the satellite and the downstream interface towards the aircraft. The actual multicast subscribers on board the aircraft are the user terminals (UT) located behind the mRCST as shown on Figure 4.1.

The MIP HS/RS-based approaches are each implemented during a handover when the aircraft in Figure 4.1 crosses the overlapping areas of:

- GW_B1 and GW_B2; GW_B3 and GW_B4 for GWH.

- GW_B2 and GW_B3 for SH.

Handover latency, signalling cost and the number of packets lost due the handover process are some of the most important factors in performance evaluation of any mobility protocol. Handover latency is defined here as the time period during a handover process where the mobile node (IP multicast receiver/source) cannot receive or send user traffic through its satellite interface due to the handover process from one point of attachment in a satellite network (i.e. GW) to another. The one way message transmission (end-to-end) delay, $D_m$ from a node on the ground segment to the remote satellite terminal (e.g., in the aircraft) via the satellite over wired and wireless (satellite) links is given by [38, 68, 69]:

$$D_m = \left( \frac{M_s\, h_{X-Y}}{d_{wd}} + L_{wd} \right) + \left( \frac{M_s\, h_{Y-Z}}{d_{sl}} + L_{sl} \right) \qquad (4.1)$$

Where $M_s$ = message size; $h_{X-Y}$ = number of hops between nodes X and Y in wired links; $h_{Y-Z}$ = number of hops between nodes Y and Z in satellite links; $L_{wd}/L_{sl}$ = Latency on wired and satellite links respectively; $d_{wd}/d_{sl}$ = data rate on the wired and satellite links respectively.

Handover signalling cost ($C_s$) is the signalling overhead incurred as a result of the handover process from one point of attachment in a satellite network (i.e. GW) to another. Here, the handover signalling cost is mainly the location update cost that a network suffers as consequence of supporting mobility. Handover signalling cost depends on the handover signalling messages and the distances

these messages have to travel in terms of number of hops. The signalling cost C is calculated as the product of the message size and the number of hops traversed by the message and has the units of bytes hops [38, 70],:

$$C = M_s h_{SD}$$ *(4.2)*

Where $M_s$ = message size in bytes and $h_{SD}$ = number of hops from source node to destination node.

To develop analytical mobility modelling for the MIP HS/RS-based approaches at GWH and SH, the standard GWH procedure in mobile satellite systems defined in the DVB-RCS specification in [17]  and the IP address acquisition process for DVB-RCS  in [17] are used. The MIP HS/RS-based approaches are each integrated into the standard DVB-RCS GWH handover signalling sequence given in [17].

## 4.3 Analytical mobility modelling for mobile IP multicast receivers

For GWH, two scenarios can be envisaged for the satellite network depending on the type of on-board satellite payload. For transparent (bent pipe) satellites, the HA of the aircraft (mRCST) or the rendezvous point (RP) for the multicast group will normally be located at the terrestrial network or ground segment of the satellite network (preferably at the mRCST's home GW). In satellite systems with layer 3 regenerative OBP, the HA or RP can be configured on-board the satellite as suggested in [71]. The location of the HA/RP on-board the satellite has the potential to reduce GWH latency and signalling cost since the CoA registration to the HA will take a shorter time and incurs a lower signalling cost. For SH, having the HA/RP on-board the satellite will not yield similar positive impact as in GWH except in satellite constellation with inter-satellite links. This

is due to the fact that for handover from one GEO satellite to another, a different GW must be used to forward multicast traffic to the aircraft after the SH. Therefore, this eliminates any gains in propagation latencies and signalling cost provided by the on-board multicast replication and routing/switching capabilities. It should be noted that a RP is required only in multicast shared trees where PIM-SM is used as the multicast routing protocol.

### 4.3.1 Using MIP HS-based approach

#### 4.3.1.1 Gateway handover (GWH) with HA at GWs

The content of Figure 4.2 is put together from the information gathered from [17, 18, 72, 73]
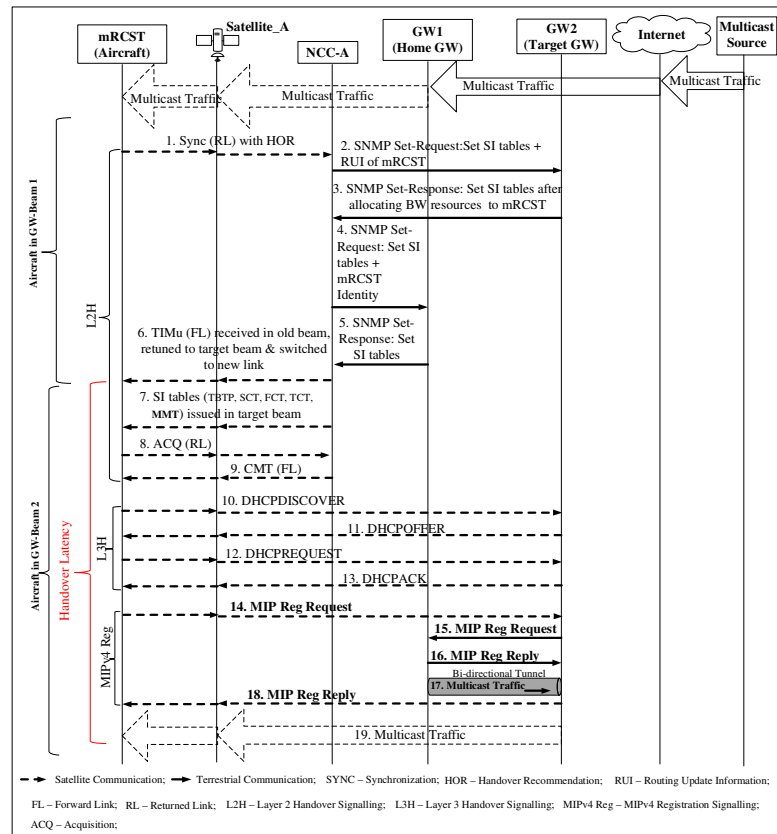


Figure 4.2 GWH signalling sequence for MIP HS-based approach – HA at GWs.

Let $h_i$ = number of hops for message $i$; $M_i$ = size of message $i$ and $D_i$ = end-to-end delay for message $i$ (equation 4.1); where $i$ = message number in Figure 4.2 indicating the specific message).

From Figure 4.2, the GWH latency for the HS-based approach with HA at GWs $L_{GWH}^{HS-HA\_GW}$ is given by:

$$L_{GWH}^{HS-HA\_GW} = T_{Tx/Rx} + \sum_{i=7}^{19} D_i \qquad (4.3)$$

Where $T_{TX/RX}$ = Aircraft's satellite Transmitter/Receiver retuning time.

Assuming that during the GWH process the source continues to transmit multicast packets and that there is no buffering of the transmitted packets. If the average multicast session arrival rate at the aircraft's satellite interface is $\lambda_s$ and the average multicast session length in packets is $E_s$, then the number of packets lost due to GWH latency, $\psi_{Lost}$ is given by [38]:

$$\psi_{Lost\_GWH}^{HS-HA\_GW} = \lambda_s E_s L_{GWH}^{HS-HA\_GW} \qquad (4.4)$$

Where $L_{GWH}^{HS-HA\_GW}$ = GWH latency calculated in Equation 4.3.

From Figure 4.2, the signalling cost per GWH for this scheme is given by:

$$C_{GWH}^{HS-HA\_GW} = C_{SYNC} + 4C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} + 4C_{DHCP} + 4C_{MIP} + 2C_T \qquad (4.5)$$

Where $C_T$ is the cost of tunnelling an IPv4 packet header and the rest of the terms in Equation 4.5 represent the cost of the signalling messages shown in Figure 4.2. Substituting the cost value (message size × hop distance) for each term in Equations 4.5 and re-arranging implies the cost is given by:

$$C_{GWH}^{HS-HA\_GW} = \alpha \sum_{i=1,6-14,18} h_i M_i + \beta \sum_{i=2-5,15-17} h_i M_i \qquad (4.6)$$

Where $\alpha$ and $\beta$ are weighting factors for wireless (satellite) and wired links, respectively. They are used to emphasize the link stability [38, 70]. It should be

noted here that the message size of each encapsulated (tunnelled) IP packet must include the size of an IP packet header in addition to its own message size. This concept is maintained throughout this work. Therefore in Equation 4.6, the $M_{14}$, $M_{15}$, $M_{16}$ and $M_{18}$ message sizes must each include the size of an IPv4 packet header.

### 4.3.1.2    Gateway handover (GWH) with HA at OBP
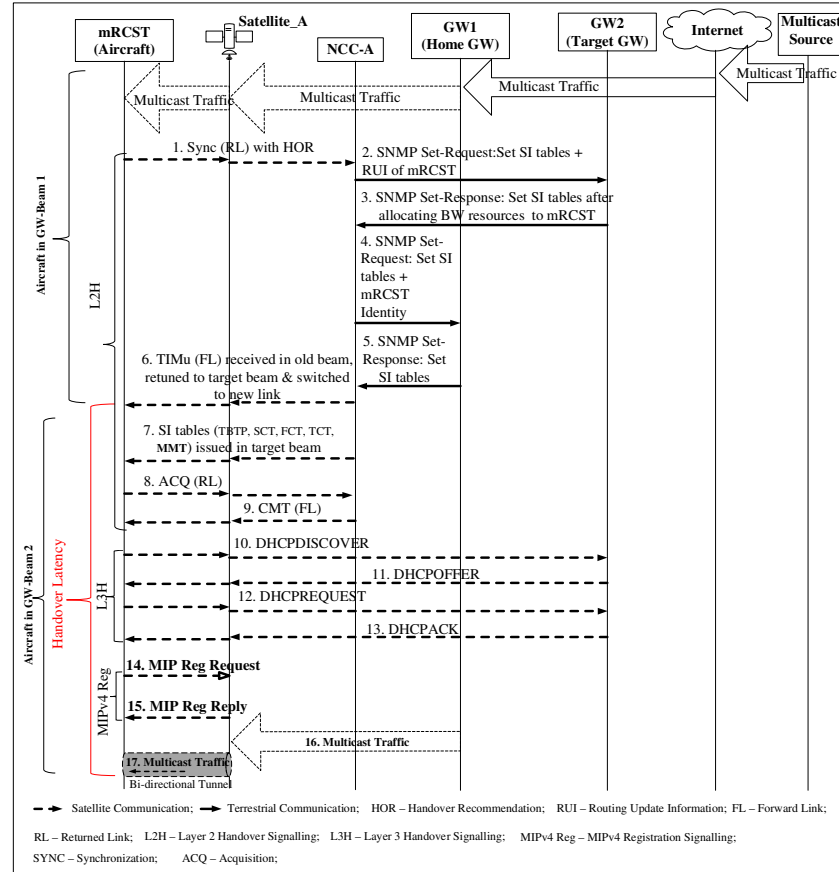


Figure 4.3 GWH signalling sequence for MIP HS-based approach – HA at OBP

Figure 4.3 shows the GWH signalling sequence for the MIPv6 HS-based approach with HA at OBP. From Figure 4.3, the GWH latency is given by:

$$L_{GWH}^{HS-HA\_OBP} = T_{Tx/Rx} + \sum_{i=7}^{17} D_i \qquad (4.7)$$

The number of packets lost due to GWH latency here is given Equation 4.4, where the GWH latency is that given by Equation 4.7.

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Using Figure 4.3, the signalling cost per GWH for the MIP HS-based scheme with HA at OBP is given by:

$$C_{GWH}^{HS-HA\_OBP} = \alpha \sum_{i=1,6-14,18} h_i M_i + \beta \sum_{i=2}^{5} h_i M_i \tag{4.8}$$

### 4.3.1.3 Satellite handover (SH) with HA at GWs
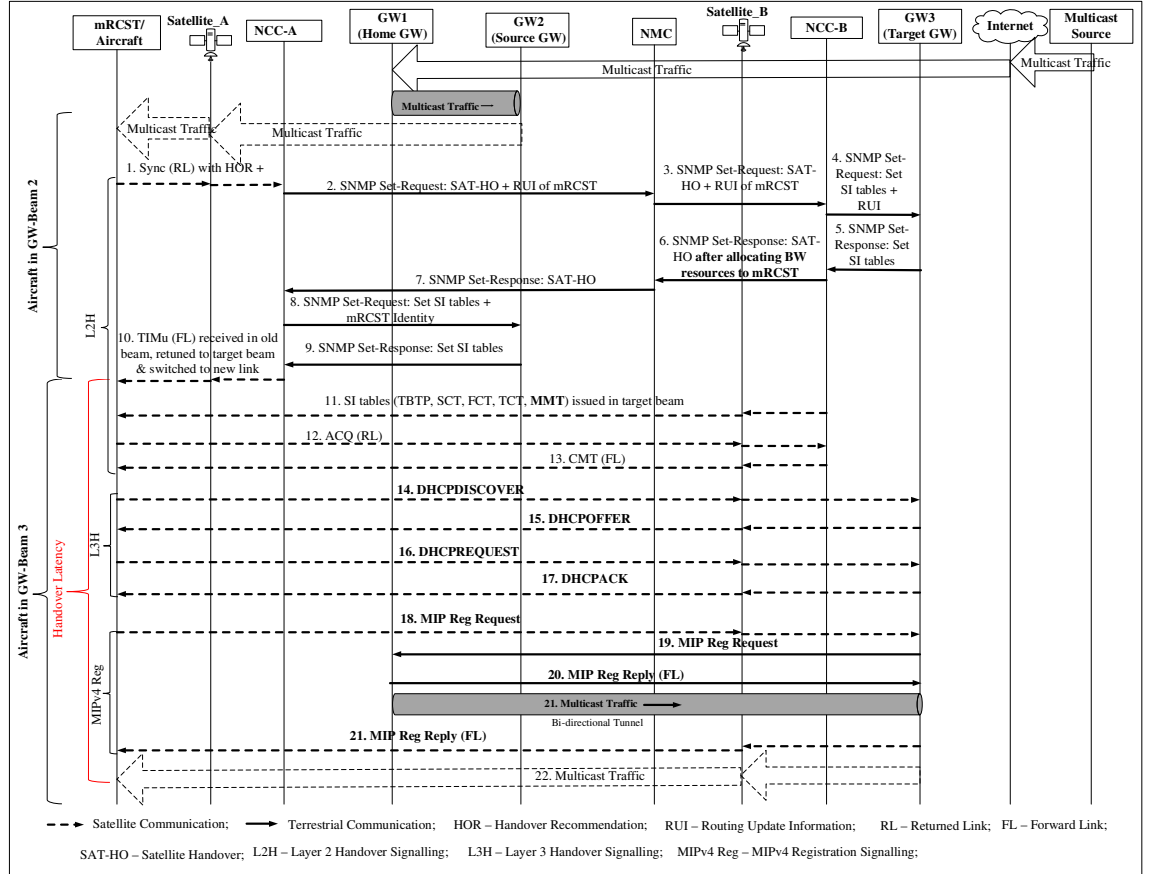


Figure 4.4 SH signalling sequence for MIP HS-based approach

Figure 4.4 shows the signaling sequence for the MIPv4 HS-based approach during satellite handover.

The SH latency $L_{SH}$ for the HS-based approach using Figure 4.4 is given by:

$$L_{SH}^{HS-HA\_GW} = T_{Tx/Rx} + \sum_{i=11}^{22} D_i \tag{4.9}$$

Similarly, the number of packets lost due to SH latency is given by Equation 4.4, where the handover latency here is the SH latency given by Equation 4.9.

From Figure 4.4, the signaling cost per SH for the MIPv4 HS-based scheme is given by:

$$C_{SH}^{HS-HA\_GW}=C_{SYNC}+8C_{SNMP}+C_{TIM}+C_{SI}+C_{ACQ}+C_{CMT}+4C_{DHCP}+4C_{MIP}+2C_{T} \qquad (4.10)$$

$$C_{SH}^{HS-HA\_GW}=\alpha\sum_{i=1,10-18,21}h_{i}M_{i}+\beta\sum_{i=2-9,19,20}h_{i}M_{i} \qquad (4.11)$$

### *4.3.1.4 Satellite handover (SH) with HA at OBP*

For satellite handover, having the HA on-board the satellite will only be advantageous if there are inter-satellite links between satellites. In the absence of inter-satellite links, a HA on-board the home satellite will have two major drawbacks in a satellite handover scenario:

• Multicast traffic from a source on the ground segment destined for the mobile receiver will have to undergo a double hop transmission over two different satellites to reach the mobile receiver after SH. This implies longer SH latency, more packet losses at SH and an inefficient use of satellite bandwidth resources.

• Packet end-to-end delay will be increased as traffic is routed/tunnelled through two different satellites to reach a mobile receiver in a foreign network.

For satellite operators that provide global coverage for mobile services like the aeronautical, maritime, etc. industries, it is not advisable to configure the HA on-board the satellite. For regional coverage where one GEO satellite is sufficient to provide the required coverage, having the HA on-board the satellite will have significant benefits as stipulated in [71].

### 4.3.2 Using MIP RS-based approach

Similar to MIP HS-based approach described above, in the MIP RS-based approach, the RP can also be configured at the OBP [71] in a regenerative satellite payload with layer 3 capabilities. The idea of RP is mostly applicable in ASM where the Core-Based Tree (CBT) is used. In such a scenario, multicast sources will unicast their traffic to the RP on-board the satellite which is now the root of the multicast delivery tree. From the point of view of the receivers, the RP is the source of the multicast traffic. The RP configured on the OBP will potentially reduce the GWH latency and signalling cost compared to a scenario where it is located on the ground segment of the satellite network. The presence of the RP on-board the GEO satellite has no impact on the SH as a different GW must be used to forward multicast traffic to the aircraft after the SH.

In SSM, the source-based tree (or the shortest path tree) where the multicast source is at the root of the distribution tree is used.

#### *4.3.2.1 Gateway handover (GWH) with RP at GWs*

From Figure 4.5, the GWH latency L$_{GWH}$ for the RS-based approach is given by:

$$L_{GWH}^{RS-RP\_GW} = T_{Tx/Rx} + \sum_{i=7}^{17} D_i \qquad (4.12)$$

The number of packets lost due to GWH latency is given Equation 4.4, except for the fact that the GWH latency here is that given by Equation 4.12.

Also from Figure 4.5, the signalling cost per GWH for this scheme is given by

$$C_{GWH}^{RS-RP\_GW} = C_{SYNC} + 4C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} + 4C_{DHCP} + C_{IGMP} + C_{PIM-SM} \qquad (4.13)$$

---

$$C_{GWH}^{RS-RP\_GW} = \alpha \sum_{i=1,6-14} h_i M_i + \beta \sum_{i=2-5,15} h_i M_i \qquad (4.14)$$
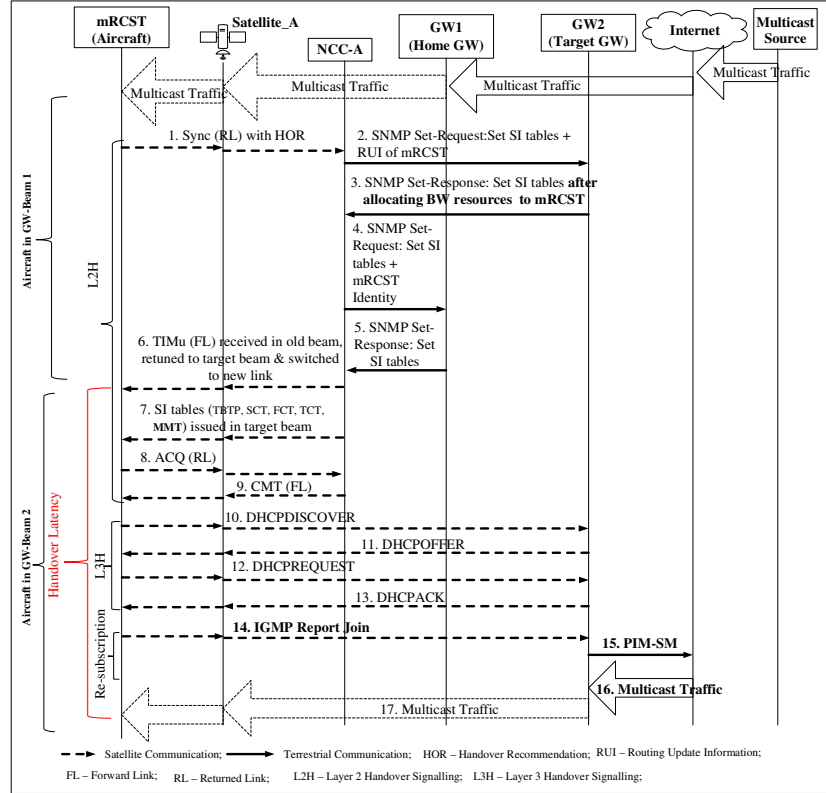


Figure 4.5 GWH signalling sequence for MIP RS-based approach

### 4.3.2.2 Gateway handover (GWH) with RP at OBP

The signalling sequence for the MIP RS-based with RP on board the aircraft is very similar to that in Figure 4.5. The only difference here is that the IGMP issued by the aircraft after GWH to re-subscribe to the multicast groups terminates on-board the satellite (OBP). Due to the fact that the data from the multicast groups requested by the aircraft after handover is already at the OBP, PIM-SM is not issued as was the case in Figure 4.5. Thus, having RP on-board the satellite will potentially reduce GWH latency and signalling cost. The GWH latency for MIP RS-based scheme with RP at OBP is given by:

$$L_{GWH}^{RS-RP\_OBP} = T_{Tx/Rx} + \sum_{i=7-14,17} D_i \qquad (4.15)$$

The number of packets lost in this scheme due to GWH latency is given by Equation 4.4 where the GWH latency here is that calculated in Equation 4.15.

The signalling cost per GWH for when the RP is configured on-board the satellite is given by:

$$C_{GWH}^{RS-RP\_OBP} = C_{SYNC} + 4C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} + 4C_{DHCP} + C_{IGMP} \qquad (4.16)$$

$$C_{GWH}^{RS-RP\_OBP} = \alpha \sum_{i=1,6-14} h_i M_i + \beta \sum_{i=2}^{5} h_i M_i \qquad (4.17)$$

### 4.3.2.3 Satellite handover (SH) with RP at GWs
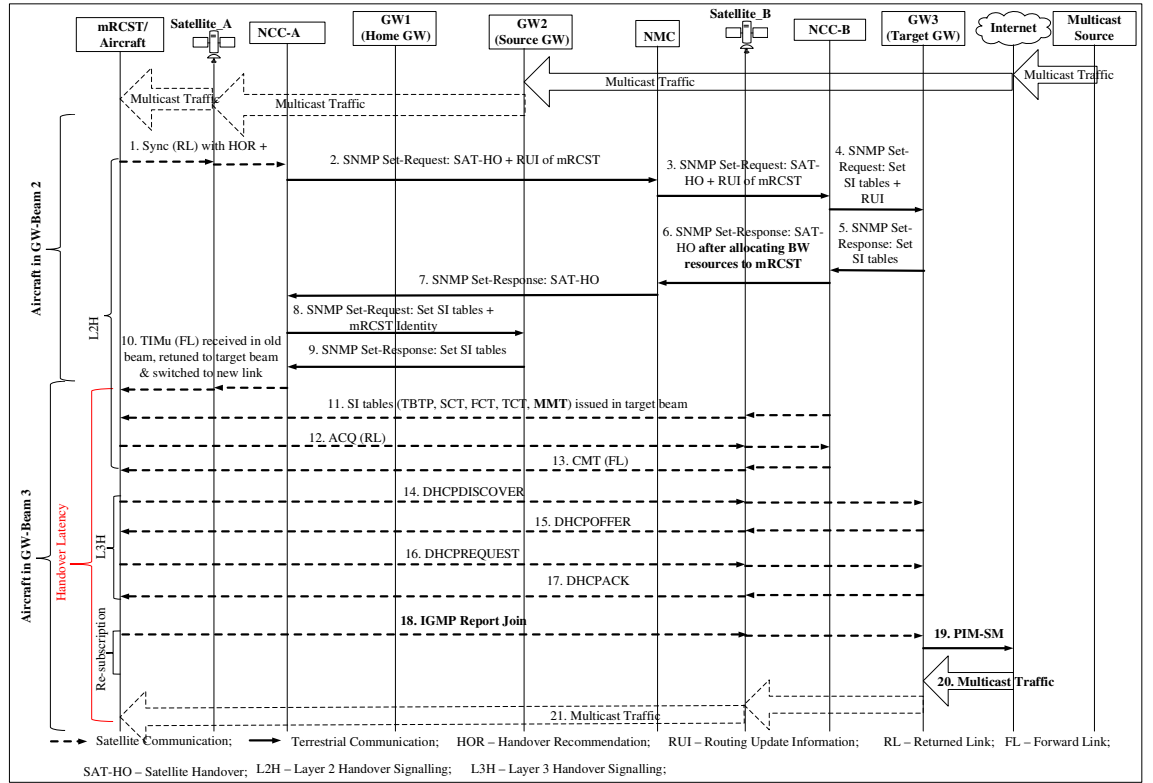


Figure 4.6 SH signalling sequence for MIP RS-based approach

From Figures 4.5 and 4.6, GWH latency, L$_{GWH}$ and SH latency, L$_{SH}$ for the MIPv4 RS-based approach are identical. This means that the number of multicast packets lost due to GWH latency are exactly equal to those lost due to SH latency.

Using Figure 4.6, the signalling cost per SH for the MIPv4 RS-based scheme is given by:

$$C_{SH}^{RS-RP\_GW}=C_{SYNC}+8C_{SNMP}+C_{TIM}+C_{SI}+C_{ACQ}+C_{CMT}+4C_{DHCP}+C_{IGMP}+C_{PIM-SM} \quad (4.18)$$

$$C_{SH}^{RS-RP\_GW}=\alpha \sum_{i=1,10-18}h_iM_i+\beta \sum_{i=2-9,19}h_iM_i \quad (4.19)$$

### *4.3.2.4    Satellite handover (SH) with RP at OBP*

Similar to the explanation in Section 4.3.1.4 above, configuring a RP at OBP will results in a negative impact on SH latency, number of packets loss, packet-end-to-end delay, etc., during a SH process. Although configuring a RP at OBP for a regional satellite network that requires just one satellite may have some advantages, for global satellite network providers for aeronautical, maritime, etc., industries, having a RP at OBP is not advisable/recommended.

## 4.4 Analytical mobility modelling for mobile IP multicast sources

Considering the cost of satellite bandwidth resources and scalability issues, SSM is the best form IP multicasting over satellite since the receiver can choose to subscribe to specific multicast source(s) it is interested in receiving multicast traffic from. So, SSM can reduce the amount of unwanted traffic within the satellite network compared to ASM.  This implies that the implementation of SSM in a satellite environment will save more satellite resources compared to ASM. Since MIP RS-based approach does not provide IP multicast source mobility support in SSM, the analytical mobility modelling here will be based on the MIP HS-based approach which provides source mobility support in both SSM and ASM.

### 4.4.1 Gateway handover (GWH) with HA at GWs
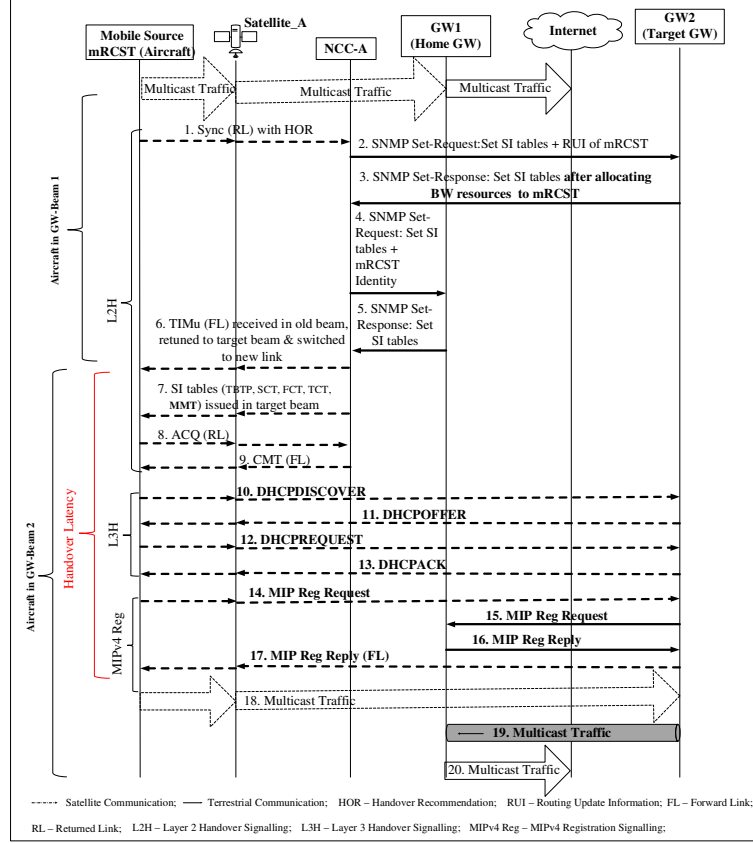


Figure 4.7 GWH signalling sequence for Source Mobility Support – MIP HS-based approach HA at GWs

Figure 4.7 shows, the GWH signalling sequence for the mobile multicast source when the MIP HS-based approach with HA at GWs is used to support source mobility.

From Figure 4.7, the mobile multicast source GWH latency $L_{s\_GWH}$ for the MIP HS-based approach is given by:

$$L_{S\_GWH}^{HS-HA\_GW} = T_{Tx/Rx} + \sum_{i=7}^{17} D_i \qquad (4.20)$$

Using Figure 4.7, the mobile source signalling cost per GWH for the MIP HS–based approach is given by:

$$C_{S\_GWH}^{HS-HA\_GW} = C_{SYNC} + 4C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} + 4C_{DHCP} + 4C_{MIP} + 2C_T \qquad (4.21)$$

$$C_{GWH}^{HS-HA\_GW} = \alpha \sum_{i=1,6-14,17} h_i M_i + \beta \sum_{i=2-5,15,16} h_i M_i \qquad (4.22)$$

The cost of delivering a packet to receivers within the satellite network (mesh communication) before GWH in MIP HS-based approach is given by:

$$C_{PD\_before}^{HS-HA\_GW} = \alpha h_{18} M_{18} \qquad (4.23)$$

After the GWH, the routing path of the packet changes as the mobile source now in a foreign network has to tunnel the multicast traffic through the foreign GW (GW2 in this case) to its home GW ( GW1) for delivery into the source-specific tree. This implies that the multicast data will undergo a double hop communication over the satellite from the mobile source to the listening RCSTs/RSGWs. Thus, the packet delivery cost after GWH is given by:

$$C_{PD-after}^{HS-HA\_GW} = \alpha h_{18}(2M_{18}) + \beta h_{19} M_{19} \qquad (4.24)$$

Where M19 is tunnelled traffic (size of IPv4 packet header included).

The packet delivery cost per multicast session before and after GWH can be determined using the average session transmission rate $\lambda_S$, from the mobile source and the average session length in packets $E_S$ [68, 70] . This is calculated as the product of $\lambda_S$, $E_S$ and $C_{PD}^{M\,3U}$ (where $C_{PD}^{M3U}$ is the packet delivery cost for one multicast packet). This implies packet delivery cost per multicast session is given by [68, 70]:

$$C_{PD\,/\,S\_before}^{HS-HA\_GW} = \lambda_S\, E_S\, C_{PD\_before}^{HS-HA\_GW} \qquad (4.25)$$

$$C_{PD\,/\,S\_after}^{HS-HA\_GW} = \lambda_S\, E_S\, C_{PD\_after}^{HS-HA\_GW} \qquad (4.26)$$

Where $C_{PD/S\_before}^{HS-HA\_GW}$ and $C_{PD/S\_after}^{HS-HA\_GW}$ are packet delivery cost per multicast session before and after GWH respectively.

