HANDOVER MANAGEMENT ALGORITHMS IN LEO SATELLITE COMMUNICATION NETWORKS

by

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ABSTRACT

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Since Low Earth Orbit (LEO) satellite constellations have important advantages over Geosynchronous Earth Orbit (GEO) satellite systems such as low propagation delay, low power requirements and more efficient spectrum allocation due to frequency reuse between satellites and spotbeams, they are considered to be used to complement the existing terrestrial fixed and wireless networks in the evolving global mobile network. However, one of the major problems with LEO satellites is their higher speed relative to the terrestrial mobile terminals, which move at lower speeds but at more random directions. This high mobility characteristic of LEO satellites causes mobile users to hand over between footprints of adjacent satellites very frequently. Therefore, handover management in LEO satellite networks becomes a very challenging task for supporting global mobile communication. Efficient and accurate methods are needed for LEO satellite handovers between the moving footprints. The main concern of researches done in this area is providing a reliable service to the user that prevents a communication from being dropped due to a handover.

Currently, there are many studies dealing with the problems of handover management issues in LEO satellite communication networks. Related work in this area focuses on the development of new mobility management architectures as well as improving the handover decision mechanisms to quickly and accurately trigger handovers. The thesis discusses only the basic handover management schemes used in LEO satellite networks and points out their drawbacks. Handover decision schemes are not covered by this thesis. The thesis also includes a survey of recent handover management protocols proposed for LEO satellites.

By taking into consideration the inconvenience and incompleteness of the current proposals in literature, this thesis proposes two new mobility management schemes for LEO satellite communication networks.

The first one focuses on a new Seamless Handover Management Scheme for LEO Satellites (SeaHO-LEO), which utilizes the handover management protocols aiming at decreasing latency, data loss, and handover blocking probability. To show the performance of the proposed algorithm, an extensive set of simulations both for the proposed algorithm and well known handover management methods is run as a baseline model. The simulation results show that the proposed algorithm is very promising for seamless handover especially in highly crowded networks.

In addition to this, another interesting handover management model called Satellite Mobility Pattern Based Handover Management in LEO Satellites (PatHO-LEO), which takes mobility pattern of both satellites and mobile terminals into consideration to minimize the handover messaging traffic, is presented in this thesis. Minimization of handover messaging traffic is achieved by the newly introduced Billboard Manager which is used for location updates of mobile users and satellites. The Billboard Manager makes the proposed handover model much more flexible and easier than the current solutions, since its centrical characteristic supports the manageability of the whole system. The analytical work done for this evaluation shows that the proposed PatHO-LEO architecture has a significantly lower mobility management cost.

ÖZET

LEO UYDUSU İLETİŞİM AĞLARI İÇİN YENİ ELDEĞİŞTİRME YÖNETİMİ ALGORİTMALARI

Düşük-Yer Yörüngesi (LEO) uydu sistemleri, evrensel gezgin ağların gelişiminde var olan karasal sabit ve telsiz ağların tamamlayıcısı olarak düşünülmektedirler çünkü Düşük-Yer Yörüngesi uydu sistemleri Yer ile Eş zamanlı Yörünge (GEO) uydu sistemlerine kıyasla düşük yayılım gecikmesi, düşük güç gereksinimleri gibi önemli getirilere sahiptirler. Ancak, Düşük-Yer Yörüngesi uyduları ile ilgili başlıca sorunlardan biri bu uyduların düşük hızla fakat daha rasgele yönlere haraket eden karasal gezgin terminallere nispeten daha yüksek hızda hareket etmeleridir. Düşük-Yer Yörüngesi uydularının hızlı harekete etme özellikleri gezgin kullanıcıların sıklıkla komşu uydular arasında eldeğiştirmesine sebep olmaktadır. Bundan dolayı, evrensel mobil iletişimi geliştirme amacı ile yola çıkıldığında, Düşük-Yer Yörüngesi uydu sistemlerinde meydana gelen uydular arası eldeğiştirmelerin yönetimini sağlayabilmek oldukça uğraştırıcı bir iş haline gelmiştir. Düşük-Yer Yörüngesi uydularının yayınlarının etkili olduğu yeryüzü alanları arasında gerçekleşen eldeğiştirmelerin idaresi için etkili ve eksiksiz metodlar gerekmektedir. Bu konudaki temel endişe son kullanıcılara eldeğiştirmelerin sebep olabileceği kesintilere karşı güvenilir bir servis sağlayabilmektir.

Günümüzde Düşük-Yer Yörüngesi uyduları arasında gerçekleşen eldeğiştirmeler esnasında karşılaşılan problemlerle başa çıkabilmek için çeşitli çalışmalar mevcuttur. Bu konuda yapılan çalışmalar, yeni hareket yönetim sistemlerinin tasarlanmasına ve eldeğiştirme sürecindeki karar verme aşamasının eldeğiştirmeleri hızlı ve doğru bir şekilde tetikleyecek yönde geliştirmeye odaklanmıştır. Bu tez çalışması, şu ana kadar Düşük-Yer Yörüngesi uydu ağları için önerilen eldeğiştirme sistemlerini irdelemekte ve bu sistemlerin eksiklerini ortaya çıkarmaktadır. Eldeğiştirme sürecindeki karar verme aşaması bu tez çalışmasının içeriğinde yer almaz. Bu tez ayrıca yakın zamanda Düşük-

Yer Yörüngesi uyduları için önerilen eldeğiştirme yönetimi modellerinin bir araştırması niteliğini taşır.

Bunlarla beraber, bu tez çalışması kapsamında incelenen sistemlerin eksiklik ve sakıncaları gözönüne alınarak, Düşük-Yer Yörüngesi uydu iletişim ağları için iki yeni Eldeğiştirme Yönetim Sistemi önerilmektedir.

Önerilen ilk model Düşük-Yer Yörüngesi uyduları için eldeğiştirme esnasındaki bekleme süresini, veri kaybını ve eldeğiştirmenin bloklanma olasılığını düşürmeyi hedefleyen kısaca SeaHO-LEO olarak adlandırılan yeni bir Eldeğiştirme Yönetim Sistemi üzerine yoğunlaşmaktadır. Önerilen modelin performasını değerlendirebilmek için bilinen hareket yönetimi modelleri ile karşılaştırmalı ve kapsamlı bir dizi simülasyon gerçekleştirilmiştir. Simülasyon sonuçları önerilen eldeğiştirme modelinin özellikle çok kalabalık ağlar için umut verici olduğunu göstermektedir.

Ayrıca, PatHO-LEO olarak adlandırılan, uyduların ve gezgin terminallerin seyir şablonlarını gözönüne alarak eldeğiştirme sırasında oluşan mesajlaşma trafiğini en aza indirgemeyi amaçlayan bir başka Eldeğiştirme Yönetim Modeli de bu tezde sunulmaktadır. Eldeğiştirme sırasında oluşan mesajlaşma trafiğinin en aza indirgenmesi, gezgin kullanıcıların ve uyduların konum değişikliklerini bildirebilecekleri yeni merkezi bir Konum Bildirim Yöneticisi'nin (Billboard Manager) tasarlanması ile sağlanmıştır. Bu yeni merkezi Konum Bildirim Yöneticisi önerilen modelin var olan sistemlere kıyasla daha da esnek olmasını ve kolay idare edilebilir olmasını sağlamaktadır. Bu model ile ilgili yapılan analitik çalışma PatHO-LEO mimarisinin oldukça düşük bir hareket yönetim maliyetinin olduğunu göstermiştir.

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LIST OF SYMBOLS/ABBREVIATIONS

D	Area density of nodes
ID_{UMP}	UMP Identity
IP_{MN}	IP of MN
IP_{SAT}	Satellite Identity
L_{sat}	Satellite's coverage boundary length
$R_{HO}(t)$	Rate of handover occurrence
R	Rate of boundary crossing event
S_C	Current satellite
S_N	Next (new) satellite
t_F	Time in a footprint
V_{sat}	Footprints velocity
α	Ratio of active mobile nodes to the total number of nodes
λ	Rate of newly coming connections to a mobile node
AA	Agent Advertisement
AR	Access Router
BM	Billboard Manager
CDMA	Code Division Multiple Access
CN	Corresponding Node
CoA	Care of Address
CONN_ACTIVATE	Connection Activate Message
DHCP	Dynamic Host Configuration Protocol
DHCPv6	Dynamic Host Configuration Protocol for IPv6
EET	Expected Entry Time
FA	Foreign Agent
FDMA	Frequency Division Multiple Access
FSM	Finite State Machine
GEO	Geostationary Earth Orbit

HA	Home Agent
HO_RELEASE	Release Resource
HP_REQUEST	Handover Preparation Request Message
HP_RESPONSE	Handover Preparation Response Message
HR_REQUEST	Handover Ready Request Message
HR_RESPONSE	Handover Ready Response Message
ISL	Inter Satellite Link
LAN	Local Area Network
LD	Location Directory
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MH	Mobile Host
MIP	Mobile IP
MN	Mobile Node
MT	Mobile Terminal
PatHO-LEO	Satellite Mobility Pattern Based Handover Management Procedure for LEO Satellite Communication Networks
QoS	Quality of Service
Reach.ID	Reachability Identity
Route.ID	Routing Identity
SAA	Stateless Address Autoconfiguration
SCTP	Stream Control Transmission Protocol
SeaHO-LEO	Seamless Handover Management Procedure For LEO Satellite Communication Networks
SMP	Satellite Mobility Pattern
SUMP	Satellite and User Mobility Pattern
TDMA	Time Division Multiple Access
TraSH-SN	Transport Layer Seamless Handoff Scheme for Space Networks
TSL	Terminal Satellite Link
UMP	User Mobility Pattern
UT	User Terminal

1. INTRODUCTION

Terrestrial wireless networks such as cellular networks provide mobile communication services with limited geographical coverage. In order to provide global coverage to a more varied user population, satellite communication networks are utilized to coexist with terrestrial networks. Therefore, the role of satellites is changing from the traditional telephony and TV broadcast services to user oriented data services. This trend is expected to continue in the future. Due to this reason, next generation mobile networks will use smart satellites that will incorporate functions such as switching, buffering and beam switching in addition to signal reproduction. Small and large LEO constellations are expected to become a candidate in the cellular market.

A typical LEO satellite takes about 100 minutes to orbit the Earth, which means that a single satellite is "in view" of ground equipment for only a few minutes [1]. As a consequence, if a transmission takes more than the few minutes that any one satellite is in view, a LEO satellite system must hand over between satellites to complete the transmission. In general, this can be accomplished by constantly relaying signals between the satellite and various ground stations, or by communicating between the satellites themselves using "inter-satellite links" [1, 2]. LEO satellites are also designed to have more than one satellite in view from any spot on the Earth at any given time, minimizing the possibility that the network will loose the transmission. Due to the fast-flying satellites, LEO systems must incorporate complicated tracking and switching equipment to maintain consistent service coverage. This thesis focuses on the handover management of satellite networks which is a crucial design problem for supporting mobile communication services in the coexisting terrestrial and LEO satellite networks.

The advantage of the LEO system is that the satellites' nearness to the ground enables them to transmit signals with a small amount of delay, unlike GEO systems. Also, since the signals to and from the satellites need to travel a relatively short distance, LEO systems can operate with much smaller user equipment (e.g., antenna) than systems using a higher orbit. In addition, a system of LEO satellites is designed

to maximize the ability of ground equipment to see a satellite at any time, which can overcome the difficulties caused by obstructions such as trees and buildings [1].

One of the proposed models is Mobile IP (MIP) [3] for handover management in satellite networks. It enables a TCP connection to remain alive and receive packets when a mobile host moves from one point of attachment to another. Although MIP is a widely used approach applied to satellite networks, it has some important drawbacks including high handover latency and high packet loss.

Therefore, the question that naturally arises is: How can we find an alternative approach for mobility support and to carry out handovers that will be applicable for integration of data communications in both terrestrial and satellites networks using multiple interfaces? Since most of the applications in the Internet are end-to-end, SeaHO-LEO, a seamless mobility solution as an alternative to MIP for handovers is proposed and developed. To minimize the messaging traffic generated during the handover procedure, another mobility management model called PatHO-LEO has also been developed.

The objective of this thesis is to describe the proposed schemes called A Seamless Handover Management Scheme for LEO Satellite Networks (SeaHO-LEO) for supporting mobility, its design issues, and Satellite Mobility Pattern Based Handover Management in LEO Satellites (PatHO-LEO) and their suitability for satellite networks with and related design and performance issues. The basic idea of SeaHO-LEO is to use ISLs to prevent data loss while setting up a new path, thus achieving a seamless handoff between adjacent subnets. SeaHO-LEO can cooperate with normal IPv4 or IPv6 infrastructure without the support of Mobile IP. SeaHO-LEO has also a number of advantages such as easier deployment because of no change required in the Internet infrastructure, co-operation with Internet's security protocols, efficient utilization of network bandwidth due to the absence of tunnelling, etc. The aim of the PatHO-LEO is to eliminate the handover messages as much as possible. It offers satellites and mobile users to register with their mobility patterns to a central service provider database. Since all the handover information such as new subnet, new IP, etc. are known before

the handover procedure in PatHO-LEO, lots of handover related messages are no more necessary to complete handover between satellites.

The main contributions of this paper can be listed as follows:

- Discussing different types of handover scenarios in LEO satellite networks.
- Proposing and developing SeaHO-LEO and PatHO-LEO to solve the problems of MIP in satellite networks. The aim is to achieve seamless handover between satellites. Here by seamless, we mean low latency and low packet loss during handover process.
- Proposing a central server called Billboard Manager for location updates of mobile users and satellites.
- Illustrating the handover procedures, signalling procedures and location management procedures in SeaHO-LEO and PatHO-LEO.
- Analyzing the performance measures of proposed handover management models and comparing them with MIP and other recent proposals.

The rest of this thesis is organized as follows. Chapter 2 summarizes general characteristics of geostationary and non-geostationary mobile earth orbit satellites including handover characteristics and architectures in LEO satellite constellations. Chapter 3 gives a brief discussion of mobility management in terrestrial mobile networks and LEO satellite networks. Also, basic handover management schemes for LEO Satellites and recent proposals are covered in this chapter. Chapter 4 describes in detail the signal flow and the simulation results of the Seamless Handover Management Scheme for LEO Satellite Networks (SeaHO-LEO). In Chapter 5, Satellite Mobility Pattern Based Handover Management in LEO Satellites (PatHO-LEO) and its mobility management cost analysis are explained in detail. Finally, Chapter 6 concludes the thesis and discusses future work.

2. MOBILE SATELLITE COMMUNICATION NETWORKS

The geostationary and non-geostationary (mobile earth orbit) satellite networks will complement the existing terrestrial fixed and wireless networks in the evolving global mobile network. Satellite networks are seen as the solution to providing global location independent coverage (e.g., land, sea or air) to wireless mobile end-users. The emergence of satellite technologies including onboard routing and Inter-Satellite Links, are enabling the vision of an 'Internet in the sky', which is capable of providing location independent high-quality access to common communications applications (e.g., telephony, email, World Wide Web).

This chapter introduces mobile satellite communications networks in the context of providing personal communications services to mobile end-users. Section 2.1 gives general characteristics of geostationary and non-geostationary satellite networks. Section 2.2 gives detailed information about LEO satellite networks. Section 2.2.1 describes the characteristics of the LEO, and discusses the relative advantages and disadvantages in terms of providing personal communications services. Section 2.2.2 provides a brief overview of the technical aspects of the Iridium and Teledesic LEO satellite constellations, which are used throughout this thesis as the reference constellations. Section 2.3.2 defines types of handover, and examines the two major categories of handover in a LEO satellite network. Finally, Section 2.3.3 gives the mathematical model of handover occurrence in LEO satellite networks.

2.1. Geostationary and Non-Geostationary Satellite Networks

Satellite systems can be classified in two categories: Geostationary and Non-geostationary Earth Orbit satellite systems. A geostationary orbit is a circular orbit in the equatorial plane with an orbital period equal to that of the Earth, which is achieved at an orbital height of 35786 km. A satellite in a geostationary orbit will appear fixed

above the surface of the earth. The footprint or service area of a geostationary satellite covers almost one third of the earth's surface, so that near-global coverage can be achieved with a minimum of three satellites in orbit. At this height, communications through a GEO satellite entail a round-trip transmission delay of at least 250 ms. This GEO latency is the source of the annoying delay in many intercontinental phone calls. What can be an inconvenience on voice transmissions; however, can be implausible in real-time applications such as video-conferencing, as well as many standard data protocols-even the protocols underlying the Internet. Advanced digital broadband networks will be packet-switched networks, in which voice, video and data are all packets of digitized bits. It is not feasible to separate out applications that can tolerate delay from those that cannot. As a result, the network has to be designed for the most demanding application.

Traditional geostationary satellites will continue to play an important role, particularly in providing broadcast services, but increasingly mobile earth orbit satellites will be used to provide personal communications services comparable in performance to terrestrial wireless services. Non-geostationary satellite systems appear as an attractive solution to provide global coverage and ensure reliable communication for the most demanding applications. Two categories of orbits have been envisaged: Low Earth Orbit (LEO) at an altitude of about 1,000 km and Medium Earth Orbit at an altitude of about 10,000 km. Subject to such orbits, the satellite moves continuously relative to the earth surface. Permanent global communications entail the use of several satellites, organized in constellations, with several satellites per orbit plane and several orbit planes per constellation. The traffic generated by a User Terminal is then supported by satellites successively passing over the service zone, and must be handed over from one satellite to the next.

