SIGMA for Seamless Handover in Space

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Abstract— **NASA has been interested in having Internet connectivity in space for quite some time. This would allow scientists with direct Internet access to data and devices on the satellites. The rotation of Low Earth Orbiting (LEO) satellites around the Earth result in handover of satellites between ground stations. Two types of handover can be observed in space: Link layer and Network layer. Researchers at The University of Oklahoma and NASA Glenn Research Center have been developing a Seamless IP diversity-based Generalized Mobility Architecture (SIGMA) to ensure smooth handovers of end to end connections between nodes on Earth and satellites. In this paper, we provide a survey of the various types of handovers in the space environment, followed by simulation results of SIGMA handover performance in a space environment.**

I. INTRODUCTION

Future space communications will be based on commercial off-the-shelf Internet technology in order to reduce costs. This will also extend existing Internet over the space. Spacecrafts (like satellites) will communicate with ground stations on Earth and among themselves to carry data traffic by setting up end-to-end connections. Depending on the altitude, satellites can be classified into three types: Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geosynchronous Earth Orbit (GEO). GEO satellites are stationary with respect to Earth, but LEO and MEO satellites move around the earth, and are handed over between ground stations as they pass over different areas of Earth. This is analogous to mobile computers being handed over between access points as the users move in a terrestrial network.

LEO satellite systems have some important advantages over GEO system as the component of next generation Internet. These include lower propagation delay, lower power requirements both on satellite and user terminal, more efficient spectrum allocation etc. However, due to the non-geostationary characteristics and high speed movement of LEO satellites, ongoing connections through a satellite has to be frequently transferred to a new spotbeam or satellite. Transfer of a connection to a new spotbeam or satellite is called *handover*. Three types of link layer handovers are observed in LEO satellite systems [1]: (a) Satellite handover, (b) Spotbeam handover, and (c) Inter Satellite Link (ISL) handover. Satellite handover refers to the switching between the satellites, whereas spotbeam handover involves switching of connections between spotbeams. Inter Satellite Link (ISL) handovers occur in the polar area due to change of connectivity patterns of satellites. Moreover, it may happen that a connection endpoint (satellite or user terminal) has to change its IP address due to high rotational speed of LEO satellites. In that case, to keep ongoing communications alive, a network layer handover is also required. Thus, the mobility management in LEO satellite systems is more challenging.

Existing literature review shows that most of the research in the area of satellite handover is on link layer handovers [1], [2] [3], [4]; network layer handover issues have not investigated in depth. National Aeronautics and Space Administration (NASA) is currently studying the use of Internet protocols for space communications [5]. NASA is studying, testing and evaluating the possible use of Internet technologies and protocols in data communication with spacecrafts, and network layer handovers issues in space networks in projects like Global Precipitation Measurement (GPM), Operating Missions as Nodes on the Internet (OMNI), Communication and Navigation Demonstration on Shuttle (CANDOS) mission, and the GPM project [6]. Current trend in space Internet technology is to apply Mobile IP (MIP) [7] (developed by IETF) in satellites to suffice satellite handovers in these projects. CISCO along with NASA has developed a Mobile Router which contains all Mobile IP functionalities to support satellite based data communications [8].

However, MIP suffers from a number of drawbacks in a mobile network environment. The most important ones identified to date are high handover latency, high packet loss rate during handover, inefficient routing, conflict with security solutions (like IPsec) and requirement for change in Internet infrastructure. These drawbacks of MIP in handling handover have been extensively studied in the literature, and several improvements [9] of MIP based handover scheme have been proposed to solve the existing drawbacks.

In spite of these improvements to MIP, there are still unsolved problems during handover. Most of the state-of-the-art handover schemes are based on MIP which is known to have intrinsic drawbacks described earlier. Therefore, significant challenges exist in designing new handover schemes based on MIP. To address these problems, we earlier proposed a novel transport layer based end-to-end mobility management scheme called SIGMA [10]. This scheme minimizes handover latency and packet loss with minimum signaling overhead during handover by exploiting IP diversity to achieve soft handover. IP

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diversity refers to having multiple IP addresses in one mobile host. Advantages of SIGMA in satellite environments have been described in our previous work [11]. In this paper, we use some interesting satellite scenarios to show the performance of SIGMA in satellite networks. When a satellite looses link layer connection with the ground station, we consider three scenarios to keep the IP level ongoing connections alive using ISL by connecting to neighboring LEO or GEO satellite. We show that, in order to maximize throughput during those scenarios, the connection should always be handed over to the neighboring LEO satellite.