## 4.4.2 Gateway handover (GWH) with HA at OBP
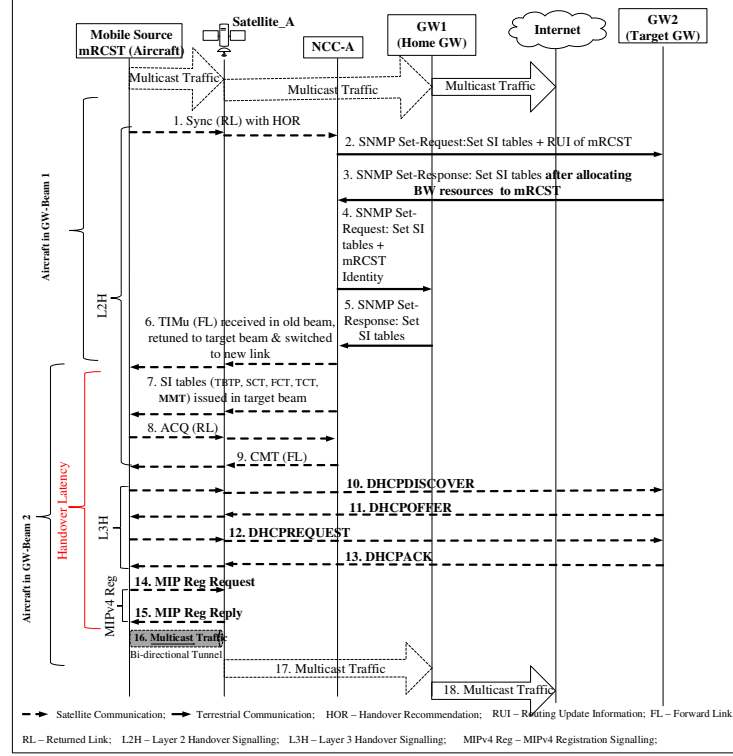


Figure 4.8 GWH signalling sequence for Source Mobility Support – MIP HS-based approach HA at OBP

For the MIP HS-based approach with HA at OBP, once the mobile source obtains a CoA in the target GW (GW2), it is registered to its HA at OBP. The mobile source then, tunnelled IP multicast packets from the visited satellite beam to its HA at OBP for onward delivery to the already established multicast tree. It should be noted that in this scenario, the mobile multicast source's HA is always at the root of the multicast delivery tree.

From Figure 4.8, the mobile multicast source GWH latency $L_{s\_GWH}$ for the MIP HS-based approach with HA at OBP is given by:

$$L_{S\_GWH}^{HS-HA\_OBP} = T_{Tx/Rx} + \sum_{i=7}^{15} D_i \qquad (4.27)$$

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From Figure 4.8, the signalling cost per GWH for the MIP HS–based approach is given by:

$$C_{S\_GWH}^{HS-HA\_OBP} = C_{SYNC} + 4C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} + 4C_{DHCP} + 2C_{MIP\_rq/rp-sl} + 2C_{T-sl} \qquad (4.28)$$

$$C_{S\_GWH}^{HS-HA\_OBP} = \alpha \sum_{i=1,7-15} h_i M_i + \beta \sum_{i=2}^{5} h_i M_i \qquad (4.29)$$

The packet delivery cost before GWH within the satellite network is identical to that given in Equation 4.23.

The packet delivery cost after GWH within the satellite network is given by:

$$C_{PD\_after}^{HS-HA\_OBP} = \alpha \sum_{i=16}^{17} h_i M_i \qquad (4.30)$$

The packet delivery cost per multicast session before and after GWH with HA at OBP are given Equations 4.25 and 4.26 respectively. The only difference here is that the packet delivery cost after GWH given in Equation 4.30 is used in Equation 4.26.

## 4.5  Results from analytical mobility modelling

It is assumed here that the average number of hops between any two GWs, a GW and NCC or NCC and NMC under one satellite footprint are equal. If this is denoted as $h_{sf}$, then $h_{sf}$ is equal to $h_{NA-GW1}$, $h_{GW1-GW2}$, $h_{NA-GW2}$ and $h_{NA-NMC}$ as described above. Similarly, it is assumed that the average number of hops between any two GWs or NCCs belonging to different satellites or, an NCC and NMC under two different satellite footprints are equal. If this is denoted as $h_{2sf}$, then it implies that $h_{2sf}$ is equal to $h_{NA-GW3}$, $h_{GW1-GW3}$, $h_{GW2-GW3}$, $h_{NA-NB}$ and $h_{NB-NMC}$.

Different values of $\beta$ and $\alpha$ have been used to emphasize the link stability in wired and wireless links respectively. In terrestrial networks, the ratio of wired link stability ($\beta$) to that of wireless link stability ($\alpha$) ranges from 1:1.5 to 1:2 [38, 70]. For satellite communications, the stability of a satellite link might related to the link's availability. In general, this is true for fixed satellite communications. For mobile satellite communications, there are other factors like for example, antenna pointing that might affect the link stability. This, coupled with the fact that satellite links are generally less stable than wireless terrestrial network links, the values of $\beta = 1$ and $\alpha = 2$ have been adopted in this work.

Table 4.1 Notation, message size and number of hops

| Notation | DESCRIPTION | Value |
|---|---|---|
| $M_{SYNC}$ | Synchronization (SYNC) burst message | 12 bytes |
| $M_{IGMP}$ | IGMP Join message | 64 bytes |
| $M_{SNMP}$ | SNMP Request/Response + SI tables + RUI + allocated BW messages | 636 bytes |
| $M_{TIM}$ | Terminal Information message | 35 bytes |
| $M_{SI}$ | SI tables (TBTP, SCT, FCT, TCT, MMT) message | 152 bytes |
| $M_{ACQ}$ | Acquisition Burst message | 12 bytes |
| $M_{CMT}$ | Correction Message Table | 30 bytes |
| $M_P$ | IP Multicast Packet (data) | 120 bytes |
| $M_{MMT}$ | Multicast Map Table message | 30 bytes |
| $M_{PIM-SSM}$ | PIM-SSM message | 68 bytes |
| $M_{IGMP}$ | IGMP message | 64 bytes |
| $M_{DHCP}$ | DHCPDISCOVERY/DHCPOFFER/ DHCPRQUEST/DHCPACK message | 300 bytes |
| $M_{MIP-rq}$ | MIPv4 Registration Request message | 74 bytes |
| $M_{MIP-rp}$ | MIPv4 Registration reply message | 48 bytes |
| $M_{IPv4}$ | Size of IPv4 header in tunneling | 20 bytes |
| $h_{sl}$ | Number of hops between any 2 satellite terminals via satellite | 1 |
| | | 2 (L3 OBP) |
| $h_{sf}$ | Average number of hops between GWs/NCC/NMC via terrestrial networks under one satellite footprint ($h_{NA-GW1}$, $h_{NA-GW2}$, $h_{GW1-GW2}$, $h_{NB-GW3}$, etc.) | 16 |
| $h_{2sf}$ | Average number of hops between GWs/NCCs/NMC via terrestrial networks under 2 separate satellite footprints ($h_{NA-GW3}$, $h_{NA-NB}$, $h_{GW1-GW3}$, etc.) | 25 |
| $h_{GW-INT}$ | Average number of hops between any satellite GW and an Internet node | 10 |

Table 4.1 shows the notations, messages sizes and number of hops used in this section. These parameters are adopted from [7, 17, 38, 73-75]. The parameters in Table 4.1 and the following, are used for the numerical evaluation: $\alpha = 2$, $\beta = 1$, $\lambda_s = 10$, $E_s = 10$, $T_{TX/RX} = 1$ second, $d_{wd} = 100$ Mbps, $d_{sl} = 5$ Mbps, GEO satellite link latency from aircraft (mRCST) to satellite GW on ground $L_{sl} = 260$ milliseconds, $L_{wd} = 0.5$ milliseconds [17, 38, 70, 75, 76].

## 4.5.1 Handover latency
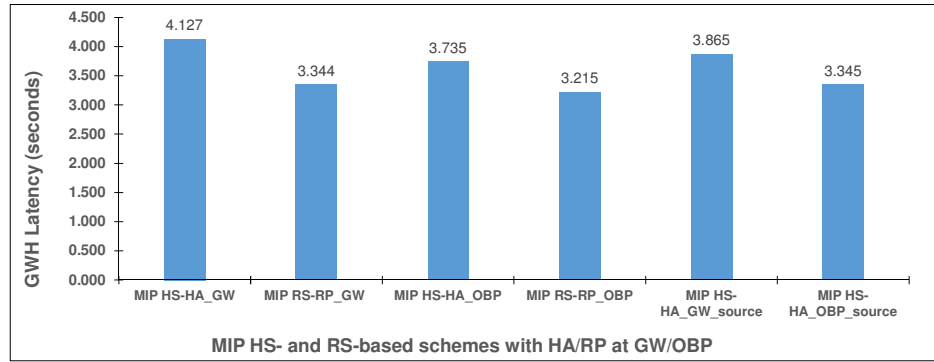


Figure 4.9 Comparison of GWH latency for HS- and RS-based schemes

In Figure 4.9, MIP HS-HA_GW and MIP HS-HA_OBP represent MIP HS-based approach with HA configured at GW and OBP respectively, MIP RS-RP_GW and MIP RS-RP_OBP represent the MIP RS-based approach with RP configured at GW and OBP respectively, MIP HS-HA_GW_source and MIP HS-HA_OBP_source represent the MIP HS-based approach for mobile source with HA configured at GW and OBP respectively.

Figure 4.9 compares the GWH latency for the MIP HS/RS-based approaches during a GWH scenario for an IP mobile multicast receiver/source when the HA/RP is configured either at the GW or OBP. These results are obtained by substituting the numerical values of the parameters in Equations 4.3, 4.7, 4.12, 4.15, 4.20 and 4.27 developed for GWH latency for each scheme described above.

From Figure 4.9, it can be seen that for either the MIP HS-based or MIP RS-based approaches, the GWH latency for OBP satellites (i.e., HA/RP at OBP) is generally lower than that for transparent satellites (i.e., HA/RP at GW).

Table 4.2 Comparison of GWH latency of MIP HS- HA_GW and the rest of the schemes considered.

| Schemes | Comparison with MIP HS-HA_GW |
|---|---|
| MIP HS-HA_OBP | 9.49% |
| MIP RS-RP_GW | 18.98% |
| MIP RS-RP_OBP | 22.09% |
| MIP HS-HA_GW_source | 6.34% |
| MIP HS-HA_OBP_source | 18.95% |

Table 4.2 shows the percentage increase in GWH latency for the MIP HS-HA_GW scheme, compared with those of the other schemes shown in the table. From Figure 4.9 and Table 4.2, it is clear that the MIP RS_RP_OBP scheme with the least GWH latency (3.21 seconds) is the best in terms of GWH latency from amongst the schemes considered while the MIP HS-HA_GW with the highest GWH latency (4.13 seconds) is the worst.

## 4.5.2 Number of packets lost due to handover latency and satellite capacity required for retransmission
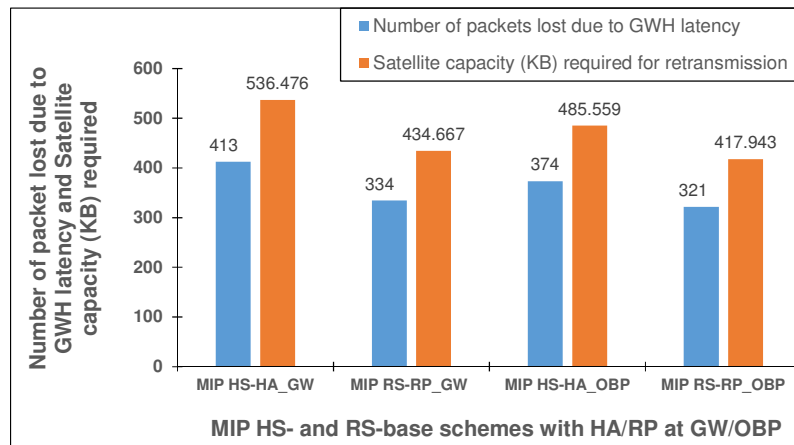


Figure 4.10 Comparison of number of packets lost due to GWH latency satellite capacity required for retransmission

Figure 4.10 shows the number of packet lost due to GWH latency for each scheme and the equivalent satellite capacity resources required to retransmit them if the IP multicast session was for a non-real time application like file transfer where reliability is required (i.e., reception of every packet is mandatory). The results for the number of packet lost are obtained by substituting the numerical values of the parameters in Equation 4.4 for various schemes. From this equation the number of packets lost due to GWH latency is directly proportional to the GWH latency provided $\lambda_s$ and $E_s$ are kept constant. This implies that the percentage lost in number of packets due to GWH latency for the various schemes in Figure 4.10 compared to that of MIP HS-HA_GW scheme will be similar to those presented in Table 4.2. The results for the total minimum satellite capacity required for retransmission for each scheme following a GWH is given by the product of the number of packets lost and size of each packet. Here, the size of one packet is assumed to be 1300 bytes. From Figure 4.10, a small difference in GWH latency of about 0.783 second between the MIP HS-HA_GW and MIP RS-RP_GW, could result in an extra huge satellite capacity of about 101.809 Kilobytes (KB) to be used to retransmit the lost multicast packets.

In unicast communication, satellite resources might not be wasted due to GWH latency. This is because during the GWH latency period, user traffic is simply buffered at the serving GW for non-real time applications and later tunnelled to the target GW for delivery to the mRCST after completion of the GWH. This implies that during the GWH latency period, no transmission of user traffic over the satellite air interface (to the mRCST) takes place, thus preventing any waste of satellite resources. In IP multicast communication over satellites, during the GWH latency period of one or more mobile multicast receivers (mRCSTs),

transmission of user traffic continues normally. This due to the fact many other receivers (fixed or mobile) under the satellite footprint which are not involved in any handover process are still listening to the same multicast transmission. For reliable IP multicast communication, this implies that any multicast packets lost during the GWH latency period by the mobile subscriber undergoing a GWH process will have to be retransmitted after the GWH is completed. This retransmission is viewed as additional utilisation of the satellite resources and any IP multicast mobility support scheme that could reduce the number of retransmitted packets will be considered a better scheme for IP multicast handover management over satellite.

For IP multicast communication where reliability is not required, Figures 4.9 and 4.10 also show that for the considered schemes, the long GWH latencies and large number of packets lost during a GWH, will have a significant negative impact on the quality of service (QoS) and Service Level Agreements (SLA).

Although the SH process is always longer than the GWH process, as shown in the signalling sequences in Figures 4.2, 4.3, 4.4, 4.5 and 4.6 for each of the schemes considered for IP multicast receiver mobility support, the GWH latency and SH latency for any particular scheme are almost identical to each other. This implies that the number of multicast packets lost due to a GWH process are equal to those lost due to a SH process.

### 4.5.3 Signalling cost
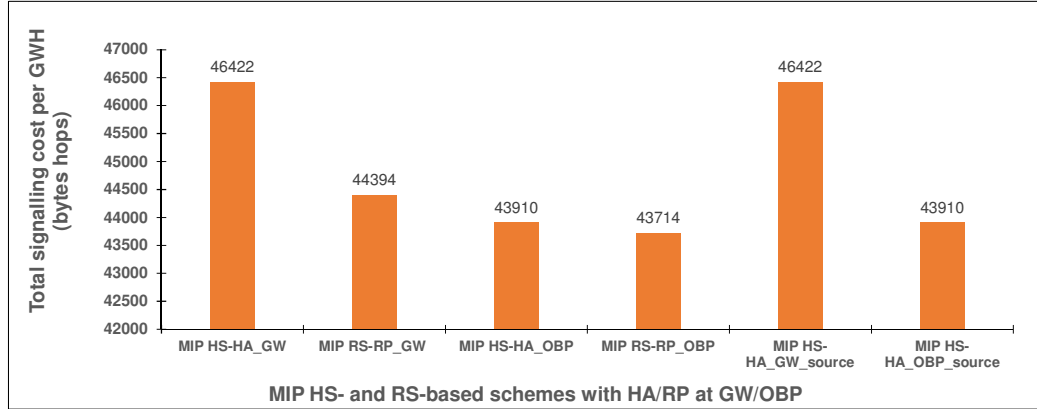


a.   Total signalling cost per GWH
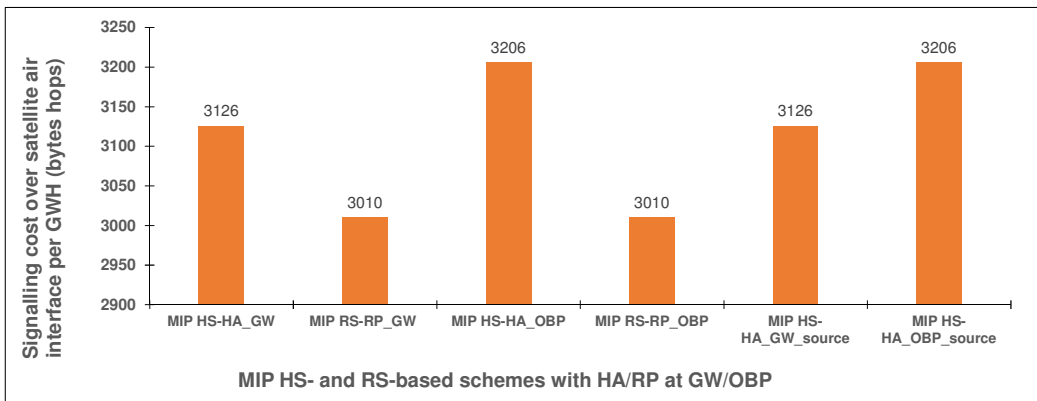


b.   Signalling cost over the satellite air interface per GWH

Figure 4.11 Comparison of signalling cost per GWH

The total signalling cost per GWH for all the MIP HS/RS-based schemes under consideration are shown in Figure 4.11a. These results are obtained by substituting the numerical values of the parameters in Equations 4.6, 4.8, 4.14, 4.17, 4.22 and 4.29. From Figure 4.11a, it can be seen the MIP HS-based approach generally incurred more signalling cost compared to the MIP RS-based approach i.e., about 4.37% more for schemes where the HA/RP is configured at the GW and about 0.5% more for schemes where the HA/RP is configured at the OBP. The higher signalling cost in the MIP HS-based approaches compared to the MIP RS-based approaches is due to the additional signalling cost incurred in registering the CoA at the HA. For IP multicast

communication, registration of the CoA during a GWH is not required in MIP RS-based approach.

Figure 4.11b on the other, shows the signalling cost over the satellite air interface. Due to the high cost of the satellite bandwidth resources compared to the terrestrial network resources, it is important to show the signalling cost over the satellite air interface for the various schemes. This might give an indication of the schemes which are likely to be more cost effective in terms of handling GWH signalling. From Figure 4.11b, it shows that the MIP RS-based schemes have lower signalling cost over the satellite air interface compared to MIP HS-based approaches and therefore, are likely to be more cost effective as far as GWH signalling is concerned. Surprisingly, the signalling cost over the satellite air interface for the MIP HS-HA_OBP_source scheme is higher than that for MIP HS-HA_GW_source. The reason for this is due to the extra cost of establishing an IP tunnel over the satellite air interface between the mobile source and the OBP in the MIP HS-HA_OBP_source scheme where as in the MIP HS-HA_GW_source scheme there is no IP tunnel required over the satellite air interface. The location of the IP tunnel in the MIP HS-HA_GW_source scheme during a GWH is within the terrestrial segment of the network between the target GW and home GW. The first portions of Equations 4.26 and 4.33 which give the signalling cost over the satellite air interface account for this difference.

Figure 4.12 shows the effect of varying the weighting factor of the satellite link ($\alpha$) on the total signalling cost per GWH for the MIP HS-HA_GW scheme. The results here are obtained by separately substituting the values of $\alpha = 1$, 1.5 and 2 in Equation 4.6. From Figure 4.12, it can be seen that there is a small increase on the total signalling cost per GWH of about 1.7% when the weighting

factor of the satellite link increases from 1.5 to 2. This basically means that there is an increase of about 0.34% in total signalling cost per GWH for every 0.1 increase in the weighting factor of the satellite link.
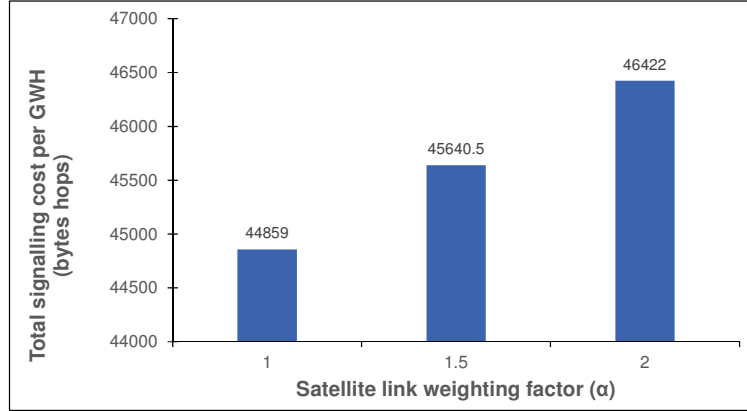


Figure 4.12 Effect of varying satellite link weighting factor on total signalling cost per GWH for MIP HS-HA_GW scheme

### 4.5.4 Packet delivery cost for source mobility

Using Equations 4.25, 4.26 and the numerical values for the parameters from Table 4.1, the results shown in Figure 4.13 for IP multicast source mobility are obtained. These results show that the cost of delivering multicast packets per session after GWH is always greater than that before GWH.
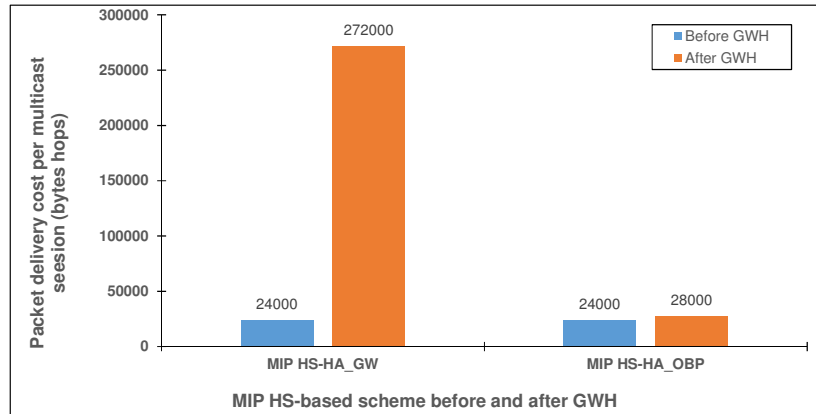


Figure 4.13 Comparison of number of packet delivery cost before and after GWH for HS-based scheme

As shown in Figure 4.13, for the MIP HS-based approach when the HA is located at the GW there is a 91.18% increase in the packet delivery cost per

session after GWH compared to that before GWH. With HA at OBP, the increase in the packet delivery cost per session after GWH is about 14.29%.

### 4.5.5  Significance of the results

According to the International Telecommunication Union (ITU) in [77], the maximum data transfer delay for real time applications should be less than 400 milliseconds and for non-real time applications 1200 milliseconds (for 95% of the data). Also, in the DVB specification [17], it is stated that the handover time is primarily determined by the mRCST's receiver re-tuning time (1 – 2 seconds) and return link fine synchronisation time.

Based on the above mentioned standards, the values of the GWH latency obtained for both the MIP HS-based and RS-based approaches, are obviously higher than is required. These show that for the terrestrial MIP HS/RS-based approaches to be used in the satellite environment, some modification to the current form is required. Figure 4.10 illustrates how a small increase in GWH latency can cause a significant increase in utilisation of the satellite resources in some IP multicast applications. This implies that small differences in GWH latency (of say 1 – 2 seconds) could result in a significant difference in the amount of satellite resources consumed and consequently, financial cost.

From the above analysis of the results, it can be deduced that these IP multicast mobility support schemes defined for terrestrial network might not be suitable for satellite environment in the current form. So, modification to their current form is required or entirely new IP multicast mobility support schemes for the satellite environment are needed to support IP multicast communication during GWH/SH.

## 4.6  Summary

In this chapter, analytical mobility modelling has been developed for GWH when the:

- HA is configured at satellite GWs and on the OBP (for regenerative satellites with layer 3 OBP) for MIP HS-based approach.

- RP is configured at satellite GWs and on the OBP for MIP RS-based approach.

Analytical mobility modelling during SH has also been developed for MIP HS/RS-based approaches when the HA and RP respectively are configured at the satellite GWs.

Results obtained from the analytical mobility modelling and detailed analysis have been presented.

The results and analysis in this chapter suggest that for efficient IP Multicast mobility support in a multi-beam satellite network, modifications to the MIP HS/RS-based schemes defined for terrestrial networks are required or entirely new schemes are needed. The next chapter therefore gives a full description of some proposed IP multicast receiver mobility support schemes in a global satellite network.

# 5  PROPOSED IP MULTICAST RECEIVER MOBILITY SUPPORT SCHEMES IN A MULTI-BEAM SATELLITE NETWORK

This chapter presents one of the major contributions of this thesis. Here, novel solutions are proposed on how to support on-going IP multicast session when a mobile satellite receiver in a line-of sight (LOS) scenario (e.g., aircraft, maritime vessels, etc.) is undergoing a gateway/satellite handover. Also in this chapter, analytical mobility models for each of the proposed schemes are developed for GW/satellite handover latency, number of packets lost due to GW/satellite handover latency and GW/satellite handover signalling cost.

All the proposed schemes in this chapter are implemented on the reference satellite network architecture shown in Figure 4.1 of Chapter 4.

## 5.1  Satellite Home Subscription (SHS)-based approach

It is proposed here that each satellite GW should have the HA and FA functionalities in addition to their normal responsibilities. This implies that under each satellite IP network (or GW Beam) shown in Figure 4.1, there will be only one HA and one FA. It is also proposed here that the mode of acquisition of a CoA by an mRCST while away from its home network be a "foreign agent care-of address" [18], where the mRCST's CoA is the IP address of the FA. This FA CoA which is provided through Agent Advertisement messages by the FA is of particular importance in a satellite environment due to the following reasons:

- Since the path followed by mRCSTs (e.g., airliners, maritime vessels, etc.) in LOS scenarios is always know in advance, it implies that the CoAs that any particular mRCST will use in a LOS scenario will also be known in advance.

This is due to the fact that these CoAs will be the IP addresses of the FAs i.e., target GWs along the path of the mRCST, thus making it possible to eliminate mobility agents' advertisement. Therefore, the advance knowledge of the mRCST's CoA in the target GW, has two key benefits: firstly, it can reduce the GW/satellite handover latency as pre-registration of the mRCST's CoA (in the target GW) at its HA just before handover initiation is possible and secondly, it can reduce signalling overhead during GW/satellite handover as elimination of mobility agents' advertisement is possible.

- The FA CoA allows many mRCSTs to share the same CoA. This will eliminate the tunnel convergence problem between the HA and FA in situations where many mRCSTs from the same IP home network happen to be located in one foreign network. This also will conserve the IPv4 addresses which are already limited.

Due to the advance knowledge of the mRCST's CoA in the target GW, it is proposed that the Synchronization (SYNC) [17] burst which carries handover recommendation to the NCC should carry the mobile IP registration message [18] from the mRCST to its HA at GW1 (Figure 4.1) Since there is only one HA and one FA in each local network of the gateways, only one bi-directional tunnel can be established between the home network and the visited network at any point in time no matter how many mRCSTs from the home network are located at the visited network. Therefore, this eliminates the tunnel convergence problem experienced in HS-based approaches in terrestrial networks.

It is assumed that the OBP which separates the uplink and downlink transponders of each beam has a data link layer capability (layer 2 switch). When an mRCST moves across different spot beams within a GW Beam, beam handover takes place. Beam handover is considered as a lower-layer handover

in which the NCC coordinates the handover procedure and no higher layer involvement is required in the implementation. Details of beam handover detection/recommendation, decision and execution can be found in [17, 24, 78]. There is little or no change in the multicast delivery tree apart from the fact that if the aircraft is the first member of the group in the target spot beam, then NCC during handover execution will instruct the OBP to forward multicast traffic for the group to target beam and also the handover command (with information about resources to be used in new beam) to the mRCST (aircraft). On-going multicast and other higher layer communications inside the aircraft will go on unperturbed in a seamless handover.

### 5.1.1 Gateway handover (GWH) in SHS

Upon reception of the handover recommendation from the aircraft (mRCST) shown in Figure 4.1 as it enters the overlapping area between GW Beams 1 and 2, NCC-A will retrieve the target beam identity from its database and determine whether the beam belongs to a different GW. In order to minimise GWH latency, it is proposed here that the MIP registration message from the mRCST (aircraft) to its HA at GW1 be carried in the handover recommendation message. NCC-A will realize that the target beam (GW B2) is served by a different gateway, GW2 and so, a GWH is decided. NCC-A will then update its service information (SI) tables which include Terminal Burst Time Plan (TBTP), Super-frame Composition Table (SCT), Frame Composition Table (FCT) and Time-slot Composition Table (TCT). Signalling between NCC-A, GW1 and GW2 is then carried out to prepare for GWH. NCC-A will send an SNMP Set-Request message to the GW2 for events synchronization to ensure that the GW2 gets ready for connection with the mRCST (aircraft). The updated SI tables, together with the routing update information of the aircraft, unicast IP address of

the HA at the current serving gateway (GW1) will be included in this message. The routing update information is generally implemented by sending the location change information to the broadcaster, which is generally handled by the location management scheme. Upon reception of the Set-Request signalling, the target GW (GW2) will allocate bandwidth resources for the aircraft according to the new burst time plan and also forward the MIP registration request from the aircraft to GW1 (aircraft's home agent). Note should be taken here that the MIP registration request forwarded by GW2 to GW1 has the IP address of GW2 as the source address and the IP address of GW1 as the destination address [18]. This implies that the IP address of GW2 is the CoA of the incoming aircraft (mRCST). The association of the HA (GW1) and CoA of the aircraft is called binding. After receiving the CoA, the HA creates a binding cache entry that maps the permanent IP address, the multicast group address and the CoA of the aircraft and then sends a binding acknowledgement i.e., the MIP registration reply to the GW2 (aircraft) indicating that the forwarding of traffic for the aircraft is set. Once the binding process is completed, a bi-directional tunnel [27] is established between the HA at GW1 and FA at GW2, and the HA is ready to tunnel all subsequent multicast packets destined for the aircraft to GW2 [79, 80]. The acknowledgement SNMP Set-Response message is then sent from the GW2 to the NCC-A. NCC-A will now send a Set-Request message to GW1, which includes the aircraft identity and the SI tables. Upon receiving the Set-Request message from NCC-A, GW1 will buffer the FL user traffic of the aircraft to be tunnelled to FA at GW2 during handover. GW1 will then acknowledge NCC-A by sending it a SNMP Set-Response message. GWH always entails beam handover [17, 24, 78]. Upon reception of the SNMP Set-Response message from GW1, a GWH command is

issued to the aircraft from NCC-A in a Mobility Control Descriptor carried in a Terminal Information Message Unicast (TIMu) message using old beam. TIMu message also contains new Time-division multiplex (TDM), SF_ID, Group_ID, Logon_ID, Program Identifiers (PIDs) necessary for logging on and functioning in the new beam.
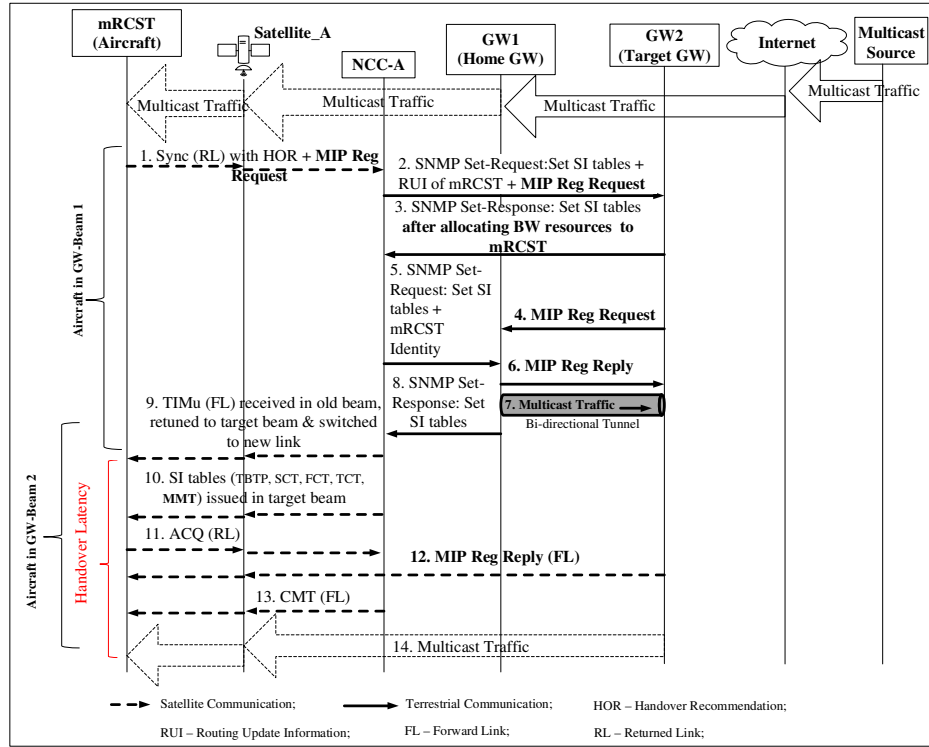


Figure 5.1 SHS-based approach signalling sequence at GWH
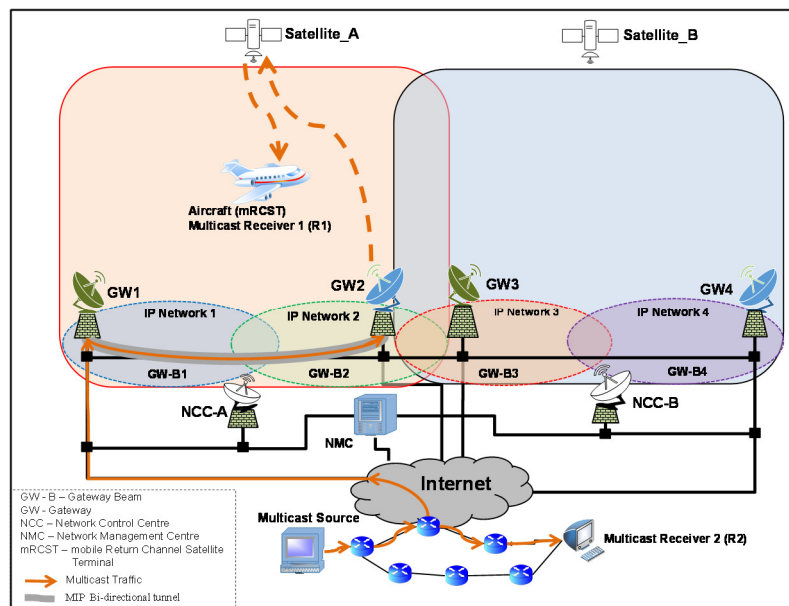


Figure 5.2 Aircraft now served by GW2 after GWH- SHS

GW1 updates its route mapping table and released resources used by the aircraft. Once the aircraft receives the handover command, it synchronizes with NCC-A and GW2. After finishing the retuning and synchronisation processes, the mRCST (aircraft) issues an ACQ message to NCC-A. The synchronisation process and the issuing of ACQ burst imply that the aircraft has established connection with the new link provided by GW2. So, GW2 can now issue the MIP registration reply to the aircraft, which subsequently receives the multicast traffic from the new beam which comes through the new gateway, GW2. The GWH is completed when the aircraft (mRCST) receives the Correction Message Table (CMT) message from NCC-A.