LEO satellites, and to a lesser extent MEO satellites, exhibit terrestrial wireless-like characteristics, including a small propagation delay ideal for interactive communications, and low transmit power requirements making small handheld terminals a reality. The evolution towards mobile earth orbit satellite networks has resulted in a multitude of proposals, including Iridium [4] (LEO), Globalstar [5] (LEO), ICO [6]

(MEO), Ellipso [7] (Molnya and Tundra elliptical orbits), Constellation (LEO), ECO-8 (LEO), Courier (LEO) [8], Odyssey [9] (MEO), Teledesic [10] (LEO), M-Star/Celestri (LEO), SkyBridge (LEO), Orblink (MEO), Orbcomm [11] (LEO), Leo One (LEO), and AprizeStar [12] (LEO). Each constellation targeted a particular market, such as voice, broadband data, satellite radio, or messaging. Infact, most of these constellations were never built due to a lack of funding, however Iridium and Globalstar, targeting the voice market, and Orbcomm, targeting the messaging market, were built and are in operation today. While the future profitability of such constellations remains unclear, future technological advancements should lower development, launch, and management costs, and increase data rates, resulting in a more cost/performance competitive service than is currently available today.

2.2. Low Earth Orbit Satellite Networks

2.2.1. The Low Earth Orbit

The Low Earth Orbit is an instance of a more general orbit referred to as the mobile earth orbit. Generally, the mobile earth orbit describes an inclined circular orbit, in which satellites appear to move across the sky as viewed from a fixed point on the Earth. There are two types of circular mobile earth orbits: 1) LEO, which is located at altitudes between 500 km and 1,500 km, and 2) MEO, which is located at altitudes between 5,000 km and 13,000 km [1]. At these altitudes, a single satellite is able to cover only a small portion of the Earth's surface, and therefore multiple satellites are required to provide global coverage. For example, Iridium uses 66 LEO satellites at an altitude of 780 km [13], Globalstar uses 48 LEO satellites at an altitude of 1,400 km [14], and the now defunct ICO planned to use 10 MEO satellites at an altitude of 10,390 km [15]. MEO constellations are generally placed into moderately inclined orbits (i.e. up to 70 degrees inclination), and LEO constellations are placed into highly inclined orbits (i.e. up to 90 degrees inclination), which are also referred to as polar orbits. This thesis focuses on the LEO constellations. A simple illustration outlining the major components of a LEO satellite constellation is shown in Figure 2.1, which is based on a diagram in [16] and modelled on the Iridium constellation. The backbone network

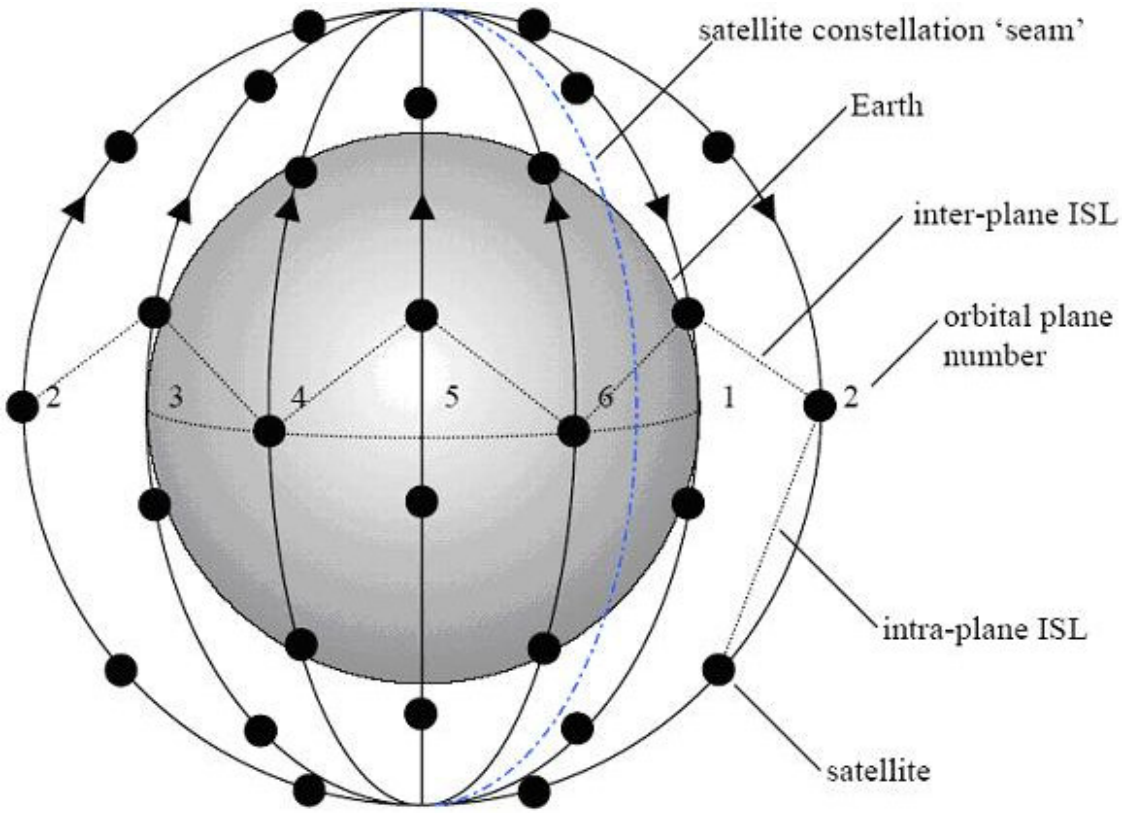


Figure 2.1. Major components of a LEO satellite constellation

of a mobile earth orbit satellite network can be either terrestrial-based or space-based. Use of a terrestrial-based backbone network requires each satellite to simultaneously be in view of the end-user and a ground gateway, which limits the areas to which service can be provided to the areas surrounding a ground gateway. Globalstar is an operational LEO satellite network that uses a terrestrial-based backbone network. The Globalstar coverage map is shown in Figure 2.2 [17], and shows that coverage is limited to certain landmasses where ground gateways have been installed, and the surrounding coastal waters. Use of a space-based backbone network requires each satellite to have ISLs to neighbouring satellites, and onboard routing. A space-based backbone network provides the ability to communicate end-to-end using only the satellite network, or to communicate via the satellite network through a ground gateway. Iridium is an operational LEO satellite network that uses a space-based backbone network. Iridium is capable of providing service to the entire globe including the Polar Regions.

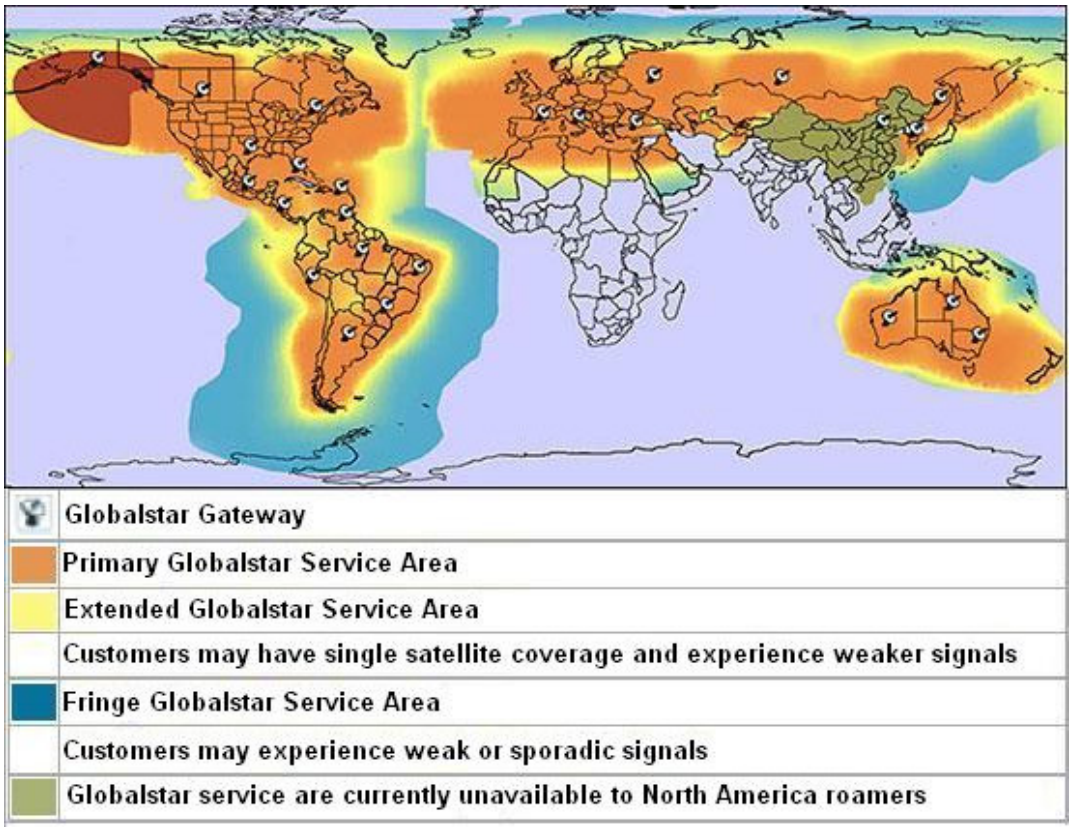


Figure 2.2. Globalstar service area map

2.2.2. Low Earth Orbit Reference Constellations

LEO satellite systems can alternatively be classified as follows:

- Little LEO : Orbcomm, VITA
- Big LEO : Iridium, Globalstar, ICO
- Broadband LEO : Teledesic

In this section, one of big and one of broadband LEO mobile satellite systems are covered. Details of Iridium and Teledesic constellations are given in this section. Furthermore, Table 2.1 lists the general characteristics of reference LEO constalletions such as ICO, Globalstar, Iridium, and Teledesic.

Iridium. Iridium is the first commercially operational LEO satellite network incorporating onboard processing, routing, and ISLs. Iridium provides a low bandwidth service, capable of supporting voice telephony, paging, and has recently been upgraded

Table 2.1. Some characteristics for some mobile satellite systems

Characteristics	ICO	GLOBALSTAR	IRIDIUM	TELEDESIC
Number of satellites	10 active 2 spares	48 active 8 spares	66 active 6 spares	288 active
Altitude (km)	10390	1410	780	1375
Coverage	global	$\pm 70^\circ$ latitude	global	global
Minimum Elevation	20°	20°	8°	40°
ISL (GHz)	no	no	22.5-23.5	60
Footprint diameter	12900 km	5850 km	4418 km	1650 km
Period (minutes)	358.9	114	100.1	113
Sat. visibility time	115.6 min	16.4 min	9 min	5 min
Access Method	FDMA TDMA	CDMA	FDMA TDMA	FDMA TDMA
Min. Mobile Link Prop. Delay (msec)	34.5	4.63	2.60	2.32
Max. Mobile Link Prop. Delay (msec)	48.0	11.5	8.22	3.40
On-board Processing	?	no	yes	yes
Lifetime (year)	12	7.5	5-8	10

to support Short Message Service [18]. A model of the Iridium constellation is shown in Figure 2.3 [19]. The following technical information is summarised from *An Overview of the Iridium Low Earth Orbit (LEO) Satellite System* [13].

The Iridium constellation consists of 66 satellites plus in-orbit spares, configured as 6 circular orbital planes of 11 satellites, at an inclination of 86.4 degrees. Orbital planes 1 and 6 are counter-rotating, thus exhibit the seam effect, and all other orbital planes are co-rotating. Satellites orbit at an altitude of 780 km, resulting in an orbit period of 100.13 minutes with an average view time of 9 minutes. From the Earth, the minimum elevation angle to see a satellite is 8.2 degrees, and either one or two satellites are visible at any given point in time. The Terminal-Satellite Links (i.e. users uplink

and downlink) use the L-Band frequencies of 1616 MHz to 1626.5 MHz, and use the same frequency for the uplink and the downlink. Both the gateway feeder links and the ISLs use Ka-Band frequencies.

Each Iridium satellite has a footprint diameter of 4,418 km, comprising 48 spot beams of approximately 600 km in diameter, each having 4 full-duplex Time Division Multiple Access channels on 20 frequencies, thus supporting 80 simultaneous users. Full-duplex operation is supported by dividing the TDMA frame into uplink timeslots and downlink timeslots, thereby avoiding contention. Full-duplex voice channels are supported at 4,800 bps, and half-duplex data channels at 2,400 bps [20]. Each satellite has intra-plane ISLs to its adjacent fore and aft neighbours, and inter-plane ISLs to its adjacent left and right orbital neighbours.

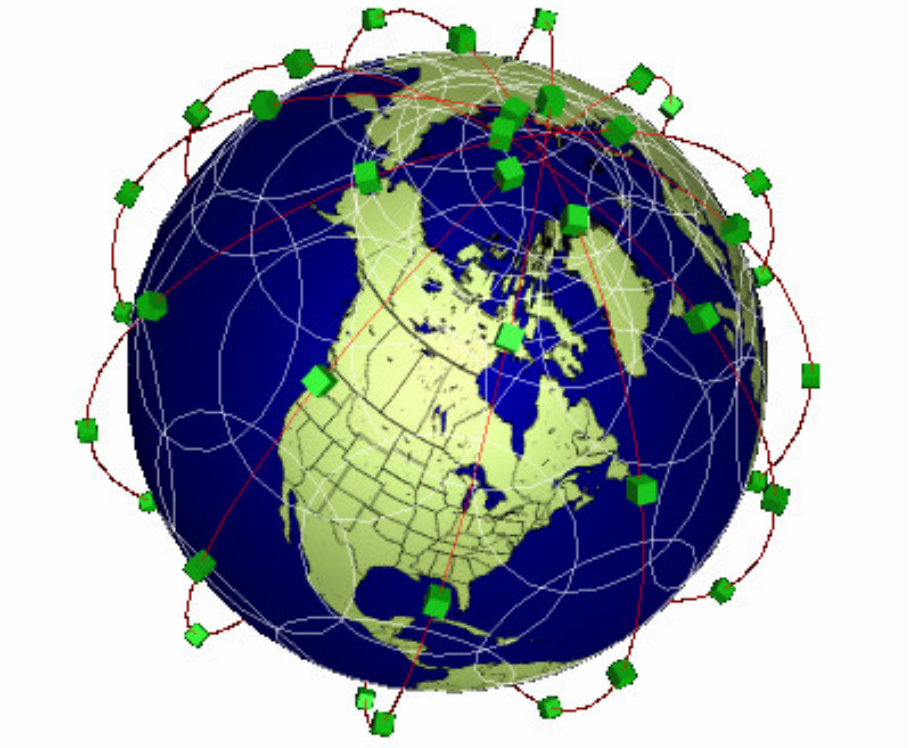


Figure 2.3. The Iridium constellation

Teledesic. The Teledesic constellation was the most promising and ambitious of the broadband LEO satellite constellation proposals. The Teledesic constellation was to have onboard processing, fast packet switching, and optical (i.e. laser) ISLs.

Teledesic promised to provide a high bandwidth, high quality service comparable with the terrestrial optical fibre network, capable of supporting high-speed data applications (e.g., Internet, LAN interconnect, and multimedia communications). Originally scheduled for commercial service starting in 2002, funding and technological issues delayed development. In October 2002, all development and construction was officially suspended, and in July 2003, Teledesic relinquished its frequency licenses and ceased to exist as a company.

The Teledesic constellation experienced numerous redesigns since its inception in 1994. Originally designed to consist of 840 LEO satellites, it was subsequently redesigned to 288 LEO satellites in 1997, and in early 2002 was redesigned to consist of 30 satellites in MEO. A model of the Teledesic constellation is shown in Figure 2.4 [19]. The following technical information is summarised from *Technical Overview of the Teledesic Network* [21].

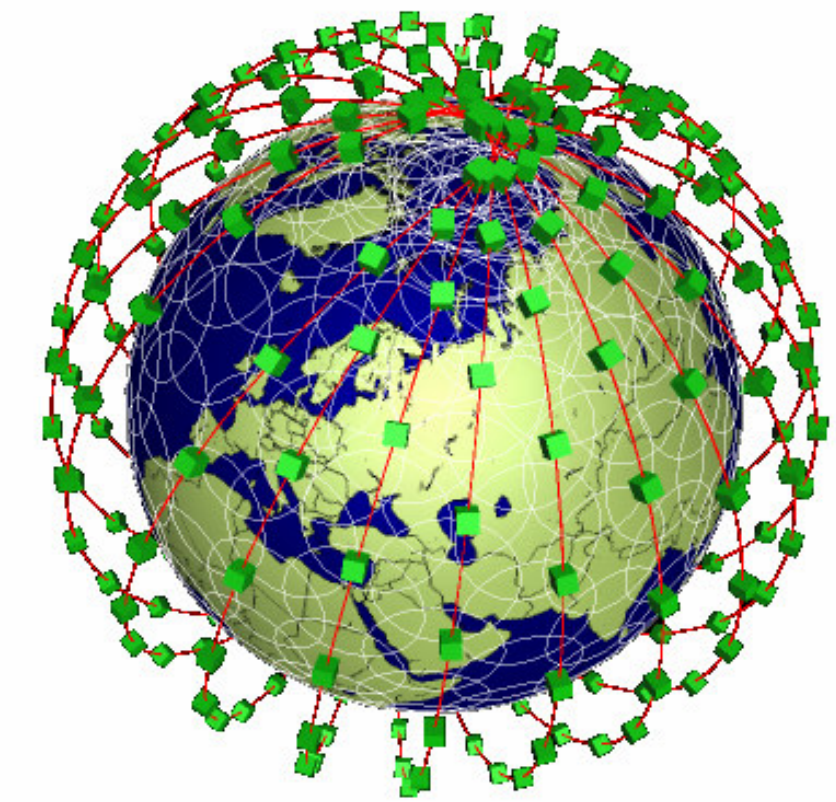


Figure 2.4. The (288 satellite) Teledesic constellation

The Teledesic constellation consists of 288 satellites, configured as 12 circular orbital planes of 24 satellites, in a near-polar inclination. Satellites orbit at a nominal altitude of approximately 1,375 km, resulting in an orbit period of 113 minutes, with an average view time of approximately 5 minutes. To minimise line-of-sight obstacles and the path exposed to rain fade, the minimum elevation angle to communicate with a satellite is 40 degrees, and there is always at least one satellite in view.