The *objective* of this paper is to illustrate and thoroughly analyze the performance of SIGMA, an transport layer based handoff scheme, in a LEO satellite environment. As far as the authors are concerned, this paper will be the first of its kind to report results on the performance of a transport layer handover solution in satellite networks. Our main *contributions* in this paper are to (1) provide a survey of LEO satellite handover schemes, (2) show the performance of SIGMA as a end-to-end mobility management scheme in satellite networks, and (3) analyze the throughput and delay characteristics of SIGMA during typical satellite handovers.

The rest of the paper is organized as follows: Section II summarizes the handover schemes in LEO satellite networks. In Section III, we present the basics of spotbeam handover and classify different spotbeam handover schemes. Next, in Section IV, a brief introduction and classification of network layer handovers is given. Section V illustrates the SIGMA architecture in satellite environment. Section VI describes the simulation scenario and simulation parameters. In Section VII, we present the results and analysis of SIGMA simulations in satellite environment. Finally, concluding remarks are given in Section VIII.

II. HANDOVER IN LEO SATELLITE SYSTEMS

LEO satellites are not stationary with respect to a fixed user on earth surface. Due to constant rotation of the LEO satellites, the visibility period of a satellite in a cell is very small. For this reason, a user terminal can be served by a number of spotbeams and satellites during a connection. To support continuous communication over a LEO satellite system, we may need to change one or more links as well as the IP address of the communication endpoints. Thus, both link layer and higher layer handovers may be required for satellite networking. Handovers in satellite networks can be broadly classified as:

- **Link Layer Handover:** Link layer handover occurs when we have to change one or more links between the communication endpoints due to dynamic connectivity patterns of LEO satellites. It can be further classified as:
  - **Spotbeam Handover:** When the end point users cross the boundary between the neighboring spotbeams of a satellite, an intrasatellite or spotbeam handover occurs. Since the coverage area of a spotbeam is relatively small, spotbeam handovers are more frequent (every 1-2 minutes) [1].
  - **Satellite Handover:** When the existing connection of one satellite with the end user's attachment point is transferred to another satellite, an intersatellite handover occurs.
  - **ISL Handover:** This type of handover happens when a LEO satellite passes over the polar area. Due to the change of connectivity patterns in neighboring satellites, the inter-satellite links (ISL) have to be switched off temporarily near the polar areas. Then the ongoing connections using these ISL links have to be rerouted, causing ISL handovers.

  The performance of different link layer handover schemes can be evaluated using two classic connection level QoS criteria [3]:
  - call blocking probability (P_b), the probability of a new call being blocked during handover.
  - forced termination probability (P_f), the probability of a handover call being dropped during handover.

  There is a tradeoff between P_b and P_f in different handover schemes. The priority can be given via different treatments of new and handover calls to decrease handover call blockings [12].
- **Network Layer Handover:** When one of the communication endpoints (either satellite or user end) changes its IP address due to the change of coverage area of the satellite or mobility of the user terminal, a network or higher layer handover is needed to migrate the existing connections of higher level protocols (TCP, UDP , SCTP, etc.) to the new IP address. This is referred to as Network or higher layer Handover. Three different schemes can be used during this call transfer process [13]. They are:
  - Hard handover schemes: In these schemes, the current link is released before the next link is established.
  - Soft handover schemes: In soft handover schemes, the current link will not be released until the next connection is established.
  - Signalling Diversity schemes: Similar to soft handover. Only exception is that, in signalling diversity schemes, signalling flows through both old and new link and the user data goes through the old link during handover [13].

Among all the link layer handovers, spotbeam handover issues have been studied in depth in the literature, as it is the most frequent link handover experienced in LEO systems. The network layer handover has also recently received a lot of attention from the space network community. Therefore, this paper restricts itself to the survey of *spotbeam* handover and *network layer* handover schemes.

III. SPOTBEAM HANDOVER

The service area or footprint of a satellite is a circular area on the earth surface. In order to achieve frequency reuse, the footprint of an individual satellite is divided into smaller cells or spotbeams. This results better frequency utilization through the use of identical frequencies in non-adjacent spotbeams which are geographically well separated to limit interference [14]. To ensure uninterrupted ongoing communications, a current communication link should be handed off to the next spotbeam if needed. A spotbeam handover involves the release of the communication link between the user and the current spotbeam and acquiring a new link from the next spotbeam to continue the call (Fig. 1). Since both spotbeams are served by the same satellite, no other satellite is involved in the handover process.