Figure 5.1 illustrates the GWH signalling sequence during GWH while Figure 5.2 shows the aircraft now receiving multicast traffic through GW2 after a successful GWH.

### 5.1.2  Satellite Handover (SH) in SHS

When the aircraft reaches the overlapping area between GW Beams 2 and 3, it will detect the need for handover [17, 24, 78], and will send a handover request/recommendation (containing MIP registration message) to the NCC-A. Upon reception of the handover recommendation from the aircraft, NCC-A will retrieve the target beam identity from its database and determine whether the beam belongs to a different gateway and/ or satellite. Once NCC-A realized that the target beam belongs to another satellite, then it will start procedures for a satellite handover. Signalling between NCC-A, NMC and NCC-B (which controls satellite resources in the target beam i.e., GW B3) is carried to see whether it is ready to accept a moving-in mRCST (aircraft). Satellite handover is coordinated by the NMC which controls the whole global satellite network. To maintain a good level QoS and also SLA of the on-going communications in the aircraft,  a

good estimate of the amount of resources (bandwidth) required by the moving-in aircraft and the type of communication going on will be communicated to NCC-B.
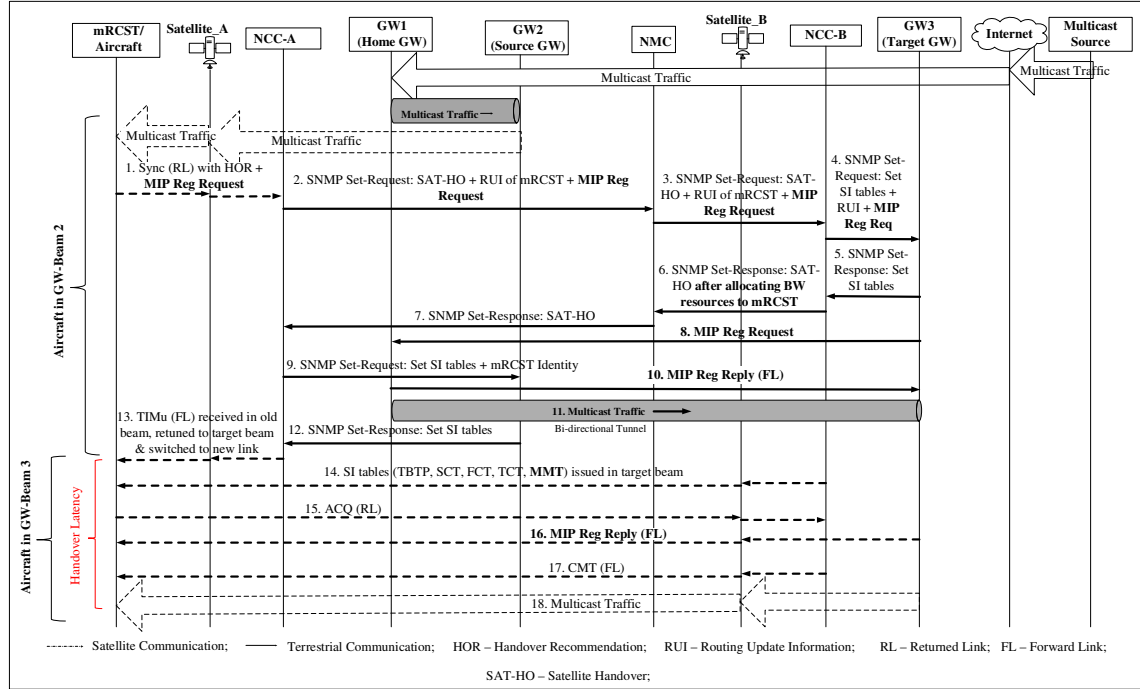


Figure 5.3 SHS-based approach signalling sequence at satellite handover
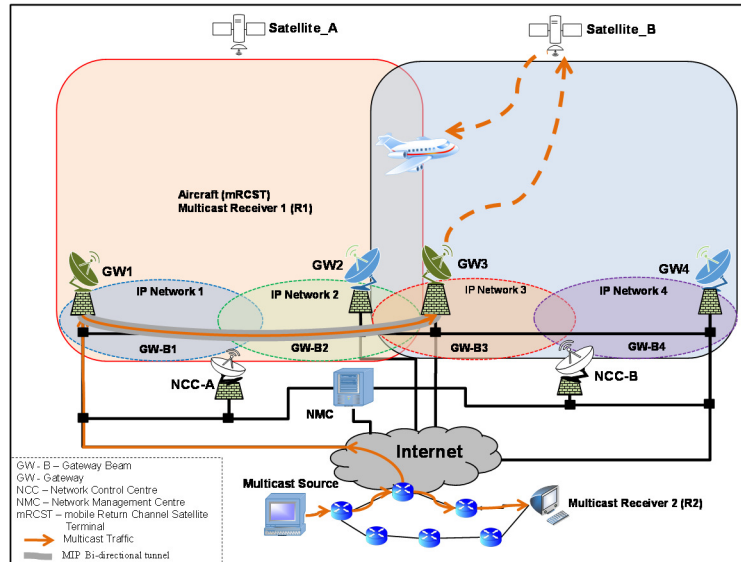


Figure 5.4 Aircraft now served by GW3 after satellite handover- SHS

If NCC-B confirms that the required resources are available and that it is ready to accept the aircraft, then, NCC-A will send a handover command to the aircraft. Upon reception of the handover command, the aircraft (mRCST)

90

synchronizes to the new GW B3 under the control of the new NCC-B. During the communication between the two NCCs, NMC and the target gateway (GW3), the MIP registration message from the mRCST (aircraft) is delivered to GW3. If the multicast groups with members in the aircraft are new to GW3, then the FA at GW3 will forward its IP address as the CoA of the mRCST (aircraft) to HA at GW1 for binding update. This will result in a bi-directional tunnel formed between GW1 and GW3 as illustrated by the multicast communication signalling sequence in Figure 5.3 and the new multicast delivery tree to aircraft in Figure 5.4.

The advantage of SHS based approach is its simplicity since the mRCST does not need to re-join the multicast group as its serving gateway changes. However, this approach suffers from triangular routing through the home network, which increases the join latency which could have a significant negative impact on satellite networks. The fact that SHS relies completely on the HA to forward multicast traffic to the mRCSTs implies a single point of failure, which is very risky. Also, tunnelling through HA incurs overheads in home network.

### 5.1.3  Analytical mobility modelling for SHS-based approach

**Gateway handover (GWH)**

From Figure 5.1, the GWH latency $L_{GWH}$ for the SHS-based approach is given by:

$$L_{GWH}^{SHS} = T_{Tx/Rx} + \sum_{i=10}^{14} D_i \qquad (5.1)$$

The number of packets lost due to GWH latency in this scheme are given by Equation 4.4, where the GWH latency used is that calculated in Equation 5.1.

From Figure 5.1, the signalling cost per GWH for the SHS scheme, $C_{s\_GWH}^{SHS}$ is given by:

$$C_{s\_GWH}^{SHS} = C_{SYNC} + 4C_{SNMP} + 5C_{MIP-rq/rp} + 2C_T + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} \qquad (5.2)$$

Where $C_T$ is the cost of tunnelling an IPv4 packet header and the rest of the terms in Equation 5.2 represent the cost of the signalling messages shown in Figure 5.1. Substituting the cost value (message size × hop distance) for each term in Equations 5.2 and re-arranging implies $C_{s\_GWH}^{SHS}$ is given by:

$$C_{s\_GWH}^{SHS} = \alpha \sum_{i=1,9-13} h_i M_i + \beta \sum_{i=2-6,8} h_i M_i \qquad (5.3)$$

It should be noted that the size of an IP packet header must be added to the size of any IP packet signalling message that is encapsulated (tunnelled).

**Satellite handover (SH)**

From the signalling sequences in Figures 5.1 and 5.3, it can been seen the GWH latency, $L_{GWH}^{SHS}$ and the SH latency, $L_{SH}^{SHS}$ are identical. For a constant $\lambda_s$ and $E_s$, if the $L_{GWH}^{SHS}$ and $L_{SH}^{SHS}$ are equal, from Equation 5.2, it implies that the number of packets lost due to GWH and SH are exactly the same.

Similarly to Equation 5.4 and from Figure 5.3, the signalling cost per SH for the SHS scheme, $C_{s\_SH}^{SHS}$ is given by:

$$C_{s\_SH}^{SHS} = C_{SYNC} + 8C_{SNMP} + 7C_{MIP-rq/rp} + 2C_T + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} \qquad (5.4)$$

$$C_{s\_SH}^{SHS} = \alpha \sum_{i=1,13-17} h_i M_i + \beta \sum_{i=2-10,12} h_i M_i \qquad (5.5)$$

## 5.2 Satellite Remote Subscription (SRS)-based approach

Similarly, the advance knowledge of the mRCST's CoA in the target GW implies that the mRCST can issue the IGMP [13] join report message to the target GW at the beginning of the GWH procedure. This will make the target GW (upon reception of the IGMP join report) to join the multicast groups of interest to the mRCST before the GWH procedure is completed i.e., similar to multicast pre-registration scheme described in MSA (Section 3.2.1.2.2 of Chapter 3). It is therefore proposed here that the SYNC burst [17] which carries the handover recommendation to the NCC should also carry the IGMP join report message from the mRCST to the target GW.

### 5.2.1 Gateway Handover (GWH) in SRS

When the aircraft enters the overlapping area between GW Beams 1 and 2, the handover detection and decision is exactly the same as in SHS-based approach described above. The main difference here is that the SYNC burst carries the aggregate IGMP report join message destined for the GW2 (target GW) instead of the MIP registration message as in the SHS-based approach. This aggregate IGMP report contains the entire multicast membership status of the aircraft (mRCST). When the target GW (GW2) which is about to take the responsibility of serving the aircraft finally receives the IGMP report message, it will then join all the multicast groups that are contained in the IGMP report, in order to continue the multicast services to the aircraft when the GWH is completed. This is designed in such a way that the tree reconstruction from the Internet to the target GW (GW2) is completed before GWH procedure is completed. This will ensure that multicast traffic to the mRCST resumes immediately following GWH completion.

Figure 5.5 illustrates the signalling sequence involved in SRS based approach while Figure 5.6 shows the changes in the multicast delivery tree (from the one in Figure 4.1). Here, there is no binding of the GW2 (FA) IP address to the HA at GW1 as was the case in SHS-based approach.
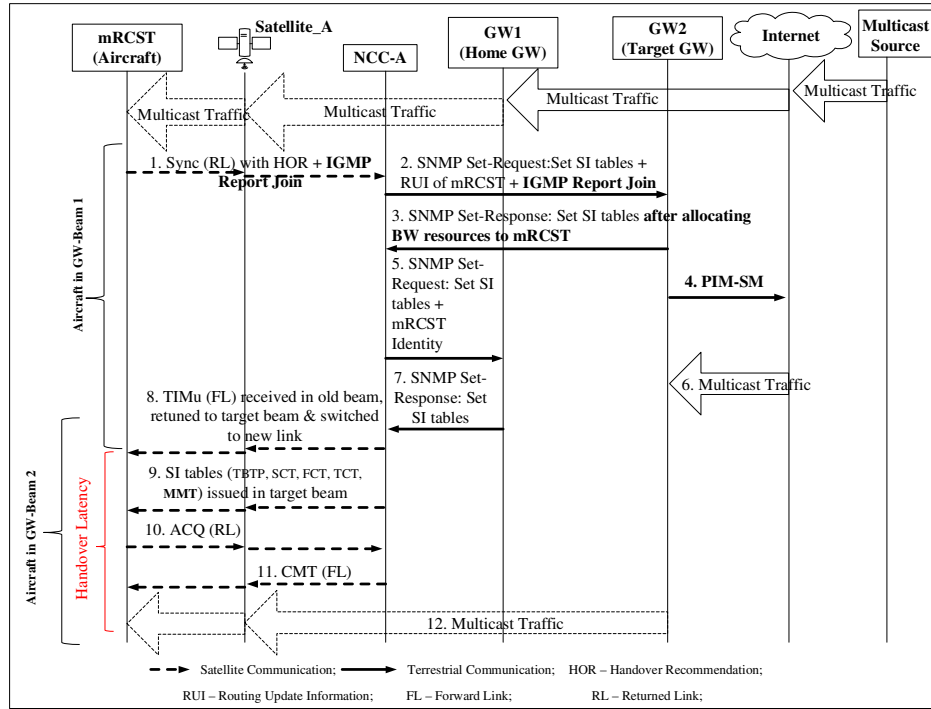


Figure 5.5 SRS-based approach signalling sequence at GWH
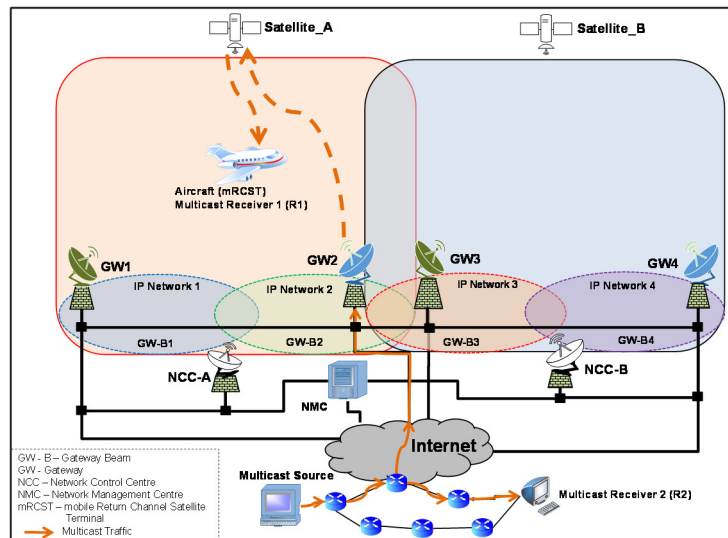


Figure 5.6 Aircraft now served by GWA2 after GWH –SRS

At the overlapping area between GW Beams 2 and 3 as the aircraft continues in its journey, a satellite handover will take place. Upon reception of the IGMP

report join message which originated from aircraft (mRCST), the GW3 will join the multicast group(s) that has members in the aircraft as it assumes the responsibility of serving the aircraft.

## 5.2.2 Satellite Handover (SH) in SRS
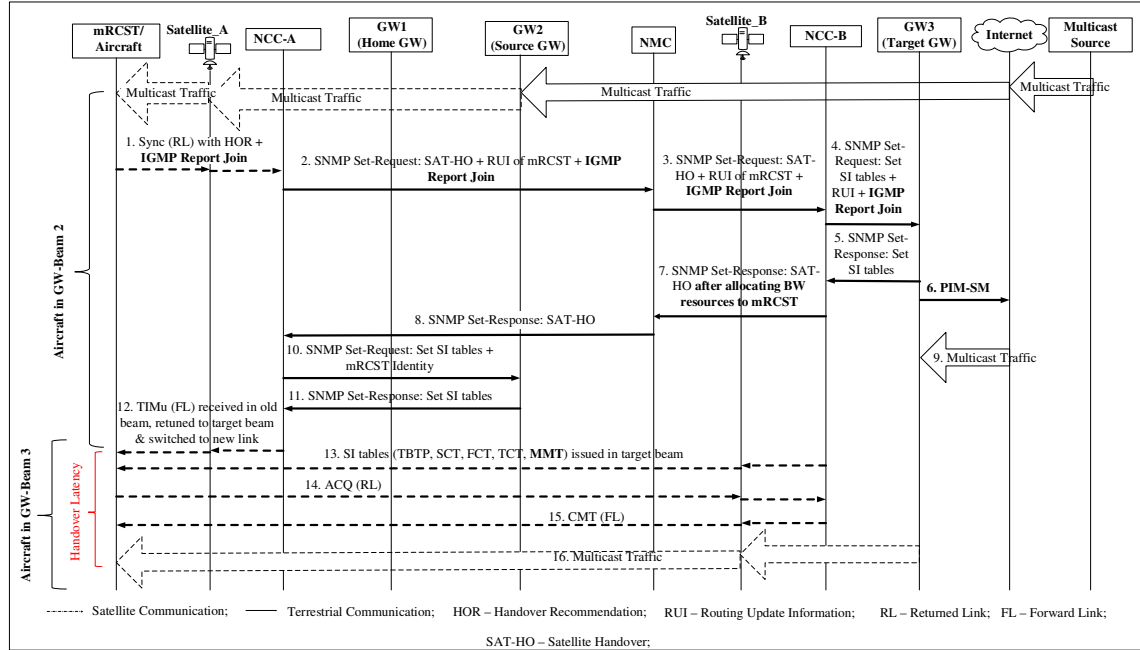


Figure 5.7 SRS based signalling sequence at satellite handover
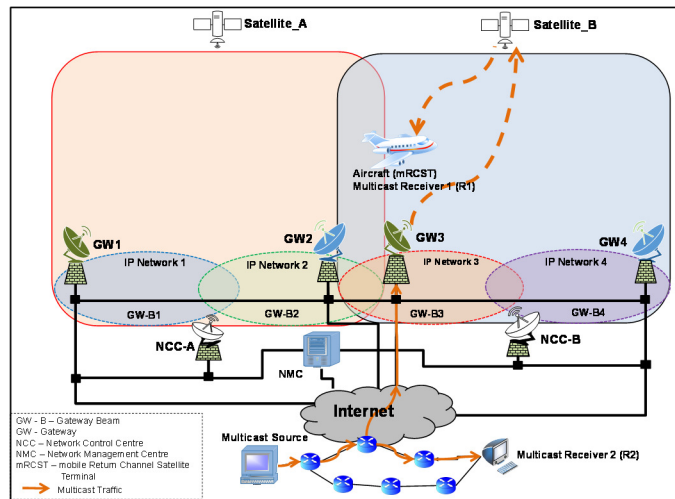


Figure 5.8 Aircraft now served by GW3 after satellite handover-SRS

Figure 5.7 illustrates the signalling sequence required while Figure 5.8 illustrates the multicast delivery path, for the SRS-based approach at satellite handover.

Generally, the SRS-based approach enjoys route optimization compared to the SHS-based approach since multicast traffic is routed from source directly to the gateway serving the aircraft through the shortest possible path.

### 5.2.3  Analytical mobility modelling for SRS-based approach

**Gateway handover (GWH)**

From the signalling sequence in Figure 5.5, the GWH latency, $L_{GWH}^{SRS}$ for the proposed SRS-based approach is given by:

$$L_{GWH}^{SRS} = T_{Tx/Rx} + \sum_{i=9}^{12} D_i \qquad (5.6)$$

Similarly the number of packets lost due to GWH latency in the SRS-based approach is also given by Equation 4.4, where the GWH latency is that given in Equation 5.6.

The signalling cost per GWH for the SRS scheme using Figure 5.5, $C_{s\_GWH}^{SRS}$ is given by:

$$C_{s\_GWH}^{SRS} = C_{SYNC} + 4C_{SNMP} + 2C_{IGMP} + C_{PIM} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} \qquad (5.7)$$

$$C_{s\_GWH}^{SRS} = \alpha \sum_{i=1,8-11} h_i M_i + \beta \sum_{i=2-5,7} h_i M_i \qquad (5.8)$$

**Satellite handover (SH)**

From the signalling sequences in Figures 5.5 and 5.7, the GWH latency, $L_{GWH}^{SRS}$ and the satellite handover latency, $L_{SH}^{SRS}$ for the proposed SRS-based approach are identical. So, the number of packets lost due GWH and SH latencies are also identical.

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From Figure 5.7 and similar to Equation 5.10, the signalling cost per SH for the

SRS scheme, $C_{s\_SH}^{SRS}$ is given by:

$$C_{s\_SH}^{SRS} = C_{SYNC} + 6C_{SNMP} + 4C_{IGMP} + C_{PIM} + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} \qquad (5.9)$$

$$C_{s\_SH}^{SRS} = \alpha \sum_{i=1,12-15} h_i M_i + \beta \sum_{i=2-8,10,11} h_i M_i \qquad (5.10)$$

## 5.3  Multiple interface-based approach

Recently, mobile communication devices with multiple network interfaces (e.g., smart phones) are becoming more and more common. Currently, multi-homed mobile devices are mainly used for maintaining connectivity and achieving desired application quality of service. For example, when link quality on a given network interface drops below a certain threshold value, the multi-homed mobile device will initiate a handover to another network interface with better link quality. A common example of this is the handovers between 3G, High Speed Packet Access (HSPA) and HSPA+ networks in new smartphones when travelling in a car from one city to another. Here, a novel multi-homing-based solution for achieving seamless mobility for IP multicast application in multi-beam satellite networks during handover is proposed.

It is assumed in this approach that all mRCSTs have multiple satellite interfaces i.e., multi-homed.  This approach seeks to exploit the multiple satellite interfaces of the mRCSTs to support ongoing IP multicast communication during GW/satellite handover.

 Due to the large round trip delay in GEO satellite networks, all handover procedures in multi-beam satellite networks can cause serious link quality degradation or even disconnection of an on-going session. Handover latency

(period when the mRCST cannot receive or send user traffic because of the link switching delay) constitutes the primary cause of packet loss during handovers. Longer round trip delays in satellite networks imply longer handover latency, meaning more packets loss.

The proposed Multiple Interface (MI) - based scheme here leverages on the group communications features of IP multicast and the fact that anyone can join or leave a multicast group at any time.
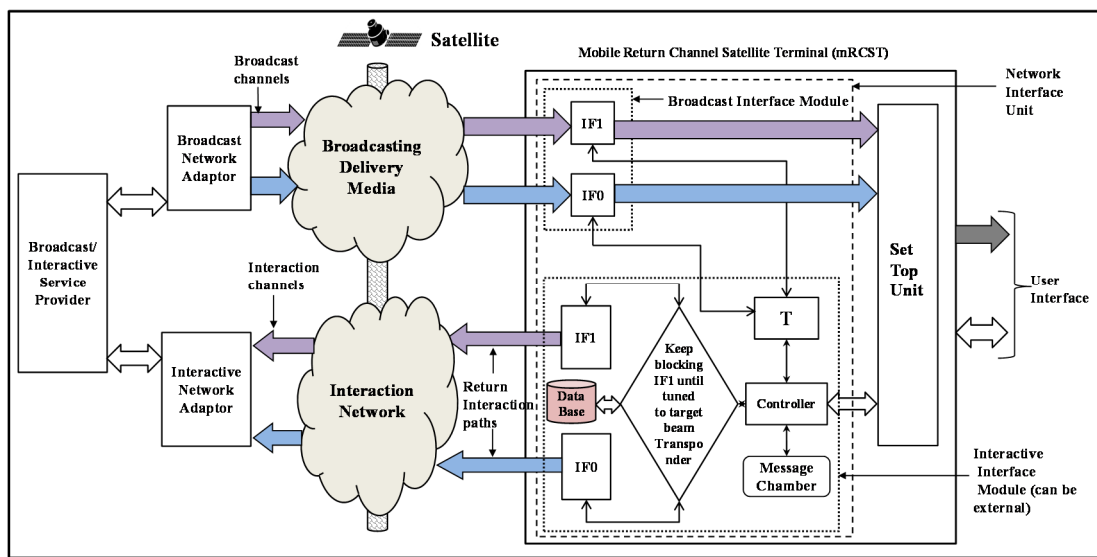


Figure 5.9 Multi-homed mRCST for satellite interactive system

Figure 5.9 shows the proposed internal architecture of a multi-homed mRCST for Satellite Interactive System containing new features/entities in addition to the standard RCST given in [74]. These new features include:

- An additional broadcast interface (IF1) (i.e., for receiving data via DVB-S) in the broadcast interface module with its corresponding additional interactive interface (IF1) (i.e., for sending data via DVB-RCS) in the interactive interface module, making the mRCST a multi-homed device.

- A database which holds information about the global map of the interactive satellite network (i.e., information about beams, their locations and

frequency, gateways - location and IP addresses) as well as all active connections in the mRCST.

- A message chamber which can issue IGMP join report and leave messages during handover between IF0 and IF1.

- The controller which manages the data base, the interfaces and has complete control over which interface the traffic leaves/enters the mRCST especially when the two are active (i.e., during handover).
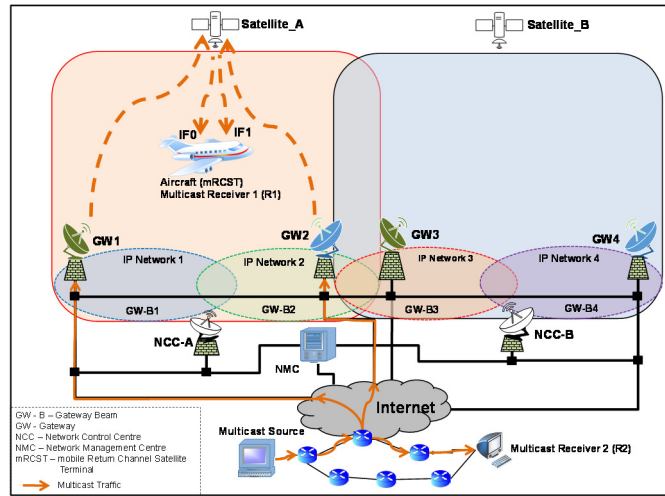


Figure 5.10 Multicast receiver mobility at GWH for a multi-homed mRCST

It is assumed that the aircrafts, ships, trains etc., are each equipped with an mRCST, GPS (or Galileo) receiver and the global satellite network map. The GPS/Galileo and the global satellite network map on these mobile platforms can therefore enable them to perform analysis of their position information and then signal for handover whenever necessary. As shown in Figure 5.9, the multi-homed mRCST contains two pairs of satellite network interfaces, IF0 and IF1 in the broadcast interface module with their corresponding pairs in the interactive interface module. The interfaces in the broadcast interface module are used for receiving FL traffic and signalling while those in the interactive interface module are used to send RL traffic and signalling. If FL traffic is received through IF0 in broadcast interface module, then the reply (RL traffic) will be sent out through

IF0 in the interactive interface module. The same holds for traffic received through IF1 in the broadcast interface module.

When the multi-homed mRCST (aircraft) shown in Figure 5.10, with an on-going multicast session through interface IF0 enters an overlapping area of two satellite beams belonging to different GWs, it will detect the presence of the new satellite beam. The controller will then consult the database within the mRCST to confirm whether the detected new beam is the target GW Beam. If the detected new beam is the target GW Beam, IF1 through instructions from the controller will then establish a connection with the target GW Beam using normal logon procedure. This is closely followed by the message chamber issuing an aggregate IGMP join report through IF1 to the NCC to join all the multicast groups that the mRCST is a member of. Due to the fact that anybody can join or leave a multicast group at any time, when the second interface IF1 joins the multicast session, there is no need to prove that that the two interfaces (IF0 and IF1) belong to the same device. This is contrary to unicast communication where a second interface of the same device joining a unicast session will have to undergo a series of security procedures to prove that the two interfaces belong to the same device. Therefore, this makes the handover hidden from the satellite network i.e., as far as the satellite network is concerned, the second interface (IF1) may just be another RCST/mRCST that has logged on to the satellite network and established communication.

After this, the controller starts directing all other new communications or connections from the mRCST through IF1. Immediately IF1 starts receiving traffic from all the on-going multicast session(s), the message chamber will issue an IGMP leave message through IF0. Eventually, all communications or connections from and to the mRCST are channelled through IF1 and once this

happens then IF0 enters a stand-by/log-off state. Considering the fact that in a GEO satellite network, the area of overlapping beams can stretch for many miles, it is possible to keep the old connection through old point of attachment (GW1) alive until the new one via GW2 is set up and all communications transferred to the new link. When the mRCST enters the next area of overlapping GW Beams, whether belonging to the same satellite or a different one (i.e., satellite handover), the same procedure is followed that will see all communications on mRCST transferred back to IF0 from IF1. This scheme assumes that there is always satellite resources available in the target beam to accommodate the incoming mobile satellite terminal.

Duplicate packet transmissions that may occur during GWH/SH in this scheme is one of the trade-offs proposed by this scheme in order to completely eliminate GWH/SH latency and packet losses due to handover latency. The duplicate packets received on-board the multi-homed mRCST can however be prevented from being forwarded to the user terminals. This could be achieved by implementing the Duplicate Packet Detection (DPD) scheme specified in [81] where each packet is given some form of identification (e.g., a sequence number). The multi-homed mRCST which may receive duplicate packets during handover then needs to keep track of previously forwarded packets so that duplicates are not forwarded [81].

*The advantages of this scheme are:*

- It is simple to implement

- Minimal handover latency

- There are no packet losses at all due to handover as the handover is completely and truly seamless

*The disadvantages of this scheme are:*

- There is no support for unicast traffic.

- During GWH/SH when the two interfaces are simultaneously in use, more satellite resources are used in transmitting identical data (duplicate packets) in the both the current and target beams.

- Cost: An additional interface on the mobile satellite terminal for mobility support means that the financial cost of purchasing the terminal will increase. Also, there could be an increase in the operational cost since satellite resources will be used in both the current and target beams during handover to transmit identical data packets.