A satellite has a footprint diameter of 1,650 km, and each spot beam covers an area approximately 80 km in diameter. Each satellite is connected via ISLs with up to 8 neighbouring satellites in the same and adjacent orbital planes (The 8 ISLs consist of 4 intra-plane ISLs (1 ISL to each closest fore and aft satellites, and 1 ISL to each 2^{nd} closest fore and aft satellites), and 1 or 2 inter-plane ISLs to satellites in the adjacent left and right orbitalplanes.), forming a geodesic (or mesh) network. Teledesic planned to support symmetrical and asymmetrical communications at up to 64 Mbps, with the ability to adjust Bandwidth on Demand according to the instantaneous data requirements of end-user applications.

2.3. Handover Characteristics of LEO Satellite Networks

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

2.3.1. Difference from Terrestrial Networks

Table 2.2 summarizes the main differences between terrestrial and LEO satellite networks. In LEO satellite networks, the size of coverage is larger than that in terrestrial networks and thus the number of nodes in the coverage area is likely to be large. LEO satellites (ARs) move faster than mobile nodes resulting in the movement of the network itself. Consequently, handovers occur due to satellite movements, and mobile nodes seem to be always moving (relatively to the network) even if they are indeed steady in the same geographical position. Additionally, relative movements of

mobile nodes are more considerably global than that in terrestrial networks. Given the possible high number of end users, this compels LEO satellite networks to work under high-mobility conditions.

Table 2.2. Comparison of network characteristics

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

2.3.2. Satellite Handover Types

LEO satellites are mobile with respect to end-users. From a fixed point on the Earths surface, satellites appear to rise from below the horizon, move across the sky, and then set below the horizon, in a similar manner to that of the Sun or the Moon. There is at least one satellite above the horizon at all times. To provide a continuous communications service to an end-user, the communications connection to the setting satellite must be transferred to another in-view satellite. The transfer of a connection across satellite coverage areas is referred to as *handover*. For example, in the Iridium constellation, an end-user is in the coverage area of a satellite for approximately nine minutes (Section 2.2.2). During this period, the spot beam coverage areas move over the end-user, resulting in a number of spot beam handovers, and eventually the satellite sets below the horizon, resulting in a satellite handover.

The mobility of an end-user is insignificant to the mobility of the LEO satellite. For example, a satellite in the Iridium constellation has a spot beam diameter of 600 km, and a velocity relative to the Earth of 26,804 km/h [13]. Thus, it takes roughly 80 seconds for the spot beam coverage area to move over the end-user, and prompt a handover. In contrast, communications devices located onboard humans, automobiles, and marine vessels have velocities ranging up to roughly 100 km/h, at

which speed it takes six hours to travel the 600 km spot beam diameter required to prompt a handover. Even if the communications device were located onboard an aircraft travelling at 1,200 km/h, it would still take 30 minutes to travel the distance required to prompt a handover. Hence, end-user mobility is insignificant, and satellite handover occurs frequently and predictably as a result of satellite mobility.

Handover in LEO satellite networks can be classified as:

1. *Intra-satellite handover*, which is defined as handover between spot beams managed by a common satellite,
2. *Inter-satellite handover*, which is defined as handover between spot beams managed by neighbouring satellites.

Since each satellite produces many narrow spot beams, intra-satellite handover occurs most frequently. However, because the same satellite manages both spot beams, the intra-satellite handover does not have a significant functionality or performance impact on network layer protocols (i.e. end-user information is still routed via the same satellite). Inter-satellite handover occurs relatively less frequently. However, because communications must be transferred to a spot beam managed by another satellite, it has a significant impact on the functionality and the performance of network layer protocols. The inter-satellite handover is therefore the most complex in terms of the functionality required to support the handover, and is the most critical in terms of the Quality of Service provided during the handover. Therefore, the focus of this thesis is on inter-satellite handover.

Strictly speaking, there is also a third classification of handover referred to as link handover, which involves the handover of an intermediate connection segment of a larger end-to-end connection. The need for link handover arises in a connection-oriented network when the network connectivity changes (e.g., when ISLs are turned off near the poles). A link handover re-establishes the intermediate connection segment, and transfers communications onto the new segment, in order to provide a continuous communications connection to the end-user. Link handover is not directly considered

in this thesis.

Intra-Satellite Handover. Intra-satellite handover refers to a handover between spot beams managed by a common satellite, as illustrated in Figure 2.5 [22]. As the Mobile Terminal approaches the edge of the current spot beam, it requests handover to the succeeding spot beam by signalling a handover request to the associated satellite. The satellite determines that it manages the succeeding spot beam, and performs intra-satellite handover procedures. Since the same satellite manages both spot beams, this type of handover can be performed very quickly and with minimal interruption to communications.

The rates of intra-satellite handover can be viewed from the perspective of a satellite, MT, and a connection. To determine typical handover rates, consider a satellite in the Iridium constellation that (for simplicity) manages 49 spot beams arranged in a 7×7 grid, each capable of supporting 80 simultaneous users, with visibility for nine minutes [13]. From a single satellite perspective, 3,920 intra-satellite handovers occur every 77 seconds, which equates to 51 handovers per satellite per second ((49 spot beams $\times$ 80 users per spot beam) / (9 minutes / 7 spot beam handovers per visibility period) $\approx$ 51 intra-satellite handovers per satellite per second). From a MT perspective, handover occurs every 77 seconds ((9 minutes / 7 spot beam handovers per visibility period) $\approx$ 77 seconds per intra-satellite handover). From a connection perspective, at least two handovers occur every 77 seconds (i.e. handover of the connection source and destination MTs), which in reality can be higher due to the spot beam footprint size and pattern of arrangement.

Admission control algorithms and schemes for reducing the blocking rate for handover connection and new connections is the main concern included in the researches done in this area [23].

Inter-Satellite Handover. Inter-satellite handover refers to a handover between spot beams managed by neighbouring satellites, as illustrated in Figure 2.6 and Figure 2.7 [22]. As the MT approaches the edge of the current spot beam, it requests

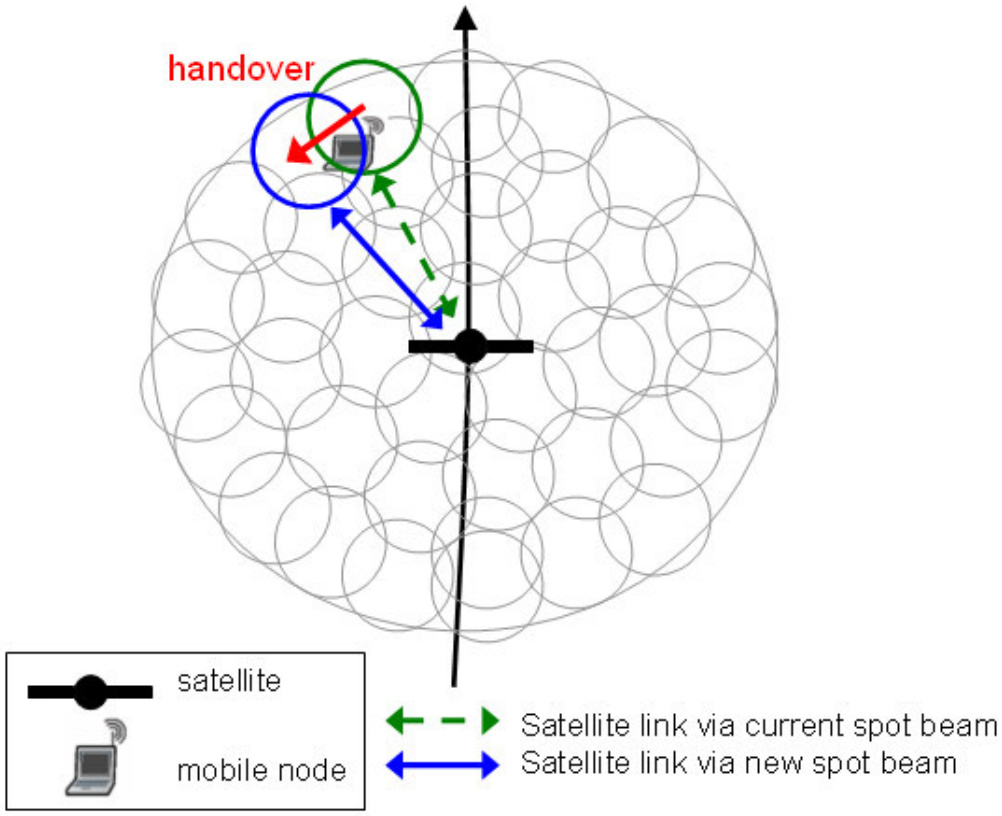


Figure 2.5. Intra-satellite handover in the Iridium constellation

handover to the succeeding spot beam by signalling a handover request to the associated satellite. The satellite determines that a neighbouring satellite manages the succeeding spot beam, and performs inter-satellite handover procedures. Since the associated satellite must transfer communications to a neighbouring satellite, there is a possibility of causing a significant interruption in communications during handover.

To determine typical inter-satellite handover rates from the perspective of a satellite, MT, and a connection, again consider a satellite in the Iridium constellation that (for simplicity) manages 49 spot beams arranged in a 7 × 7 grid, each capable of supporting 80 simultaneous users, with visibility for nine minutes [13]. From a single satellite perspective, 3,920 inter-satellite handovers occur every nine minutes, which equates to seven handovers per satellite per second ((49 spot beams × 80 users per spot beam) / (9 minutes) ≈ 7 inter-satellite handovers per satellite per second). From a MT perspective, on average handover occurs every nine minutes. From a connection perspective, at least two handovers occur every nine minutes (i.e. handover of the con-

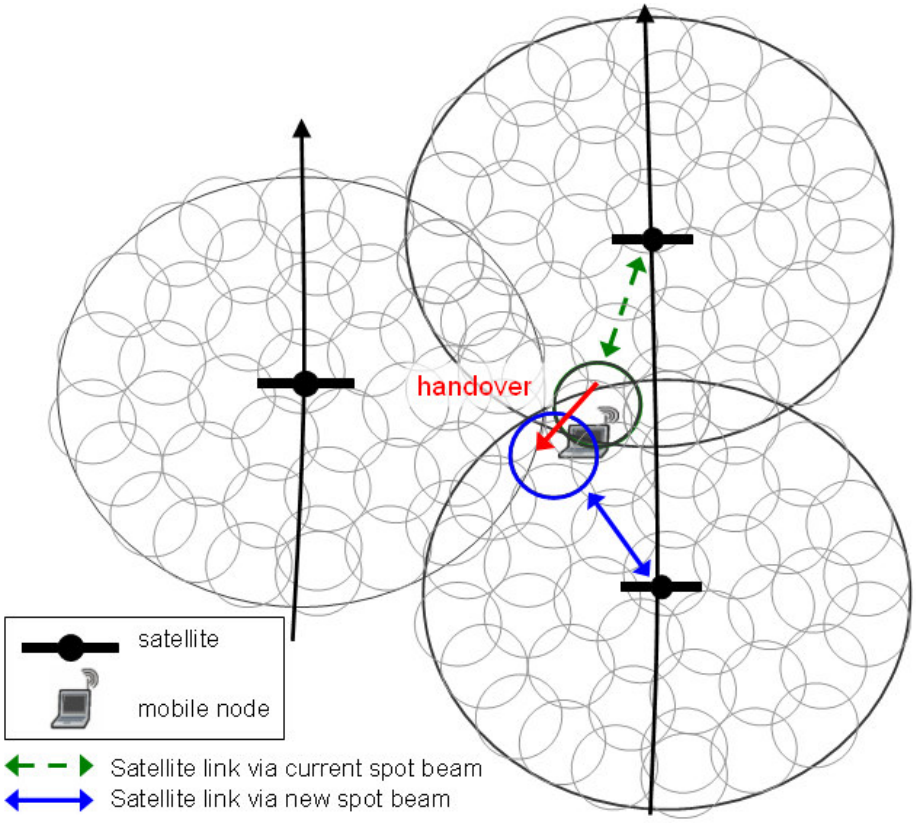


Figure 2.6. Intra-orbit inter-satellite handover in the Iridium constellation

nection source and destination MTs), which in reality can be higher due to the phasing of satellites in adjacent orbital planes.

The phase of satellites in adjacent orbital planes is generally staggered to provide continuous Earth coverage while reducing the number of orbital planes required. Therefore satellites in adjacent orbital planes may be used to provide coverage to a specific location during different portions of time. Thus inter-satellite handover can be further decomposed into intra-orbit and inter-orbit handover. An intra-orbit handover refers to a handover between satellites in the same orbital plane, and an inter-orbit handover refers to a handover between satellites in adjacent orbital planes, as illustrated in Figure 2.6 and Figure 2.7, respectively [22].

The researches which are done in this area focus on algorithms for the dynamic rerouting of a connection and the admission control of handover calls to ensure QoS requirements, because the change of satellite will affect the routing of the ongoing

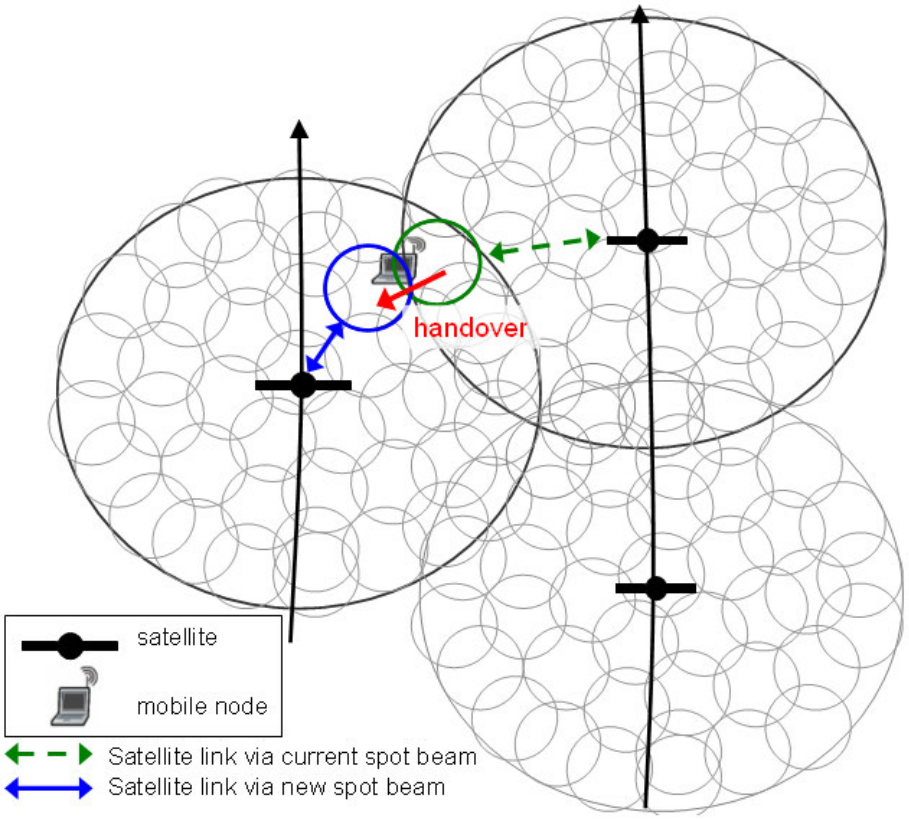


Figure 2.7. Inter-orbit inter-satellite handover in the Iridium constellation

session and the resource allocation of the satellites [24].

2.3.3. Characteristics of Handover Occurrence

Handovers are of significant importance in mobility management. Their occurrence takes place when a mobile node crosses over the coverage boundary. To evaluate the characteristics of handover occurrence, the model described in [25] is used. This boundary crossing event is modeled as shown in Figure 2.8 [25]. For the sake of simplicity, a coverage boundary is assumed to be a straight line, and locations of mobile nodes are presumed to follow a uniform distribution. In Figure 2.8, mobile nodes are located in fixed positions. A coverage boundary of length L moves with velocity V from left to right during a period of time Δt. According to this model, nodes that belong to the area with surface $L \cdot V$ will be required to perform handover during the time Δt. Denoting the area density of nodes as D, the rate of boundary crossing event,

R, can be expressed as:

$$R = V \cdot L \cdot D. \tag{2.1}$$

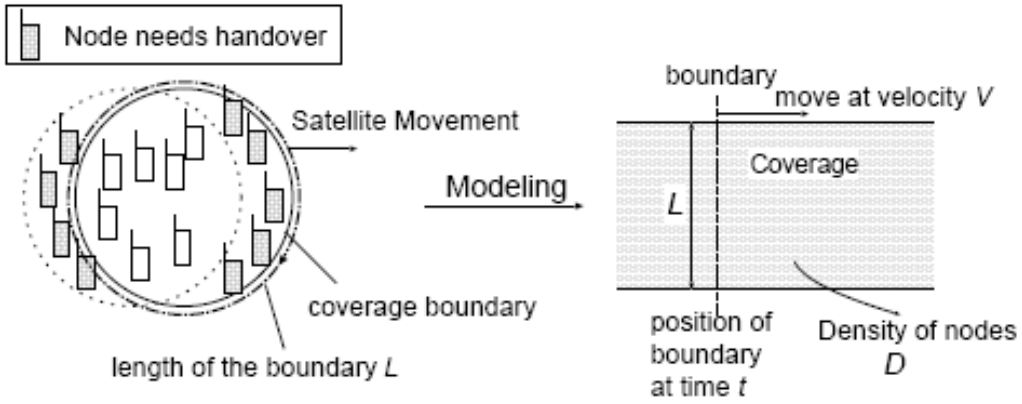


Figure 2.8. Boundary crossing event modelling

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

$$R_{HO}(t) = V_{sat} \cdot L_{sat} \cdot \int_{V_{sat} \cdot (t-\Delta t)}^{V_{sat} \cdot t} D_L(V_{sat} \cdot t) dt, \tag{2.2}$$

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

Since satellites are assumed to cover wide areas and move fast, V_{sat} and L_{sat} are large. From Equation 2.2, it becomes evident that $R_{HO}(t)$ takes large values even for small values of Δt. Furthermore, this rate of handovers is likely to become even larger in a very populated area (large values of $D_L(V_{sat} \cdot t)$).