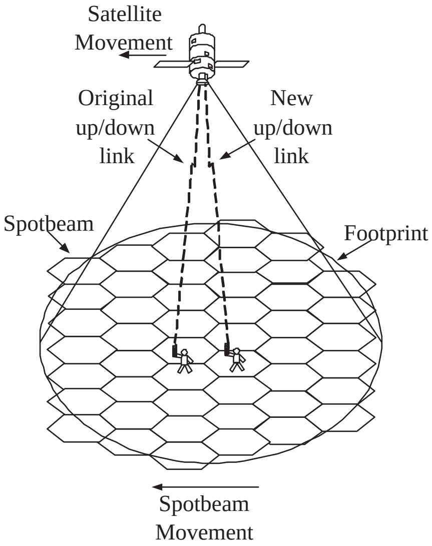

Fig. 1. Spotbeam handover scenario.

Due to small spotbeams and high satellite speed, spotbeam handovers are the most common type of handovers experienced in LEO satellite systems [1]. We can consider the user mobility negligible compared to high satellite speed. As a result, the deterministic and constant movement of the satellites makes the solving of the spotbeam handover problems easier. During the handover process, if a new link or channel can not be found in the next spotbeam, the ongoing call should be dropped or blocked. From the user viewpoint, the interruption of a call is less desirable than the blocking of a newly arrived call [1]. It will be the best for a user if handovers can be guaranteed, ensuring smooth ongoing calls. Again, the selection of a suitable policy in resource management (channel allocation) can ensure new channel availability during handover. Thus, the channel allocation strategies and the handover guarantee are the prime issues in managing handover requests.

To solve spotbeam handover problem, several handover policies/schemes are proposed in the literature. We can classify the spotbeam handover schemes according to two different criteria:

- channel allocation strategies
- handover guarantee

A. Classification based on Channel Allocation Strategies

Various channel allocation strategies can be used to assign a channel to a call. Handover requests can also be considered a transferred call for the next cell, requiring allocation of a channel. Based on channel allocation strategies, handover schemes can be divided into three broad categories [2] [15] as follows:

- Fixed Channel Allocation (FCA) based handover schemes
- Dynamic Channel Allocation (DCA) based handover schemes
- Adaptive Dynamic Channel Allocation (ADCA) based handover schemes

1) FCA based Handover Schemes: In FCA schemes, a set of channels is permanently assigned to each cell, according to frequency reuse distance [15] [2]. A handover call can only be given a channel if any channel belonging to the set of the cell is available. If no channel is available, the call is blocked or, in the worst case, dropped. Fixed channel allocation schemes have a very simple implementation due to fixed predefined channel distribution [2].

An interesting variation of FCA based handover scheme is Channel Sharing Handover [16]. Channel Sharing Handover uses a channel allocation scheme called channel sharing scheme [16], where channels can be shared between adjacent cells. This scheme offers a significantly lower call blocking probability (P_b) for the same handover dropping probability (P_f) when compared to FCA based schemes [16].

2) DCA based Handover Schemes: DCA based handover schemes use dynamic channel allocation, where channels are grouped together in a *central pool*. Any cell requiring a channel use a channel from the pool satisfying the channel reuse distance [15] [2]. Allocated channels are removed from the common channel pool during call time. When the call is terminated, the channel is transferred to the central pool for future reuse. DCA based schemes provide important advantage of coping up with traffic variations and overload conditions in different cells. This adaptability of DCA schemes makes it a fundamental channel allocation strategy in third generation cellular networks. It is concluded that there is a reduction of P_b and P_f in DCA compared to FCA based schemes under same conditions.

3) ADCA based Handover Schemes: Adaptive Dynamic Channel Allocation (ADCA) is an extension of DCA scheme (Sec. III-A.2). It uses guard channel during handover (Handover with Guard Channel (HG), described in Sec. III-B.2.a). Cho et al. [14] proposed a new connection admission control scheme based on ADCA, called *Geographical Connection Admission Control* (GCAC), for LEO satellites to limit the handover blocking probability. Based on user location information, GCAC estimates the future handover blocking probability (P_b) of a new call and existing calls [14]. From the estimated P_b, the GCAC technique either accepts or rejects a call. The GCAC algorithm guarantees that the "handover blocking probability (P_b) is less than a a target handover blocking probability (P_{QoS})" [14].