### *Analytical mobility modelling for multiple interface-based approach*

In this scheme, the GWH/SH latency is zero. During handover (GWH or SH) as explained above, the second interface establishes connection and start receiving traffic through the new network before the old interface is disconnected from the old point of attachment. This implies that the multi-homed mRCST (aircraft) will always be able to send or receive user traffic at all times during a handover process.
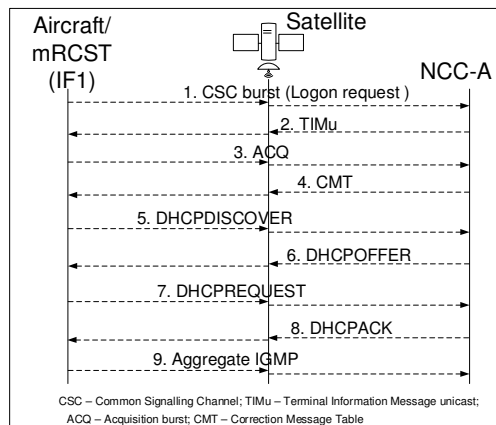


Figure 5.11 RCST logon signalling sequence

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The GWH and SH signalling cost for the multiple interface-based approach will be the same, and also, will be equal to the RCST network entry or logon signalling cost. Figure 5.11 shows the logon plus joining the multicast groups signalling sequence [74] for the second interface (IF1) of an mRCST when the aircraft enters the overlapping area of two satellite beams belonging to different GWs or satellites. From Figure 5.11, the GWH/SH signalling cost for the multiple interface-based approach $C_{s\_GWH/SH}^{MI}$ this is given by:

$$C_{s\_GWH/SH}^{MI} = C_{CSC} + C_{TIM} + C_{ACQ} + C_{CMT} + 4C_{DHCP} + C_{IGMP} \qquad (5.11)$$

$$C_{s\_GWH/SH}^{MI} = \alpha \sum_{i=1}^{9} h_i M_i \qquad (5.12)$$

## 5.4 PMIPv6-based approach

It is proposed that the global satellite network forms one PMIPv6 domain under the administration of one satellite network operator. One of the main challenges of employing PMIPv6-based IP mobility management in a multi-beam satellite network is choosing the right location to configure the LMA, MAG and MTMA/MR. Two schemes have been proposed here based on the capability of satellite payload i.e., regenerative OBP with layer two capability (switching) and regenerative OBP with layer three capability (routing). The regenerative OBP is chosen here instead of the transparent payload, so as to take advantage of the on-board replication of multicast packets. Multicast packets replication on-board the satellite will save the scarce and expensive satellite resources and also, reduce the round trip delay by half in mesh topology where the multicast source is a RCST. While in the satellite network architecture with layer 2 OBP, the LMA and MAG which are layer 3 devices can only be configured on the ground segment, a layer 3 OBP provides the option of configuring the LMA or MAG

either on-board the satellite ( i.e., on the OBP) or on the ground segment.  In the scheme with layer 2 OBP, it is proposed that the MAG be configured on each satellite GW on the ground segment while in the scheme with layer 3 OBP, the MAG is proposed to be configured on-board the satellite i.e., satellite MAG (s-MAG). In both cases, an MLD proxy is configured on the MAG/s-MAG. The advantage of having the s-MAG on-board the satellite is that one s-MAG can now serve the whole GEO satellite footprint regardless of the number of IP networks within the footprint. This reduces the number of MAGs within the PMIPv6 domain and therefore financial cost.

### 5.4.1  Scheme with MAG on ground segment (Layer 2 OBP)

It is proposed that:

- A MAG be configured on each satellite GW and that each MAG acts as an MLD proxy.

-  Each satellite footprint has one LMA and one MR/MTMA. The LMA is dedicated to unicast traffic and the MR/MTMA to multicast traffic.

- The regenerative OBP supports on-board replication of multicast packets at layer 2.

- The policy profiles of all mobile RCSTs authorized for global network-based IP mobility management are proposed to be stored at all the LMAs and MAGs. Each mRCST's policy profile must contain the mRCST's identifier (e.g., MAC address), home network prefix (HNP), Link-local address (LLA) and the IPv6 address of its LMA/MR/MTMA.

### *5.4.1.1      Gateway handover (GWH)*

As shown in Figure 5.12, the multicast source is a fixed node located on terrestrial network and while the receivers are located both on the satellite and

terrestrial networks. The aircraft (mRCST) is a satellite–based mobile multicast receiver while multicast receiver 2 (R2) is a fixed terrestrial-based multicast receiver. Due to the presence of the regenerative OBP on-board the satellite and its ability to replicate IP multicast packets, only one copy of the multicast traffic is sent up to satellite no matter the number of GW Beams (or spot beams) under the satellite's footprint with interested receivers. To efficiently utilize the satellite bandwidth resources, the downlink forwards multicast traffic only to the GW Beams or spot beams that have at least one receiver.
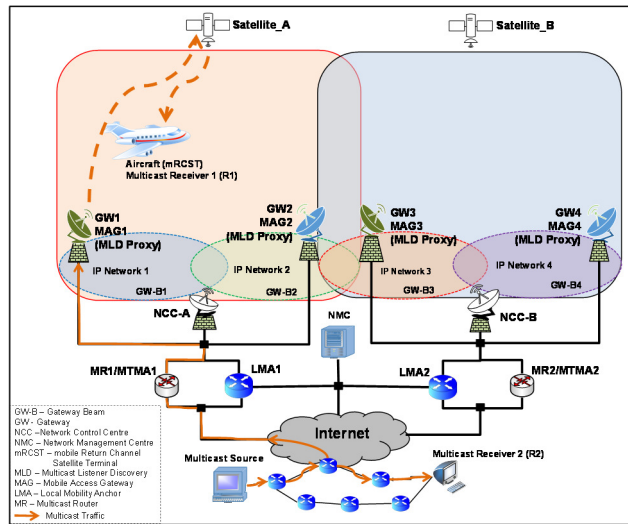


Figure 5.12 Satellite PMIPv6-based IP multicast receiver mobility support –
MAG on Ground Segment

Note should be taken here that the role play by the proposed PMIPv6-based support is mainly at the execution phase of the GW/satellite handover process. GWH occurs when the aircraft (mRCST) enters the overlapping area between GW-B1 and GW-B2. The whole GWH process is divided into 2 phases:

**Phase 1 - Handover detection and decision:**  As the aircraft enters the overlapping area between GW-B1 and GW-B2, it uses its GPS/Galileo receiver to perform the analysis of its position information, then executes handover detection algorithm and sends a handover recommendation to NCC-A with a

specified target beam identity. Upon reception of the handover request, NCC-A using its data base determines that it is a GWH. Signalling between NCC-A, GW1 and GW2 then follows, resulting in the aircraft acquiring satellite bandwidth resources in GW_B2 (target beam) [17]. When GW2 receives the resource request for the aircraft, MAG2 configured in GW2 gets the aircraft's identity. Now knowing the identity of the aircraft (mRCST), MAG2 can then extract the mRCST's HNP, LLA, and the IPv6 address of the LMA serving the aircraft (i.e., LMA1) from the MNs' policy profile store contained in all MAGs within the domain as proposed above.

**Phase 2 – Handover execution:** This begins when the aircraft receives the handover command in a Mobility Control Descriptor carried in a TIMu [17]. Once the aircraft receives this command, it retunes to the target beam and switches to new link provided by GW2/MAG2. Then MAG2 using the mRCST unique LLA extracted from the policy profile, issues the DHCPOFFER message containing an IPv6 address from the mRCST's HNP. When the IP mobility unaware aircraft sees its home network LLA and IPv6 address (from its HNP), it believes that it is in its home network despite the fact that it is now connected to a foreign network. Since the aircraft (mRCST) receives its layer 3 configuration details (IPv6 address) immediately after switching to the target beam, this prevents it from issuing router solicitation message and thus saving satellite bandwidth resources. Following the DHCPOFFER, MAG2 through the mRCST's LLA issues the General MLD Query to learn about the multicast group membership status of the newly connected aircraft. In response, the aircraft sends back the MLD Report containing all multicast groups that it is subscribed to. Once MAG2 receives the MLD Report, it checks its multicast membership table to see whether the requested groups already exist. If they are, then MAG2 simply adds

the aircraft to the list of downstream receivers and then informs NCC-A to make necessary signalling with the OBP and aircraft to ensure that the aircraft receives the multicast traffic. Here, it is assumed that aircraft is the first member of this multicast group in GW-B2. There is a difference in the signalling sequence for the DR and MTMA mode.
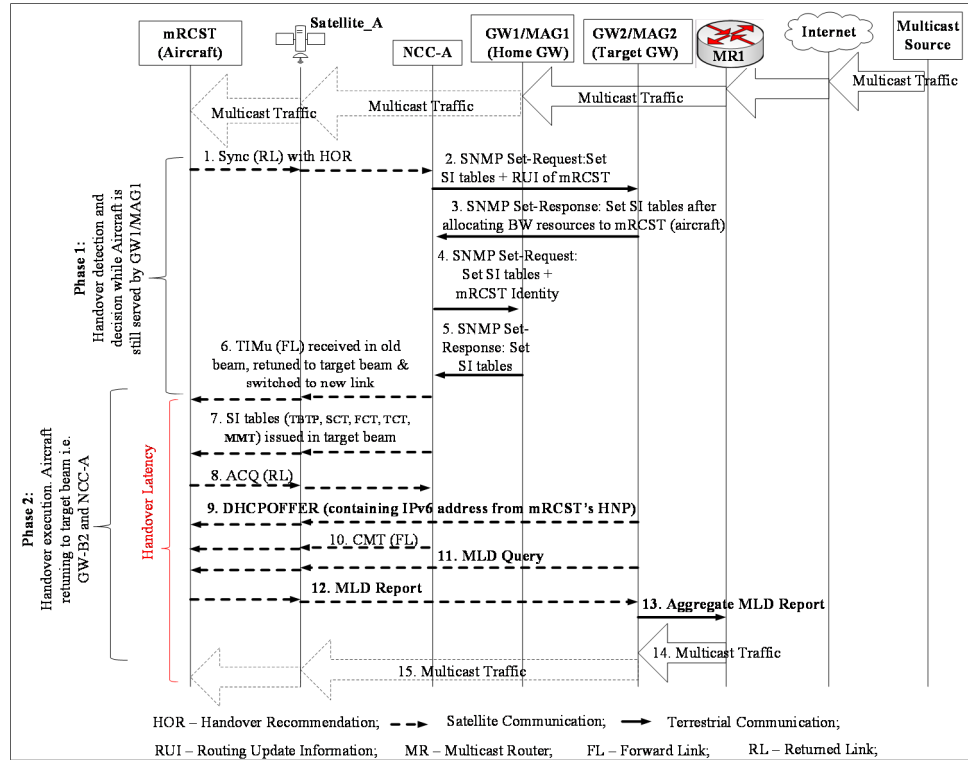


Figure 5.13 GWH signalling sequence for satellite PMIPv6-based IP multicast receiver mobility support – DR mode
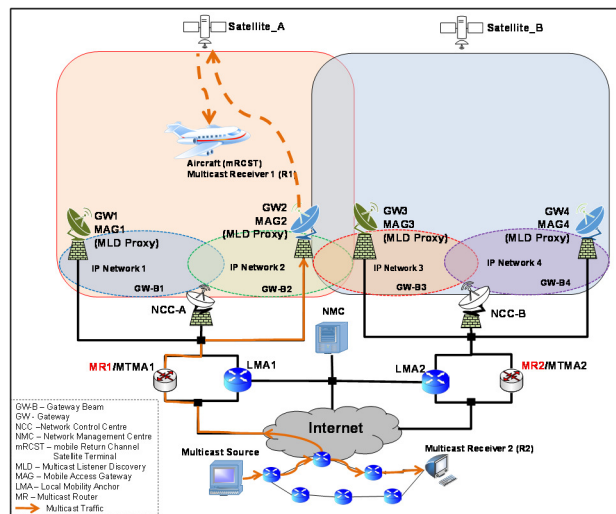


Figure 5.14 Multicast delivery tree to aircraft (mRCST) after GWH - DR mode

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**DR mode:** The aircraft being first member of the group in GW-B2 implies that when MAG2 receives the MLD Report from the aircraft, it will issue an aggregate MLD Report to MR1 for all multicast group subscriptions required to serve all its downstream interfaces as illustrated in Figure 5.13.

Figure 5.14 shows the changes in the multicast delivery tree for the DR mode after the aircraft (mRCST) undergoes a GWH from GW1 to GW2.
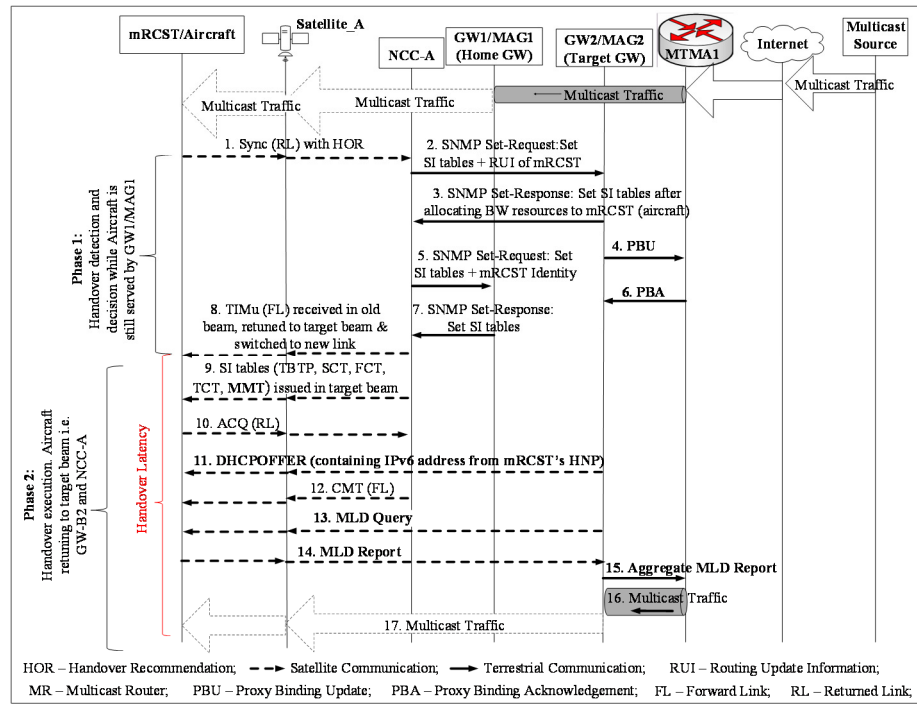


Figure 5.15 GWH signalling sequence for satellite PMIPv6-based IP multicast receiver mobility support – MTMA mode
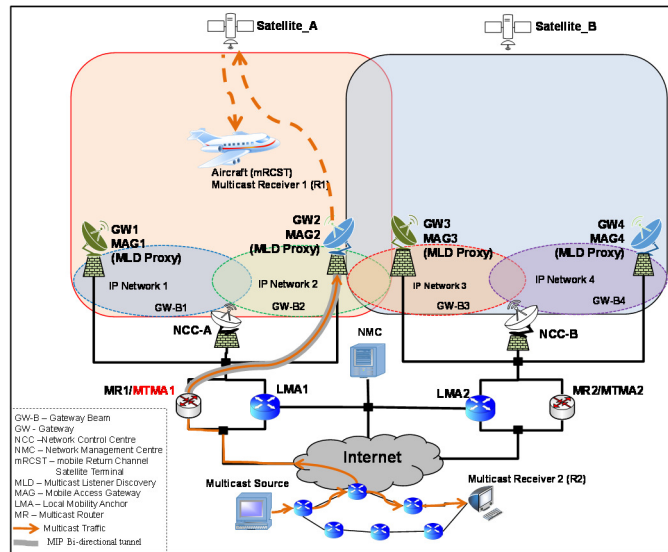


Figure 5.16 Multicast delivery tree to aircraft (mRCST) after GWH - MTMA mode

**MTMA mode:** It is proposed here that each MAG should establish only one multicast tunnel to the MTMA located within the satellite footprint as shown in Figures 5.15 and 5.16 for all its multicast needs. This is very important in this satellite scenario to solve the tunnel convergence problem at the MAGs since mRCSTs from different GW Beams having different home MTMAs and subscribed to the same multicast group can coincidently find themselves under the service area of one MAG. This tunnel could be pre-configured or established dynamically when the MAG subscribed to its first multicast group. In such a situation, when MAG2 receives the MLD Report from the aircraft, it will issue an aggregate MLD Report to MTMA2 as shown in Figure 5.15 for multicast groups which it has not yet subscribed to.

Figure 5.16 illustrates the changes in the multicast delivery tree for the MTMA mode after the aircraft (mRCST) undergoes a GWH from GW1 to GW2.

### 5.4.1.2 Satellite handover (SH)

SH will take place when the aircraft enters the overlapping area between GW Beams 2 and 3. The process and procedure for the SH is very similar to that of GWH described above. The only difference is that the NMC which has the knowledge of the whole global satellite network and NCC-B which controls resources in Satellite_B, are also involved in the handover process (together with NCC-A). This is due to the fact that the target GW here i.e., GW3 belongs to a different satellite (Satellite_B) and therefore its satellite resources are controlled by a different NCC (NCC-B) as shown in Figure 5.12.

**DR Mode:** While Figure 5.17 illustrates the SH signalling sequence, Figure 5.18 shows the new multicast delivery tree from the source to the aircraft after SH for the DR mode.
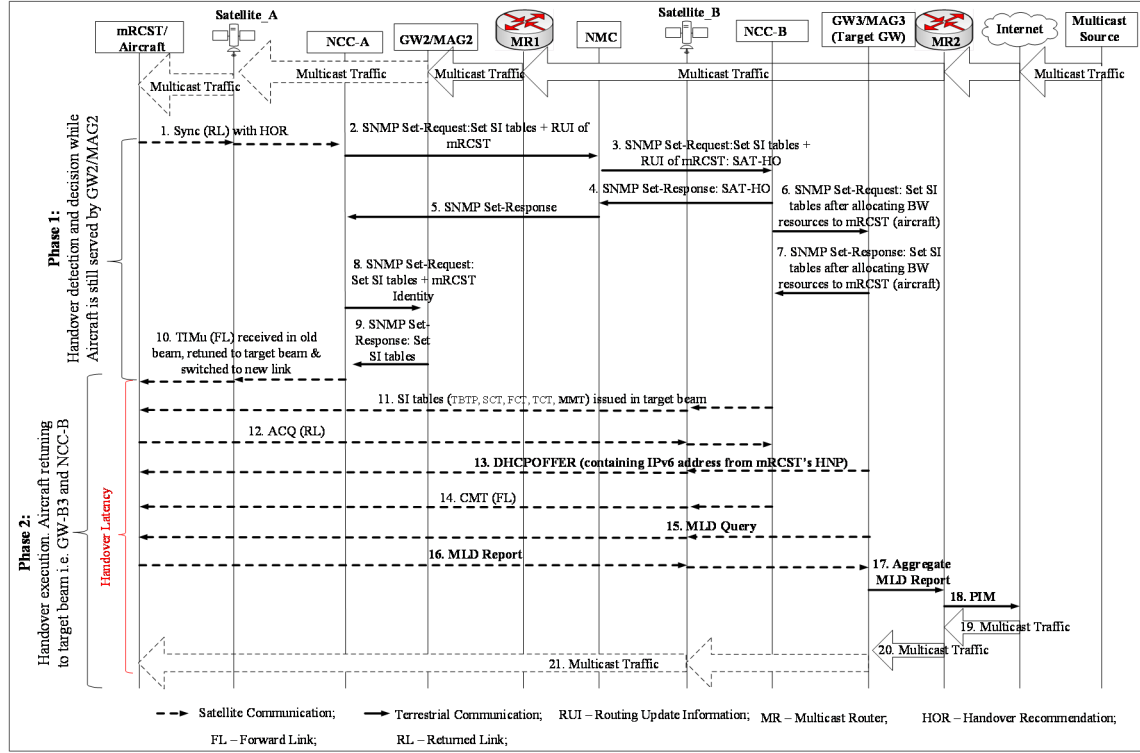


Figure 5.17 SH signalling sequence for satellite PMIPv6-based IP multicast receiver mobility support - DR mode
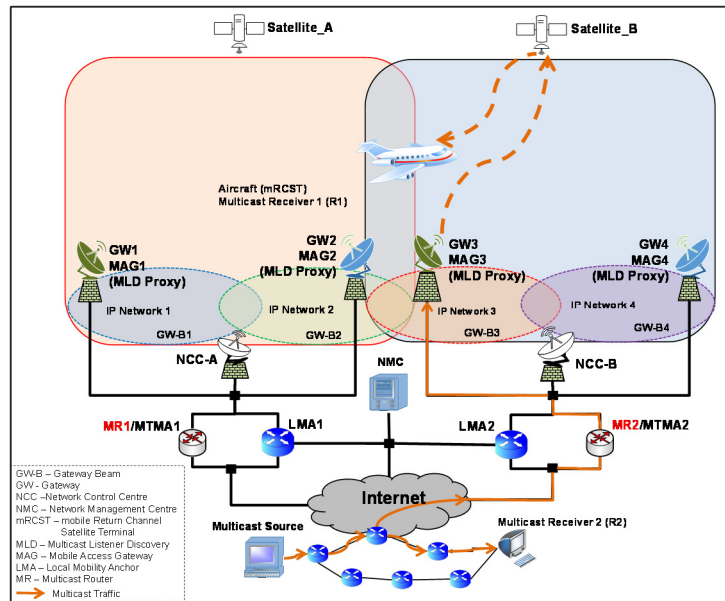


Figure 5.18 Multicast delivery tree to aircraft (mRCST) after SH - DR mode

**MTMA mode:** Figures 5.19 and 5.20 show the signalling sequence and the multicast delivery tree in the MTMA mode at SH respectively.
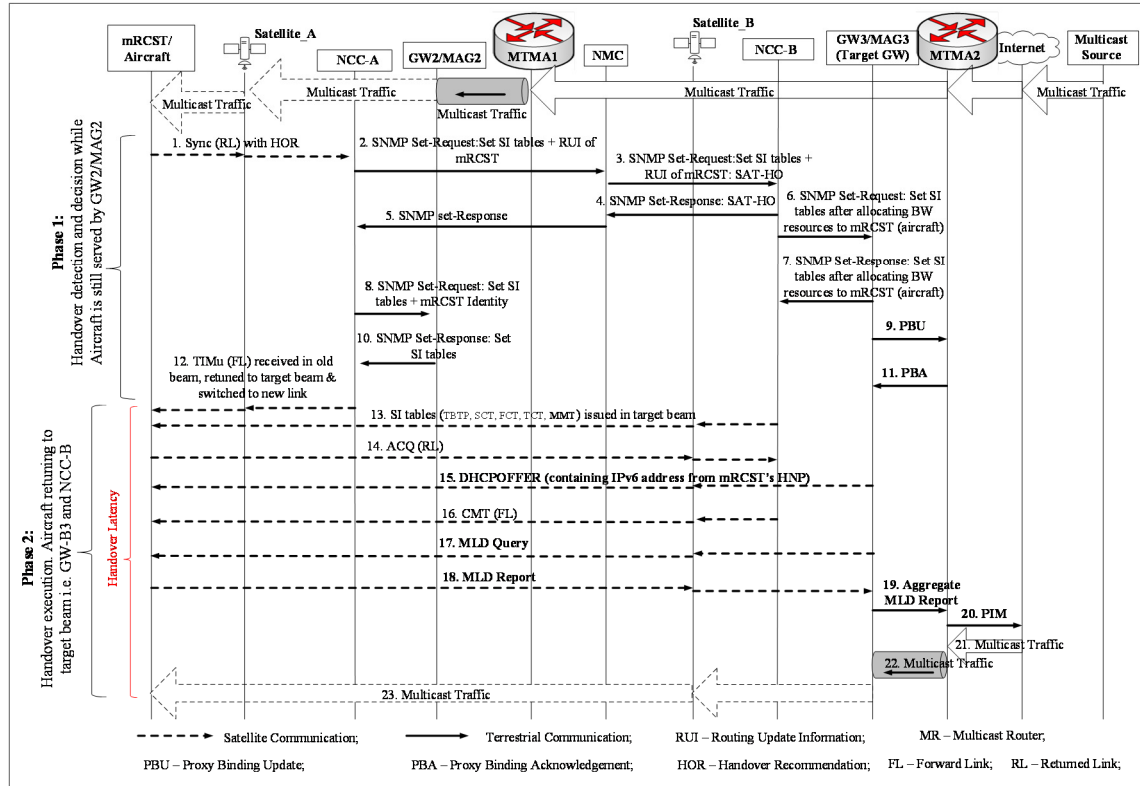


Figure 5.19 SH signalling sequence for satellite PMIPv6-based IP multicast receiver mobility – MTMA mode
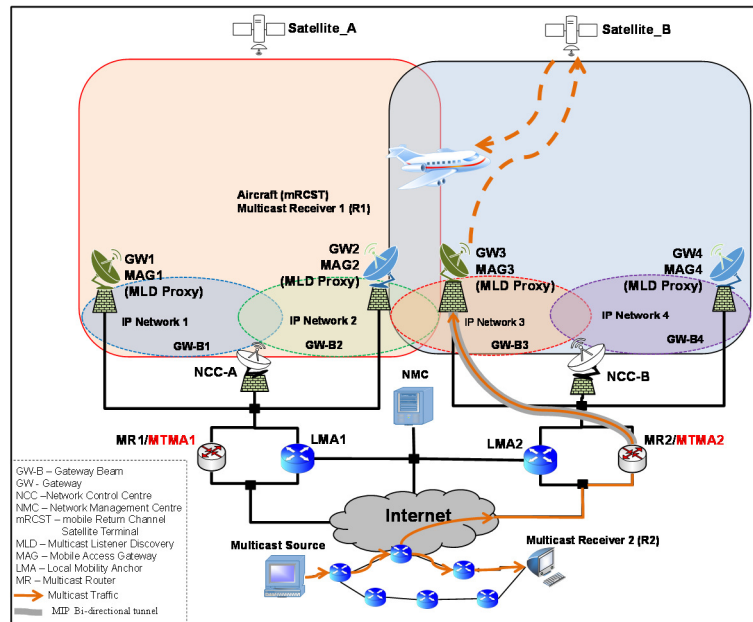


Figure 5.20 Multicast delivery tree to aircraft (mRCST) after GWH - MTMA mode

### 5.4.1.3 Analytical mobility modelling for PMIPv6-based approach with MAG on ground segment

**Gateway handover (GWH)**

**DR mode:** From the signalling sequence in Figure 5.13, the GWH latency for the DR mode of the PMIPv6-based approach with MAG on the ground segment is given by:

$$L_{GWH\_DR}^{PMIP\_MAG\_G} = T_{Tx/Rx} + \sum_{i=7}^{15} D_i \qquad (5.13)$$

Using Equation 4.4 and the GWH latency in Equation 5.13, the number of packets lost due to GWH latency in the DR mode in this approach can be calculated.

Using Figure 5.13, the signalling cost per GWH for the DR mode of the PMIPv6-based approach with MAG on the ground segment, $C_{GWH\_DR}^{PMIP\_MAG\_G}$ is given by:

$$C_{GWH\_DR}^{PMIP\_MAG\_G} = C_{SYNC} + 4C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} + C_{DHCP} + C_{CMT} + 3C_{MLD} \quad (5.14)$$

$$C_{GWH\_DR}^{PMIP\_MAG\_G} = \alpha \sum_{i=1,6-12} h_i M_i + \beta \sum_{i=2-5,13} h_i M_i \qquad (5.15)$$

**MTMA mode:** From Figure 5.15, the GWH latency for the MTMA mode in this approach is given by:

$$L_{GWH\_MTMA}^{PMIP\_MAG\_G} = T_{Tx/Rx} + \sum_{i=9}^{17} D_i \qquad (5.16)$$

The number of packets lost due to GWH latency in the MTMA mode is given by Equation 4.4, where the GWH is that in Equation 5.16.

Similarly, using Figure 5.15 the signalling cost per GWH for the MTMA mode of the PMIPv6-based approach with MAG on the ground segment, $C_{GWH\_MTMA}^{PMIP\_MAG\_G}$ is given by:

$$C_{GWH\_MTMA}^{PMIP\_MAG\_G} = C_{SYNC} + 4C_{SNMP} + C_{PBU/PBA} + C_{TIM} + C_{SI} + C_{ACQ} + C_{DHCP} + C_{CMT} + 3C_{MLD} \qquad (5.17)$$

$$C_{GWH\_MTMA}^{PMIP\_MAG\_G} = \alpha \sum_{i=1,8-14} h_i M_i + \beta \sum_{i=2-7,15} h_i M_i \qquad (5.18)$$

**Satellite handover (SH)**

**DR Mode**: From Figure 5.17, the SH latency for the DR mode of the PMIPv6-based approach with MAG on the ground segment, $L_{SH\_DR}^{PMIP-MAG-G}$ is given by:

$$L_{SH\_DR}^{PMIP\_MAG\_G} = T_{Tx/Rx} + \sum_{i=11}^{21} D_i \qquad (5.19)$$

The number of packets lost due to SH latency in the DR mode is given by Equation 4.4, where the SH latency is that given in Equation 5.19.

Making using of Figure 5.17, the signalling cost per SH for the DR mode, $C_{SH\_DR}^{PMIP-MAG-G}$ is given by:

$$C_{SH\_DR}^{PMIP\_MAG\_G} = \begin{pmatrix} C_{SYNC} + 8C_{SNMP} + C_{TIM} + C_{SI} + C_{ACQ} \\ + C_{DHCP} + C_{CMT} + 3C_{MLD} + C_{PIM} \end{pmatrix} \qquad (5.20)$$

$$C_{SH\_DR}^{PMIP\_MAG\_G} = \alpha \sum_{i=1,10-16} h_i M_i + \beta \sum_{i=2-9,17,18} h_i M_i \qquad (5.21)$$

**MTMA Mode:** From Figure 5.19, the SH latency for the MTMA mode of the PMIPv6-based approach with MAG on the ground segment, $L_{SH\_MTMA}^{PMIP-MAG-G}$ is given by:

$$L_{SH\_MTMA}^{PMIP\_MAG\_G} = T_{Tx/Rx} + \sum_{i=13}^{23} D_i \tag{5.22}$$

The number of packets lost due to SH latency in the MTMA mode is given by Equation 4.4, where the SH latency is that given in Equation 5.22.

Using Figure 5.19, the signalling cost per SH for the MTMA mode, $C_{SH\_MTMA}^{PMIP\_MAG\_G}$ is given by:

$$C_{SH\_MTMA}^{PMIP\_MAG\_G} = \begin{pmatrix} C_{SYNC} + 8C_{SNMP} + C_{PBU/PBA} + C_{TIM} + C_{SI} \\ + C_{ACQ} + C_{DHCP} + C_{CMT} + 3C_{MLD} + C_{PIM} \end{pmatrix} \tag{5.23}$$

$$C_{SH\_MTMA}^{PMIP\_MAG\_G} = \alpha \sum_{i=1,12-18} h_i M_i + \beta \sum_{i=2-11,19,20} h_i M_i \tag{5.24}$$

## 5.4.2 Scheme with MAG on-board satellite (PMIPv6_DR_MAG_sat)

Figure 5.21 shows the satellite-terrestrial network architecture in this scheme used to support IP multicast receiver mobility in a global multi-beam GEO satellite network. The OBPs in each of the satellites are assumed to have layer 3 routing capability.
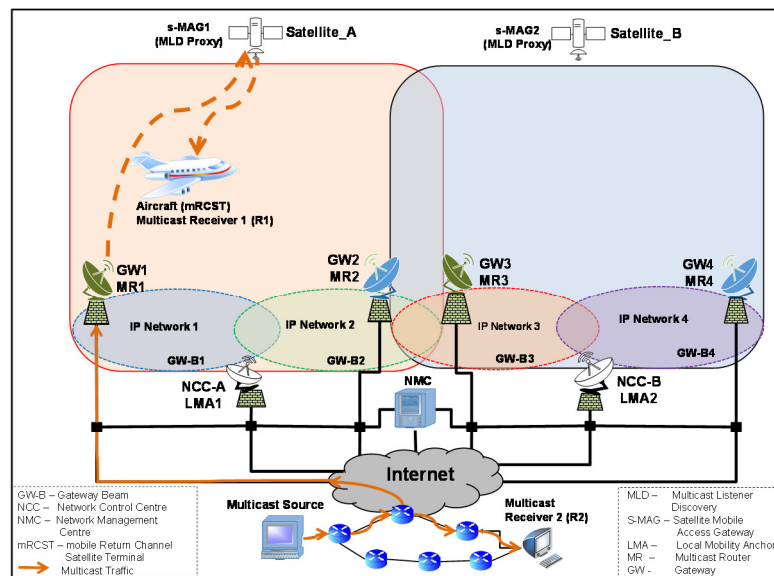


Figure 5.21 Satellite PMIPv6-based IP multicast receiver mobility support –
MAG on-board satellite (s-MAG)

It is proposed that:

- An LMA be configured at each NCC.

- An MAG, i.e., satellite MAG (s-MAG) be configured on-board each satellite (i.e., on the OBP).

- A multicast enabled router be located at each GW.

The OBP and the s-MAG are controlled by the NCC. The main functions of the LMA are to:

- Keep a binding cache entry (BCE) for each aircraft (mobile RCST) that is away from its home network.

- Track aircraft movements and update the location of aircraft in its database using the BCE and that on the s-MAG after every gateway handover (GWH).

- Issue unique LLA and HNP to each aircraft (mRCST) from the aircraft's home GW IP address space.