3. MOBILITY MANAGEMENT IN IP/LEO SATELLITE NETWORKS

3.1. IP/LEO Satellite Networks

IP/LEO satellite networks are specifically designed to provide IP communication directly to mobile nodes. Throughout this thesis, mobile nodes are assumed to be directly connected to LEO satellite networks. Due to the dynamic properties of LEO satellite networks, certain aspects of IP communication, such as routing and multicasting, are likely to encounter some difficulties. More deatiled researches related with routing in IP/LEO networks can be found in [26, 27, 28, 29, 30]. Therefore, the relationship between IP protocols and satellite networks as layer 2 media is the key issue for the realization of IP/LEO satellite networks. Especially, a cooperative design with IP broadcasting [31] is required to exploit satellites abilities of broadcasting. The main idea behind the design is to match the coverage area of satellites with IP broadcast domain. Thus, satellites are modeled as Access Routers [32] and are assigned a given IP broadcast domain.

Figure 3.1 depicts the underlying model. An IP communication path consists of three components, namely mobile nodes, edge satellites, and intermediate satellites. Each mobile node is assigned a particular IP address. Along a given path, edge satellites are given a certain number of addresses and play the role of ARs. Intermediate satellites are limited to only transmitting IP packets between edge satellites. Furthermore, in the proposed handover management models, we assume that the direction of the traffic flow is from Corresponding Node to MN which illustrates the applications like file downloading or web browsing by the mobile users. The CN does not move, so its location is fixed. Also, we used the ISL Model depicted in Figure 3.2 throughout this thesis. We assumed that one satellite has 3 Inter-orbit Satellite Links with the satellites lying on its left neighboring orbit, 3 Inter-orbit Satellite Links with the satellites lying on its right neighboring orbit, and 2 Intra-orbit Satellite Links with satellites on the

same orbit.

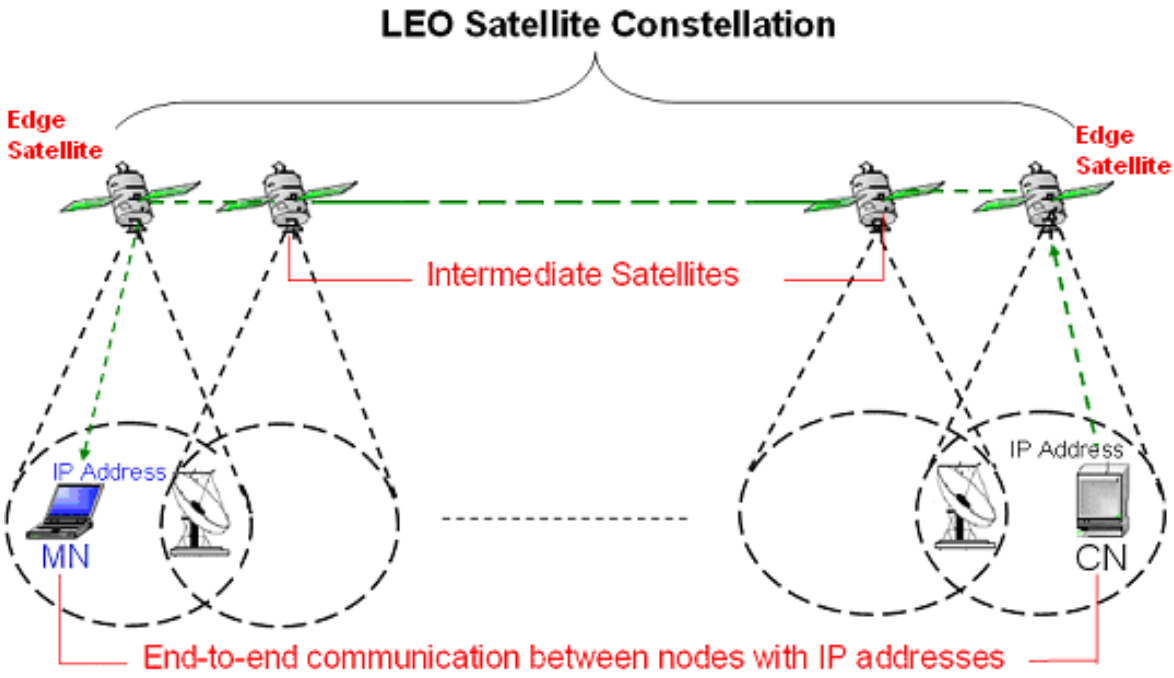


Figure 3.1. IP/LEO satellite networks

This section described the IP/LEO satellite network model that will be used in the proposed models explained in this thesis. This thesis aims to integrate IP protocols with LEO satellite networks, while focusing on the interactions between mobile nodes and edge satellites.

3.2. General Mobility Management Principles

The main concern of mobility management is to locate MNs in the network and to guarantee a seamless data transmission upon change in nodes position. Mobility management basically contains two operations, namely binding update and data delivery.

The binding update operation aims to associate Reachability Identity and Routing Identity of each node [33]. The Reach.ID (Home Address) indicates a unique name of the node and is not subject to change, whereas the Route.ID (Forwarding Address)

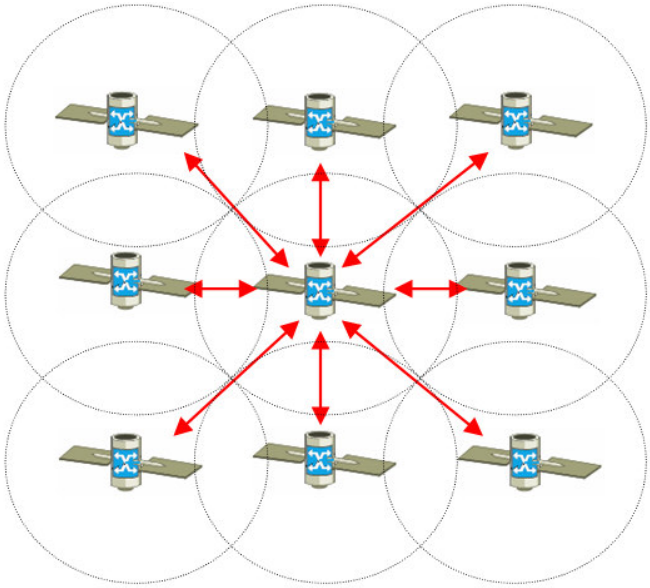


Figure 3.2. ISL Model

specifies the position of the node in the network and changes in response to node movement. When a mobile node changes its position, the Route.ID changes as well and the old binding is no longer valid. To update the binding, mobile nodes are requested to send their new Route.ID to the Location Directory [34]. The component that records the association between the Reach.ID and Route.ID of a mobile host is called a location directory. The LD contains the most up-to-date mapping between a mobile host and its associated foreign network. Mobile Hosts are required to send updates to the LD whenever they move to a new location. Figure 3.3 [34] shows the terms of general mobility management scheme.

The main problem of this procedure arises when LD is geographically too far from mobile nodes. In this case, the cost of binding update becomes very expensive, especially in a high-mobility environment such as satellite networks [35]. Although a handover is a local process that concerns only the MN, the old AR, and the new AR, a binding update is a global process that may affect other network elements in addition to the three adjacent entities.

Route.ID can be used to indicate the position of the MN; therefore, no further operation is needed to do data transmission seamlessly. However, using Route.ID as the precise location of the MN requires frequent update of MNs registration even upon

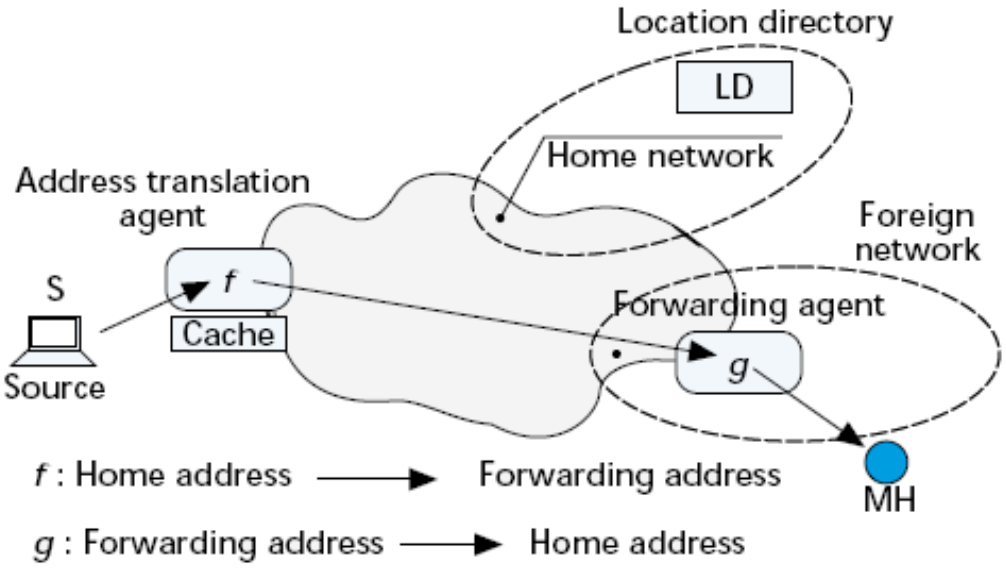


Figure 3.3. Illustration of general mobility management terms

a slight movement of the nodes. Thus, the required update cost can be very huge.

On the other hand, when Route.ID is used to indicate location of the MN roughly, an additional operation called paging is needed to find precise position of the MN. Paging is a procedure that allows a wireless system to search for an idle mobile host when there is a message destined for it, such that the mobile user does not need to register its precise location to the system whenever it moves. However, the paging cost can be very high in case of wide paging areas. As a result, Route.ID has a significant importance on the mobility management cost. The role of the Route.ID should be chosen carefully according to mobility management issues of underlying network.

3.3. Mobility Management in IP Networks

In terrestrial IP networks, IP addresses are designed for Route.IDs and are also used as Reach.IDs in higher layers. This causes an important problem for mobility management in IP networks since a MN can not be identified in the higher layers when its IP address changes after handover.

The most dominant protocol among existing mobility management protocols is Mobile IP that was proposed to solve this problem by using two different IP addresses

for the two locations of MNs. First location is called as Home Network and identified by a Home Address which serves as a Reach.ID. Second location is Foreign Network and identified by a Care of Address which functions as a Route.ID. Home Agent plays the role of Location Directory in Mobile IP. Upon a handover occurrence, nodes are assigned different CoAs according to the connected AR. Recall that new CoAs shall be notified to the Home Agent for binding maintenance. LIN6, a recently proposed mobility management protocol, uses LIN6 addresses to refer to the Route.ID of mobile nodes. Similarly to CoA of Mobile IP, LIN6 addresses are decided according to the AR that mobile nodes are connected to. In these protocols, locations of nodes are precisely managed by binding update upon every handover occurrence. The details of MIP and its drawbacks will be discussed in Section 3.5.

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

The most representatives of mobility management protocols that introduced a loose location management of idle nodes are Paging Mobile IP [36] and Cellular IP [37]. In these protocols, the coverage area of a certain number of ARs is considered as a single paging area. When a packet data destined for an idle node arrives at one of the ARs in a paging area, the AR broadcasts a paging request to all the other ARs that sequentially send paging messages within their own coverage areas. Upon receipt of the paging message, the idle node in question responsively becomes active. In such case, the idle node is not required to perform binding updates within the whole paging area. The node should update its binding only when it crosses the paging area boundary. By so doing, binding update frequency can be reduced.

In the remainder of this section, the advantages and downfalls of both precise and loose management schemes will be further investigated to decide the most appropriate scheme for IP/LEO satellite networks.

3.4. Mobility Management Issues in LEO Satellite Networks

Usage of Mobile IP is one of the solutions for mobility management over IP/LEO satellite networks. However, applying Mobile IP to LEO satellite networks will result in a precise management of mobile nodes location, and consequently an invocation of binding update upon each handover occurrence. Given the high frequency of handover occurrences in LEO satellite networks, as explained in Section 2.3.3, a large number of binding update requests is likely to be generated, all, in a single burst. To process such bursts of binding update requests, a massive amount of network bandwidth and computational load are required. This is intuitively a critical issue for scalability of mobility management in IP/LEO satellite networks.

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

Since it is not possible to avoid the frequent occurrence of handovers in LEO satellite networks, new mobility management protocols are needed to develop to minimize binding update and related mobility management costs.

3.5. Present Handover Management Algorithms for LEO Satellite Networks

The most widely used protocol for mobility management over satellite networks is Mobile IP. MIP is the standard proposed by the Internet Engineering Task Force

(IETF) to handle mobility of Internet hosts for mobile data communications [3]. The MIP enables IP host mobility without breaking the high level connection. It enables a TCP connection to remain alive and receive packets when an MN moves from one point of attachment to another. MIP is based on the concept of Home Agent and Foreign Agent for routing of packets from one point of attachment to the next. During handover from the HA to the FA, a MN registers with the FA, waits for the allocation of channels, and updates its location in the HA database. The traffic flow of MIP is depicted in Figure 3.4. When MN moves to a new domain, a location update is sent to HA. Therefore, the HA is informed by the Care of Address of the MN. The packets from the CN to MN are encapsulated and forwarded to MN's current CoA. Then, these packets are decapsulated and delivered to upper layer protocols. In this procedure, binding update is the operation in which HA is informed by the CoA of the MN. When a mobile node changes its position, the CoA changes as well and the old binding is no longer valid.

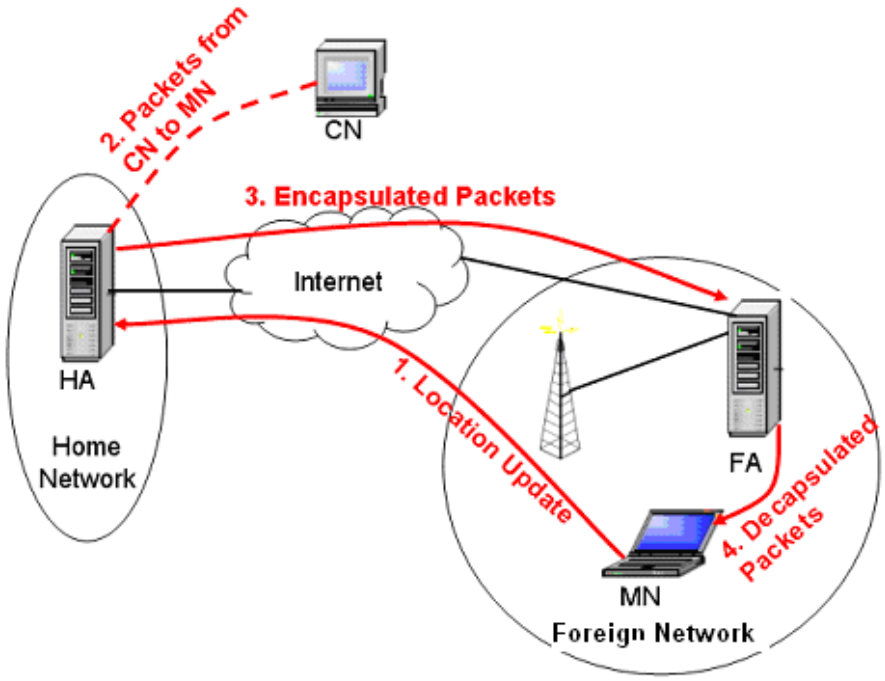


Figure 3.4. Handover flow of Mobile IP

Although MIP is a widely accepted concept in both industry and research [38], it has a number of important drawbacks. First problem is *high handover latency*. A MN needs to wait for completion of the steps, which are discovering the new CoA,

registering the new CoA with the HA (binding update), and forwarding packets from the HA to the current CoA, before it can receive forwarded data from the previous point of attachment. Since the frequency of handover occurrences in LEO satellite networks is very high, a large number of binding update requests is likely to be generated in a single burst. To process such bursts of binding update requests, a massive amount of network bandwidth and computational load are required. Secondly, *high packet lost* rate is another drawback of MIP. During the HA registration period, some or all of the packets directed to the MN's old CoA will be lost because the old point of attachment does not know the new point of attachment of the MN so that it cannot communicate with the MN during this period. Thirdly, it has an *inefficient routing path* since large amount of data is routed to the HA, and then tunnelled to the MN. This may decrease the scalability issues as the number of MNs managed by a HA increases. Finally, the MIP *conflicts with network security solutions* such as Ingress Filtering and firewalls. It is hard to duplicate HA to various locations to increase survivability and manageability since HA must reside in MN's home network. Therefore, this model needs some modifications to be applicable to internet infrastructure.

Atiquzzaman at el. proposes another mobility management protocol for satellites called transport layer seamless handoff scheme for space networks (TraSH-SN) which is based on the association of two IP addresses (one obtained from the current subnet and another obtained from the next subnet) [39]. This model uses a new transport protocol for Internet namely SCTP (Stream Control Transmission Protocol) to associate two IP addresses. According to the model, after MN enters to a new footprint, it obtains a new IP in new domain. Then, MN notifies CN about the new IP. When the new satellite becomes more efficient, MN lets CN set primary address to new IP address. MN also updates a central server called Location Manager. Finally, it deletes and deactivates old IP. Figure 3.5 depicts the signal flow of TraSN-SN.

Although, this model provides an increased throughput during handover, the handover blocking probability increases very rapidly since it allocates two IP addresses in association during handover process. Besides, no information on analysis of mobility management cost of the model is given in this work.