B. Classification based on Handover Guarantee

A number of handover schemes provide guaranteed handover to prevent calls from being blocked or dropped during handover. Other schemes try to ensure best service by prioritizing handover over the new calls, but do not ensure any handover guarantee. Based on handover guarantee, handover schemes can be classified as:

- Guaranteed Handover (GH) schemes
- Prioritized Handover schemes

1) Guaranteed Handover Schemes: In a guaranteed handover (GH) scheme, a new call is assigned a channel only if there is an available channel simultaneously in the current cell and the next transit cell. If such channels can not be found immediately, the call is blocked. As the name indicates, this scheme guarantees each handover to be successful. Maral et al. [17] proposed a guaranteed handover scheme. In that scheme, when the first handover occurs, new channel reservation request will be issued to the next candidate transit cell. If all the channels in the candidate transit cell are busy, the handover request is queued in a FIFO queue until the next handover. Thus, this scheme provides almost zero P_f while the value of P_b is unacceptably high. This is due to the early channel reservation (also known as channel locking in GH) for a call which is still not transferred to the cell, exhibiting bad resource management. To improve resource allocation, a few modified GH schemes are proposed: (a) Elastic Handover Scheme [18], (b) TCRA Handover Scheme, and (c) DDBHP Scheme. All of them provide techniques to delay the channel allocation for the next cell by a calculated time, and trade off the handover guarantee to a certain extent.

a) Elastic Handover Scheme: The elastic handover scheme is based on Elastic Channel Locking (ECL) scheme [18]. The idea behind the ECL scheme is that an entering call does not issue a channel locking request to the next cell immediately; instead it postpones the request for a period of time until T_a [18]. The time T_a is decided by the QoS requirement for handover failure probability.

b) TCRA based Handover Scheme: Boukhatem et al. [19] proposed a Time based Channel Reservation Algorithm (TCRA) to improve GH performance and resource utilization. TCRA is a variation of ECL (Sec. III-B.1.a) except that the time instant to send the channel reservation request (T_a in ECL) is calculated using the estimated user location in the current cell, instead of the QoS parameters in ECL.

c) DDBHP Scheme: Dynamic Doppler Based Handover Prioritization Technique (DDBHP): DDBHP is yet another variation of GH scheme proposed by Papapetrou et al. [20]. This method uses Doppler effect in order to determine the terminal location, and to reserve channels at the estimated time in the next servicing cell. The system must reserve channel for the next cell in the corresponding time interval, called handover threshold (t_{tH}) [20]. Clearly, different values of t_{tH} will provide different level of service.

2) Prioritized Handover Schemes: Probability of handover failure is a common criteria for performance evaluation of handovers in satellite networks. In non-prioritized schemes, handover requests are treated equally as new calls, thereby increasing the probability of call dropping during handover [2]. As discussed in Section III, from user's viewpoint, ongoing call dropping is less desirable than new call blocking. Thus, handover prioritization schemes have been proposed to decrease handover failure at the expense of increased call blocking [2]. These prioritized handover techniques can be used along with the channel allocation strategies defined in Sec. III-A to increase handover performance. The following are different handover prioritization categories:

a) Handover with Guard channel (HG): HG scheme [21] [22] provides successful handover by reserving a set of channels (either fixed or dynamically adjustable) exclusively for handovers [2]. The remaining channels can be used for handover or normal calls. This reduces the probability of forced termination of calls during handover, while increasing new call blocking probability as fewer channels are available for new calls. Therefore, an important design issue is carefully choosing the number of guard channels [2].

b) Handover with Queueing (HQ): HQ scheme takes advantage of the overlapping area between adjacent cells [15]. While in the overlapping area, a mobile host can be served by any of the cells. This makes provision of queueing the handover requests for a certain time period equal to the time of mobile host's existence in the overlapping area [2]. When a new channel becomes available, the cell checks the queue for waiting requests and grants the channel to the longest waiting request. Several schemes, depending on the strategy to order the handover requests in the queue, have been proposed. First in first out (FIFO) scheme [21] [23] is the most common queueing discipline where handover requests are ordered according to their arrival times.

A more complex scheme called MBPS (Measurement Based Priority Scheme), is based on dynamic priority, where the handover priorities are defined by the power levels of the corresponding calls (received from the satellite) from their current spotbeam [24]. The objective is to first serve the call with the most degraded link. Another alternative priority scheme is called LUI (*Last Useful Instant*) scheme [15] where a handover request with a longer residual queueing time is queued ahead of other requests.

c) Channel Rearrangement based Handover: This scheme is only used with dynamic channel allocation schemes [25] and manages handover requests in exactly the same manner as new call attempts. Whenever a call termination occurs in a cell, the scheme performs a channel rearrangement to de-allocate the channel which becomes available in the greatest number of cells.

d) HQ+HG Handover: HQ+HG scheme takes advantages of both guard channel and queueing schemes.