The LMA located at the NCC in a satellite environment is responsible for tracking the aircraft's movement instead of the MAG as is stated in the standard PMIPv6 protocol [20] because the NCC is the first entity to know about the aircraft's handover request. Since user traffic does not pass through the NCC, the LMA located at the NCC cannot be the topological anchor point for the aircraft's HNPs. So, the LMA here will only perform the mobility management functions. It is proposed that the GW of the GW Beam from where the aircraft originates should serve as the topological anchor point for the aircraft's HNP. Following this proposal, therefore, it implies that whenever the mRCST moves out of its home GW Beam, a bidirectional tunnel will have to be established between the GW in the GW Beam where it is currently located and the mRCST home GW for unicast communication.

The s-MAG on-board the satellite will serve as an MLD proxy where its upstream interface is the s-MAG's interface that links it to the GWs on ground segment while its downstream interface is one which connects the s-MAG and the remote RCSTs/mRCSTs. The s-MAG is proposed to have the following functions:

• Keeps a BCE for each aircraft that is away from its home network.

• Joins multicast groups on behalf of downstream subscribers i.e., acting as an MLD proxy.

• Provides access links to all downstream subscribers.

Table 5.1 Binding cache entry (BCE) kept by LMA & s-MAG

| Aircrafts (mRCSTs) | Beams | GWs | Mac Address | HNP | Link-Local Address | Multicast Subscription |
|---|---|---|---|---|---|---|
| mRCST1 | B1 | GW1 | MAC1 | HOA1 (from HNP1) | LLA1 | (S1, G1), (S2, G5), etc. |
| mRCST2 | | | | | | |

Details of the BCE for each aircraft kept by the LMA and s-MAG are shown in Table 5.1. These include the aircraft's current beam and serving GW, identity (MAC address), home IP address (HOA1) from its HNP, unique LLA1 and multicast subscription details.

### 5.4.2.1    *Gateway handover (GWH)*

When the aircraft (mRCST) shown in Figure 5.21 enters the overlapping area between GW Beams 1 and 2, GWH will take place. During the GWH process, as soon as the GWH command is issued (in TIMu message) following the signalling between the aircraft (mRCST), NCC-A, GW1 and GW2, NCC-A updates the BCEs at LMA1 and s-MAG1 with a proxy binding update (PBU) to match the aircraft's new location.  An update of the s-MAG1's BCE for the aircraft triggers the s-MAG1 to issue Router Advertisement (Rtr Adv) message

to the aircraft, advertising the aircraft's HNP using its unique LLA. When s-MAG1 receives the ACQ burst from the aircraft to NCC-A confirming successful GWH, this triggers the s-MAG1 now acting as the MLD proxy to issue an MLD Query to the aircraft enquiring its multicast membership status.
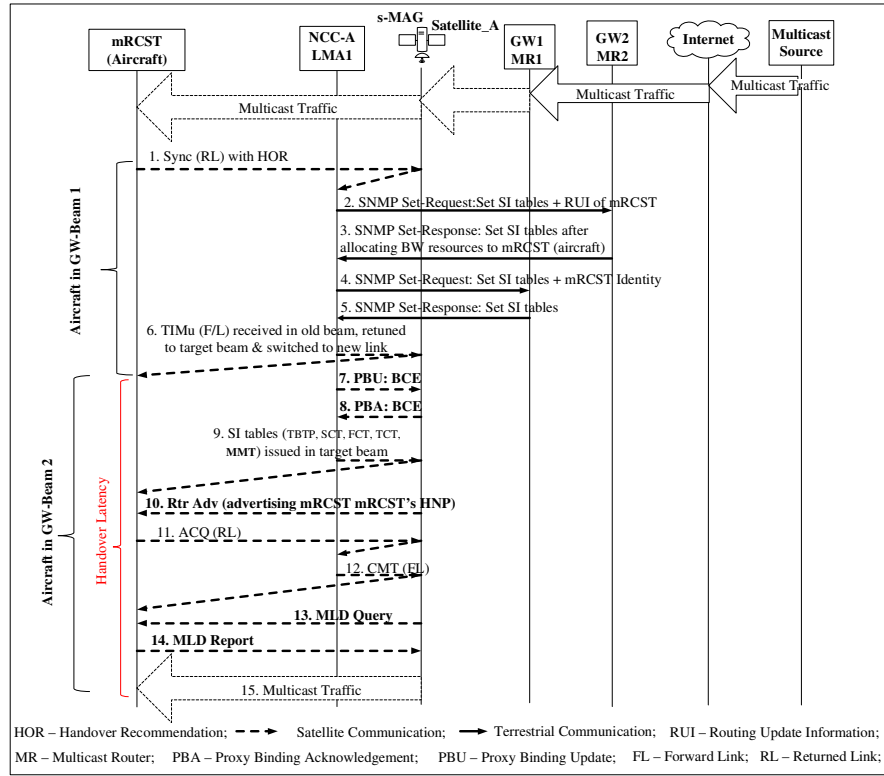


Figure 5.22 GWH signalling sequence for satellite PMIPv6-based IP multicast receiver mobility – MAG on-board satellite

The aircraft then sends an MLD Report to s-MAG1 containing all its multicast groups of interest. Upon reception of this MLD Report, s-MAG1 updates the multicast routing table on its downstream interface and then forwards multicast traffic from all groups of interest to the aircraft.  If new multicast groups that s-MAG1 is not yet a member of are contained in the MLD Report, the s-MAG will then issue an aggregate MLD Report through its upstream interface for new multicast subscription to any of the multicast routers (MR1 or MR2) at the GWs under its satellite footprint. Figure 5.22 shows the signalling sequence for the proposed PMIPv6-based IP multicast receiver mobility support during GWH in satellite networks. Since the aircraft is still using its home IPv6 address (or an

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IPv6 address from its HNP) and the same LLA, it thinks that it is still in its home network despite the fact the aircraft is now in a foreign IP network. This whole process is repeated each time the aircraft moves from one IP network to another within the same satellite footprint.

### 5.4.2.2 Satellite handover (SH)

At satellite handover when the aircraft (mRCST) enters the overlapping area between GW Beams 2 and 3, the handover procedure is very similar to that described above for a GWH. The only difference here is the involvement of the NMC, GW3, NCC-B and s-MAG2 in the handover signalling process as shown in Figure 5.23.
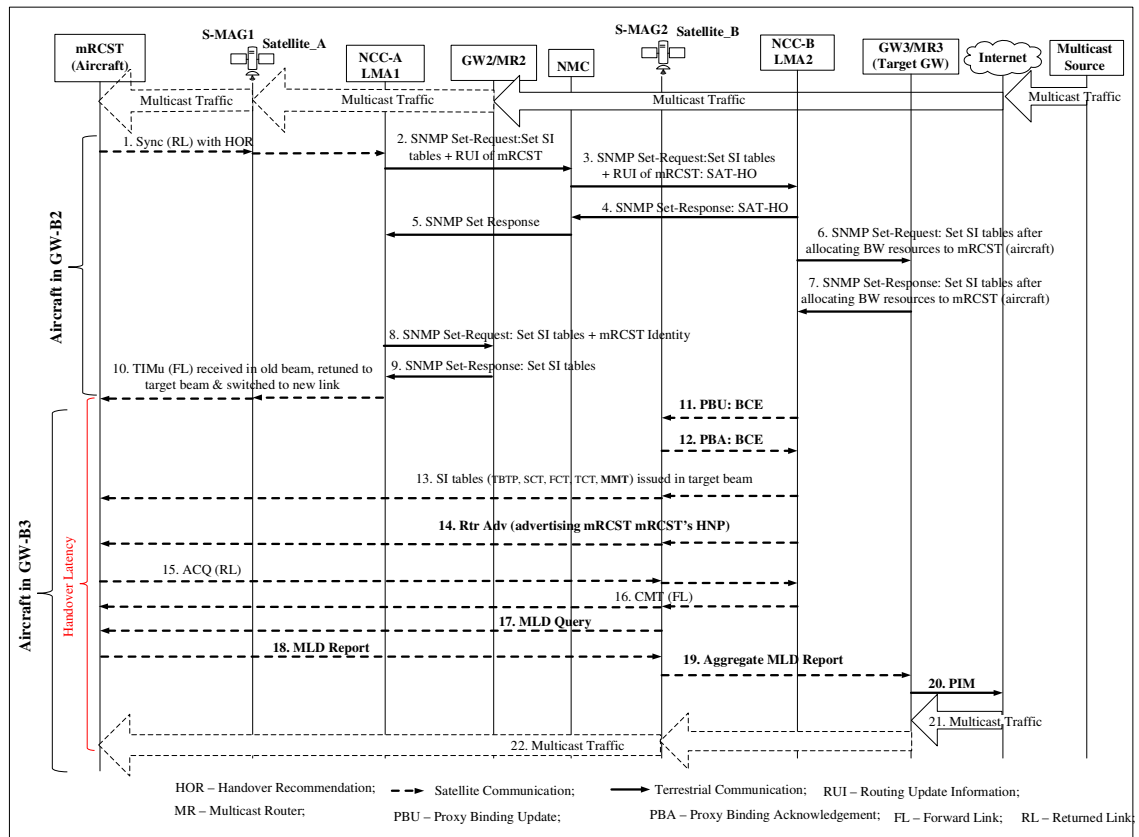


Figure 5.23 SH signalling sequence for satellite PMIPv6-based IP multicast
receiver mobility – MAG on-board satellite

In Figure 5.23, it is assumed that s-MAG2 (in Satellite_B) is not yet a member of the multicast groups that are ongoing in the aircraft and will have to join those

groups. So, when s-MAG2 receives the MLD Report from the aircraft, an aggregate MLD Report is issued to MR3 (at GW3) which is the designated multicast router in GW Beam 3. This will result in the reconstruction of the multicast delivery tree via MR3 (GW3) to the aircraft in the new location as shown in Figure 5.24.
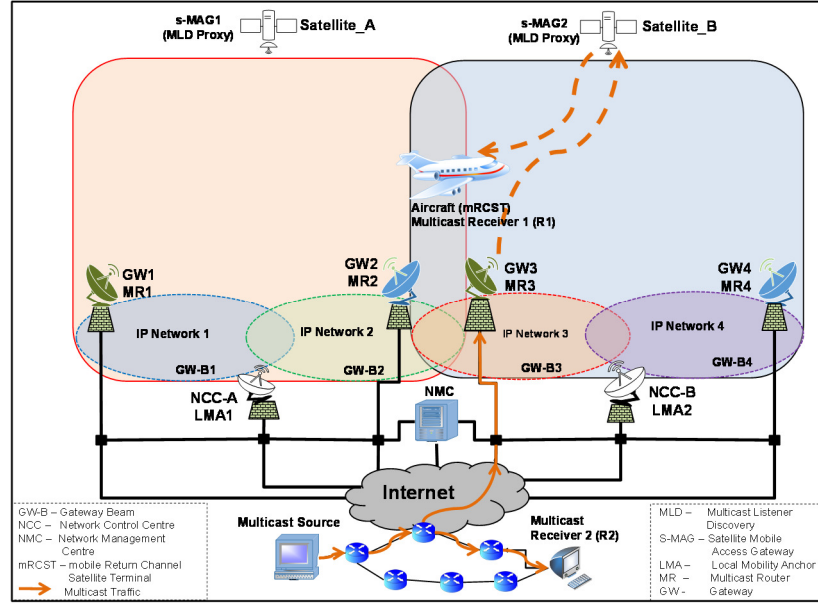


Figure 5.24 Multicast delivery tree to aircraft (mRCST) after SH

### 5.4.2.3 *Analytical mobility modelling for PMIPv6-based approach with MAG on-board satellite*

**Gateway handover (GWH)**

From Figure 5.22, the GWH latency for the PMIPv6 approach with MAG on-board the satellite is given by:

$$L_{GWH}^{PMIP\_MAG\_S} = T_{Tx/Rx} + \sum_{i=7}^{15} D_i \qquad (5.25)$$

Where $D_{R\_Adv}$ = transmission delay due to router Advertisement message.

Using Equation 4.4, where the GWH latency is that given in Equation 5.25, the number of packets lost due to GWH latency in this scheme can be calculated.

From Figure 4.22, the signalling cost per GWH for this scheme is given by:

$$C_{GWH}^{PMIP\_MAG\_S} = \begin{pmatrix} C_{SYNC}+4C_{SNMP}+C_{TIM}+2C_{PBU/PBA}+C_{SI} \\ +C_{R\_Adv}+C_{ACQ}+C_{CMT}+2C_{MLD} \end{pmatrix} \qquad (5.26)$$

$$C_{GWH}^{PMIP\_MAG\_S} = \alpha \sum_{i=1,6-14} h_i M_i + \beta \sum_{i=2}^{5} h_i M_i \qquad (5.27)$$

**Satellite handover (SH)**

From Figure 5.23, the SH latency for the PMIPv6 approach with MAG on-board the satellite is given by:

$$L_{SH}^{PMIP\_MAG\_S} = T_{Tx/Rx} + \sum_{i=11}^{22} D_i \qquad (5.28)$$

The number of packets lost due to SH latency in this scheme is given by Equation 4.4, where the SH latency is that in Equation 5.28.

From Figure 5.23, the signalling cost per SH for this scheme is given by:

$$C_{SH}^{PMIP\_MAG\_S} = \begin{pmatrix} C_{SYNC}+8C_{SNMP}+C_{TIM}+2C_{PBU/PBA}+C_{SI} \\ +C_{R\_Adv}+C_{ACQ}+C_{CMT}+3C_{MLD}+C_{PIM} \end{pmatrix} \qquad (5.29)$$

$$C_{SH}^{PMIP\_MAG\_S} = \alpha \sum_{i=1,10-19} h_i M_i + \beta \sum_{i=2-9,20} h_i M_i \qquad (5.30)$$

## 5.5 Comparison of the proposed IP multicast receiver mobility support schemes

Table 5.2 shows a comparison of the proposed IP multicast receiver mobility solutions against some key parameters. The mobility type indicates whether the proposed solution is a host-based solution where the mRCST is required to be an IP mobility aware node or a network-based solution where the mRCST remains IP mobility unaware node just like any fixed standard IP node. The

mobility type has an implication on whether the mRCST's software needs modification or not. As shown in Table 5.2, all host-based solutions required software modification to support IP mobility while the network-based solutions do not.

Table 5.2 Comparison of proposed IP multicast receiver mobility solutions

|  |  | IP Mobility entities | Mobility Type | mRCST software modification | Handover latency | Optimized routing after handover | Use of IP tunnel |
|---|---|---|---|---|---|---|---|
| SHS | | HA, FA | Host | Yes | High | No | Yes |
| SRS | | LMR | Host | Yes | Low | Yes | No |
| Multiple Interface | | LMR | Host | Yes | Negligible | Yes | No |
| PMIPv6 - MAG on ground segment | DR Mode | LMA, MAG, MR | Network | No | Low | Yes | No |
| | MTMA Mode | LMA, MAG, MTMA | Network | No | Medium | No | Yes |
| PMIPv6-MAG on board satellite | | LMA, s-MAG, MR | Network | No | Low | Yes | No |

The handover latency for SHS-based approach is described as high due to the effects of MIP protocol implementation where the mRCST is required to obtain an IP address in visited network, register this IP address to its HA and an IP tunnel established between HA at home GW and FA at target GW. The handover latency for the MTMA mode of PMIPv6 with MAG on ground segment is described as medium. Though this approach is similar to SHS-based approach, the mRCST does not need to obtain an IP address from the visited network and all IP signalling is done by wired nodes on the terrestrial portion of the network. Therefore, this makes the handover latency in MTMA mode smaller compared to that in SHS-based approach. In the SRS-based, DR mode of PMIPv6 with MAG on ground segment and PMIPv6-based with MAG on board satellite approaches, the handover latency is described as low. This is because in these approaches, the mRCST uses the local multicast

infrastructure in the visited network and does not have to pass through its home network to receive multicast traffic. The negligible handover latency in the multiple interface-based approach is due to the fact that throughout the handover period the reception of multicast traffic by the multi-homed mRCST does not stop. The is because the second interface joins the multicast groups and starts receiving traffic before the old interface loses connection as described in Section 5.3. As shown in Table 5.2, if a scheme uses IP tunnel through home network to serve an mRCST at a foreign network, it implies that routing after handover is not optimized.

## 5.6  Summary

This chapter presents the proposed solutions to IP multicast receiver mobility problems during a gateway/satellite handover in a LOS scenario as the mobile receiver moves across different beams of the same interactive satellite network. Five different schemes based on home subscription, remote subscription, multiple interface (multi-homing) and PMIPv6 concepts have been proposed for IP multicast receiver mobility support. Detailed account of each scheme with illustrative diagrams, network architecture and signalling sequence during GW/satellite handovers have been given. A comparison against some key mobility parameters of the five proposed schemes for receiver mobility support is also given. Analytical mobility modelling for each of the proposed schemes for GWH/SH is given.

In new generation of satellite systems with OBP, a full-mesh, single-hop communication between two or more satellite terminals/gateways is supported. This means that mobile satellite terminals might not only be IP multicast receivers but also, could be mobile IP multicast sources. As discussed in

Chapter 3 above, support for mobile multicast sources is quite different from that of mobile receivers especially in SSM. The next chapter, presents a detailed account of the proposed IP multicast source mobility support scheme in SSM for a multi-beam satellite network.

# 6 PROPOSED IP MULTICAST SOURCE MOBILITY SUPPORT SCHEME IN SSM FOR A MULTI-BEAM SATELLITE NETWORK

In this chapter, a novel RS-based scheme for IP multicast source mobility support in SSM for GWH in a multi-beam satellite network is proposed. Just like in Chapter 5, the proposed scheme is implemented on the reference satellite network architecture shown in Figure 4.1 of Chapter 4 for a LOS scenario. Analytical mobility model as well as simulation using Network Simulator-3 (NS-3) [82] of the proposed scheme are presented.

## 6.1 The M3U-based scheme for source mobility support in SSM

Up till now RS-based approaches have been used to support IP multicast source mobility only in any-source multicast (*, G). The proposed approach here introduces Multicast Mobility Management Unit (M3U) which enables the RS-based approach to support IP mobile multicast sources within a regenerative satellite network in SSM. The support for multicast source mobility within a satellite network in general and for SSM in particular coupled with the fact that the RS-based approach can be made to support source mobility in SSM, have made this proposed scheme quite a novel idea.

In a satellite environment where bandwidth resources are very expensive, SSM is the most suitable form of IP multicast where receivers request to receive multicast data only from the sources they are interested in. With this understanding, the IP multicast source mobility support scheme proposed here is that for SSM. In order to develop an effective solution to support source mobility in SSM, the following general assumptions have been made:

- The satellite terminals like the regenerative satellite gateways (RSGW), RCSTs and mRCSTs are assumed to be IP nodes with layer 3 capability.

- The regenerative OBP which provides on-board connectivity between different beams has layer 2 capability (switch) and can replicate multicast packets at layer 2

- The NCC will act as the IGMP Querier for the satellite network in addition to its normal functionalities.

- The NCC enables the establishment of point-to-multipoint connection between mobile source (mRCST) and all listening RCSTs/RSGWs.

- All RCSTs function as IGMP Proxy, i.e., IGMP Router and Querier on its user interface (interface towards the internal LAN) and an IGMP Host on the satellite interface.

- All RCSTs, mRCSTs, RSGWs and terrestrial multicast receivers are mobility-aware nodes and can process mobility instructions.
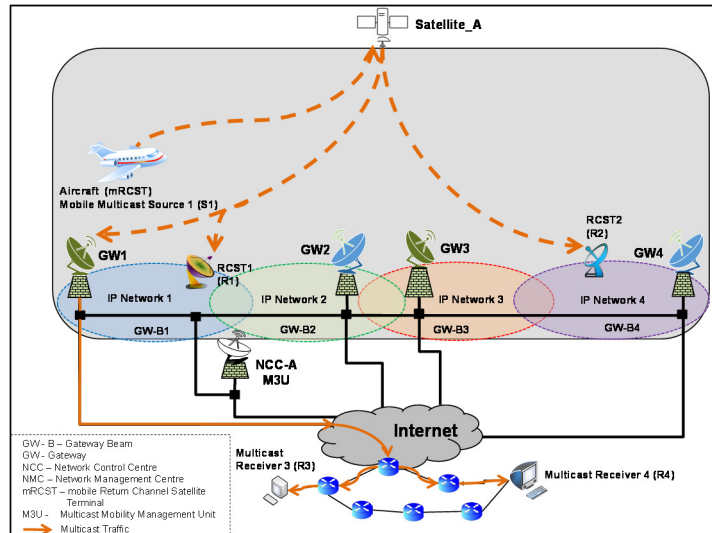


Figure 6.1 Mobile IP multicast source (aircraft) at home network

Figure 6.1 shows the network architecture, where the mobile IP multicast source i.e., the aircraft equipped with the mRCST is located in its home network at GW Beam 1. This mobile multicast source (S1) is sending traffic to the

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multicast group 1 (G1). RCST1 located at GW-B1, RCST2 at GW-B2 and R3 and R4 both located in the Internet, have all subscribed to the multicast channel (S1, G1) and are receiving multicast traffic from the aircraft as illustrated in Figure 6.1.

Table 6.1 Proposed new messages

| | Service Interface Update Message (SIUM) | Source Handover Message (SHM) | Channel Update Message (CUM) | CUM Notification Message (CNM) |
|---|---|---|---|---|
| **Type** | Multicast | Unicast - Internal Signaling | Multicast | Unicast |
| **Source** | NCC | M3U | Mobile source | Mobile source |
| **Destination** | All SSM RCSTs or RSGWs Receivers + Mobile source | NCCu | ALL SSM Receivers | NCC |
| **Content** | IP addresses of mobile source in both old and target GWs. Instructions to update source list (add mobile source new IP address) in service interface of specified channel. | A Request to establish point-to-multipoint link between mobile source (new CoA) & all listening RCSTs/GWs (from previous tree) | IP addresses of mobile source in both old and target GWs. Instructions for receivers to update channel subscription to new mobile source IP address | Acknowledgement of SIUM reception and notification that CUM has been issued |
| **Purpose** | To avoid each listening RCST/GW from sending IGMP Join Report on to the satellite air interface after receiving channel re-subscription from SSM receivers behind RCSTs/GWs. | To establish new delivery tree to all listening RCSTs/GWs without them sending any IGMP join report to new channel (CoA, G). To reduce tree establishment time. | For all SSM end receivers to update their channel subscription from (S, G) to CoA, G) For Internet receivers to start building the new delivery tree to the target GW. | To ensure that CUM is issued through old link before mobile source switches to new link. |

Since GW1 is the home GW for the aircraft, then the multicast router in GW1 will serve as the designated multicast router for the mobile source (aircraft). Therefore, multicast receivers in the terrestrial network as shown in Figure 6.1 are served through GW1. The mobile source sends out just one copy of multicast traffic and the OBP replicates the traffic, one for each of the two beams that have interested receivers.

A new M3U responsible for control plane signalling to provide mobility support for multicast sources is proposed. This new M3U entity located at the NCC is equipped with the following:

- A database of all mRCSTs, each identified by its physical (MAC) and IP addresses.

- A 'Message Chamber' which can issue the new proposed signalling messages shown in Table 6.1.

Four new types of messages shown on Table 6.1 have been proposed. It is proposed that any mRCST should be able to issue CUM and CNM after receiving SIUM from the NCC during GWH. Details of these messages are given in Table 6.1. GWH takes place when the mobile source enters the overlapping area between GW-B1 and GW-B2.

Figure 6.2 shows the proposed signalling sequence to support IP multicast source mobility for SSM at GWH. This signalling sequence contains the proposed new messages integrated into the standard GWH signalling sequence as described in the DVB-RCS specification in [17]. NCC-A acting as satellite IGMP querier keeps control of the multicast groups and also builds the SSM tree based on the on-board connectivity between different beams. When NCC-A receives an IGMP join report for SSM, the M3U checks the source-list to see if

some sources are mRCSTs. If some sources are identified as mRCSTs, the M3U will keep a record of them in its database. Periodically, NCC-A sends out the Multicast Map Table (MMT) [11] to all multicast receivers within the satellite network. The MMT which contains the list of IP multicast addresses each associated with a specific Program Identifier (PID) enables listening RCSTs/GWs to receive multicast traffic from groups which they have subscribed to.
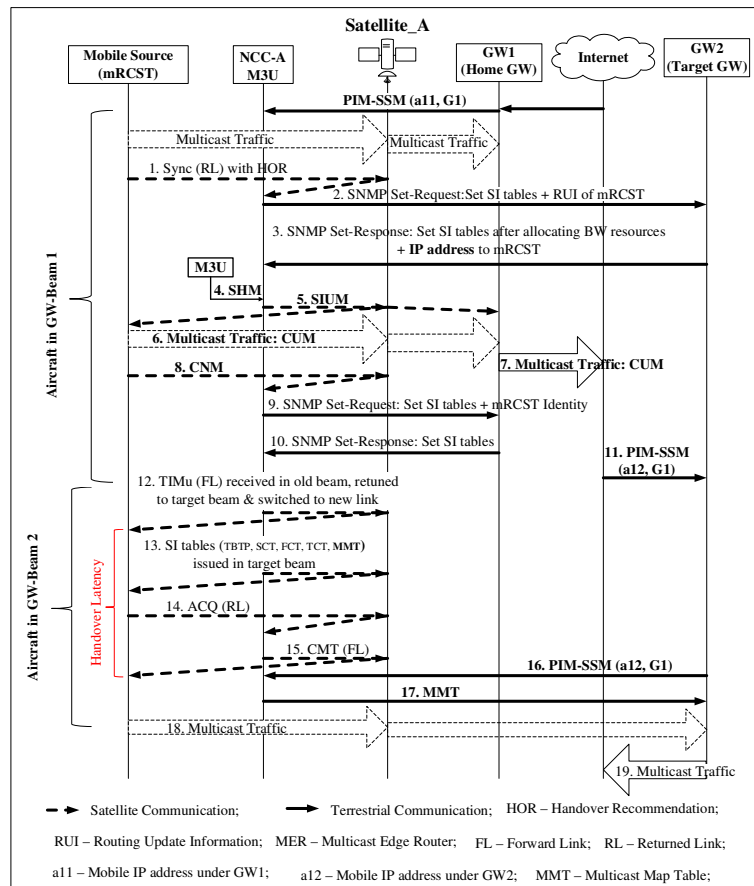


Figure 6.2 Signalling sequence at GWH for the IP mobile multicast source

As shown in step 4 of the signalling sequence in Figure 6.2, once NCC-A receives the SNMP Get-Response message from target GW (GW2) containing the new IP address of the aircraft (mobile source), the M3U immediately issues the SHM to the NCC unit (NCCu). The SHM requests the NCCu to establish a point-to-multipoint link between the mobile source and all the listening

RCSTs/GWs (from knowledge of previous tree). SHM is internal signalling within the NCC (i.e., between M3U and NCCu). Upon reception of SHM, the NCCu will make the resources available and then instructs the OBP to establish the required connections. This is immediately followed by the M3U issuing the SIUM to all RCSTs/GWS involved in this particular channel, including the mobile source. The SIUM contains both the mobile source old and new IP addresses in the old and new GWs, respectively. The SIUM also contains instructions for all listening RCSTs/GWs to update source list (add mobile source new IP address) on the service interface for requesting IP multicast reception [3]. This will create a new channel that contains the mobile source new IP address (CoA i.e., a12 in Figure 6.2) under the target GW (GW2). This action ensures that subsequently, when the RCSTs/GWs receive IGMP join Report from downstream receivers for this new channel, no IGMP report will be sent to the satellite air interface since the channel already exist in the RCST/GW multicast routing table. The creation of this new channel by the SIUM is possible in satellite networks because the NCC knows:

- The MAC and IP addresses of all active RCSTs/GWs,

- The newly acquired IP address of the mobile source,

- All RCSTs/GWs that are members of the channel involving the mobile source.

Therefore, the NCC can enable the establishment of a point-to-multipoint connection between the mobile source and all the listening RCSTs/GWs directly. This reduces the amount of traffic on the satellite air interface, thus saving scarce and expensive satellite bandwidth resources. The PID of the channel may remain the same. Upon reception of SIUM, the mobile source

immediately issues CUM, i.e., CUM is triggered by reception of SIUM. The CUM is sent just like any multicast user traffic by the mobile source through source-specific tree in order for it to reach all SSM receivers, especially those outside the satellite network. The issuing of CUM triggers the mobile source to also issue CNM to the NCC. The reception of CNM by NCCC indicates two important pieces of information, namely that SIUM was successfully received by the mobile source and that CUM has been issued. This is very crucial here because if the NCC executes step 8 in Figure 6.2 when the mobile source has not received SIUM and therefore has not issued CUM, then contact with the receivers outside the satellite network will be lost. This is because the execution of steps 8 - 11 in Figure 6.2, will result in:

- Satellite resources used by the mobile source in current beam being cut off.

- The mobile source will retune and switch to the target beam.

- The multicast traffic from the new channel (a12, G1) after GWH (due to the mobile source IP address change at GWH) will not reach receivers outside the satellite network since they subscribed to the old channel (a11, G1). The a12 and a11 represents the mobile source IP addresses in the target beam (GW-B2) and old beam (GW-B1) respectively.

So, if steps 8 -11 are executed when CUM has not been issued by mobile source, there will no way to inform multicast receivers outside the satellite network to update their subscription to the new channel (a12, G1). Note should be taken here that the NCC/M3U or the mobile source may not know the identity of the receivers outside the satellite network. This implies that during the GWH process, multicast receivers outside the satellite network can only be

reached by the mobile source through the old GW (GW1) before the mobile source switches links to target GW.
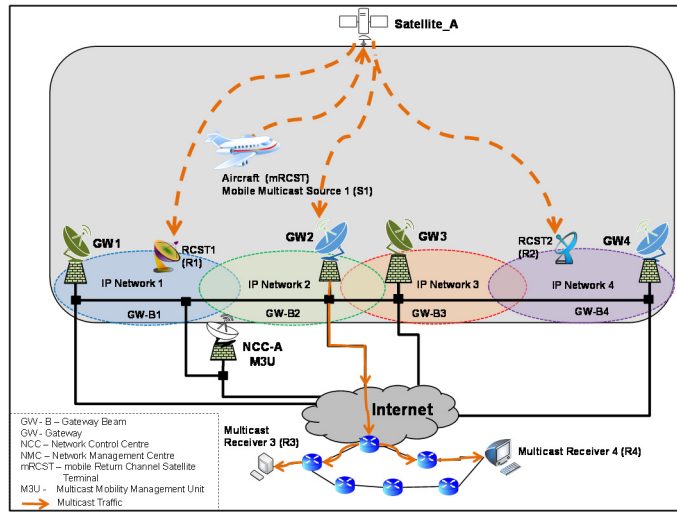


Figure 6.3 Mobile source now at foreign network (GW-B2)

To reach them, the mobile source will have to multicast control messages (CUM in this case) just like the normal multicast packets which eventually will reach all subscribed group members. Therefore, it is imperative that CUM is issued before step 8 in Figure 4.26 is executed. Upon reception of CUM by SSM receivers in the Internet, a new SSM delivery tree construction to the target GW is triggered as shown in Figure 6.3 (compared to that in Figure 6.1). Figure 6.3 shows the mobile source now in GW-B2 after a successful GWH. If the Target GW was not a member of the old multicast channel, it will issue a PIM-SSM Join [7] to NCC as soon as it gets the updated channel subscription request (PIM-SSM Join) from receivers in the Internet. The target GW now becomes part of the mesh receivers within the satellite network as it assumes the responsibility of serving receivers in the Internet. But if the target GW was already a member, a multicast reception state will simply be created against the interface upon which the PIM-SSM Join was received.

When the SSM receivers in the LAN behind the listening RCSTs receive the CUM, they will update their channel subscription by issuing unsolicited IGMP join report towards the RCST. Upon reception of the IGMP join report, the RCST (IGMP Proxy) will check its multicast routing table to see whether the requested channel already exist. On checking, the RCST will discover the existence of the requested channel in its multicast routing table thanks to the action of SIUM as described above. Therefore, this will prevent the RCST from issuing IGMP join Report onto the satellite air interface, thus saving satellite bandwidth resources.