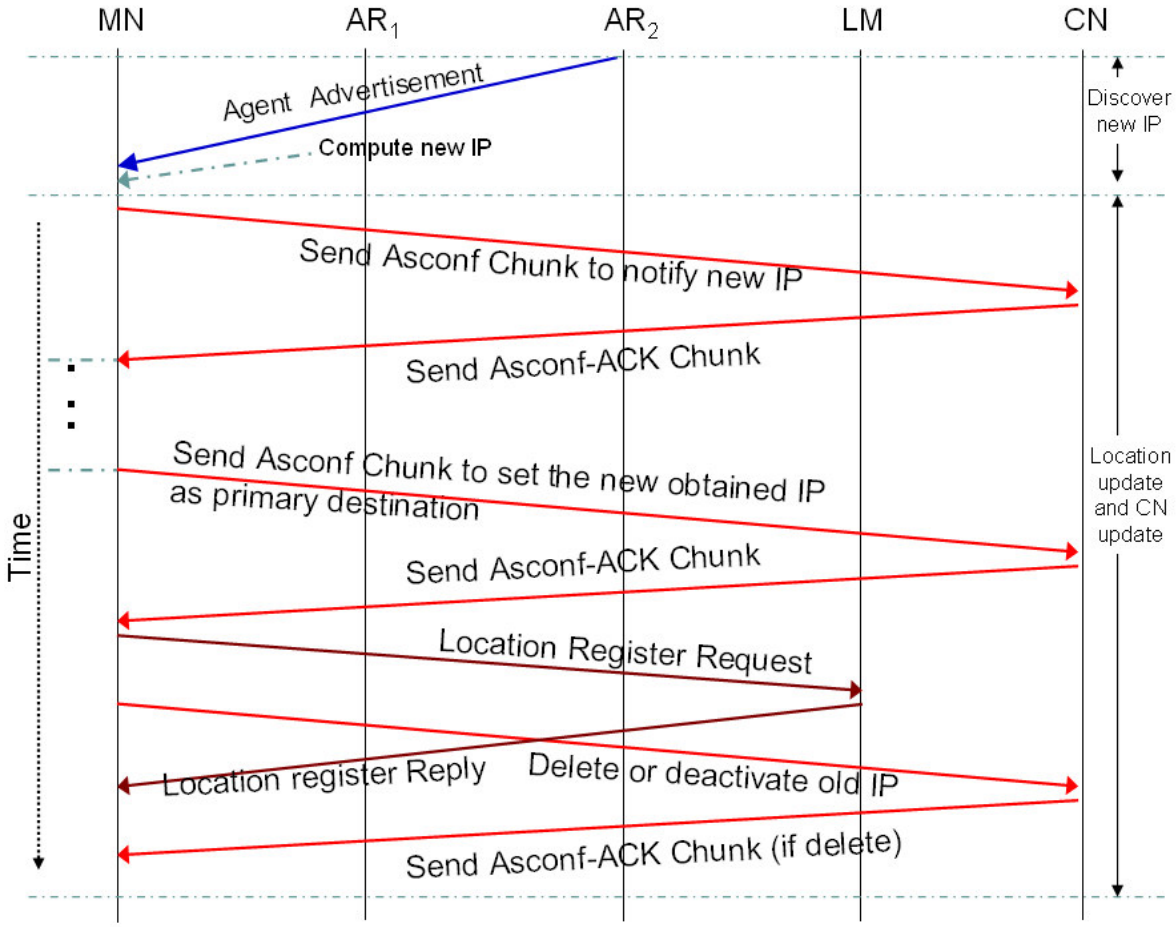


Figure 3.5. Signalling flow of TraSH-SN

4. SeaHO-LEO: A SEAMLESS HANDOVER MANAGEMENT PROCEDURE FOR LEO SATELLITE COMMUNICATION NETWORKS

The objective of this chapter is to describe our proposed schemes called A Seamless Handover Management Scheme for LEO Satellite Networks (SeaHO-LEO) [40, 41] for supporting mobility and its design issues. Section 4.1 gives the details of signalling flow of SeaHO-LEO. Comparision of SeaHO-LEO with MIP and TraSH-SN is done in Section 4.2. Finally, simulation results of SeaHO-LEO are presented in Section 4.3.

4.1. SeaHO-LEO Procedure

We developed an efficient and seamless handover scheme called SeaHO-LEO which would be applicable to satellite environment. To make LEO satellite networks entirely independent of terrestrial networks, terrestrial stations are assumed not to be involved in the management of LEO satellite networks for SeaHO-LEO model.

The research results in [42] show that the mean number of available satellites for a given MN is at least two for latitudes less than 60 degrees. This means that MN is within the footprint of two satellites most of the time, which makes our model effective for handover management of satellites to reduce packet loss and handover latency.

The whole handover procedure is depicted in Figure 4.1. Table 4.1 lists the messages used in SeaHO-LEO protocol. SeaHO-LEO procedure is divided into four steps which are described as follows:

1. *Calculate a new IP.* The handover preparation procedure generally begins when the MN moves into the overlapping coverage area of two adjacent satellites' footprints. As illustrated in Figure 4.1, when the MN receives the agent advertisement (AA) from the new satellite (i.e. S_N), it will start the steps of obtaining a new IP

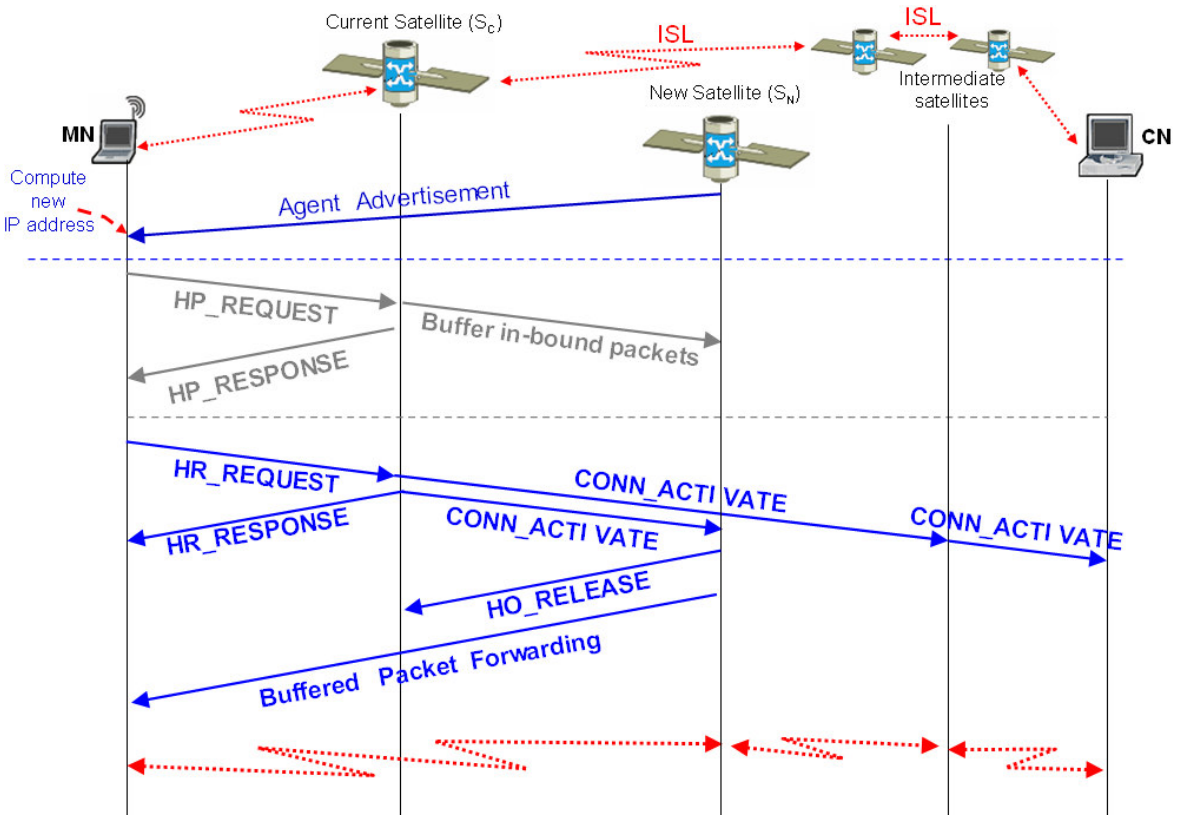


Figure 4.1. Signalling flow of SeaHO-LEO

address. The MN measures the received signal strength, and determines the need for handover when the signal strength of the current radio link deteriorates below a certain threshold while still allowing communications. If there are more than one candidate satellites for handover, MN should choose the best one according to the connections QoS parameters. After it determines the best canditate satellite, it starts obtaining a new IP for new satellite. Obtaining new IP address can be performed with a Dynamic Host Configuration Protocol (DHCP) [43], Dynamic Host Configuration Protocol for IPv6 (DHCPv6) [44], or IPv6 Stateless Address Autoconfiguration (SAA) [45]. The main difference of these methods is generation of IP address by a server (DHCP/DHCPv6) or by the MN itself (IPv6 SAA). Since the IPv6 SAA significantly reduces the required signalling time, it is recommended for the proposed handover protocol. In calculating new IP step, MN only requires the address to be unique and routable.

2. *Send Handover Preparation Request to Current Satellite.* After MN computes a new IP address, it sends a Handover Preparation Request (i.e. HP_REQUEST) to the current satellite (S_C). This message includes new IP of MN, and the IP of

Table 4.1. Message types for SeaHO-LEO

Message	Length (bits)	Content
HP_REQUEST	256	new IP of MN + IP of S_N
HP_RESPONSE	256	ACK. message
HR_REQUEST	128	new IP ready message
HR_RESPONSE	128	ACK. message
CONN_ACTIVATE	128	new IP of MN
HO_RELEASE	128	Release Resource message

S_N. After S_C receives HP_REQUEST, it replies to MN by sending a Handover Preparation Response (i.e. HP_RESPONSE) message to indicate the success of receiving the new IP. At that time, S_C also starts buffering all in-bound packets on S_N during the handover. Thus, all the in-bound packets coming to the S_C for MN will also be sent directly to the next satellite S_N by using ISL between S_C and S_N. The buffering mechanism creates a virtual path between CN and the new satellite S_NThis buffering procedure is an intelligent one in which the current satellite does not send the packets whose acknowledgements from MN delivered by S_C. Therefore, S_N receives onyl packets that are not received by MN.

3. *Start to use new IP to send data packets.* When MN moves further into the footprint of the new satellite S_N, data path between MN and S_N becomes increasingly more reliable that data path between MN and current satellite S_C. At that time, MN may want to start to redirect data traffic to the new IP to increase the possibility of successful delivery of data packets to the MN. Therefore, MN sends a Handover Ready Request (i.e. HR_REQUEST) to current satellite S_C to say that new IP is available for data transmission. When S_C receives HR_REQUEST message, new IP is sent to CN by the message CONN_ACTIVATE. When CN receives the new IP, it replies to current satellite with an acknowledgement indicating the success of obtaining the new IP. After S_C receives HR_REQUEST message, it also stops buffering the in-bound packets on next satellite S_N since the new IP is ready to receive new packets. At that point, S_C sends a CONN_ACTIVATE message to S_N to make connection establishment complete. When S_N receives this message,

it understands that MN will communicate with CN via S_N. In other words, new IP is ready for the communication. Therefore, the final message causes the next satellite S_N to forward all the buffered packets to the MN. As soon as the new IP becomes ready to receive packets, S_N sends all the buffered packets to MN and starts communication with MN. Moreover, S_N sends a HO_RELEASE message to S_C to complete disassociation and release of radio resources at the old satellite.

4. *CN starts to use new satellite.* After CN receives the new IP of the MN, it sends the next data packets to MN via new satellite S_N.

4.2. Comparision of SeaHO-LEO with Basic Models

Compared to MIP system where each subnet has to locate a location management component (HA) causing a really difficult task of dealing with a large number of location management entities, SeaHO-LEO model reduces the system complexity and maintenance cost. The SeaHO-LEO provides efficient utilization of network bandwidth because of the absence of tunnelling, and also does not need any change in the existing internet infrastructure. SeaHO-LEO uses the efficiency of ISL. It creates a virtual path between CN and new satellite; therefore, it prevents data loss during handover. Moreover, it allocates radio resources of only one satellite during the handover. Unlike TraSH-SN, it does not need any terrestrial equipment or a central server to manage handover. It is completely independent from terrestrial networks. Therefore, the SeaHO-LEO model is very effective to provide continues communication between a CN and a MN whose mobility is random.

4.3. Simulation and Results

The performance of the handover management schemes are evaluated by using OPNET. Actually, more that one topology are constructed in OPNET to simulate the SeaHO-LEO. Figure 4.2 presents the top level of one example of the OPNET developed network. The network includes 6 LEO satellite nodes (altitude 1000 km, inclination 98), a fixed terminal node (CN), and a mobile node (MN). During the simulations, the satellite ephemeris (Latitude, Longitude and Altitude) are predicted thanks to a file

imported from the Satellite Tool Kit. In the simulation environment, the mean number of available satellites for a given MN is two as shown in Figure 4.2. Furthermore, we applied the parameters in Table 4.2. t_F defines the maximum time that a MN can stay in a satellite footprint. A CN generates traffic according to a Poisson distribution function.

Table 4.2. Simulation parameters of SeaHO-LEO

Parameter	Value
Footprint Length	1650 km
t_F (time in a footprint)	5.10 min
V_{sat} (Footprint's velocity)	5.3922 km/sec
Simulation Time	1800 sec

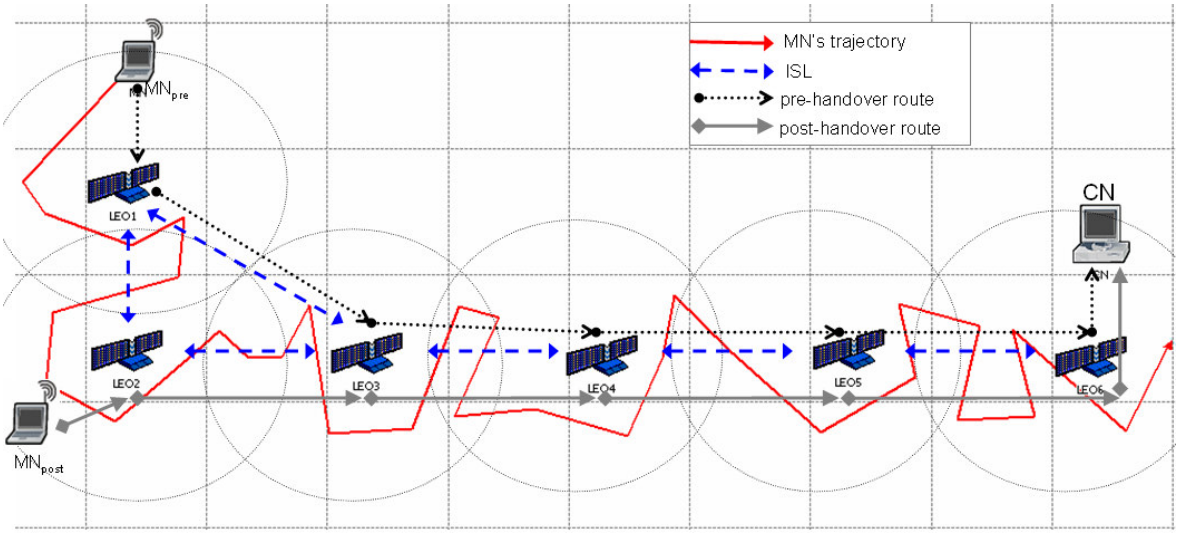


Figure 4.2. OPNET network model for SeaHO-LEO

In order to evaluate the performance of the SeaHO-LEO, it is compared to the MIP scheme and the TraSH-SN scheme [39]. One of the performance measures of a handover management scheme is the transport layer throughput. Therefore, each algorithm is evaluated by analyzing the MNs' average throughput during the handover process. Another performance measure to understand the behaviour of the algorithms under crowded networks is handover call blocking probability. Thus, we further analyze the models under dense networks.

Figure 4.3 compares the MN's average throughput during a handover process.

Since TraSH-SN lets a MN to use two IP addresses at the same time, the resulting throughput is relatively higher. In Mobile IP, due to the tunneling between HA and FA, the throughput of the channel between MN and CN converges to zero during the handover. When the handover process is completed, the throughput reaches a reasonable value. Our model SeaHO-LEO throughput is better than MIP and very close to TraSH-SN's throughput.