IV. NETWORK LAYER HANDOVER

As mentioned earlier in Section II, due to the movement of the satellites and the mobile users, the communication endpoints (user or satellites) may have to change their IP address, requiring a network layer handover. Fu et al. [11] identify two scenarios requiring network layer handover as follows:

- **Satellite as a Router:** As satellites move, communicating fixed/mobile hosts come under new satellite footprints or spotbeams. Different satellites or even different spotbeams can be assigned with different IP network addresses. This requires a network layer handover during the change of communication links form one satellite or spotbeam to another.

- **Satellite as a Mobile Host:** When a satellite works as an end point of a communication by generating and receiving data, it can be regarded as a mobile host. Thus, like a mobile host it always changes its communication attachment point requiring a network layer handover.

In the first scenario (Fig. 2), satellites do not have any onboard equipment to produce or consume data. They merely act as routers in the Internet. Each satellite, or even a spotbeam, can be assigned an IP address. In such cases, handover between satellites (Intersatellite handover) or spotbeams (spotbeam handover) may also require network layer handover [11]. Hosts are handed over between satellites or spotbeams as they come under the footprint of a new satellite or spotbeam.

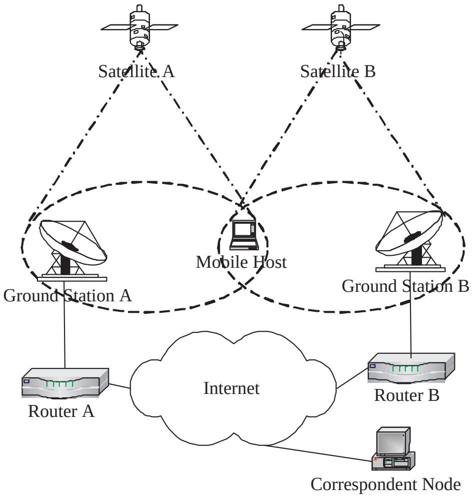

Fig. 2. User handover between the satellites.

In the second scenario, satellites can act as communication endpoints with all the onboard equipments which exchange data with ground stations on earth. As in Fig. 3, the satellite's footprint is moving from ground station A to B, while the satellite is bound with an IP address from ground station A. During movement, the satellite should maintain continuous connection with ground stations on earth. Thus, the IP address of the satellite has to be changed when it is handed over to ground station B, requiring network layer handover. Three different strategies can be used for network layer handover [13]: (a) Hard handover schemes (b) Soft handover schemes (c) Signalling Diversity schemes.

A. Hard Handover Schemes

In hard handover schemes, the current link is released before the next link is established [13], which may result in connection blocking during handover. NASA [6] is using Mobile IP [7], which uses hard handover, to build future space communication networks.

Mobile IP (MIP) [7] manages mobility of Internet hosts at the network layer while keeping the upper layer connections alive. Mobile IP is based on the concept of Home Agent (HA) and Foreign Agent (FA) (which requires modification to existing routers in Internet) for routing packets from previous point of attachment to the new one [7]. Mobile IPv6 does not need an FA as it uses IPv6 address autoconfiguration mechanism. Fig. 4 shows a Mobile IP based handover scenario where the satellite is acting as a Mobile Host (MH). When the satellite/MH determines that it is on a foreign network, it obtains a new Care of Address (CoA) from the new Foreign Agent (FA) (Ground Station B in Fig. 4) . It registers the CoA address with the gateway router acting as Home Agent (HA) [26] (Fig. 4). The registration process begins when the satellite disconnects from the old point of attachment (Ground Station A) and starts to obtain a new CoA. After the registration process completes, data can be sent to the satellite using new CoA. Datagrams destined for the MH are intercepted by the home agent. Then, the HA tunnels the data to the FA, FA decapsulates and delivers them to the satellite. During the registration period (at time h), the MH is unable to send or receive packets through its previous or new point of attachment [26], giving rise to a large handover latency and high packet loss rate. Several schemes have been proposed in the literature