### 6.1.1  M3U operation and processing
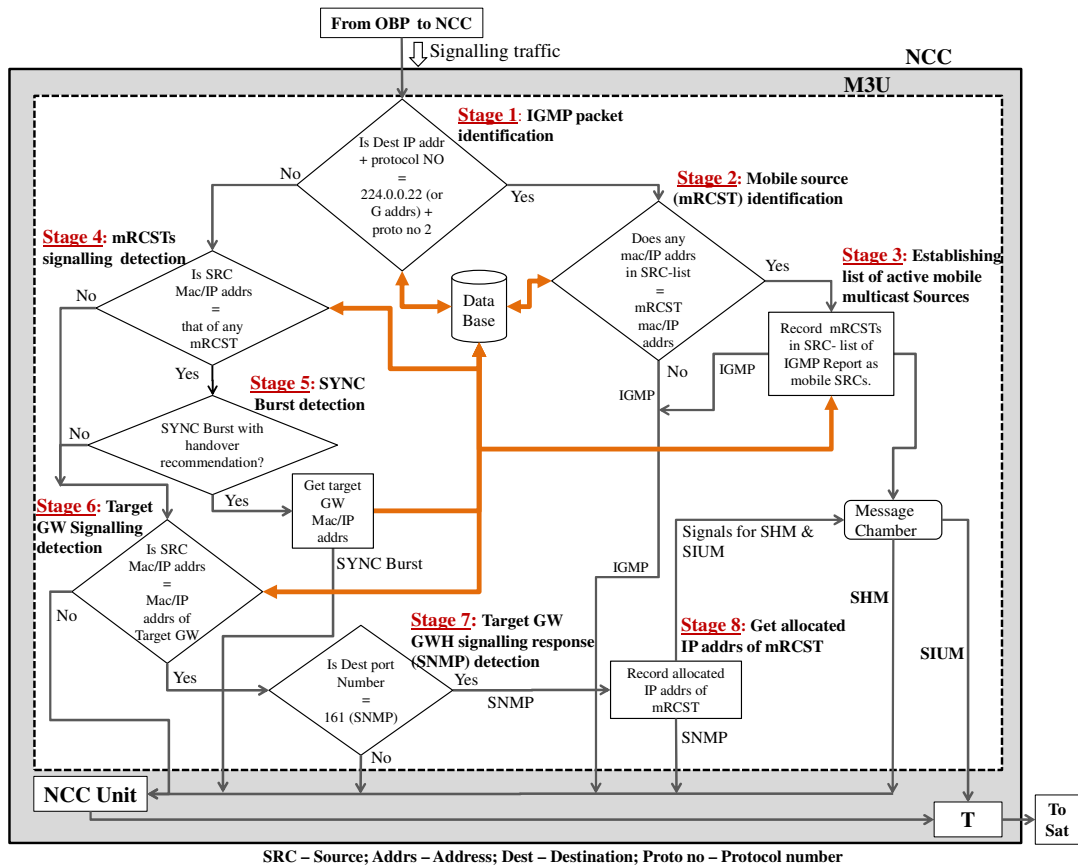


Figure 6.4 M3U source mobility support processing for SSM during GWH

Figure 6.4 shows the processing flowchart of the control plane information (signalling traffic) through the M3U. For correct signalling to take place, M3U must be able to identify the following:

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- An IGMP packet (i.e., an unsolicited IGMP join report) in order to add the requesting RCST/GW on the delivery tree.

- Mobile multicast source or receiver and differentiate between the two.

- GWH request and target GW.

- Target GW signalling (SNMP) to get the mRCST newly allocated IP address.

### 6.1.1.1      IGMP Packet Identification

When the NCC receives any signalling traffic, the M3U checks the IP destination address and the protocol number on the IP packet to determine whether it is an IGMP packet. If the IP destination address is equal to 224.0.0.1 (for IGMPv1&2) or 224.0.0.22 (for IGMPv3) and the protocol number is equal to 2, then the IP packet is an IGMP packet and is sent to Stage 2 in Figure 6.4, otherwise, it is sent to Stage 4

### 6.1.1.2      mRCST identification

In Stage 2 of Figure 6.4, the task is to determine whether the source-list in the received IGMP packet contains any mobile source (mRCST). The M3U  checks the IP addresses contained in the source-list against the list of mRCSTs in the database to find out whether the requesting RCST/GW is requesting to receive multicast traffic from a mobile source (mRCST) or not. If source-list contains any mRCSTs, then those mRCSTs are mobile multicast sources. The mRCSTs contained in source-list of received IGMPv3 join report are then recorded in Stage 3 as mobile sources based on the analysis in Stage 2 given above. Finally, the IGMP packet is then forwarded to the NCC (querier).

### 6.1.1.3      mRCST signalling detection

At Stage 4, the main task is to separate signalling traffic coming from any mRCST from those of fixed RCST. To do this, the M3U has to check the source

mac/IP address of the signalling traffic received against the database to establish whether it is coming from an mRCST or not. All signalling traffic coming from any mRCST is sent to Stage 5 for close examination to find out whether they are SYNC burst containing handover recommendation while the rest is sent to Stage 6. Once it is confirmed that it is a SYNC burst in Stage 5, with handover recommendation, then the target GW identity can be determined and its MAC/IP address recorded. Following this process, a table of mRCST versus target GW (identified by their MAC/IP addresses) can be established for all mRCSTs in the whole interactive satellite network. This now prepares the M3U to expect GWH signalling response from the target GW.

### 6.1.1.4 Target GW response detection and the mRCST allocated IP address recording

Now, knowing the identity of the target GW (from the handover recommendation), signalling traffic from the target GW can be tracked within the NCC to find out whether it is the response to the GWH request initiated by the NCC. This is very important because earlier knowledge of the allocated IP address to the mRCST by the target GW contained in this GWH response is very crucial here for further signalling.

Therefore, Stage 6 examines the source MAC/IP address of all signalling traffic to see whether it is that of the target GW. If it does, then the packet is sent to Stage 7, if not, then to NCCu. In Stage 7, the destination port number of the packet is checked to find out whether it is equal to that of SNMP (i.e., 161), the signalling protocol used in GWH as specified in [17]. If this is true, then, the packet is sent to Stage 8, where the allocated IP address to the mRCST in the target beam is extracted and recorded. Once the M3U is aware of the mRCST's

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IP address in the target beam, it immediately issues the SHM to the NCCu, requesting for a point-to-multipoint connection establishment as explained above. It is therefore imperative that the M3U gets the mRCST's IP address in the target beam as soon as possible in order to minimise the multicast handover latency during GWH. If the destination port is not equal to 161, then, the packet is simply sent to the NCCu for normal signalling. The issuing of SHM is immediately followed by that of SIUM to all mesh SSM receivers including the mobile source as explained above.

### 6.1.2  Uniqueness and importance of the proposed scheme

The uniqueness about this proposal are:

- The new re-subscription mechanism of the satellite receivers and gateways to the new multicast channel (CoA, G) after every GW handover without the issuing of IGMP join report over the satellite air interface.

- The absence of encapsulation (tunnelling) and triangular routing paths throughout the system.

If all the listening RCSTs/mRCSTs were to individually issue IGMP join reports to the satellite air interface for re-subscription after every GWH, the total number would be enormous and will put a lot of strain on the satellite bandwidth resources. The proposed solution will significantly save satellite bandwidth resources and therefore money.

### 6.1.3  Analytical mobility modelling for M3U-based approach

From Figure 6.2, the GWH latency for the M3U-based solution for IP multicast source mobility support scheme is given by:

$$L_{S\_GWH}^{M3U} = T_{Tx/Rx} + \sum_{i=13}^{15} D_i \qquad (6.1)$$

Also from Figure 6.2, the signalling cost per GWH for the M3U –based scheme is given by:

$$C_{S\_GWH}^{M3U} = \begin{pmatrix} C_{SYNC} + 4C_{SNMP} + C_{SIUM} + C_{CUM} + C_{CNM} + C_{PIM-SSM} \\ + C_{TIM} + C_{SI} + C_{ACQ} + C_{CMT} + C_{PIM-SSM} + C_{MMT} \end{pmatrix} \qquad (6.2)$$

$$C_{S\_GWH}^{M3U} = \alpha \sum_{i=1,5-8,12-15} h_i M_i + \beta \sum_{i=2,3,7,9-11,16,17} h_i M_i \qquad (6.3)$$

The packet delivery cost for each multicast packet to any receiver within the satellite network (i.e. mesh communication) for the M3U scheme is given by Equation 4.23.

The packet delivery cost before and after GWH under this scheme within the satellite network will remain the same. This is because the number of hops traversed within the satellite network by each packet before and after GWH are exactly the same. Therefore, the packet delivery cost per multicast session for the M3U scheme before and after GWH is given by Equation 4.25.

## 6.2  Simulation of the M3U-based approach

The main objective of simulating the proposed M3U-based scheme is to investigate the effect on the handover performance when different numbers of mobile multicast sources are requesting for handover at the same time. Network Simulator-3 (NS-3) [82] is used for the simulation of the M3U-based scheme. It should be noted that this simulation is for the scenario where both the mobile multicast source and the multicast receivers are all within the satellite network (i.e., satellite mesh communication).

## 6.2.1 Network simulator 3 (NS-3)

NS-3 is a free software and discrete-event network simulator designed to provide extensible network simulation platform primarily for the research and education communities. NS-3 which is mainly used on Linux systems, is made up of a set of libraries which can be combined together and also, with other external software libraries during a simulation. In NS-3, the simulator is entirely written in C++, with optional Python bindings. This implies that NS-3 users are expected to work using C++ and/or python software development tools from the command line interface.

## 6.2.2 Implementation of M3U on NS-3 for source mobility support in SSM

Currently in NS-3, there is no support for IP multicast dynamic membership (i.e., IGMP or MLD) where an IP node can join or leave a multicast group. In NS-3 reception of multicast datagrams was only possible by simply enabling static multicast routing on an interface leading to receiver or on a system as whole. This makes it impossible for a receiver to dynamically join or leave a multicast session. Since dynamic membership is central to the design and operation of the M3U, a multicast group management protocol which operates similarly to IGMP protocol was first developed for the M3U simulation. The IGMP protocol implemented uses two types of messages; IGMP-Join and IGMP-Leave for joining or leaving any multicast group/channel respectively. Details of each of these messages are as follows:

- **IGMP_Join message:** *RCST1; IGMP-Join_Req; Mcast group addr; mS1; src IP addr*

- **IGMP_Leave message:** *RCST1; IGMP-Leave_Req; Mcast group addr; mS1; src IP addr*

Where RCST1 = RCST permanent identification (ID), Mcast group addr = multicast group address that the RCST is requesting to join/leave, mS1 = permanent ID of mobile multicast source that the RCST is requesting to receive or stop receiving (leave) traffic from, src IP addr = mobile source IP address. The development of this IGMP-like protocol in NS-3 was achieved here by making appropriate modification to the udp-echo-server.cc file in the NS-3 source tree.

The M3U database has 3 tables:

- **rx-table:** Keeps a record of all multicast receivers (i.e., RCSTs/mRCSTs/GWs) and their associated details within the satellite network.

- **src-table:** Keeps the record of all multicast sources and associated details within the satellite network.

- **mgroups-table:** Keeps the record of all multicast groups which have at least one receiver within the satellite network.

Upon reception of an IGMP_Join or IGMP_Leave message from a RCST/GW, the M3U processes the message and extracts the required information and stores it in the appropriate table. Tables 6.2, 6.3 and 6.4 show the detailed information (or parameters) stored on the rx-table, src-table and mgroups-table respectively.

Table 6.2 Details of rx-table

| rx_ID | rx_name | rx_IP | rx_CoA | mgroup | src_CoA |
|-------|---------|-------|--------|--------|---------|
| 1 | RCST1 | 12.1.5.10 | 12.1.5.10 | 232.5.10.1 | 12.1.1.2 |
| 2 | RCST2 | 12.1.5.11 | 12.1.5.11 | 232.5.10.1 | 10.1.1.55 |

Table 6.3 Details of src-table

| src_ID | src_name | src_IP | src_CoA | mgroup |
|--------|----------|--------|---------|--------|
| 1 | mS1 | 12.1.1.2 | 12.1.5.20 | 232.5.10.1 |
| 2 | mS2 | 10.1.1.55 | 10.1.1.55 | 232.5.10.1 |

Table 6.4 Details of mgroups-table

| mg_ID | mg_address |
|-------|------------|
| 1 | 232.5.10.1 |
|  |  |

Where $rx\_ID$, $src\_ID$ and $mg\_ID$ = table ID given to a specific receiver, source or multicast group; $rx\_name$, $src\_name$ = permanent name or ID of the receiver or source; $rx\_IP$, $src\_IP$ = permanent or home IP address of the receiver or source; $rx\_CoA$, $src\_CoA$ = CoA of mobile receiver or source; $mgroup$, $mg\_address$ = multicast group address.
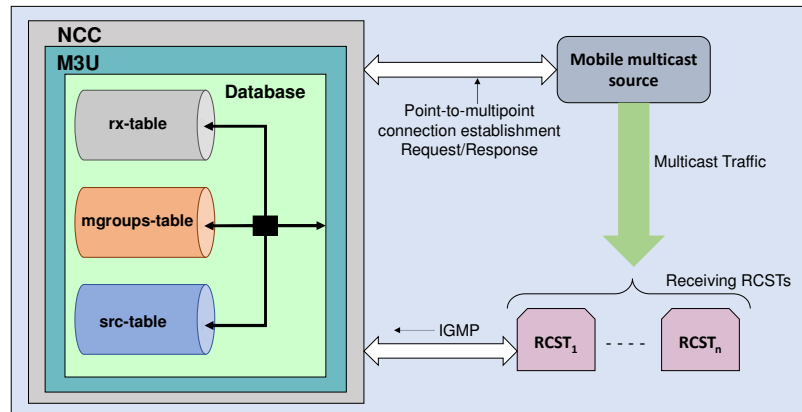


Figure 6.5 Block diagram of M3U implementation in NS-3

Figure 6.5 shows the block diagram of the overall implementation of the M3U developed in NS-3.

The reception of an IGMP packet at the NCC/M3U triggers the NCC to request the multicast source (mRCST) to open a multicast connection to multiple multicast destinations (i.e., NCC initiated point-to-multipoint connection [83]).

From the IGMP Join/Leave messages presented above, any satellite terminal requesting to receive IP multicast traffic from sources within the satellite network knows the permanent ID of the source as well as its IP address. Here, it is assumed that the requesting RCST/GW already knows the multicast source it wants to receive traffic form. So, when the NCC receives an IGMP Join report, the M3U identifies the source using the source permanent ID contained in the IGMP report as well as it's IP address. The inclusion of the source permanent ID in the IGMP Join/Leave message is very important for the proposed M3U-based source mobility support as it helps to identify the mobile source no matter whether it is at home or foreign network (home IP address or CoA).

Initially, when the mobile multicast source is at its home network, the src_CoA is equal to the src_IP (permanent home IP address). The src_CoA column in src-table (Table 6.3) indicates the active IP address of the mobile multicast source. The src_CoA column in the Table 6.3 is used as the foreign key [84] in rx-table (Table 6.2). This implies that a change in any value of src_CoA in Table 6.3 (during a GWH/SH) will automatically update the corresponding value in Table 6.2. Any changes in the value of the src_CoA in Table 6.3 triggers the M3U to issue SIUM to all receivers within the satellite network, thus preventing them from sending IGMP report for re-subscription after each GWH/SH. This saves satellite bandwidth resources.

### 6.2.3 Simulation architecture

Figure 6.6 shows the architecture used for the simulation in NS-3. Beam 1 (B1) and Beam 2 (B2) are served by different GWs and so, GWH will have to take place over the overlapping area of the two beams as the mobile multicast source moves from B1 to B2.
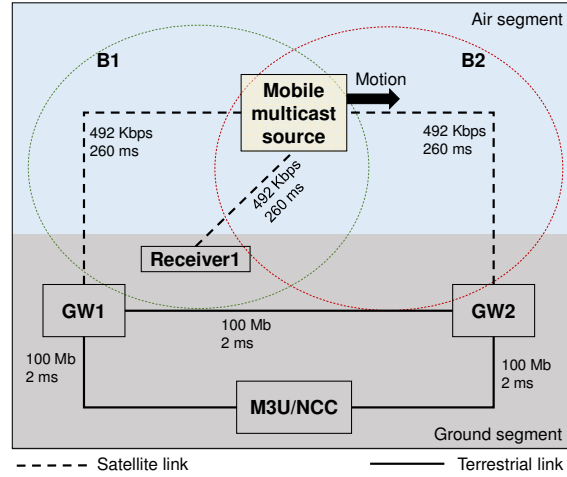
Figure 6.6 Simulation scenario

Table 6.5 shows the simulation parameters used [11, 85, 86].

Table 6.5 Simulation parameters

| Simulation parameters | Values |
|---|---|
| Beam radius | 5 Km |
| Satellite data rate | 492 Kbps |
| Terrestrial network data rate | 100 Mbps |
| Satellite link propagation delay | 260 ms |
| Terrestrial link  propagation delay | 2 ms |
| Simulation time | 30 s |

The simulation beam radius of 5 Km does not reflect the radius of a real satellite beam. The 5 Km is the radius of a wireless terrestrial network in NS-3 that was used in place of a satellite network. However, the wireless links were set to have real satellite data rate and propagation delay. Considering the performance metric that was to be measured (e.g., GWH latency, packet end-to-end delay, etc.) and the fact that these were to be measured for just one GWH, a simulation beam radius of 5 Km will not affect the results.

### 6.2.4  Scenarios

Four scenarios differentiated by the number of mobile multicast sources requesting for handover at the same time are simulated:

- Scenario 1: 1 mobile multicast source

- Scenario 2: 50 mobile multicast sources

- Scenario 3: 100 mobile multicast sources

- Scenario 4: 150 mobile multicast sources

For each of these scenarios, the following amount of data is transmitted at each transmission time slot by the source(s) to the multicast group: 534 bytes, 1024 bytes, 518 bytes, 134 bytes, 390 bytes, 765 bytes, 407 bytes, 504 bytes, 903 bytes, 421 bytes and 587 bytes. The transmission of these 11 different types of data packets is repeated continuously throughout the simulation duration.

In order to track each multicast packet from source to various destinations considering the fact that IP multicast communication uses User Datagram Protocol (UDP), each packet at source node is given a unique identifier (similar to a sequence number in TCP). This is very important in determining packet losses due GWH latency as this gives the possibility of knowing the identity of each packet lost, its transmission time and reception times.

In each scenario, the transmission time for each data packet, the time each data packet is received, the amount of each data packet received and the unique identifier for each packet are all recorded. When the mobile multicast source(s) is within the overlapping area, the time when the handover from GW1 to GW2 is initiated is recorded and the time when it is completed are all recorded.  From the statistics collected, the GWH latency, packet end-to-end delay and throughput can therefore be determined and evaluated. These performance metrics can therefore reveal how the varying number of mobile multicast sources simultaneously requesting handover could affect the performance of the proposed M3U-based scheme.

## 6.3  Summary

In this chapter, a novel approach which makes use of the remote subscription concept to support IP multicast source mobility in SSM during GWH is given. This proposed solution is the first in open literature to use the remote subscription concept to support multicast source mobility in SSM. The introduction of a new network entity called the M3U configured at the NCC is the key functional unit for the proposed source mobility support scheme. Analytical mobility modelling for the proposed M3U-based approach for GWH is also given.

Also, a brief description of the NS-3 simulator, the modifications required to support dynamic group membership, the simulation architecture, the four different scenarios and the parameters to be measured are all presented in this chapter.

In this chapter and in Chapter 5, the analytical mobility modelling and the simulation scenarios and description for the proposed schemes have been presented but no numerical results to determine how good or bad the proposed schemes are, have been given. The next chapter presents comprehensive numerical results, analysis and discussion of all the proposed schemes in Chapters 5 and 6. Here, these results are also compared with those obtained in Chapter 4 for terrestrial networks schemes identified as good candidate schemes that were implemented in a satellite environment.

# 7   RESULTS, ANALYSIS AND DISCUSSION

The detailed analytical results of all the proposed IP multicast receiver mobility support schemes (Chapter 5) in comparison with those of the MIP HS/RS-based schemes discussed in Chapter 4 are presented in this chapter. Also, analytical and simulated results from the M3U-based approach described in Chapter 6 are presented and discussed in detail in this chapter.  Detailed analysis of all the results are given.

The parameters in Table 7.1 and those in Chapter 4 are used in this chapter for the numerical evaluation. These parameters together with those in Chapter 4 are adopted from [7, 17, 38, 73-75].

Table 7.1 Notation and message size

| Notation | DESCRIPTION | Value |
|---|---|---|
| $M_{SIUM}$ | Service Interface Update message | 50 bytes |
| $M_{SHM}$ | Source Handover message | 30 bytes |
| $M_{CUM}$ | Channel Update message | 50 bytes |
| $M_{CNM}$ | CUM Notification message | 54 bytes |
| $M_{IPv6}$ | Size of IPv6 header in tunneling | 40 bytes |
| $M_{CSC}$ | Common Signalling Channel Message | 15 bytes |
| $M_{BU}$ | Binding Update Message | 112 bytes |
| $M_{BA}$ | Binding Update Acknowledgement Message | 52 bytes |
| $M_{MLD}$ | MLD Query/Report message | 72 bytes |
| $M_{R\_Adv}$ | Router Advertisement message | 80 bytes |

## 7.1   IP multicast receiver mobility support schemes

The results obtained from analytical mobility models developed for evaluating the performance of each of the proposed/existing schemes depend on the type of satellite payload and the location of some key IP mobility entities like HA/FA, MAG and RP (all layer 3 entities or functionalities). The location of these layer 3 entities can either be on the ground segment of the satellite network (e.g., at GWs) or at the OBP, depending on the type of satellite payload i.e., transparent

(or layer 2 OBP) and Layer 3 OBP payloads. For in-depth comparison, analysis and discussion of the results, it will be better to classify the results into two main categories, those from satellites with transparent (or layer 2 OBP) payload and Layer 3 OBP payload. In this way, detailed comparison and analysis within and between these two categories will be made much easier to understand.

## 7.1.1 Analytical results for satellites with transparent (or layer 2 OBP) payloads

### *7.1.1.1 Handover latency*
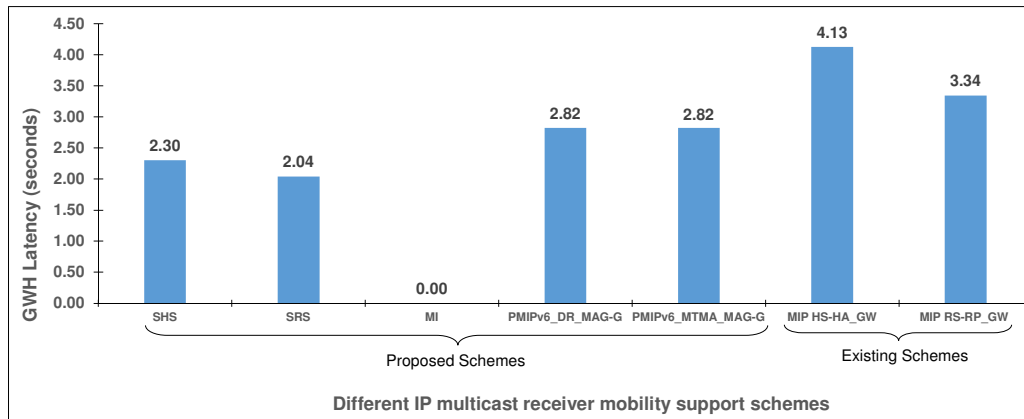


Figure 7.1 Comparing GWH latency for different IP multicast receiver mobility support schemes.

Figure 7.1 shows the GWH latency for different IP multicast receiver mobility schemes under consideration for transparent satellites or satellites with layer 2 OBP. These results are obtained by substituting the numerical values of the parameters in Equations 4.3, 4.12, 5.1, 5.6, 5.13 and 5.16 developed for GWH latency for each scheme in this category. From Figure 7.1, it can be seen that generally, the proposed schemes have lower GWH latency compared with the traditional MIP HS/RS-based approaches. The proposed Multiple Interface (MI)-Based Approach has a GWH latency of zero second. As explained in Section 5.3 of Chapter 5, during the GWH/SH process in the MI-based approach, the new connection to the target beam through the second interface (IF1) joins all

the multicast groups that are ongoing via the old connection (IF0) and starts receiving multicast traffic from those groups before the old connection is disconnected. In this way, handover latency is completely eliminated (GWH latency equals zero second) as the end users in the aircrafts, ships, etc., will experience no disruption in their multicast services due to the handover process from one satellite GW to another.

Table 7.2 Reduction in GWH latency of the proposed schemes compared to MIP

| Proposed schemes | Existing schemes | |
| --- | --- | --- |
| | MIP HS | MIP RS |
| SHS | 44.25% | 31.19% |
| SRS | 50.55% | 38.97% |
| MI | 100% | 100% |
| PMIPv6_DR_MAG_G | 31.61% | 15.59% |
| PMIPv6_MTMA_MAG_G | 31.60% | 15.58% |

Table 7.2 shows how much less the GWH latency for each proposed scheme is compared to the existing MIP HS/RS-based approaches for transparent satellites (or satellites with layer 2 OBP) where all layer 3 entities are configured on the ground segment of the satellite network. From Table 7.2, it can be seen that the GWH latencies for the proposed schemes are significantly lower than those for the traditional MIP HS-based and RS-based approaches. One of the main reasons why the GWH latencies for the proposed schemes are generally lower than those of the MIP HS-based and RS-based approaches is the efficient handover signalling procedure built in these proposed schemes. Particularly, the reduction in the signalling messages required to obtain an IP address during a GWH/SH in the proposed schemes compared to the existing MIP HS-based and RS-based approaches has a significant impact on reducing the GWH latency.

Figure 7.1 also shows that the GWH latency in MIP RS-based approach is 18.98% less than that in MIP HS-based approach. This is mainly due to the additional time required in MIP HS-based approach to set up the bidirectional IP tunnel between the target GW and the home GW after acquisition of an IP address in the target GW beam (foreign network). IP tunnels are not required in MIP RS-based approach.
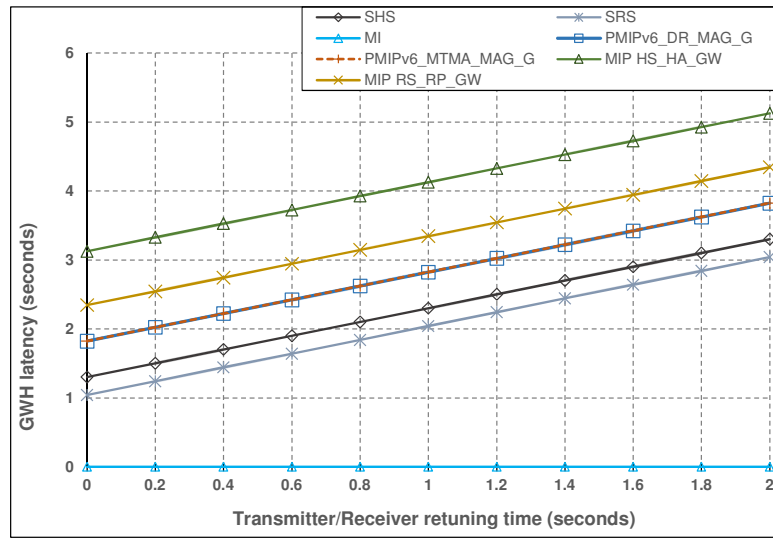


Figure 7.2 Effects of varying transmitter/receiver
retuning time on GWH latency

In DVB-RCS/S2 systems, the mRCST's transmitter/receiver retuning times ($T_{TX/RX}$) are subject to uncertainties and could range from about 500ms to about 2s, thus making $T_{TX/RX}$ one of the major contributors to higher handover latencies in DVB-RCS/S2 networks [17]. Figure 7.2 shows how the GWH latencies of the various schemes are affected by changing values of the mRCST's $T_{TX/RX}$. From Figure 7.2, it can be seen that for all schemes the GWH latency increases as $T_{TX/RX}$ increases and vice versa, except for the Multiple Interface (MI)-based approach where GWH latency remains the same (zero) at all values of $T_{TX/RX}$. Here, the proposed schemes generally perform better than the existing MIP HS/RS-based approaches. For example at $T_{TX/RX}$ = 1.4 seconds, the GWH latency for the proposed SHS-, SRS-, MI-, PMIPv6_DR- and

PMIPv6_MTMA-based approach is about 40.34%, 46.09%, 100%, 28.82% and 28.81% respectively less than that for the existing MIP HS-based approach. From the equations of GWH latency for each of the schemes developed in Chapters 4 and 5, it is clear that GWH latency is directly proportional to $T_{TX/RX}$, thus explaining why GWH latency increases with increasing $T_{TX/RX}$ and decreases with decreasing $T_{TX/RX}$ for all schemes.

Lower GWH latency implies less disruption and packet loss (as explained in next section) during the handover, thus making the proposed schemes better IP multicast receiver mobility support schemes compared with the existing MIP HS/RS-based approaches.

It is also important to note from the signalling sequences for each of the schemes described in Chapters 4 and 5, that the GWH latency is identical to the SH latency for any particular scheme. This implies that for any particular scheme GWH latency = SH latency.

### 7.1.1.2 *Multicast packets lost due to GWH latency and satellite capacity required for retransmission*
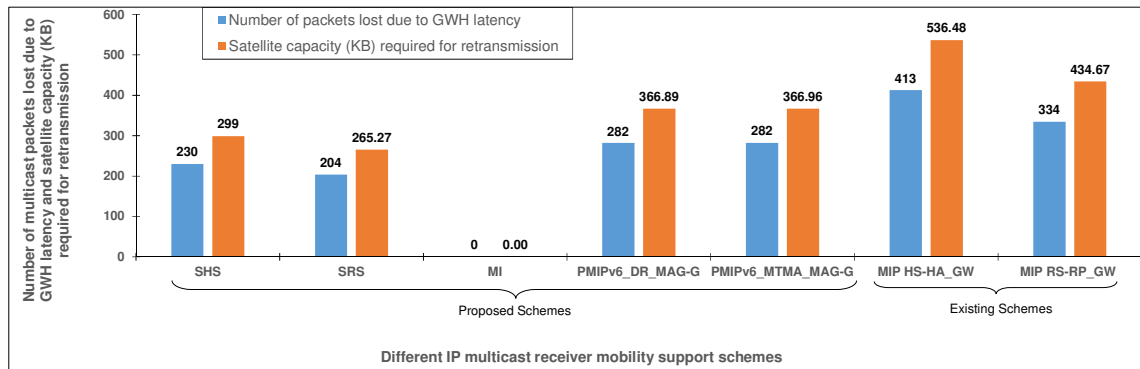


Figure 7.3 Comparison of number multicast packets lost due to GWH latency for various schemes

As shown in Figure 7.3, the number of multicast packets lost as consequence of GWH latency for the MIP HS/RS-based approaches is generally higher than

those for the proposed schemes. The percentage increase in the number of packets lost and satellite capacity required due to GWH latency for the MIP HS/RS-based approaches compared to the proposed schemes will be similar to that for the GWH latency presented in Table 7.2 above. This is due to the fact that when the other factors are kept constant, the number of packets lost due GWH latency (and consequently satellite capacity required for retransmission) for each scheme is directly proportional to the GWH latency. Figure 7.3 also compares the satellite capacity (in Kilobytes i.e., KB) required for each scheme if the lost packets due to GWH latency are to be retransmitted after completion of the GWH. Similarly as in Section 4.5.2 of Chapter 4, the size of each IP multicast packet here is assumed to be 1300 bytes. In terms of the number of packets lost and satellite capacity required for retransmission after each GWH process, Figure 7.3 shows that the MI scheme which has zero GWH latency and packet loss due to GWH latency is the best amongst the schemes considered, followed by SRS, SHS, PMIPv6_DR_MAG_G, PMIPv6_MTMA_G, MIP RS-RP_GW and MIP HS-HA_GW.  As explained in Section 5.3 above, the MI scheme is the best here because of the fact that during a GWH process in the MI, the second interface of the mRCST establishes connection with the target GW, joins all the multicast groups that are ongoing via interface 1 and starts receiving multicast packets from all the groups before the connection to the old GW (via Interface 1) is cut-off. Generally, the proposed schemes perform better in these two aspects because one of their main design objectives is to reduce the handover latency (GWH and SH) in comparison with those of the existing MIP HS/RS-based schemes.
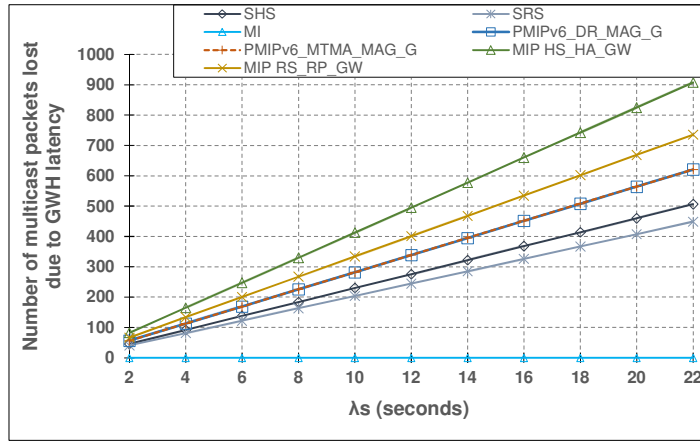
Figure 7.4 Effects of varying average multicast session arrival rate
($\lambda_s$) on number of multicast packets lost due to GWH latency

As shown in Figure 7.4, the number of multicast packets lost due to GWH

latency for each scheme increases as $\lambda_s$ increases except for the MI-based

approach where the number of multicast packets lost remains constant (zero)

no matter the value of $\lambda_s$. From the equations of the number of multicast

packets lost due to GWH latency in Chapters 4 and 5, if the GWH latency and

$E_s$ are kept constant, then, the number of packets lost is directly proportional to

$\lambda_s$ for each scheme.