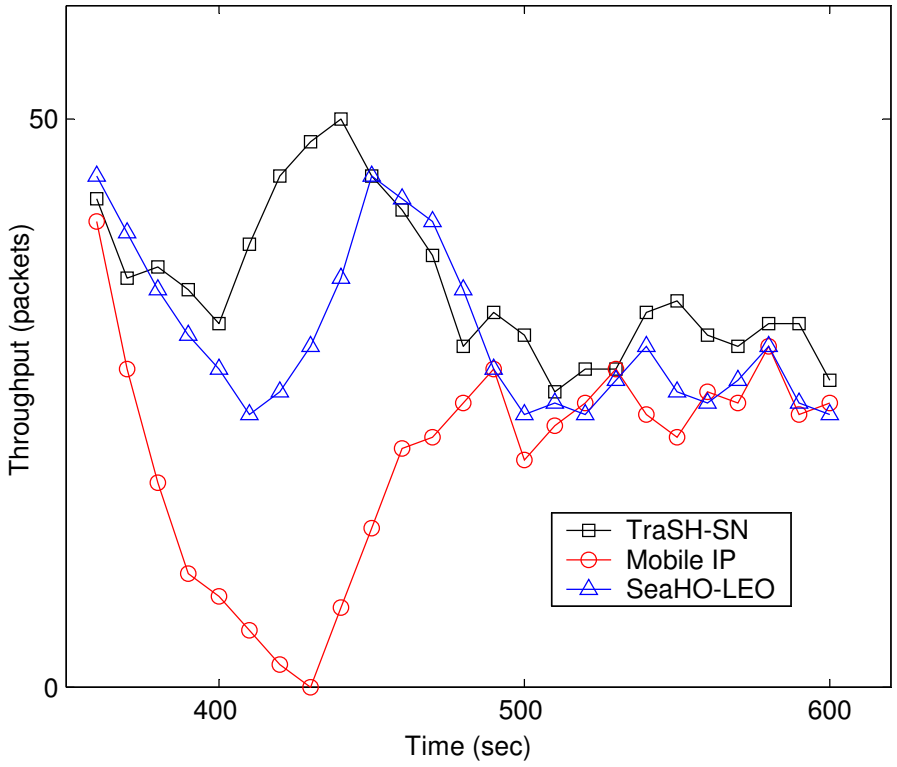


Figure 4.3. Simulation results of a MNs handover throughput

Figure 4.4 depicts the handover call blocking probabilities of TraSH-SN, MIP, and SeaHO-LEO. It is assumed that a satellite can serve 5000 mobile users at the same time. Among these three handover management models, TraSH-SN has the highest blocking probability since it establishes an association between current IP address and new IP address by allocating one channel for each subnet (i.e. one channel for current satellite's subnet and one channel for new satellite's subnet). In other words, TraSH-SN is based

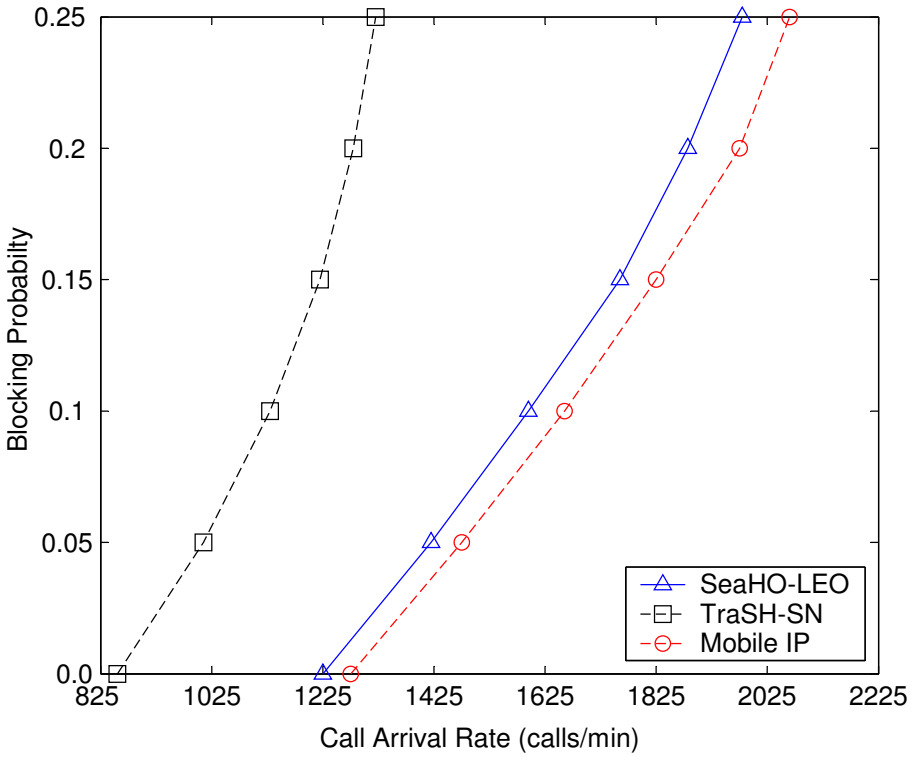


Figure 4.4. Blocking probability of a handover call

on the principle of decoupling registration causing high handover blocking probability for crowded networks. On the other hand, MIP and SeaHO-LEO have almost same level of blocking probability. As illustrated in Figure 4.4, SeaHO-LEO has very low blocking probability in contrast to TraSH-SN. Finally, Figure 4.5 shows the average

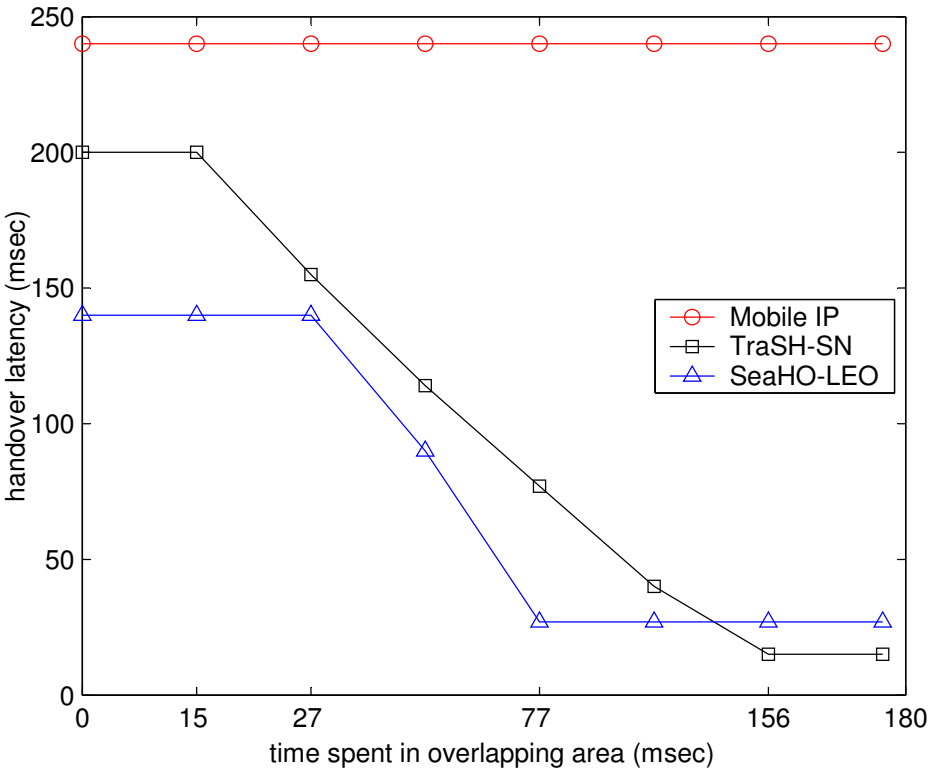


Figure 4.5. Handover latency

handover latency. Handover latency is dependent on the time taken to establish the new path segment between MN and new satellite. In other words, *handover latency* is the time invertal between last data segment received through the old path and the first data segment received through the new path from CN to MN.

In small overlapping areas, handover latency of SeaHO-LEO is better than TraSH-SN, since TraSH-SN does not have enough time to finish all the signaling. Some packets sent to the outdated AR (satellite) are lost and CN is forced to backoff by SCTP's congestion control algorithms. Therefore this process results in higher handover latency

for small overlapping areas. On the other hand, as soon as old satellite receives a HP_REQUEST message in SeaHO-LEO, it establishes a virtual communication path between the new satellite and MN by the help of ISL between it and new satellite. This process needs very small time (i.e. approximately 20 ms). Therefore, the handover latency of SeaHO-LEO is smaller than that of TraSH-SN for small overlapping areas. However, after a specific threshold, signaling of TraSH-SN requires a smaller time than SeaHO-LEO does. However, their handover latency times are very close to each other after that point. In MIP, handover latency is very high because MN has to send location update message to its HA to associate its home address and Care of Address. This binding update proceses is a very time consuming operation. MIP is incapable of receiving packets in flight during this registration process. In the case of MIP, the MN always uses its home address to send and receive packets, and it cannot contact the old FA (satellite) while registering with new FA (satellite). We can see that there is a transmission stall of about 240 ms, which represents the handover latency when using MIP. This handover latency is independent from the time spend while MN moves the overlapping area of new and old satellites.

5. PatHO-LEO: A SATELLITE MOBILITY PATTERN BASED HANDOVER MANAGEMENT PROCEDURE FOR LEO SATELLITE COMMUNICATION NETWORKS

This chapter discusses the details of the satellite mobility pattern based handover management procedure for LEO satellite networks, namely PatHO-LEO handover management model. As we mentioned in the Section 3.4, applying MIP to LEO satellite networks will result in a precise management of mobile nodes location, and consequently an invocation of binding update upon each handover occurrence. Given the high frequency of handover occurrences in LEO satellite networks, a large number of binding update requests is likely to be generated, all, in a single burst. To process such bursts of binding update requests, a massive amount of network bandwidth and computational load are required. This is intuitively a critical issue for scalability of mobility management in LEO satellite networks. In PatHO-LEO, we try to eliminate this large number of binding update done during handover processes.

5.1. PatHO-LEO Architecture

A typical LEO satellite takes less than two hours to orbit the Earth, which means that a single satellite passes over the same geographical area of the Earth in repeating periods of time (e.g., Iridium constellation satellites have a period of 100.1 min). This stable pattern of a LEO satellite provides a satellite mobility pattern (SMP) scheme which includes when and where a satellite passes over a location. On the other hand, some researches such as in [46] show that MNs also have a pattern during a specific period of time. Mobile subscribers usually follow a limited number of mobility patterns in their daily lives. For example, people generally take almost the same path and same time to go to work every day. In the user mobility pattern (UMP) scheme, an MN collects the data (location, time etc.) related to these patterns, and predicts the UMP based on the collected data.

By combining these two concepts, we come up with a novel idea to manage handovers between satellites as illustrated in Fig.9. The Satellite Mobility Pattern Based Handover Management in LEO Satellites (PatHO-LEO) [47, 41] is introduced for location updates of MNs during the handover between LEO satellites.

In this approach, MNs and satellites learn their patterns and maintain their history data in a database located in a central server that is called Billboard Manager (BM). The database in BM contains the time and the place where a MN is in and the corresponding satellite which passes over the same place at the same time with the MN. In our model, all binding update operations, which are caused by handovers occurred during a single communication between CN and MN, are reduced to a single query operation from BM Database, since all the Routing Identities, which will be used during the communication, are stored in BM. Therefore, HA of the MN does not need to be informed by MN after each handover, instead it obtains all IP addresses and routing related data from BM at the beginning of the communication. As a result, this operation eliminates a huge number of binding update operations done in MIP.

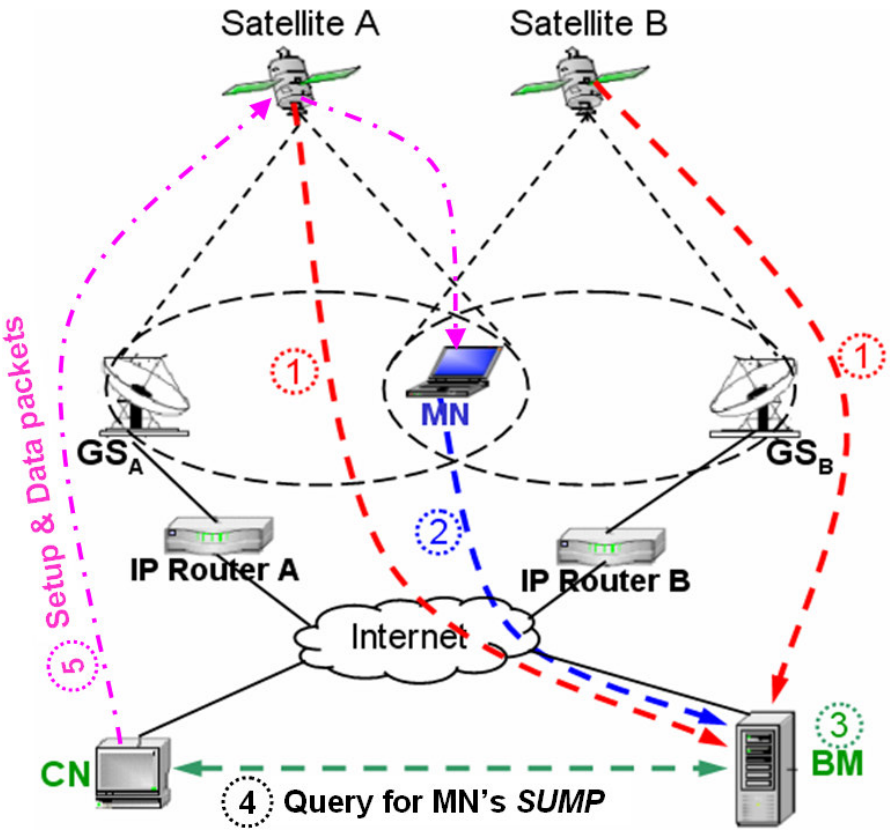


Figure 5.1. Location management in PatHO-LEO

The whole handover management scenario is divided into four parts as shown in Figure 5.1 which are described as follows:

1. *Satellites register to BM.* Satellites register to BM with their mobility patterns (SMP). If any updates are needed for a specific satellite, it also informs BM about the changes.
2. *MN registers to BM.* Once the MN accomplishes to set its path, it registers to BM with its mobility pattern (UMP). A MN can register with more than one UMP for different time intervals.
3. *BM establishes the satellite and user mobility pattern (SUMP) table.* After BM receives both SMP and UMP, it establishes a new table called SUMP table which contains the time and the place where an MN is in and the corresponding satellite which passes over the same place at the same time with the MN. Table 5.1 shows an example of the content of a SUMP table. The SUMP table is composed of the following fields:
   - UMP Identity (ID_{UMP}),
   - Satellite Identity (IP_{SAT}),
   - Expected Entry Time (EET),
   - The duration of MN on the satellite's footprint (t_F),
   - The IP of MN for the corresponding satellite (IP_{MN}).

Table 5.1. Content of Satellite and User Mobility Pattern (SUMP) Table

ID_{UMP}	IP_{SAT}	EET	t_F	IP_{MN}
0	192.122.111.37	08h43mn54s	0842s	157.158.102.12
0	192.122.111.38	08h57mn42s	1030s	157.121.101.17
0	192.122.111.39	09h13mn58s	0304s	157.125.111.19
0	192.122.111.40	09h17mn49s	1959s	157.135.121.21
0	....	....	....	....
1	192.122.111.157	20h26mn46s	0892s	81.215.211.139
1	192.122.111.158	20h40mn01s	0407s	81.213.100.141
1	....	....	....	....

In Table 5.1, ID_{UMP} have two different values 0 and 1 and each of these ID_{UMP} values identifies different patterns. For example, $ID_{UMP} = 0$ shows the pattern of the user in the weekdays, and $ID_{UMP} = 1$ shows the pattern of the user in the weekends. Therefore, a user can specify more that one pattern.

4. *CN and BM establish connection.* When a new connection is established between MN and CN, the BM informs CN about MN's pattern including its corresponding IP addresses for corresponding satellites which are on the way of MN. First, CN sends the expected call duration time to BM. BM prepares all routing related data that are valid for the given call duration time. Therefore, CN learns the time and IP pairs of MN in order to communicate via specified satellites. During a location update in the handover process, the SUMP is examined by the CN and its relevant entry with the new IP address in the new satellite's footprint is extracted and started to use by both CN and MN. BM has to manage this process precisely to avoid failures.
5. *CN sends data packets to MN.* CN makes connection setup and then starts to send data packets to MN via corresponding satellite.

5.1.1. Connection Setup and Maintenance

In the proposed SeaHO-LEO model, the location of the mobile node is loosely managed since at the beginning of the communication, it registers to BM with its mobility pattern, then it does not make location updates anymore. Hence there is a need for more careful handling of connections when a handover takes place. Another challenge is in the deviations occured in the pattern of MN. Thus this section describes a local forwarding scheme and a paging scheme for connection maintenance and setup, respectively.

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

In the connection mainantenace phase of PatHO-LEO, we use the buffering procedure described in step 2 of SeaHO-LEO model. During the communicaiton, CN monitors the SUMP table. When CN senses a handover, it sends the IP of new satellite to MN, and the active MN notifies its new satellite of its old satellite at handover occurrence time. Upon receipt of such notification, the new satellite informs the old satellite that the mobile node has indeed performed a handover. In response to that, the old satellite forwards the packets that are destined for the node to the new satellite. Recall that unlike the binding update process, this forwarding mechanism generates some control messages among only the three adjacent entities (the mobile node, the new satellite, and the old satellite). The required overhead for this local forwarding is thus smaller than the cost of the binding update. The performance evaluation takes into account this cost.

2) Paging Scheme: In the PatHO-LEO method, a paging mechanism is proposed to solve the probleme of deviations occured in the pattern of MN. CN first sends the data packet to the corresponding satellite of MN's new subnet. However, if this satellite does not find the MN in its coverage area, it sends a paging request to all its neighbours because in worst case MN is observed in the coverage area of one of the neighbour satellites of the expected satellite. These neighbour satellites broadcast paging messages. While satellites broadcast paging messages in their coverages, only mobile nodes in the footprint indicated by the prefix of an old IP address check paging messages.

5.2. Advantages of PatHO-LEO

The most significant benefits of Billboard Manager are as follows:

- Storing user location information into a central secure database, namely in Billboard Manager Database, is much more secure than scattering it in various HAs located at different sub-networks like in the case of Mobile IP,
- Centralized billboard management provides a way for an organization/service provider to control user accesses from a single server.

On the other hand, BM can become a single-point of failure although a central server model is useful for management. To overcome this problem, a satellite system administrator can allocate more than one Billboard Manager Servers to store its register satellites and mobile users. In case of more than one Billboard Manager Servers are allocated, the communication between these servers should also be well maintained. Another approach to solve this problem can be holding a copy of Billboard Manager Database in a GEO satellite. The copy database stored in the GEO satellite can be updated when any change occurs in original database. However, this operation increases the complexity of the model. Instead of making updates for each change in BM, periodic updates (i.e., making updates 1800 second-periods) can be applied to reduce traffic load and complexity.

As a result, in the PatHO-LEO handover model, all handover messaging steps are eliminated and handover latency is approximated to the time of sending only one acknowledgement sent by BM to MN and CN which is needed to handshake for handing over to new subnet on the right time. Unless the MN detects that its pattern deviates significantly from the registered SUMP, it performs the pattern based handover model. If MN breaks the pattern, then it starts to proceed with the steps of SeaHO-LEO.

This approach is capable of handling handovers between satellites accurately in a short time. However, the software is needed in both satellite and MN to generate and store SMP and UMP. Also, an efficient algorithm should be implemented for MN to learn its pattern precisely. Moreover, BM should be well designed to manage SMP and UMP of each MN efficiently and adapt to the growth in the number of mobile users gracefully. Also, time synchronization has a signicifant importance on management of PatHO-LEO procedure.

5.3. Analysis of Mobility Management Cost

This section evaluates the management cost of the proposed PatHO-LEO and compares it to that of Mobile IP.

5.3.1. Management Cost Elements

As discussed in Section 3.2, the mobility management cost consists mainly of the cost of the binding update and data delivery. The trade-off between the two costs depends on how precisely nodes location are managed. A precise management of nodes location leads to a large value of binding update cost, while a loose management method decreases the update cost. On the other hand, since additional procedures such as local forwarding and paging are envisioned, data delivery cost may increase.