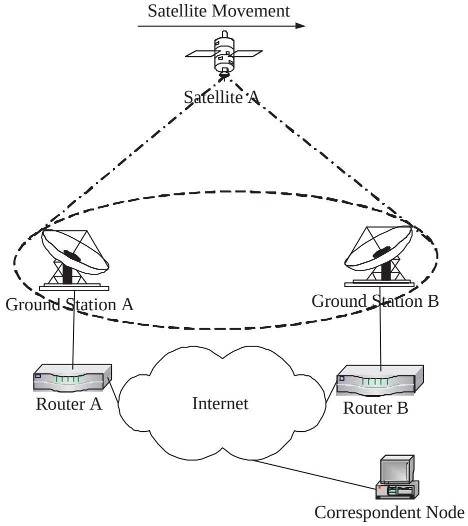

Fig. 3. Satellite handover between ground stations

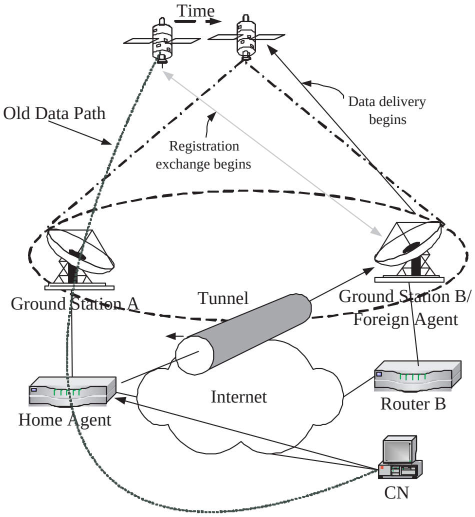

Fig. 4. MIP handover.

to reduce the above mentioned drawbacks of Mobile IP based handover [7].

B. Soft Handover Schemes

During soft handover, the current connection is not released until the next connection is firmly established. Thus, both links can be used simultaneously for handover traffic management [13]. Many soft handover schemes have been proposed in the literature for terrestrial networks, for example [27] [28]. The issue of adapting them into space networks can be investigated in future research.

C. Signalling Diversity Schemes

The signalling diversity based scheme is similar to soft handover, with the difference that the signalling procedures in signalling diversity schemes are performed through both the new and old links, while user data is sent through the old link [13]. Here, no synchronization between links is needed as the old link is used for data and the new link is used for signalling. Seamless IP diversity based Generalized Mobility Architecture (SIGMA) (previously named TRASH) [11] [10] is a signalling diversity based scheme. Detailed description of SIGMA architecture and handover procedure are included in the next section.

V. SIGMA ARCHITECTURE

In this section, we give a brief description of SIGMA handover procedure in LEO satellite networks. Details can be found in [10].

A. Handover Procedure of SIGMA

A typical satellite handover in SIGMA (using SCTP as the transport protocol) is shown in Fig. 5, where the Mobile Host (MH) is a multi-homed satellite connected with the Internet through two ground stations. Correspondent node (CN) is a single-homed node sending traffic to MH, which corresponds to the services like file downloading or web browsing by mobile users. The handover process of SIGMA can be described by the following five steps [29].

STEP 1: Obtain new IP address

Refer to Figure 5 as an example, the handover preparation procedure begins when the satellite moves into the overlapping radio coverage area of two adjacent ground stations. Once the satellite receives the router advertisement from the new access router (AR2), it should begin to obtain a new IP address (IP2 in Fig. 1).

STEP 2: Add IP addresses into the association

After the satellite obtained the IP address IP2 by STEP 1, it notifies CN about the availability of the new IP address through SCTP Address Dynamic Reconfiguration option [30].

STEP 3: Redirect data packets to new IP address

When the satellite moves further into the coverage area of ground station 2, CN can redirect data traffic to new IP address IP2 to increase the possibility that data can be delivered successfully to the satellite. This task can be accomplished by sending an a notification to CN so that it can set its primary destination address to satellites IP2.

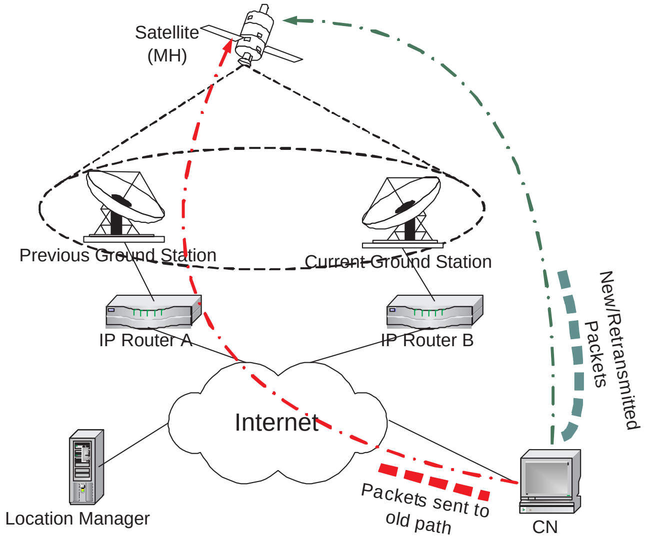

Fig. 5. An SCTP Association with Multi-homed Satellite.