### 7.1.1.3    Signalling cost

#### 7.1.1.3.1 Signalling cost at GWH and SH
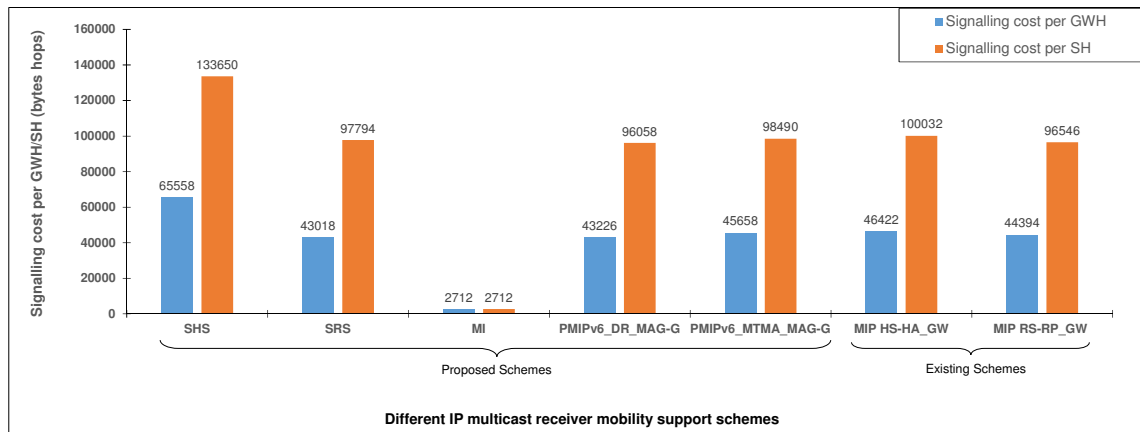


Figure 7.5 Comparison of signalling cost per GWH and SH

Figure 7.5 shows the comparison of the total signalling cost per GWH and SH

for the various schemes under consideration. The results are obtained by

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substituting the numerical values of the parameters in the GWH and SH signalling cost in equations 4.6, 4.14, 5.3, 5.8, 5.12, 5.15, 5.18 and 4.11, 4.19, 5.5, 5.10, 5.12, 5.21, 5.24 respectively. From Figure 7.5, it can be seen that for any particular scheme, the SH signalling cost is generally higher than that for the GWH. This is due to the fact that in SH handover, there more signalling messages compared to GWH as shown in the equations for SH and GWH in Chapters 4 and 5 above.

While the proposed MI-based approach incurs the least signalling cost in both GWH and SH, the proposed SHS-based approach suffers the highest signalling cost in both GWH and SH.

Table 7.3 Reduction in signalling cost of the proposed schemes as compared to MIP

| Proposed schemes | Existing schemes | | | |
| --- | --- | --- | --- | --- |
| | GWH | | SH | |
| | MIP HS | MIP RS | MIP HS | MIP RS |
| SHS | *29.19% | *32.28% | *25.15% | *27.76% |
| SRS | 7.33% | 3.10% | 2.24% | *1.28% |
| MI | 94.16% | 93.89% | 97.29% | 97.19% |
| PMIPv6_DR_MAG_G | 6.88% | 2.63% | 3.97% | 0.51% |
| PMIPv6_MTMAMAG_G | 1.65% | *2.77% | 1.54% | *1.97% |

*signalling cost of proposed scheme is more than that of either MIP HS or MIP RS

Table 7.3 gives a comparison (in terms of percentages) of how much smaller or greater the signalling cost per GWH/SH of the proposed schemes are compared with the existing MIP HS/RS-based approaches. While most of the values in Table 7.3 indicate how much less the signalling cost per GWH/SH of the proposed schemes are compared with the existing MIP HS/RS-based approaches, the values with asterisk sign (*) indicate instead, how much greater those of the proposed schemes are compared with the existing MIP HS/RS-

based approaches. Although, all the proposed schemes are designed to minimise handover signalling cost, handover latency which has a direct impact on the number of packets lost during a handover process takes precedence over signalling cost in the design of all the proposed schemes. Comparing the signalling sequences of SHS-based scheme in Figure 5.1 for GWH and Figure 5.3 for SH with those of the MIP HS-based approach in Figures 4.2 and 4.4 for GWH and SH respectively, it can be seen that for the SHS scheme the handover request/recommendation contains tunnel establishment message (MIP registration request) to its home GW in order to reduce GWH/SH latency unlike in the MIP HS-based approach. Signalling cost due to this additional MIP registration request message over the satellite air interface is what has made the signalling cost in the proposed SHS-based scheme to be greater than that for existing MIP HS-based scheme.

The number of multiple hops that the IGMP Report message contained in the handover request/recommendation message from the mRCST has to undergo in SH in the proposed SRS-based explains why the signalling cost here is greater than that in existing MIP RS-based approach. Note should be taken here that in MIP RS-based approach the handover request/recommendation message does not contain an IGMP Report message. The inclusion of the IGMP Report message in the handover request/recommendation message is to reduce the handover latency as explained in Sections 5.1 and 5.2 of Chapter 5.

From Table 7.3, the signalling cost per GWH/SH for the proposed MI-based scheme is significantly less compared with those of the existing MIP HS/RS-based approaches. This is due to fact that in the MI-based scheme, the signalling cost incurred during GWH/SH is simply the mRCST second interface

network entry (or logon) plus joining the multicast groups signalling costs as explained in Section 5.3 of Chapter 5.

As shown in Table 7.3, the signalling cost for the proposed PMIPv6 MTMA mode for SH is greater than that for the existing MIP RS-based approach for SH. One of reasons for this is the fact that in the proposed PMIPv6 MTMA mode IP tunnelling is used to deliver multicast packets to mobile receivers which are away from their home network but in MIP RS-based approach no tunnelling is used. The extra signalling cost incurred due to tunnel establishment in the proposed PMIPv6 MTMA mode might be the reason for the higher signalling cost compared to the existing MIP RS-based approach.

Also from Figure 7.5, the signalling cost when using MIP RS-based scheme for GWH and SH is about 4.37% and 3.48% respectively less than that when MIP HS-based scheme is used.

Except for the proposed SHS-based approach, all other proposed schemes generally incur less signalling cost during GWH/SH compared with the existing MIP HS/RS-based schemes.

### 7.1.1.3.2 Signalling cost over satellite air interface per GWH/SH
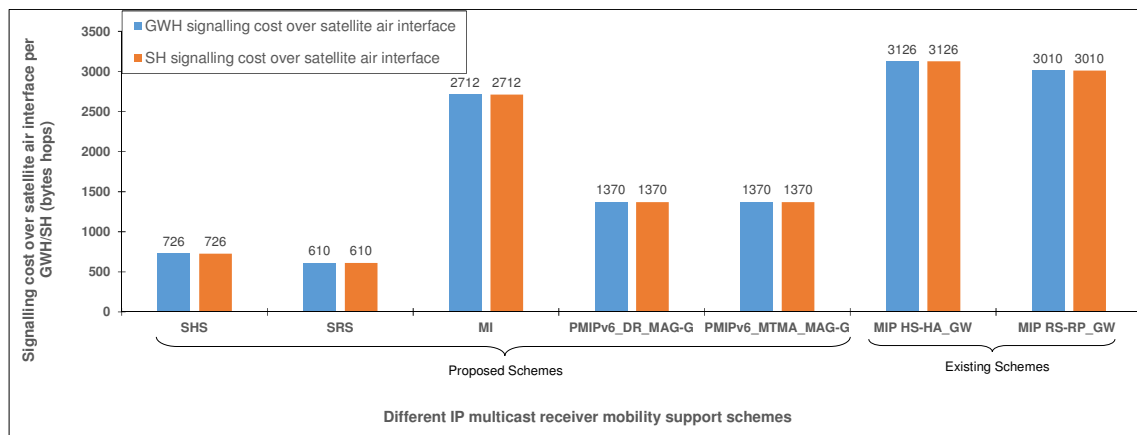


Figure 7.6 Comparison of signalling cost over the satellite air interface per GWH/SH

Considering the fact satellite network resources (bandwidth) are more expensive compared to terrestrial network resources, it is good to investigate the signalling cost that could be incurred over the satellite air interface for each of the schemes under consideration here. Figure 7.6 compares the GWH and SH signalling cost over the satellite air interface for the proposed schemes and the existing MIP HS/RS-based schemes.  These results are obtained by substituting the numerical values for the parameters of the signalling messages over the satellite air interface in the GWH/SH signalling cost equations for each scheme derived in Chapters 4 and 5. From Figure 7.6, two main observations can be made:

- GWH and SH signalling cost over the satellite air interface for each scheme are identical. Despite the fact that the total SH signalling cost is always higher than the total GWH signalling cost for each scheme as shown in Figure 7.5, the signalling cost incurred over the satellite air interface in both GWH and SH for each scheme are identical. The reason why GWH and SH signalling cost are identical over the satellite air interface is because they both have identical number and type of signalling messages over the satellite air interface. This can be seen in the equations for GWH/SH signalling cost for each scheme in Chapters 4 and 5.

- GWH and SH signalling cost over the satellite air interface for all the proposed schemes are generally lower than those for the existing MIP HS/RS-based schemes.

The values in Table 7.4 show how much less the GWH signalling cost over the satellite air interface for each proposed scheme is compared with those of the existing MIP HS/RS-based schemes.

Table 7.4 Reduction in GWH signalling cost over the satellite air interface
of the proposed schemes compared to MIP

| Proposed schemes | Existing schemes | |
|---|---|---|
| | MIP HS | MIP RS |
| SHS | 76.78% | 75.88% |
| SRS | 80.49% | 79.73% |
| MI | 13.24% | 9.90% |
| PMIPv6_DR_MAG_G | 56.17% | 54.49% |
| PMIPv6_MTMA_MAG_G | 56.17% | 54.49% |

From the values in Table 7.4, it shows that the proposed SRS-based scheme will save more satellite bandwidth resources during GWH/SH process compared with the existing MIP HS/RS-based schemes than any other proposed scheme. This is followed by the SHS-, PMIPv6 DR/MTMA- and MI-based approach which will serve the least satellite bandwidth resources compared with the MIP HS/RS-based schemes. The proposed PMIPv6 DR and MTMA modes will incur identical GWH/SH signalling cost over the satellite air interface compared with the existing MIP HS/RS-based schemes as indicated in Table 7.4.

Also, from Figure 7.6, the GWH/SH signalling cost over the satellite air interface when using MIP RS-based approach is about 3.71% less than that when MIP HS-based approach is employed.

From Figure 7.6 and Table 7.4, all the schemes can be arranged in the following order according to the satellite bandwidth resources they save during GWH/SH starting with the one that can save the most: SRS, SHS, PMIPv6 DR/MTMA, MI, MIP RS and MIP HS.

If the gateway beams are assumed to be circular and of identical dimensions, then, the border crossing rate of the aircraft i.e., the frequency at which GWH is taking place $f_{GWH}$ is given by [68, 70]:

$$f_{GWH} = \frac{2V}{\pi R} \tag{7.1}$$

Where $V$ = average speed of the IP mobile multicast receiver (aircraft) and $R$ = radius of a circular satellite gateway beam.

The total GWH signalling cost per unit time $C_{sign/t}$ for the mobile receiver is therefore given by the product of the signalling cost per GWH and frequency of GWH. From Equation 7.1 and the total GWH signalling cost models developed in Chapters 4 and 5, it implies that the total GWH signalling cost per unit time $C_{sign/t}$ for each IP multicast receiver mobility support scheme is as follows:

- The proposed SHS-based approach – From Equation 5.3;

$$C_{sign/t}^{SHS} = \frac{2V}{\pi R} C_{s\_GWH}^{SHS} \tag{7.2}$$

- The proposed SRS-based approach – From Equation 5.8;

$$C_{sign/t}^{SRS} = \frac{2V}{\pi R} C_{s\_GWH}^{SRS} \tag{7.3}$$

- The proposed MI-based approach – From Equation 5.12;

$$C_{sign/t}^{MI} = \frac{2V}{\pi R} C_{s\_GWH/SH}^{MI} \tag{7.4}$$

- The proposed PMIPv6-based approach – From Equations 5.15, 5.18 and 5.27;

$$C_{sign/t\_DR}^{PMIP\_MAG\_G} = \frac{2V}{\pi R} C_{GWH\_DR}^{PMIP\_MAGG} \tag{7.5}$$

$$C_{sign/t\_MTMA}^{PMIP\_MAG\_G} = \frac{2V}{\pi R} C_{GWH\_MTMA}^{PMIP\_MAG\_G} \tag{7.6}$$

$$C_{sign/t}^{PMIP\_MAG\_S} = \frac{2V}{\pi R} C_{GWH}^{PMIP\_MAG\_S} \tag{7.7}$$

- The MIP HS-based approach – From Equation 4.6;

$$C_{sign/t}^{HS-HA\_GW} = \frac{2V}{\pi R} C_{GWH}^{HS-HA\_GW} \tag{7.8}$$

- The MIP RS-based approach – From Equation 4..14;

$$C_{sign\,/t}^{RS-RP\_GW} = \frac{2V}{\pi R} C_{GWH}^{RS-RP\_GW}$$
(7.9)

### 7.1.1.3.3 Total GWH signalling cost Vs speed of mobile subscriber (mRCST)
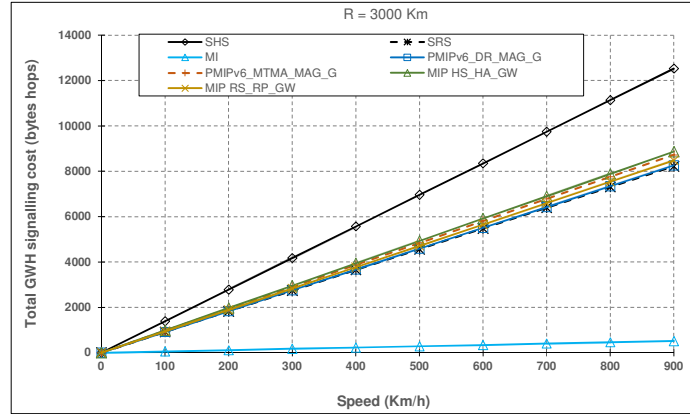


Figure 7.7 Impact on total GWH signalling cost of varying speed

In Figure 7.7, the radius of the GW Beam is set at 3000 Km (assuming each GW Beam is made up of 10 spot beams each of radius 300 Km [87]) and the total GWH signalling cost is measures as the speed of the mobile multicast receiver (mRCST) is varied from 0 to 900 Km/h (where 900Km/h is assumed to be the typical commercial speed of an airliner [88]). The results obtained show that at a constant radius of the GW Beams, the total GWH signalling cost increases as the speed of mobile receiver increases i.e., the total GWH is directly proportional to the speed of the mRCST. Inferring from Equations 7.1 – 7.9 above, this trend is expected. From Equation 7.1, the higher the speed of the mRCST, the more the frequency of GWH i.e., higher speed implies more GWHs per unit time. More GWHs per unit time imply higher total GWH signalling cost. From Figure 7.7, it can also be inferred that the provision of mobility support for satellite terminals on slow moving platforms like the maritime vessels will incur less signalling cost (overhead) per unit time compared with those on fast moving platforms like the continental airliners. Note

should be taken here that the total signalling cost between two specific locations will remain the same no matter the speed of the mobile satellite subscriber, since the number of GWHs in-between the two locations remain the same.

*7.1.1.3.4 Total GWH signalling cost Vs radius of GW Beam*
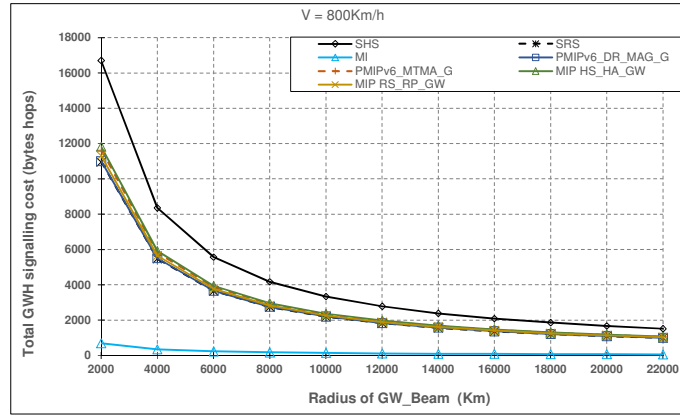


Figure 7.8 Impact on total GWH signalling cost of varying radius

Figure 7.8 shows how the total GWH signalling cost changes with varying GW Beam radius at a constant mobile subscriber's speed of 800 Km/h. Here, the total signalling cost reduces as the GW Beam radius increases and vice versa. From Equations 7.2 to 7.9 where the radius is inversely proportional to total signalling cost, the relationship between these two parameters shown in Figure 7.8 are expected. This make sense since the larger the GW Beam size (radius), the fewer the number of GWHs a mobile satellite subscriber will undergo travelling at a constant speed and the smaller the size of the GW Beam, the more the number of GWHs. Fewer number of GWHs imply less total signalling cost and more number of GWHs imply more total signalling cost for a satellite terminal travelling at a constant speed.

Although the results from Figure 7.8 shows that larger satellite beams are more beneficial than smaller ones in terms of mobility management signalling cost, this is contrary to the current trend in the general satellite beam size design which is moving towards narrow beams instead of bigger beams. Some of the

main reasons why new generation of satellite systems are being design to have smaller beam sizes are:

- Increased capacity: Dividing the satellite footprint into many narrow/spot beams and applying frequency reuse on different spot beams has resulted into tremendous increases in the overall satellite capacity. Multiple spot beam and frequency reuse concepts are behind the new high-throughput satellite systems which today can support well over 100 Gbps capacity [67].

- High data rate: Small spot beams make it possible for the satellite to focus its power over a relatively small area resulting in high power density. High power density supports high data rates.

- Lower power requirement of RCST and size of satellite terminals: High power density does not only support high data rates but also reduce the power requirement and size of satellite terminals.

A trade-off between increasing satellite capacity and data rate on one hand and reducing mobility management overhead on the other hand is therefore required by satellite designers especially those designing satellites for the global aeronautical and maritime communication services (e.g., Inmarsat).

### 7.1.2  Analytical results for satellites with layer 3 OBP payloads

#### 7.1.2.1    GWH latency
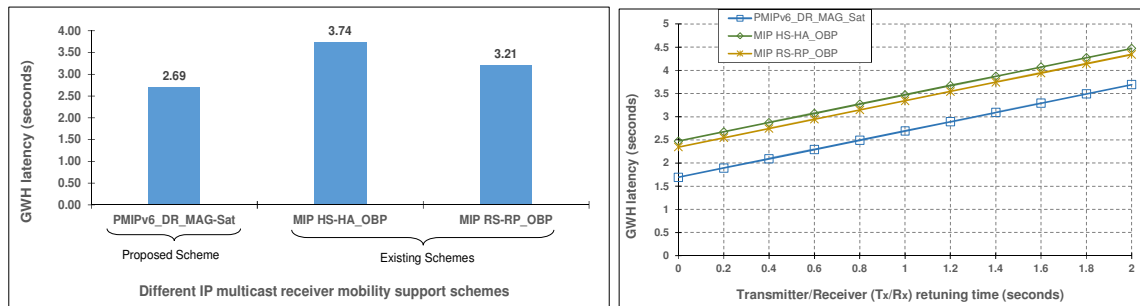


a.   GWH latency                          b. GWH latency vs $T_x/R_x$

Figure 7.9 GWH latency and GWH latency vs $T_x/R_x$ for mobile receivers

Figure 7.9a compares the GWH latency for the three schemes with layer 3 OBP payloads and Figure 7.9b shows how the GWH latency of each scheme varies with changing values of the $T_X/R_X$ retuning time. The GWH latencies of these three schemes are obtained by substituting the numerical values of the parameters in their GWH latency equations (i.e., Equations 4.7, 4.15 and 5.27). From Figure 7.9a, the proposed PMIPv6_DR_MAG_Sat scheme has the least GWH latency amongst the three i.e., 27.94% less than the MIP HS-HA_OBP scheme and 16.28% less than the MIP RS-RP_OBP scheme. The absence of layer 3 handover signalling (i.e., CoA acquisition) over the wireless domain (satellite air interface) in the proposed PMIPv6_DR_MAG_Sat scheme is one of the main reasons for its small GWH latency. This is one of the main advantages of PMIPv6-based schemes in IP mobility support.

### 7.1.2.2 *Multicast packets lost due to GWH latency and satellite capacity required for retransmission*
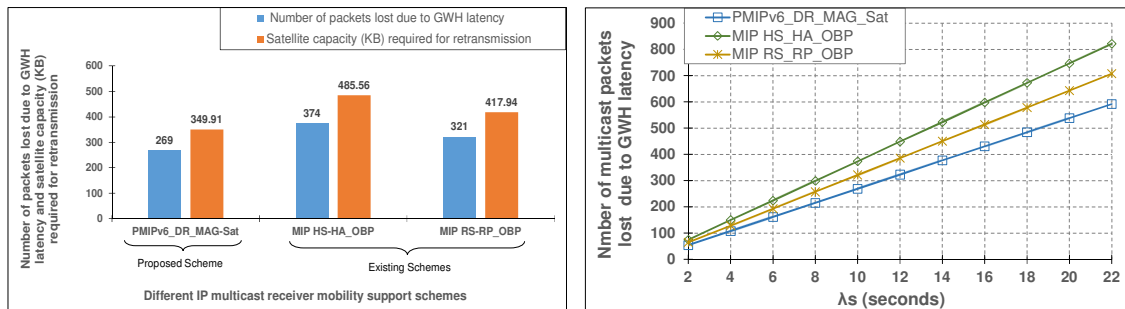


a. Number of packets lost/satellite capacity required     b. Number of packets lost per session vs $\lambda_s$

Figure 7.10 Number of multicast packets lost/satellite capacity required for retransmission due GWH latency and effects of varying multicast session arrival rate ($\lambda_s$) on number of multicast packets lost per session

Figure 7.10 just like in Figure 7.3 shows how the number of packets lost per GWH and satellite capacity required for retransmission due to GWH latency varies in the three schemes and with the average multicast session arrival rate ($\lambda_s$). Figure 7.10 is obtained by using Equation 4.4 for the MIP HS-HA_OBP, MIP RS-RP_OBP and the proposed PMIPv6_DR_MAG_Sat schemes

respectively. From Figure 7.10a, the number of multicast packets lost due to GWH latency and satellite capacity required for retransmission in the proposed PMIPv6_DR_MAG_Sat scheme are lower than those in the MIP-based approaches i.e., around 27.94% and 16.28% less than those in the MIP HS-HA_OBP and MIP RS-RP_OBP respectively. These changes in percentages are similar to those obtained in Figure 7.9 (GWH latency) since the number of packet lost and satellite capacity required for retransmission are directly proportional to the GWH latency.

Figure 7.10b shows how the number of packets lost due to GWH latency varies with changing session arrival rate at the mRCST. From Figure 7.10b, it can be deduced that the number of packets lost increases as the average session arrival rate increases and vice versa. Figure 7.10b also shows that the number of packets lost as the average session arrival rate increases when using MIP-based schemes are generally higher than that when using the PMIPv6_DR_MAG_Sat scheme. This is so, because the number of packets lost is directional proportional to the GWH latency.

### 7.1.2.3    Signalling cost per GWH

*7.1.2.3.1 Signalling cost and signalling cost over satellite air interface per GWH*

Figure 7.11 which compares the signalling cost and signalling cost over satellite air interface per GWH for the OBP schemes is obtained by using Equations 4.8, 4.17 and 5.27 for the MIP HS-HA_OBP, MIP RS-RP_OBP and the proposed PMIPv6_DR_MAG_Sat schemes respectively. For the proposed PMIPv6_DR_MAG_Sat scheme in Figure 7.11, its signalling cost per GWH is lower than those for the MIP HS-HA_OBP and MIP RS-RP_OBP schemes by 4.49% and 4.06% respectively. Also from Figure 7.11, the signalling cost over satellite air interface per GWH for the PMIPv6_DR_MAG_Sat scheme is

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significantly lower than those for the MIP HS-HA_OBP and MIP RS-RP_OBP schemes by 61.51% and 59.00% respectively.
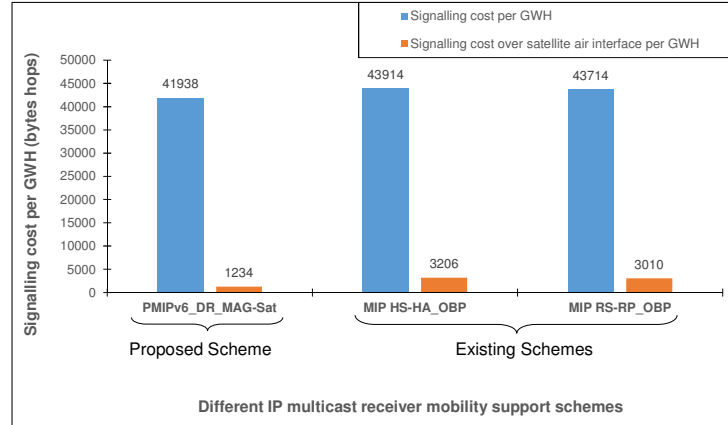


Figure 7.11 Comparing signalling cost and signalling cost over satellite air interface per GWH for the OBP schemes

As explained above, the huge difference in the signalling cost over satellite air interface per GWH between the proposed PMIPv6_DR_MAG_Sat and the two MIP-based schemes is due to efficient signalling mechanism in the wireless domain obtained in PMIPv6-based approaches during a layer 3 handover. This is brought about by the fact in PMIPv6-based approaches MNs do not participate in layer 3 handover signalling procedures [20]. The percentage differences in signalling cost over satellite air interface between these three schemes give an indication of how much financial saving the proposed PMIPv6_DR_MAG_Sat scheme could bring compared to the two MIP-based approaches taking cognisance of the cost of satellite bandwidth resources and that of terrestrial network resources.

*7.1.2.3.2 Total GWH signalling cost Vs Speed of mobile subscriber (mRCST)*

Figure 7.12 just like in Figure 7.7 above, shows that at a constant GW Beam radius, the total GWH signalling cost increases with increasing speed and vice versa as expected. This trend is similar to that established in Figure 7.7 and the

reason for this trend is embedded in Equations 7.1, 7.8 and 7.9 as explained in Section 7.1.1.3.3 above.
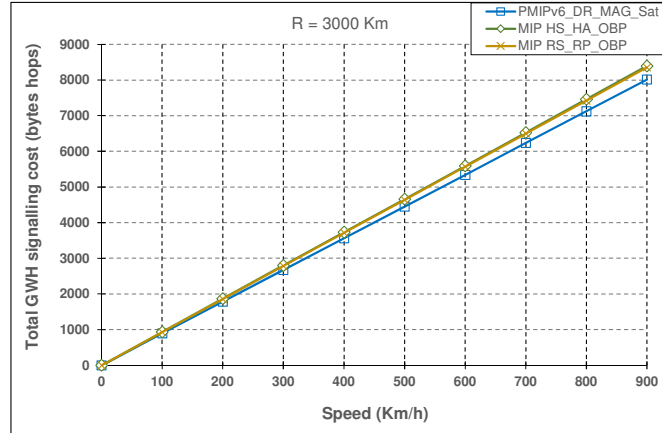


Figure 7.12 Effects of varying speed of mRCST on total GWH signalling cost

For any particular speed, Figure 7.12 also shows that the total signalling cost for the MIP-based schemes are generally higher than that for the proposed PMIPv6_DR_MAG_Sat scheme.

*7.1.2.3.3 Total GWH signalling cost Vs Radius of GW Beam*
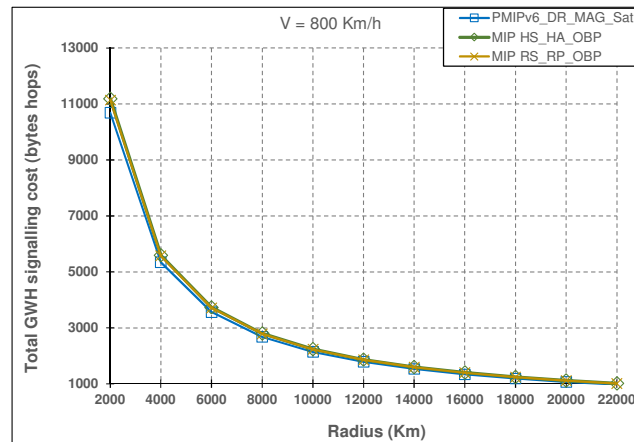


Figure 7.13 Effects of varying radius of GW Beam on total GWH signalling cost

The trend established in Figure 7.13 between the total GWH signalling cost and the changing radius of GW Beam at a constant speed for satellites with layer 3 OBP payloads is similar to that for satellites with  transparent (or layer 2 OBP) payloads explained in Section 7.1.1.3.4. Equations 7.1, 7.8 and 7.9 above

provide the main reason why this trend (where the total GWH signalling cost reduces as the radius of the GW Beam increases and vice versa) is obtained as explained in Section 7.1.1.3.4. In real life today, satellite beam sizes are getting smaller and smaller. This implies that the advantages brought in by smaller satellite beams described in Section 7.1.1.3.4 above overshadows that of larger beams portrayed in Figure 7.13.

### *7.1.3* **Summarised comparison of IP multicast receiver mobility support schemes**

Table 7.5 Comparison of IP multicast receiver mobility support schemes

| Schemes with satellites having transparent (or layer 2) OBP payloads schemes | GWH latency (s) | Number of packets lost due to GWH latency | Satellite capacity required for retransmission (KB) | Total signalling cost per GWH (bytes hops) | Signalling cost over satellite air interface per GWH (bytes hops) |
|---|---|---|---|---|---|
| SHS | 2.30 | 230 | 299.08 | 65558 | 726 |
| SRS | 2.04 | 204 | 265.27 | 43018 | 610 |
| MI | 0 | 0 | 0 | 2712 | 2712 |
| PMIPv6_DR_MAG_G | 2.82 | 282 | 366.89 | 43226 | 1370 |
| PMIPv6_MTMA_MAG_G | 2.82 | 282 | 366.96 | 45658 | 1370 |
| MIP HS-HA_GW | 4.13 | 413 | 536.48 | 46422 | 3126 |
| MIP RS-RP_GW | 3.34 | 334 | 434.67 | 44394 | 3010 |
| **Schemes with Satellites having layer 3 OBP payloads** | | | | | |
| PMIPv6_DR_MAG_Sat | 2.69 | 269 | 349.91 | 41938 | 1234 |
| MIP HS-HA_OBP | 3.74 | 374 | 485.56 | 43914 | 3206 |
| MIP RS-RP_OBP | 3.21 | 321 | 417.94 | 43714 | 3010 |

From Table 7.5, it can be seen that the MI-based approach which has a GWH latency of zero is the best in terms of GWH latency, number of packets lost due to GWH latency, satellite capacity required for retransmission (in reliable IP multicast communication scenarios) and total signalling cost per GWH. Also, the SRS scheme is best in terms of signalling cost over satellite air interface per GWH. Table 7.5 also reveals that all the proposed schemes outperform the MIP HS/RS-based approaches (originally defined for terrestrial networks) in terms of GWH latency, number of packets lost due to GWH latency, satellite capacity required for retransmission and signalling cost over satellite air interface per GWH.

## 7.2  IP multicast source mobility support schemes

In this section, results from the analytical mobility modelling and the simulation of the proposed M3U scheme are presented. These two sets of results are compared with each other as well as with those from the MIP HS-based scheme (which supports source mobility in SSM) when the HA is configured at satellite GW and OBP.