This chapter covers three main mobility management costs:

- Binding Update,
- Local Forwarding,
- Paging Cost.

5.3.2. Management Cost Definition

In [36], the management cost is computed as the product of the generated control message size, M, and the number of hops, H, required to deliver the message. Applying such definition to the paging cost, the cost should be in proportion with the number of receivers. Taking into account the broadcasting capabilities of satellites, however, the cost is also simply a product of the message size and the number of traveled hops. Equation 5.1 and Figure 5.2 indicate the definition of the cost in this evaluation.

$$Cost = M \cdot H. \tag{5.1}$$

5.3.3. Binding Update, Local Forwarding, and Paging Cost

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

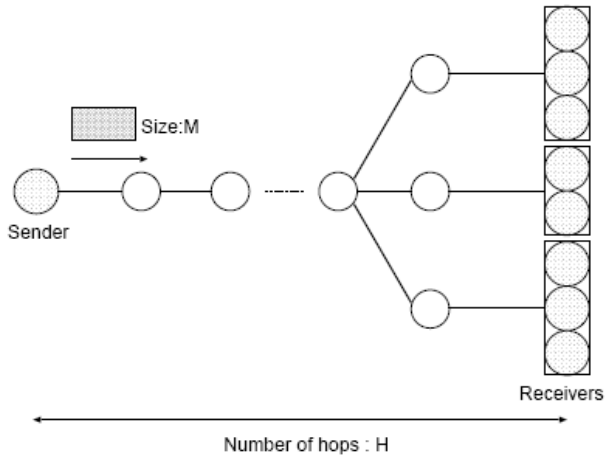


Figure 5.2. Definition of management cost

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

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

$$M \cdot H_{MN,LD}. \tag{5.2}$$

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

$$M \cdot H_{AR,AR}. \tag{5.3}$$

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

between satellites is:

$$M \cdot H_{AR,AR} \cdot (S-1). \tag{5.4}$$

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

$$M \cdot 1 \cdot S. \tag{5.5}$$

Summing Equation 5.4 and Equation 5.5, the total paging cost becomes:

$$M \cdot H_{AR,AR} \cdot (S-1) + M \cdot 1 \cdot S. \tag{5.6}$$

5.3.4. Management Cost of Mobile IP and PatHO-LEO

The cost of Mobile IP and the proposed PatHO-LEO method are defined as follows.

1) Mobile IP: In Mobile IP, the binding update cost is the product of Equation 5.2 and the rate of handover occurrence, whereas the paging cost is 0. For handover occurrence, Equation 2.2 is used. Using Equation 5.1 and Equation 5.2, the Mobile IP management cost, $\mathrm{C}_{MIP}(\mathrm{t})$, can be expressed as:

$$C_{MIP}(t) = M \cdot H_{MN,LD} \cdot R_{HO}(t). \tag{5.7}$$

2) PatHO-LEO: In PatHO-LEO, the local forwarding and paging scheme create some additional cost. Using Equation 5.2, Equation 5.3 and Equation 5.6, the PatHO-

LEO management cost, $C_{PatHO-LEO}$(t)is:

$$\begin{aligned} C_{PatHO-LEO}(t) &= M \cdot H_{MN,LD} + \\ & M \cdot H_{AR,AR} \cdot R_{HO}(t) \cdot \alpha + \\ & \{M \cdot H_{AR,AR} \cdot (S-1) + M \cdot S\} \cdot n(t) \cdot (1-\alpha) \cdot \lambda, \end{aligned} \quad (5.8)$$

where *n(t)* and α denote the total number of nodes per a coverage area at time t and the ratio of active mobile nodes to the total number of nodes, respectively. The rate of newly coming connections to a mobile node is denoted as λ.

The first term in Equation 5.8 indicates the handshaking cost. Since all binding update operations are done at the beginning of the communication, there is no binding cost during handover in the PatHO-LEO. The second term represents the local forwarding cost, whereas the third one refers to the paging cost. Observe that n(t) $\cdot$ (1 - α) $\cdot$ λ indicates paging the occurrence rate.

In all analyses, satellites coverage radius and satellites ground speed are set to 700[km] and 7[km/sec], respectively. Mobile nodes are assumed to move at velocity 17[m/sec] (60[km/sec]). Similarly to [36], 95% of all nodes are assumed to be idle and idle nodes become active on the average of three times per hour. α and λ are thus set to 5% and 0.0008, respectively. The mobility management cost is evaluated every second (Δt = 1 sec). Nodes density is calculated as the ratio of the total number of nodes to the coverage area surface.

In this evaluation, the effect of number of MN is investigated by considering various number of nodes in a coverage area. Since it is obvious that the PatHO-LEO method exhibits better performance in the case of larger number of hops between mobile nodes and Location Directory, $H_{MN,LD}$ is deliberately set to 2 to investigate the performance of the proposed method in the worst case where mobile nodes reside geographically close to the Location Directory. The number of hops between two satellites (ARs) that participate the handover process, $H_{AR,AR}$, is set to 1 as illustrated

in our ISL Model in Figure 3.2.

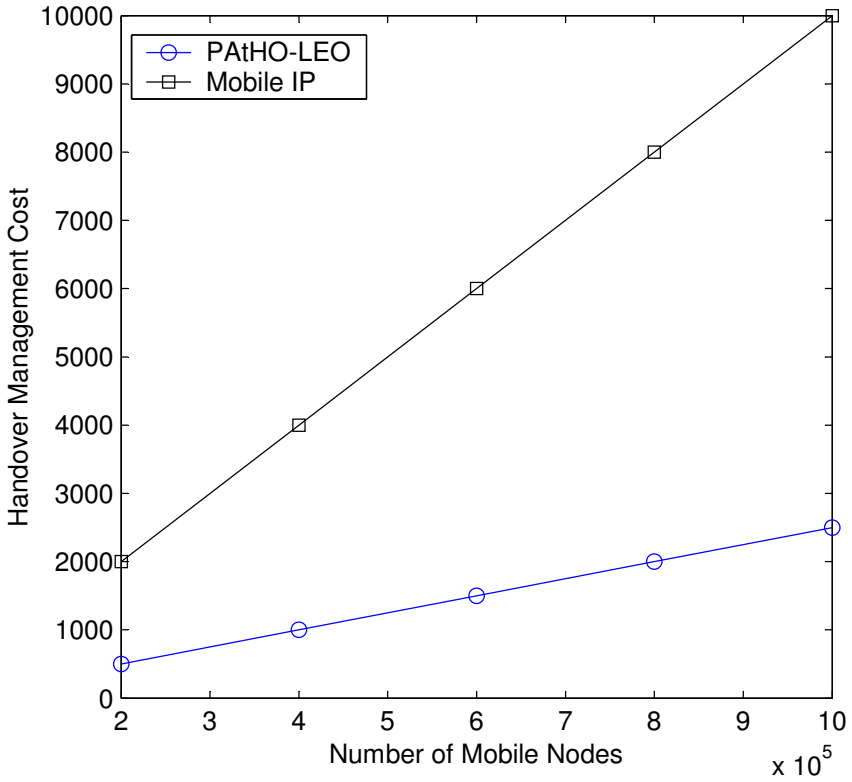


Figure 5.3. Performance evaluation in terms of handover management cost

Figure 5.3 presents the evaluation results. The figure demonstrates that the PatHO-LEO significantly outperforms the Mobile IP. Also, due to this low handover management latency in the PatHO-LEO, the throughput degradation period is also reduced. Since MN quickly starts to take service from the new satellite with a new efficient path, the low throughput becomes higher in a shorter time.

6. CONCLUSIONS

6.1. Contributions of the Thesis

In this thesis, I have proposed novel handover management mechanisms namely SeaHO-LEO and PatHO-LEO which decrease the handover latency and data loss.

We first described a simple mobility management protocol called SeaHO-LEO for LEO satellites. We also described the traditional handover scenarios such as MIP and TraSH-SN used for satellite networks to establish a reference model for performance comparisons. We tried to point out their major drawbacks. Relying on the simulation results, we showed that the SeaHO-LEO mechanism decreases latency significantly while increasing throughput in a short time. Furthermore, SeaHO-LEO model is very well-organized for dense networks in which the number of MNs is very high since the handover call blocking probability of proposed model is very low.

Moreover, to eliminate some handover messaging traffic, we proposed our second model PatHO-LEO. The PatHO-LEO mechanism employs a Billboard Manager which is responsible for location updates of mobile users as well as comes with additional benefits such as security, scalability and manageability. Also, BM reduces the system complexity since the satellite service provider only deals with a central location update manager. Comparison of PatHO-LEO model performance to that of MIP was made through a mathematical analysis. Performance evaluation results showed that management cost of PatHO-LEO is so smaller that that of MIP.

6.2. Future Works

Future works would include extensive investigation on mobility pattern based model. Mobility pattern based model needs efficient algorithms to construct reliable routing tables on BM. As mentioned before this thesis does not cover handover decision phase. Infact, the success of handover management algorithms partially realated

with handover decision methods. Therefore, designing a precise handover decision model can be thought as a future work. Furthermore, QoS model for LEO satellite IP networks is very crucial for different types of data traffic. The proposed handover management models should be reviewed under different types of traffic requirements and QoS parameters. A final problem that has also a significant importance is routing management after handover. Since handover process changes lots of routing related information, efficient routing algorithms for LEO satellite IP networks are required.

In the considered models one end point of communication (i.e. CN) is not mobile. Some modifications are required to improve the proposed SeaHO-LEO and PatHO-LEO architectures that account for mobility in both ends. Especially, PatHO-LEO model should be changed to support the mobility of CN while MN is moving randomly.

APPENDIX A: SATELLITE SIMULATION MODEL

The purpose of simulation modelling is to obtain the handover performance of each handover procedure in a LEO satellite various user. Thus it can be determined whether the expected performance of a handover procedure is acceptable, and the most appropriate handover procedure for real-world use can be identified.

OPNET Modeler [48] is a development and simulation environment incorporating tools for modelling design, discrete event simulation, and data analysis. OPNET includes a model library containing pre-developed models of many common applications and protocols such as Mobile IP.

This appendix summarises the simulation modelling work. Section A.1 introduces the OPNET Modeler development environment and describes the hierarchical nature in which the satellite models was created. Section A.2 provides an overview of the SeaHO-LEO satellite model, including the development/enhancement methodology, and a summary of the key enhancements.

A.1. Introduction to the OPNET Modeler

The OPNET Modeler development environment consists of three main editors: 1) Network editor, 2) Node editor, and 3) Process editor. The editors are organised hierarchically, such that modelling in the Network editor uses elements modelled in the Node editor, and in-turn modelling in the Node editor uses elements modelled in the Process editor. Each editor models a different characteristic of behaviour; the Network editor captures the network topology in terms of devices, links, subnetworks, and geographical context; the Node editor captures the device internal architecture in terms of functional elements and data flows between them; and the Process editor defines the behaviour of functional elements (e.g., protocols, algorithms, applications) specified using a Finite State Machine (FSM) and programming language. All editors use a graphical interface in which the user works with objects representing the modelled

systems structure and components.

A.1.1. Network Editor

The topology of the communications network is designed within the Network editor. An example network topology (also referred to as a network scenario) is shown in Figure A.1.

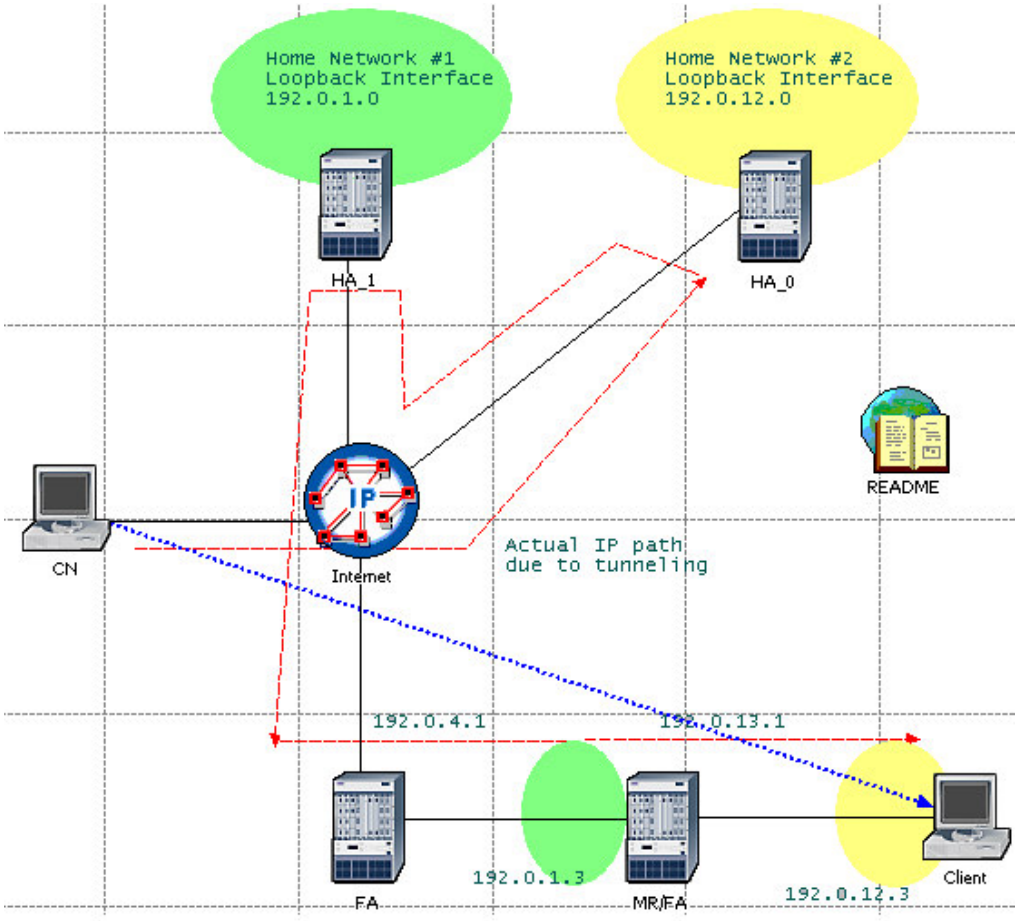


Figure A.1. Example network scenario created in the OPNET Network editor

The communicating devices are called nodes, which are created using the Node editor (Section A.1.2). Nodes communicate with each other using links, which model the physical communications channel. Within a single network scenario, there may be many instances of a node based on the same model. The term node is used to refer to a single instantiation of a node model, and the term node class is used to refer to

the set of nodes having the same model. Nodes contain parameters called attributes, which allow the user to customise the behaviour of each instance of a node.

The network domain allows geographical information to be included in the network model, using latitude/longitude and xy coordinates to physically place nodes at specific locations in the network scenario. OPNET includes a number of regional and world maps that can be overlaid on the network, to give the network scenario an impression of a real-world deployment. OPNET uses the inherent distance between nodes to automatically calculate communication delays and losses. Nodes may be designated as either fixed, mobile, or satellite. Fixed nodes remain at the specified location throughout the entire simulation run. Mobile nodes have a predefined trajectory attribute, which specifies the node location relative to time for the entire simulation run. Satellite nodes have a predefined orbit attribute which describes their motion during the simulation run.

A.1.2. Node Editor

Communication devices, such as user terminals, satellites and network switches, are designed within the Node editor. Node models are created using smaller building blocks called modules. Some modules, such as radio transmitters and receivers, have predefined functionality, but also allow certain parameters (e.g., transmission rate, modulation type) to be configured by the user. Other modules, such as processors and queues, are completely user programmable, and have their functionality defined by the underlying process model (Section A.1.3). Each module contains an independent instance of the process model. Modules commonly communicate with each other through packet streams, which allow formatted messages called packets to be passed from a source module to a destination module. An example node model showing various modules and interconnection methods is shown in Figure A.2.

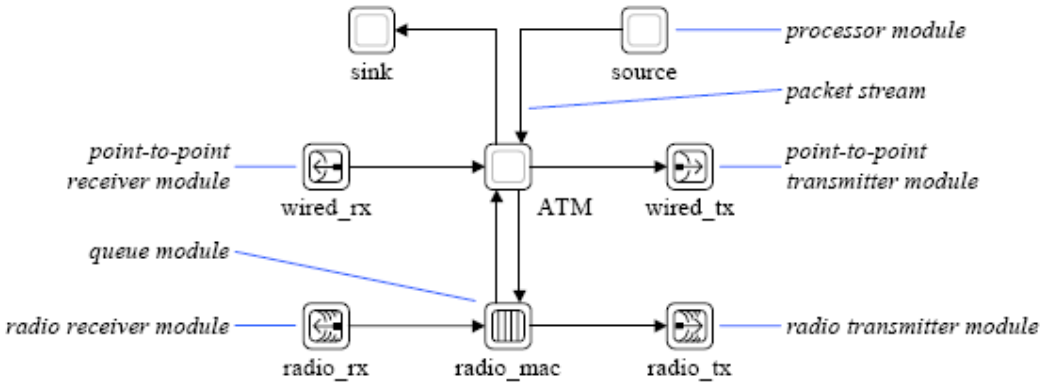


Figure A.2. Example node model created in the OPNET Node editor

A.1.3. Process Editor

The functionality of user defined node modules is specified within the Process editor, using the C/C++ programming language and a Finite State Machine (FSM) framework. An example FSM showing unforced states (red) and forced states (green) is shown in Figure A.3.

The FSM describes the set of states that the process may enter, and for each state, the conditions required to leave. Each state has enter executives and exit executives, which are lines of code that are executed as the state is entered and exited respectively. A state may be either forced or unforced. A forced state causes process execution to execute the enter and exit executives, evaluate transitions, and immediately move to the appropriate next state. An unforced state causes process execution to halt after execution of the enter executives. Process execution resumes upon the next invocation of the process; the exit executives are executed,transitions evaluated, and process execution moves to the appropriate next state.