STEP 4: Update location manager (LM)

SIGMA supports location management by employing a location manager which maintains a database recording the correspondence between MH's identity and MHs current primary IP address. Each time MH (satellite) goes through handover, it updates the location manager for future location queries.

STEP 5: Delete or deactivate obsolete IP address

When the satellite moves out of the coverage of ground station 1, no new or retransmitted data should be directed to address IP2. In SIGMA, the satellite notifies CN that IP1 is out of service for data transmission, and CN can delete IP1 from it's available destination IP list. Instead of deleting the IP address, CN can also deactivate IP1 to adapt more gracefully to MH's zigzag (often referred to as ping pong) movement patterns.

VI. SIMULATION TOPOLOGY AND PARAMETERS

In this section, we describe the simulation topology and parameters that have been used to generate and analyze the performance of SIGMA in satellite environment. We have used ns-2 simulator (version 2.26) [31] that supports SCTP as the transport protocol. We have implemented SIGMA handover for satellite networks in ns-2 to support the simulations.

A. Simulation Topology

When a satellite always covers two adjacent ground stations inside its footprint, ongoing connections can be handed over to the adjacent ground stations, making the scenario very simple to study. That is why, we try to choose some interesting simulation scenarios where connectivity between ground stations can be extended with smart handover decisions. The network topologies used in our simulations for SIGMA are shown in Fig. 6, 7 and 8. We use Iridium like Mobile Satellite Systems (MSS) (implemented in ns-2) for simulation purpose. In all the figures, the link characteristics, namely the bandwidth (Megabits/s) and propagation delay (milliseconds), are shown on the links. The three scenarios corresponding to the topologies are given below:

Two-Ground Station Constellation (TGSC): Fig. 6 shows Two-Ground Station constellation (TGSC) scenario that we used in our simulation studies. Here, a single satellite can not connect to both ground stations A and B at the same time, i.e., the ground stations are not under the footprint of a satellite simultaneously. In this scenario, satellite X acts as a Mobile Host (MH). Initially, it communicates with the CN to establish an SCTP connection and sends data through ground station A. After a short time, ground station A goes out of the coverage of satellite X. Satellite X then uses its Inter-Satellite Link (ISL) with satellite Y to communicate with CN. It hands over all its connections through ground station B to satellite Y. Later, when ground station B comes under the coverage area of satellite X (MH), all the ongoing connections are handed over to ground station B from satellite Y. This scenario will be used to illustrate how we can maintain end-to-end connectivity using SIGMA while the ground station is out of satellite coverage.

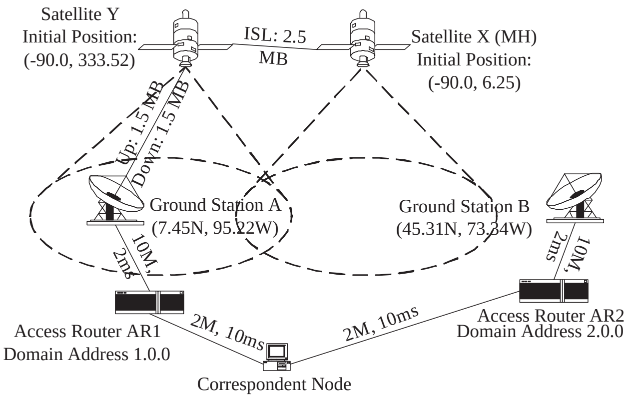

Fig. 6. Two-Ground Station Constellation (TGSC) Scenario.

One-Ground Station Constellation with ISL (OGSCI): Another scenario can be depicted where only one ground station is available to receive and transmit data from a satellite (Fig. 7). This scenario will be called One-Ground Station Constellation with ISL (OGSCL). An example of such scenario can be the Virtual Mission Operations Center (VMOC) satellite (operated by NASA) that can only transmit and receive data when it comes near one of the three special ground stations in the world [32]. As shown in Fig. 7, initially Mobile Host (satellite X) sets up connection with CN and sends data through ground station A. Later, when the ground station goes out of coverage of satellite X, data can be sent from satellite X to CN using ISL with satellite Y, and thereby increasing connection longevity.