### 7.2.1  Results from analytical mobility modelling

#### 7.2.1.1      GWH Latency



a.      GWH latency                         b. GWH latency vs Tx/Rx
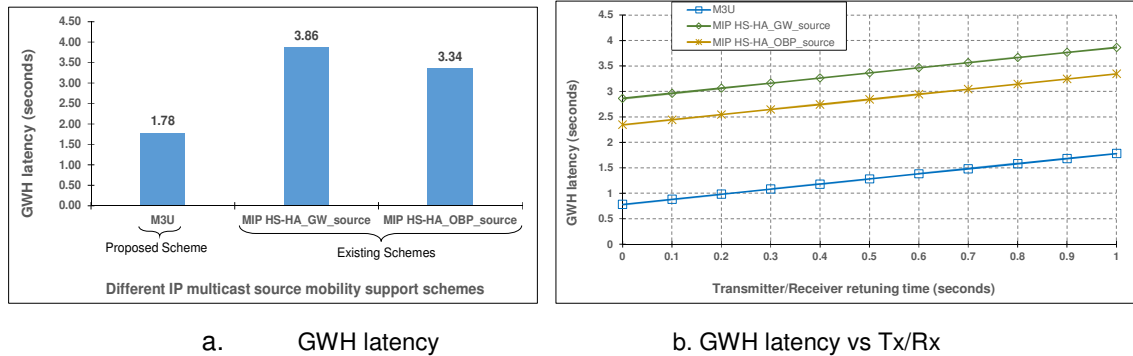
Figure 7.14 GWH latency and GWH latency vs Tx/Rx for mobile sources

Figure 7.14a which is obtained by using Equations 4.20, 4.27 and 6.1, shows that the GWH latency for the proposed M3U is lower than those for the MIP HS-HA_GW_source and MIP HS-HA_OBP_source schemes by approximately 53.89% and 46.71% respectively. This significant reduction in GWH latency of the proposed M3U, indicates how much the IP multicast communication disruption time will be reduced during a GWH scenario when using the M3U compared to the MIP HS-based approaches in order to support IP multicast source mobility in SSM. One of the main reasons for the lower GWH latency of the proposed M3U scheme compared to the MIP HS-based approaches is the fact that in the M3U scheme, MIP registration of the mobile source's CoA at it's HA is not required.

Figure 7.14b shows how the GWH latency is affected by varying transmitter/receiver retuning time (Tx/Rx) during a GWH scenario. The display in Figure 7.14b shows that the GWH latency increases as the multicast session transmission rate $\lambda_S$ increases and vice versa. This is due to the direct proportional relationship between the GWH latency and Tx/Rx in Equations 4.20, 4.27 and 6.1 when other factors are kept constant. For every single value of the Tx/Rx considered in Figure 7.14b, the GWH latency for the proposed M3U scheme is always lower than that of any of the two MIP HS-based schemes.

### *7.2.1.2 Signalling cost per GWH*

*7.2.1.2.1 Signalling cost and signalling cost over satellite air interface per GWH*

Figure 7.15 which is obtained by making use of Equations 4.22, 4.29 and 6.3, compares the total signalling cost and signalling cost over satellite air interface per GWH for the three source mobility support schemes under consideration. From this comparison, it shows that the total signalling cost per GWH for the

proposed M3U scheme is lower than those of the MIP HS-HA_GW_source and MIP HS-HA_OBP_source schemes by approximately 70.37% and 68.68% respectively. On the other hand, the signalling cost over satellite air interface per GWH for the proposed M3U is approximately 74.73% and 75.36% lower than those of the the MIP HS-HA_GW_source and MIP HS-HA_OBP_source schemes respectively.
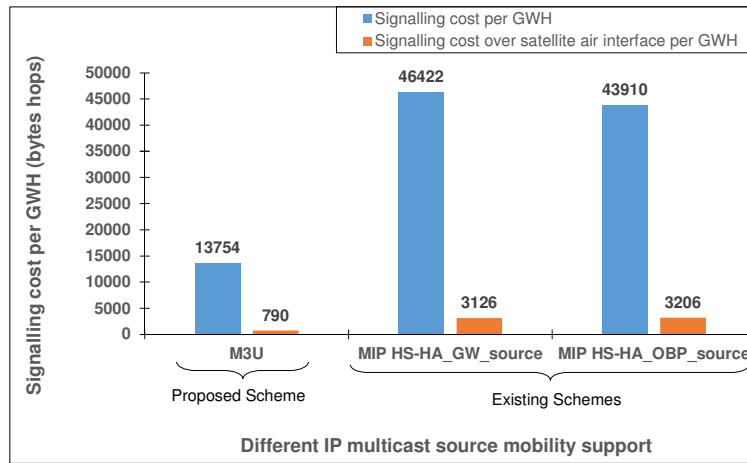


Figure 7.15 Comparing total signalling cost and signalling cost over satellite air interface per GWH for source mobility support schemes

The main reason for the significant difference in the signalling cost between the proposed M3U scheme and the two MIP HS-based schemes is the cost of MIP registration of the mobile source's CoA at its home GW during a GWH obtained in MIP HS-based approaches which is not required in the M3U scheme. As shown in Figure 7.15, the MIP HS-HA_OBP_source scheme incurs a slightly higher GWH signalling cost over the satellite air interface compared to the MIP HS-HA_GW_source. As explained in Section 4.5.3 above, this is due to the extra signalling cost of establishing an IP tunnel over the satellite air interface between the mobile source and the OBP in the MIP HS-HA_OBP_source scheme during a GHW where as in MIP HS-HA_GW_source scheme there is no IP tunnel over the satellite air interface.

The enormous differences in the signalling cost over satellite air interface per GWH between the proposed M3U and the MIP HS-based schemes give an indication of how much satellite bandwidth resources and consequently money could be saved by using the M3U instead of the MIP HS-based approaches.

### 7.2.1.2.2 Total GWH signalling cost Vs Speed

Figure 7.16 shows how the total GWH signalling cost is affected by the varying speed of the mobile source when the radius of the GW Beam is kept constant at 3000 Km. Similarly to Figures 7.7 and 7.12 above, the total GWH signalling cost increases with increasing speed and vice versa. Equations 6.3, 7.1 and 7.8 above provide the main reason for this trend.
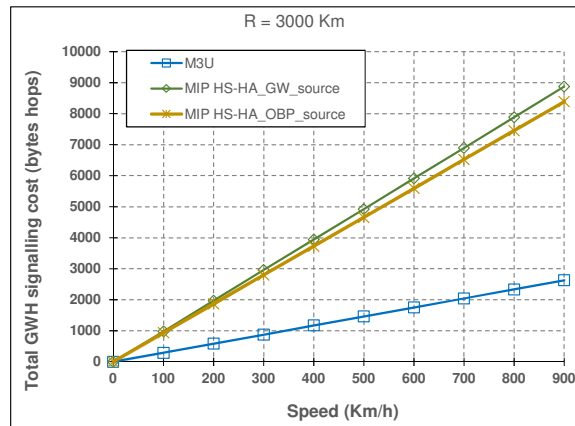


Figure 7.16 Effects of varying speed of mRCST on total GWH
signalling cost - source mobility

From Figure 7.16, the total GWH signalling cost for the proposed M3U is generally lower than those of the MIP HS-based schemes for any particular speed of the mobile source. This implies at any given speed of the mobile source, the M3U scheme remains the most efficient scheme amongst the three in terms of GWH signalling cost.

*7.2.1.2.3 Total GWH signalling cost Vs Radius of GW Beam*

The graphs in Figure 7.17 show that a constant speed of 800 Km/h, the total GWH signalling for the mobile source is inversely proportional to the radius of the GW Beam. From Equations 6.3, 7.1 and 7.8 above, this type of relationship between the total GWH signalling and the radius of the GW Beam is expected.
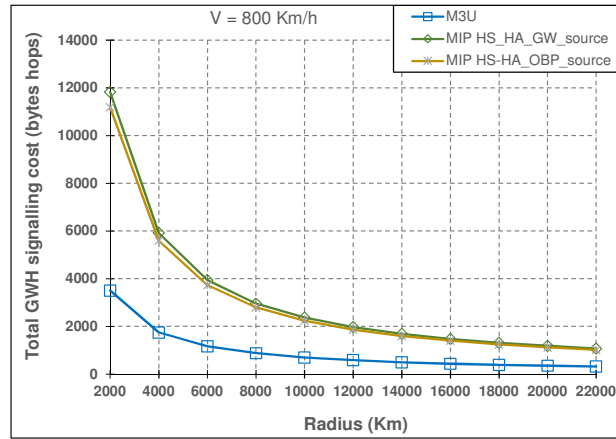


Figure 7.17 Effects of varying radius of GW Beam on total GWH
signalling cost – source mobility

Despite the fact that from the Figure 7.17 larger satellite beams will incur less total GWH signalling cost than smaller ones, the advantages of smaller satellite beams described in Section 7.1.1.3.4 above appear to be more important since new satellite designs are moving towards smaller beams.

### 7.2.1.3    *Packet delivery cost per multicast session*



a.    Packet delivery cost        b. Packet delivery cost vs λ$_s$
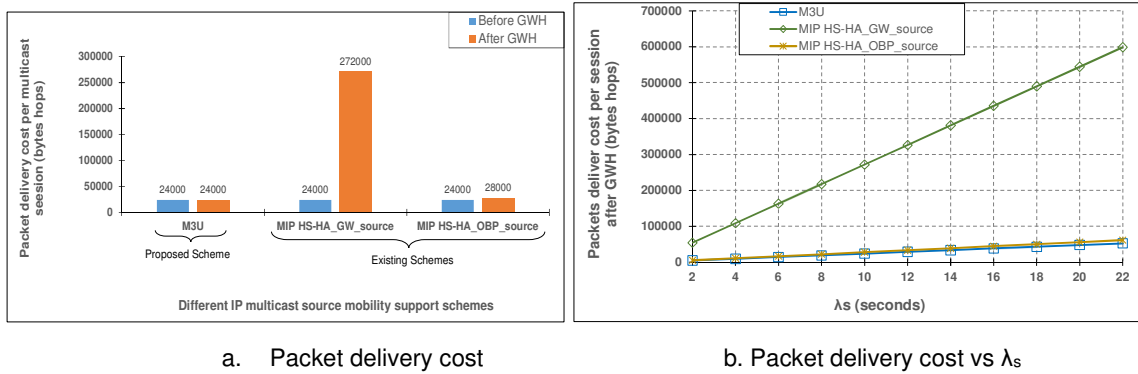
Figure 7.18 Packet delivery cost per session and effects of varying multicast
session arrival rate (λs) on multicast packets delivery cost per session

In Figure 7.18, the comparison of the packet delivery cost for receivers within the satellite network for the M3U, MIP HS-HA_GW_source and MIP HS-HA_OBP_source before and after GWH are given. The packet delivery cost in Figure 7.18 are obtained by making use of Equations 4.25, 4.26, and 5.27. As shown in Figure 7.18a, the packet delivery cost for the M3U scheme before and after GWH are identical while in the MIP HS-based approaches, the packet delivery cost after GWH is higher than that before GWH. This implies that for multicast receivers within the satellite network, the cost of delivery IP multicast traffic in SSM for the M3U will always remain the same no matter whether the mobile source is at home network (GW Beam) or away in a foreign network. This is made possible thanks to the operation of the proposed M3U which uses the basic concept of the MIP RS-based approach to support source mobility in SSM. The operation of the M3U as describe in Section 6.1 ensures that the routing of the IP multicast packets from the mobile source while away from its home network is fully optimised, this making M3U very efficient in terms of packet delivery cost. The packet delivery cost for the MIP HS-HA_GW_source after GWH is approximately 91.18% higher that before GWH. This huge difference is due to the fact main factors:

- Cost of MIP registration of the newly acquired CoA in target GW at it's home GWH

- Cost of tunnelling IP multicast traffic from the foreign GW to its home GW for delivery into the source-specific tree as explained in Section 4.4.1.

On the other hand, the packet delivery cost for MIP HS-HA_OBP_source after GWH is approximately14.29% higher that before GWH. Two reasons similar to those described above for the MIP HS-HA_GW_source scheme are responsible for this difference. The main difference here is that with the HA located at the

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OBP, the mobile source has to tunnel the IP multicast packets only to the OBP from its current location at foreign network for onward delivery to the already established multicast tree. This explains why the packet delivery cost for MIP HS-HA_OBP_source scheme is much lower than that for the MIP HS-HA_GW_source scheme.

### 7.2.2 Results from M3U simulation

Figure 7.19 shows the average packet end-to-end delay for each of the four simulated scenarios, outside the overlapping area of two beams (or simply, outside the GWH period). The average packet end-to-end delay for each scenario is obtained by subtracting the time the packet is transmitted (transmitter time) from the time that packet is received (i.e., receiver time for the packet) and then finding the average for all the packets in the scenario.
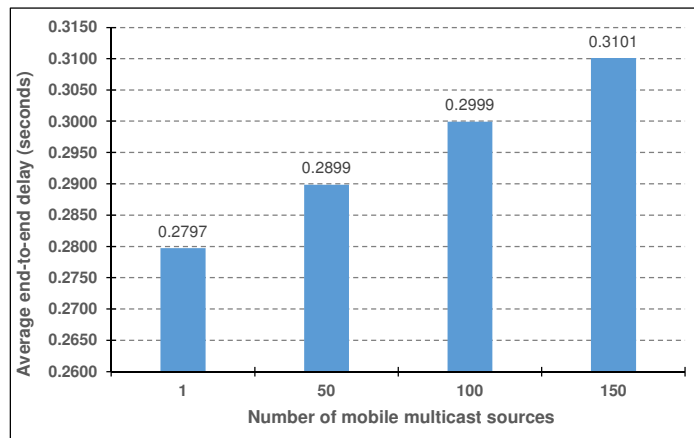


Figure 7.19  Average packet end-to-end delay for different scenarios.

It can be seen from Figure 7.19 that as the number of mobile sources increases from 1 to 50, 100 and 150, the average packet end-to-end delay increases approximately by 3.62%, 7.23% and 10.85% respectively. One of the reasons for this trend is that when the number of sources transmitting at same time increases, the amount of traffic in the network per unit time also increases. Increasing amount of traffic in the network could lead to increasing queueing

delays and therefore resulting in increasing level of congestion. Increasing

levels of congestion in the network has the potential to cause the increasing

average packet end-to-end delay observed in scenarios 1 to 4 in Figure 7.19.
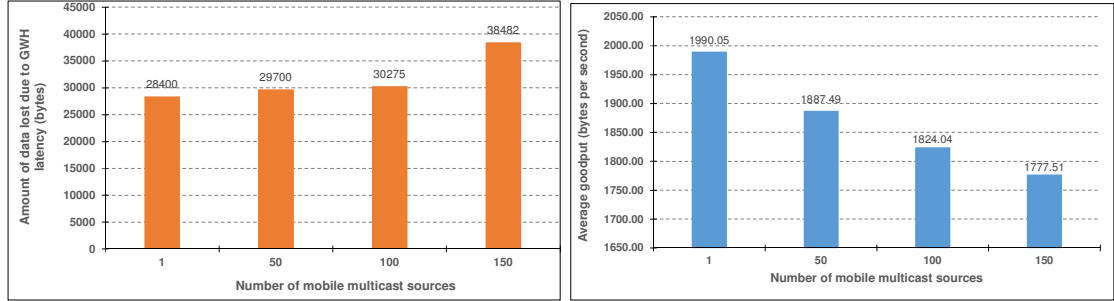


a) Amount of data lost due to GWH latency for different scenarios

b) Average throughput for different scenarios
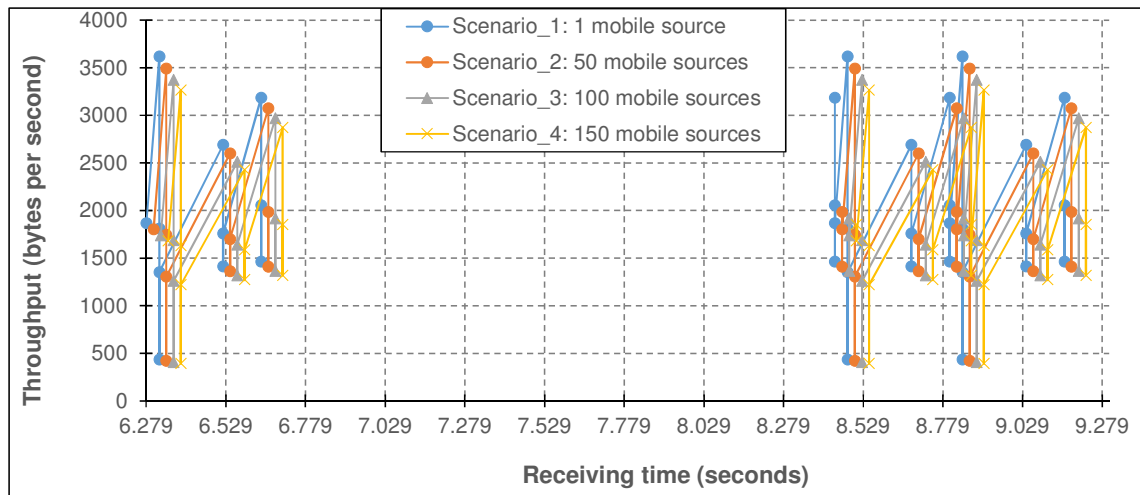


c) Effect of varying number of sources on throughput of receivers

Figure 7.20 Throughput and number of mobile sources

Figure 7.20 shows the multicast data flow when the mobile source(s) is within

the overlapping area of two satellite beams belonging to two different GWs. This

covers the period when the mobile source(s) has to perform GWH. Figure 7.20a

shows how the amount of data (in bytes) lost due to GWH latency varies as the

number of mobile multicast sources increases from 1 to 150. The amount of

data lost during GWH for each scenario is obtained by adding the packet sizes

of all packets lost during the GWH latency period. From Figure 7.20a, it can be seen that as the number of mobile sources increase, the amount data lost due to GWH latency increases. From scenario 1 (1 mobile source) to scenario 4 (150 mobile sources), the amount data lost due to GWH latency increases by 4.38%, 6.19% and 26.20% respectively. The observed trend in Figure 7.20a can be explained as follows: when the number of mobile multicast sources transmitting data to the multicast group increases, the amount of traffic in the network per unit time also increases. This increase in the amount of traffic in the network per unit time causes an increase in queuing delays. Depending on the buffer sizes of the processing nodes, increasing queuing delay may lead to packet losses if the buffers are full.

Figure 7.20b shows the average throughput for each scenario. Average throughput here is obtained by dividing the total amount of data received by the total time taken to transmit and receive the data (delay). From Figure 7.20b, the average throughput (including that during the GWH latency) decreases as the number of mobile sources increases. Figure 7.20b shows that as the number of mobile multicast sources increase from 1 to 50,100 and 150, the average throughput decreases by approximately 5.15%, 8.34% and 10.68% respectively. The reason for this trend could be due to the fact that increasing number of mobile sources transmitting multicast data and requesting handover at the same time means higher queuing and processing delay. This implies lower throughput, as the time required to transmit the same amount of data will increase.

Figure 7.20c shows how the throughput for each simulated scenario varies with receiving time. From Figure 7.20c, the empty gap in the graph where throughput is zero indicates the multicast disruption period due to GWH latency where no

data is transmitted (about 1.80 seconds in each of the four scenarios). For each data packet transmitted, throughput for scenario 1 is the highest while that for scenario 4 is the least. This is due to the fact that as the number of mobile sources simultaneously sending traffic increases, each packet experiences higher end-to-end delay (due to queuing, congestion, etc.,, thus reducing the throughput within the network. The sinusoidal zig-zag shape of the graph in Figure 7.20c is due to the fact that a cycle of 11 packets of different fixed sizes are repeatedly transmitted by the mobile source(s) throughout the simulation time. Therefore, this results in a cycle of similar throughput at the multicast receivers.

Table 7.6 Summary of M3U simulation results

| Parameter | % changes when number of mobile sources increase from 1 to: | | |
|---|---|---|---|
| | **50** | **100** | **150** |
| **Average packet end-to-end delay** ⬆ | 3.62% | 7.23% | 10.85% |
| **Amount of data lost due to GWH latency** ⬆ | 4.38% | 6.19% | 26.20% |
| **Average throughput** ⬇ | 5.15% | 8.34% | 10.68% |

Table 7.6 summarises the results obtained from the M3U simulation. From Table 7.6, it can be seen that as the number of mobile multicast sources increases from 1 to 150, the average packet end-to-end delay and the amount of data lost due to GWH latency both increase, but the average throughput within the network decreases.

### 7.2.3 Summarised comparison of all IP multicast source mobility support schemes

In Table 7.7a, the simulated and the analytical results of GWH latency for the proposed M3U-based approach are very similar, thus validating the proposed M3U-based approach.

Table 7.7 Comparison of IP multicast source mobility support schemes

a. GWH Latency

| | Proposed scheme | | Existing schemes | |
| | M3U | | MIP HS-HA_GW_source | MIP HS-HA_OBP_source |
| | Analytical | Simulated | | |
|---|---|---|---|---|
| GWH Latency | 1.78 | 1.80 | 3.86 | 3.34 |

b. Packet delivery and signalling cost

| Schemes supporting source mobility in SSM | Packet delivery cost per multicast session (bytes hops) | | Signalling cost per GWH (bytes hops) | Signalling cost over satellite air interface per GWH (bytes hops) |
| | Before GWH | After GWH | | |
|---|---|---|---|---|
| M3U (analytical) | 24000 | 24000 | 1375 | 790 |
| MIP HS-HA_GW_source | 24000 | 272000 | 46422 | 3126 |
| MIP HS-HA_OBP_source | 24000 | 28000 | 43910 | 3206 |

Also from Table 7.7a, the average GWH latency (analytical and simulated) for the proposed M3U scheme is about 53.63% and 46.41% lower than those of the MIP HS-HA_GW_source and MIP HS-HA_OBP_source schemes respectively.

From Table 7.7b, the Packet delivery cost per multicast session after GWH, the signalling cost and the signalling cost over the satellite air interface for the

proposed M3U scheme are much lower than those for the MIP HS-HA_GW_source and MIP HS-HA_OBP_source schemes.

GWH latency and signalling cost which are some of the most important factors in evaluating the performance of any mobility protocol therefore show that the proposed M3U scheme is a much better mobility management protocol compared to the MIP HS-HA_GW_source and MIP HS-HA_OBP_source schemes.

## 7.3  Summary

The results from the IP multicast receiver mobility support schemes presented above, show that the proposed SHS-, SRS-, MI- and PMIPv6-based schemes are generally better than the existing MIP HS- and MIP RS-based schemes in terms of GWH latency, number of packets lost due to GWH latency, satellite capacity required for retransmission, total signalling cost per GWH, signalling cost over satellite air interface per GWH.

Also, from the results and analysis presented above, the proposed M3U-based scheme for IP multicast source mobility support in SSM over satellite networks is generally better than the existing MIP HS- and MIP RS-based schemes in terms of GWH latency, packet delivery cost per multicast session, signalling cost per GWH and   signalling cost over satellite air interface per GWH.

The next chapter draws an overall conclusion of this study and also, presents some future work.

# 8 CONCLUSION AND FUTURE WORK

## 8.1 Conclusion

### 8.1.1 IP multicast and satellite networks

In Chapters 1 and 2, a good account of the satellite network architectures (DVB), main architectural entities, types of handovers in satellite networks, the current types of IP multicast services supported on new generation of satellite systems and IP multicast protocols adapted for the satellite environment have been presented.

### 8.1.2 IP mobile multicast and satellite networks

The challenges faced by IP mobile multicast receivers/sources in both terrestrial networks as well as satellite networks especially during a layer three handover scenario are highlighted and discussed in Chapter 3. Most (if not all) of the existing IP multicast mobility support schemes defined for terrestrial networks are compared in Chapter 3 with the view of establishing which ones could be suitable for adaptation in a multi-beam satellite network. Based on some predefined characteristics which are important for IP multicast mobility support in satellite networks, some of the terrestrial networks schemes are identified as good candidate schemes for adaptation in a multi-beam satellite network. These include the HS-based, RS-based, PMIPv6-based, MSA and MMOFA schemes.

In Chapter 4, performance evaluation of some of these good candidate schemes (HS and RS) which require minimum modifications to their current form is carried out if they are implemented over a given reference satellite network. The results obtained from this evaluation give a relatively high GWH latency, number of packets lost due to GWH latency and satellite capacity required for retransmission of the lost packets during GWH in a reliable IP

multicast communication. These results indicate that modification to these existing schemes or the need for a new set of IP multicast mobility support schemes are required in order to achieve better results.

One of the focal objectives of this research study is to design an IP multicast receiver/source mobility support scheme especially during a GW/satellite handover in a multi-beam satellite network. This objective is fulfilled in Chapters 5 where the SHS, SRS, MI and PMIPv6-based schemes are proposed for IP multicast receiver mobility support over the same reference multi-beam satellite network used for the performance evaluation of the existing schemes. The M3U-based scheme is also proposed in Chapter 6 to support IP multicast source mobility in SSM.

### 8.1.3  Summarised key novelties of the proposed schemes

#### 8.1.3.1      *IP multicast receiver mobility support schemes*

**Satellite Home Subscription (SHS)-based approach**

- Designing each satellite GW to have only one HA and one FA, serving all mRCSTs originating from and visiting the GW respectively, thus eliminating tunnel convergence problem

- The concept of advance knowledge of the mRCST's CoA in the target GWs

- Advance registration (pre-registration) of mRCST's CoA at its HA at the beginning of the GWH/SH process by embedding the MIP registration message to its HA in the SYNC burst which carries the handover recommendation to the NCC. This helps to reduce the GWH/SH latency as the IP tunnel between its home GW and target GW is established before the GWH/SH completion process. This is contrary to what is obtained in MIP

HS-based approach where the handover is completed before the process of registering the CoA to the HA is initiated.

- Chronologically integrating the additional signalling messages proposed to support the SHS at GWH into the standard DVB GWH signalling sequence.

**Satellite Remote Subscription (SRS)-based approach**

- The concept of advance knowledge of the mRCST's CoA in the target GWs

- mRCST advance (i.e., at beginning of GWH/SH process) re-subscription via the target GW to all multicast groups that it is a member of  as it enters the overlapping area of the two beams. This is done by embedding the IGMP report (join) message to the target GW into the SYNC burst. The advance re-subscription helps to reduce GWH/SH latency in two ways. Firstly, if the mRCST is the first member of any of the requested group(s) in the target GW, then, the construction of the multicast delivery tree to the target GW is initiated at the beginning of the handover, thus significantly increasing the chances of the multicast data readily available to the mRCST immediately after handover completion. Secondly, if the requested multicast group(s) already exist in the target GW, then, the mRCST is simply added to the list of downstream receivers at the beginning of the handover process.  Unlike in MIP RS-based approach where the re-subscription process is initiated only after the handover process is completed, in SRS, it is initiated at the beginning of the handover, thus saving time as shown in the results obtained.

- Chronologically integrating the additional signalling messages proposed to support the SRS at GWH into the standard DVB GWH signalling sequence.

**Multiple interface (MI)-based approach**

- The concept of using multiple satellite interfaces on an mRCST to support IP multicast receiver mobility during a GWH/SH process. This completely eliminates the GWH/SH latency when end users behind the mRCST never experience any multicast communication disruption or packet loss due to the GWH/SH process

- Architectural modifications to the standard one interface mRSCT to accommodate the additional satellite interface. The additional new features include:

  ❖ An additional broadcast interface (i.e., for receiving data via DVB-S) in the broadcast interface module with its corresponding additional interactive interface (i.e., for sending data via DVB-RCS) in the interactive interface module, making the mRCST a multi-homed device.

  ❖ A database in the mRCST which holds information about the global map of the interactive satellite network (i.e., information about beams, their locations and frequency, gateways - location and IP addresses) as well as all active connections in the mRCST.

  ❖ A message chamber which can issue IGMP join report and leave messages during handover between the two satellite interfaces (IF0 and IF1).

  ❖ The controller which manages the data base, the interfaces and has complete control over which interface the traffic leaves/enters the mRCST especially when the two are active (i.e., during handover).

**PMIPv6-based approach**

- Extending the PMIPv6 protocol defined for terrestrial networks to support IP multicast receiver mobility in satellite networks

- Proposed different locations within the satellite network where the main PMIPv6 mobility entities (LMA and MAG) could be configured in order to achieve the desired goals

- Slight modification to the functions of the LMA and MAG (compared to that defined in the standard PMIPv6 protocol for terrestrial networks) to suit the satellite environment.

*Table 8.1 Modifications to the LMA and MAG functions to suite the satellite environment*

| Proposed PMIPv6-based approach for satellite environment | Standard PMIPv6 protocol |
|---|---|
| LMA tracks mobility of mRCSTs | Mobility of MNs is tracked by MAG |
| MAG serves as topological anchor point for the mRCTS' (aircrafts') HNPs | LMA is the topological anchor point for the MNs HNPs |

- Proposed content of binding cache entry (BCE) for each mRCST (aircraft) that is away from its home network.

- The functioning of the LMA, MAG, MTMA and MR and the signalling sequences required to support IP multicast receiver mobility in during a GWH/SH for DR mode and MTMA mode in a satellite environment.

### 8.1.3.2    *IP multicast source mobility support scheme*

**Multicast Mobility Management Unit (M3U)-based approach**

- Using RS -based approach in SSM to support source mobility in satellite networks.

  ❖ Up till now RS-based approaches have been used to support source mobility only in any source multicast (*, G).

❖ Introducing Multicast Mobility Management Unit (M3U) to support RS – based approach for SSM in Satellites is quite a novel concept.

• Re-subscribe to the new channel (CoA, G) after GWH without issuing IGMP join report over the satellite air interface. The functioning of M3U ensures that no IGMP join report is sent to satellite air interface by listening satellite terminals after GWH

• IP mobility support without any encapsulation (tunnelling) and triangular routing paths, throughout the system. The operation of M3U ensures that user traffic routing is optimised and that no tunnelling is used.

### 8.1.4 Concluding remarks

With the increasing support for IP-based applications over satellite networks and increasing demand for ubiquitous communications, support for IP multicast over mobile satellite terminals is gaining importance. Despite the fact that IP multicast saves satellite bandwidth resources and therefore money for satellite operators and customers, support for global mobile IP multicast communications and dynamic group membership over satellite networks remains a serious problem with no standard solution. Although some IP multicast mobility support schemes defined for terrestrial networks (HS and RS) could be applicable in a satellite environment with minimal modifications, the evidence presented in this work show that they might not be efficient in their intended tasks. Consequently, this may result in waste of expensive satellite resources and therefore money for both the satellite operators and customers.

This work has presented four different novel approaches to support IP multicast receiver mobility and one novel scheme to support IP multicast source mobility in SSM, in a multi-beam satellite network. The results obtained from the proposed schemes are compared with those from the existing MIP HS-based

and RS-based schemes. From the results obtained, the proposed schemes generally outperform the existing HS-based and RS-based approaches in terms of GWH latency, number of packets lost due to GWH latency, satellite capacity required for retransmission, total signalling cost per GWH and signalling cost over satellite air interface per GWH.

## 8.2 Future work

This work has laid a solid foundation for future studies in IP multicast communication over satellite networks especially on mobile satellite scenarios. In this work, a PMIPv6-based IP multicast receiver mobility support scheme over satellite networks has been proposed. One area of possible future work is to extend this PMIPv6-based receiver mobility to support IP multicast source mobility over multi-beam satellite networks. This could be very important especially in SSM where changes to the IP address of the mobile multicast source during handover invalidates the source-specific tree. This creates serious problems to the entire multicast channel/group as multicast traffic from the mobile source with the new IP address (CoA) cannot be routed until some receivers explicitly join the new multicast channel (CoA, G). Extending the satellite PMIPv6-based scheme in which the IP address of the mobile satellite terminal (aircraft, etc.) does not change during any type of handover to support source mobility in SSM could eliminate the problems encountered with the current MIP-based schemes.

Another possible area of future work is to incorporate network coding (NC) over satellites into the proposed IP multicast mobility support schemes in order to build a future bandwidth efficient mobile satellite communications. NC just like IP multicast is another bandwidth saving technology. In lossy communication

channels like the satellite, it has been shown from the theoretical analysis and practical experimentation, that NC can increase throughput, robustness to packet losses and bandwidth efficiency. In mobile satellite communication where packet erasures are very common, implementing NC together with the proposed IP multicast mobility support schemes might significantly increase the overall savings in the satellite bandwidth resources.

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