Processes are arranged hierarchically, allowing a process to create and invoke a new instance of a predefined process. The creator is referred to as the parent process, and the new process is referred to as the child process. Hence a number of processes, referred to as a process group, can execute within a single processor or queue module.

The process editor allows the user to specify parameters called attributes, which

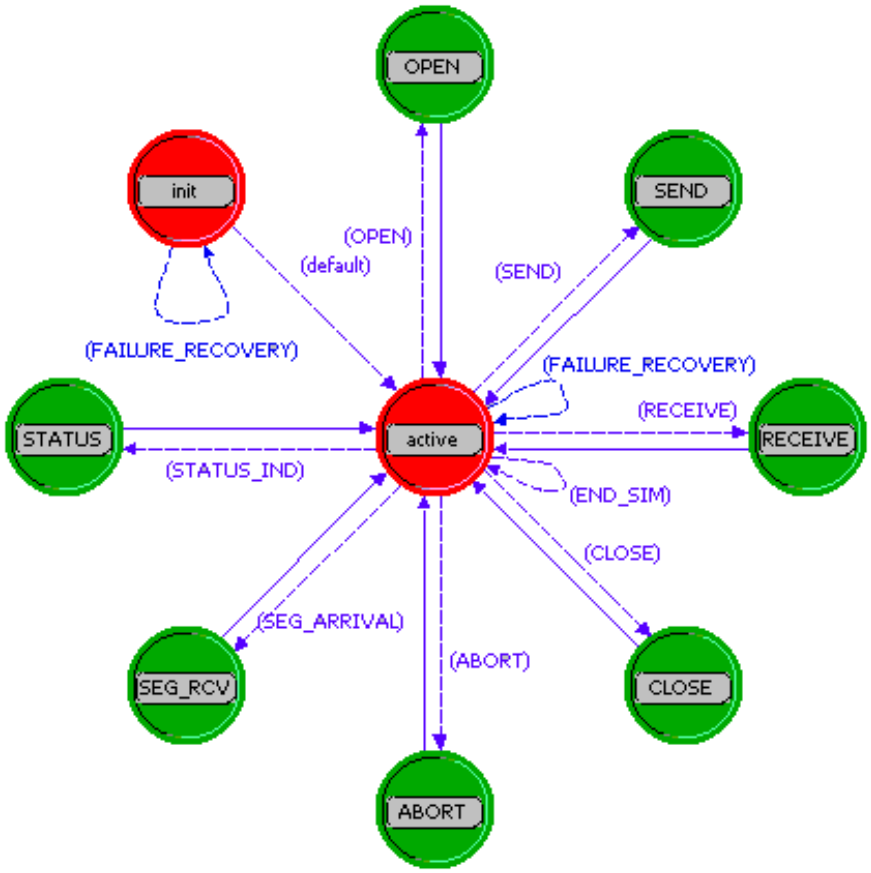


Figure A.3. Example process model created in the OPNET Process editor

are used once the process is instantiated to customise its behaviour. This facilitates the re-use of process models by eliminating the need to hardcode values, instead allowing values to be set on a per-instance basis at design time and read during simulation runtime. For example, a traffic source model may have an attribute called packet interarrival time, which can be set individually for each instance of the model, allowing the single traffic source process to generate a variety of data rates.

A.2. Handover Scenario Description: SeaHO-LEO

In this section, OPNET models of the network components described in Section 4.1 are illustrated. The fuctionality of each node is maintained according to SeaHO-LEO model.

Figure A.4 shows the internal architecture of terrestarial MN and CN nodes. In this figure, mn_rx_AA_from_SAT radio receiver that receives Agent Advertisement from new satellite is connected to handover_decision processor with a statistic wire. This statistic is mn_rx_AA_from_SAT's channel busy state. This statistic is a Boolean value (0.0 or 1.0) which represents whether any packets are currently being received or transmitted on a channel. When this channel is busy (receiving AA from new satellite), MN starts its handover decision process. The FSM of handover decision process is depicted in Figure A.5.

Figure A.7 shows the internal architecture of a LEO satellite. LEO_{old} implements the functionality of current satellite. LEO_{new} implements the functionality of next (new) satellite.

In LEO_{old}, the rx_from_MN_HPR radio receiver receives HP_REQUEST message from MN and links its busy state to start_buffering process with a statistic wire. The FSM of start_buffering process is shown in Figure A.9.

In LEO_{new}, when the rx_conn_activate_from_SAT receives CONN_ACTIVATE message from current (old) satellite, it connects its busy state to data_buffering pro-

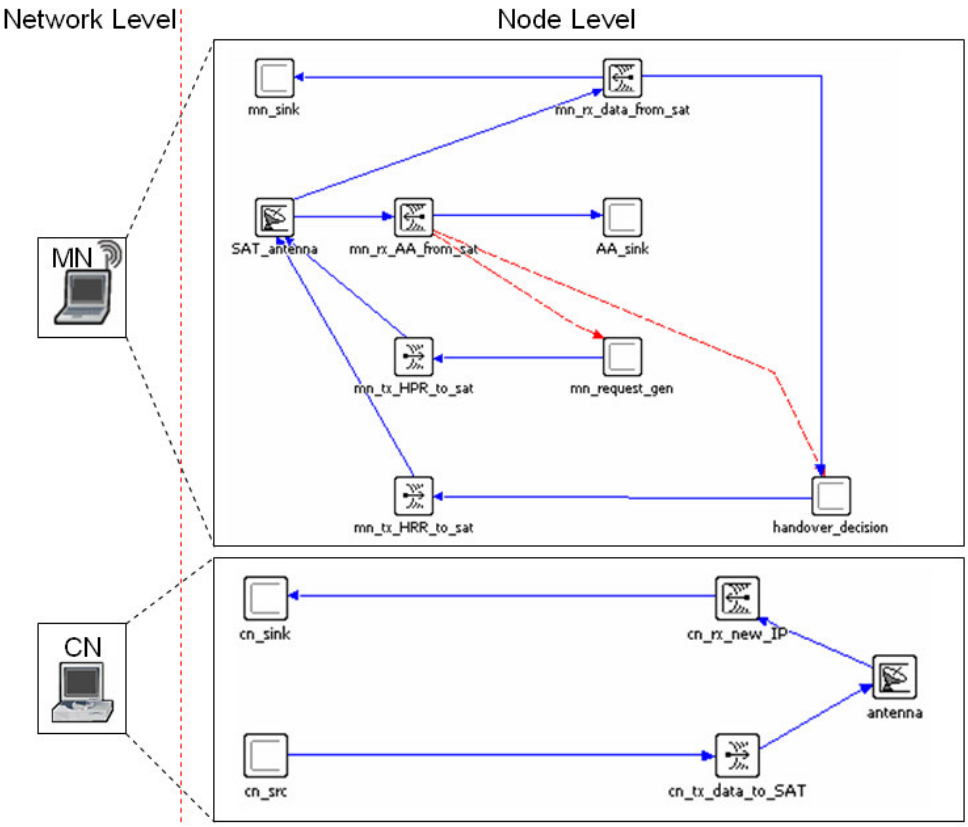


Figure A.4. OPNET terrestarial nodes internal architecture

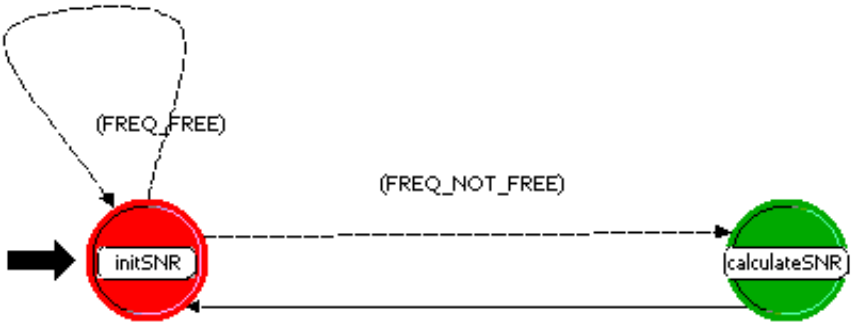


Figure A.5. Process model: handover_decision FSM

cess with a statistic wire. The FSM of data_buffering process is shown in Figure A.6. Also, another processor called AA_generator always sends Agent Advertisement message to all MNs on its coverage area. The internal FSM of AA_generator is depicted in Figure A.8.

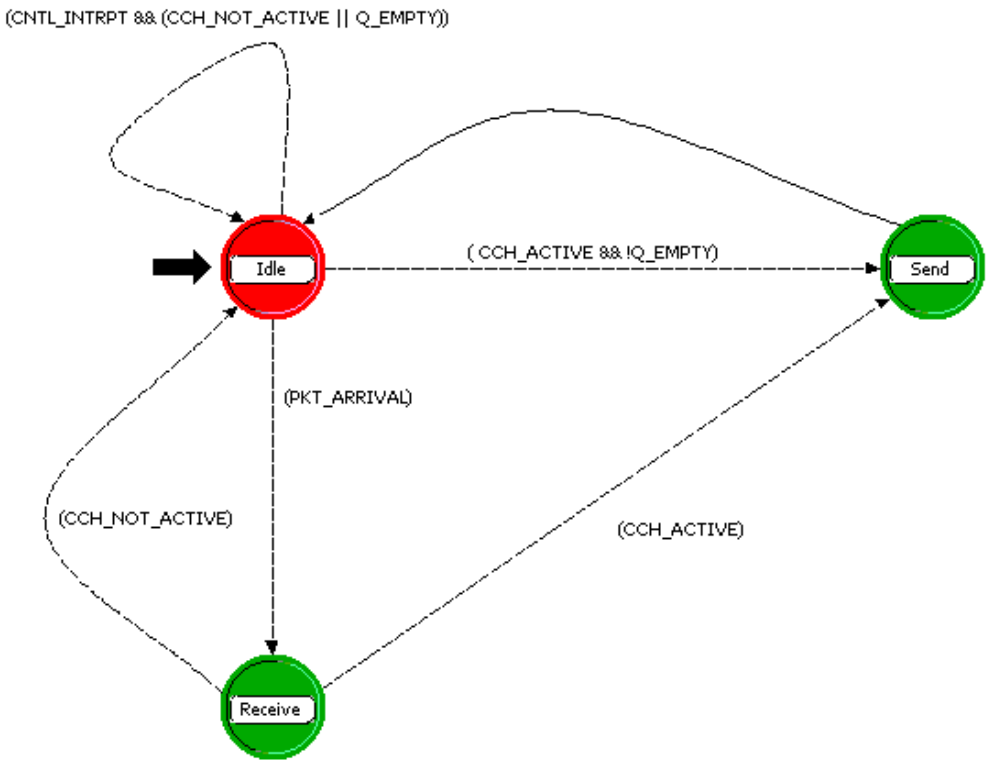


Figure A.6. Process model: data_buffering FSM

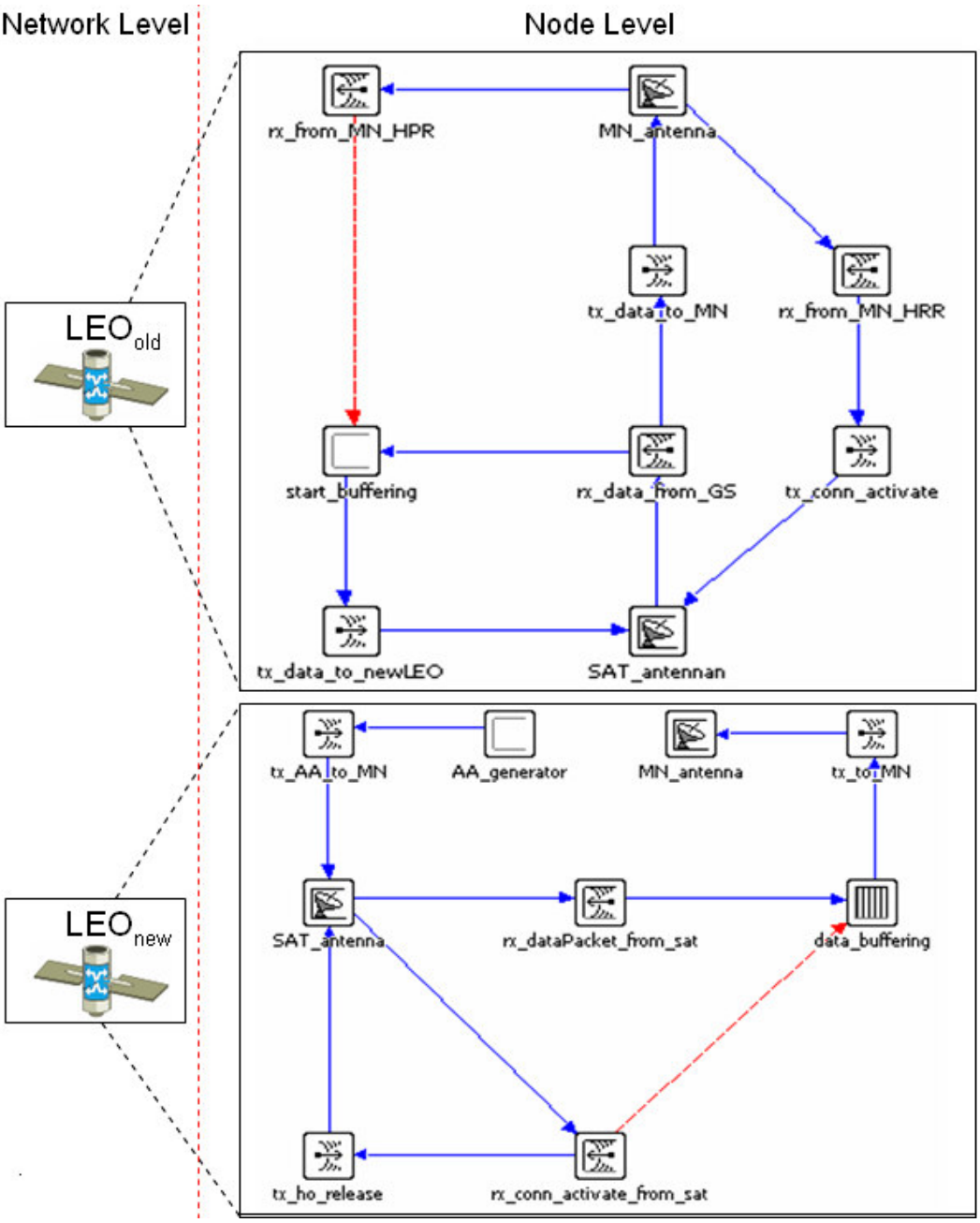


Figure A.7. OPNET LEO satellite node internal architecture

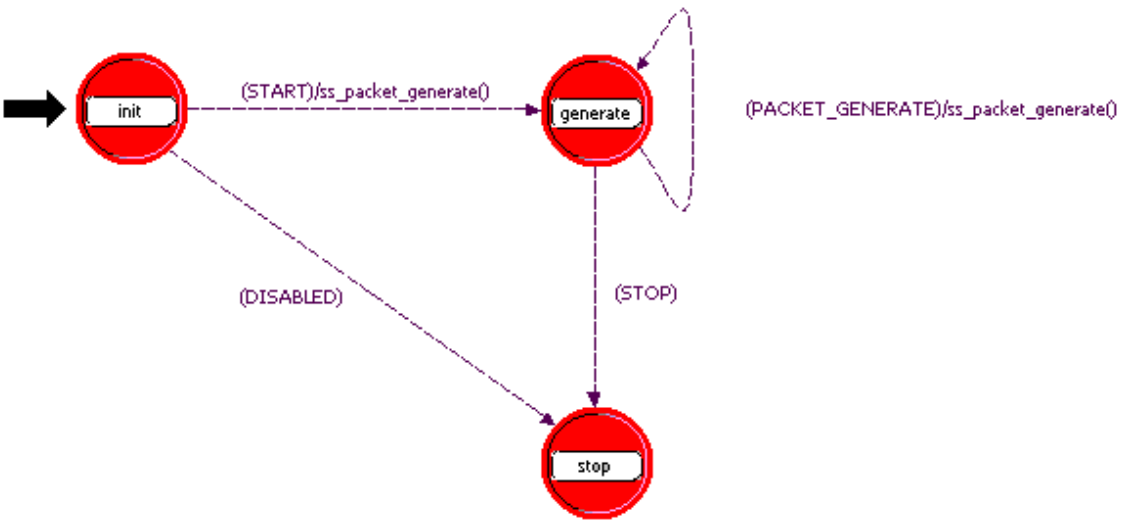


Figure A.8. Process model: AA_Generator FSM

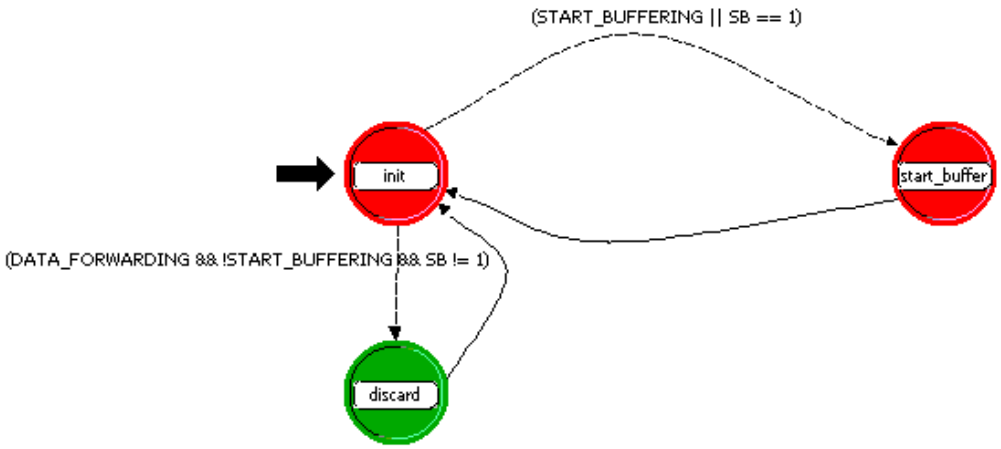


Figure A.9. Process model: start_buffering FSM

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