Mixed LEO-GEO Constellation (MLGC): When a satellite goes out of coverage from the ground station, we can redirect all the ongoing communications with the satellite using the GEO satellite. Fig. 8 shows such a scenario, which we name as Mixed LEO-GEO Constellation (MLGC). At the beginning, satellite X was transferring data to the CN through ground station A. When ground station A goes out of coverage of satellite X, it hands over all its connections to the GEO satellite to keep alive ongoing communications.

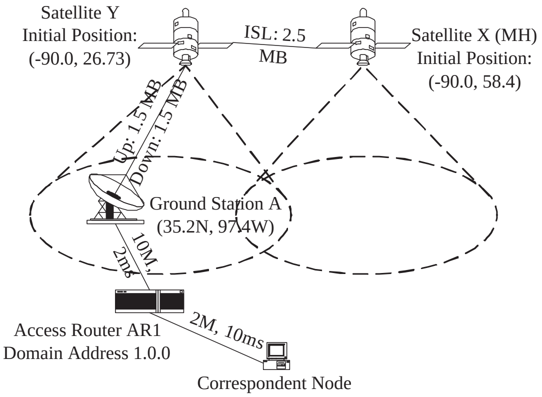

Fig. 7. One-Ground Station Constellation with ISL (OGSCI) Scenario.

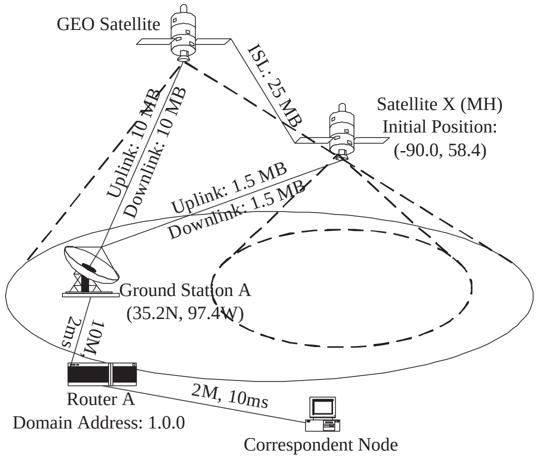

Fig. 8. Mixed LEO-GEO Constellation (MLGC) Scenario.

B. Simulation Parameters

We have used the following parameters in our simulations of the scenarios given in Sec. VI-A:

- Iridium like satellite constellation with standard parameters [33] is assumed.
- To transfer bulk data from MH to CN, a pair of FTP source and sink agents are attached to the MH (satellite) and the CN, respectively.
- We have used standard SCTP protocol as the transport layer protocol.
- Multi State error model is used to emulate the error characteristics of the satellite links.

VII. RESULTS AND ANALYSIS

In this section, we show packet trace, throughput and congestion window traces for the three SIGMA simulation scenarios described in Section VI. In all the results, we use two kinds of simulations: (1) With SIGMA and (2) Without SIGMA. During simulations without SIGMA, normal SCTP connection with link layer handover has been established. While in simulations with SIGMA, SCTP connection with both network and link layer handovers has been established.

A. Packet Trace

Fig. 9 shows the packet trace at MH (satellite) during a SIGMA handover in two ground stations constellation scenario, with data sent from MH to CN. The segment sequence numbers are shown as MOD 40. We can see that SCTP data segments are sent to CN using satellite X's (MH) old IP address (IP1 from ground station A) until time 360.001 sec. (point t_1), and then to the new IP address (IP2 from satellite Y) almost immediately (point t_2). *Handover latency* is defined as the time interval between the last data segment received through the old path and the first data segment received through the new path from the satellite to CN. As shown in Fig. 9, this time $(t_2 - t_1)$ is very small. This small handover latency is due to the time needed in first two steps of SIGMA handover procedure (Sec. V). During SIGMA handover, when two paths are alive, data packets are sent through the primary path (initially, through ground station A and later through satellite Y), and acknowledgement packets are sent through the secondary path (initially through satellite Y) (Fig. 6). Almost all these packets are successfully delivered to CN. In this way, SIGMA achieves a seamless handover because it can prepare the new path for data delivery while keeping the old path alive.

As shown in Fig. 9, only one packet is lost at time 360.0018 sec. (marked with $\times$) during SIGMA handover. We define the *packet loss rate* as the number of lost packets due to handover divided by the total number of packets sent by MH. In our simulation results, packet loss rate is negligible as only one packet is lost during SIGMA handover. Thus, SIGMA experiences low handover latency, low packet loss rate and high throughput during handovers in satellite networks. Although, only one packet trace during SIGMA handover is shown here, SIGMA behaves the same way during handover in other scenarios.

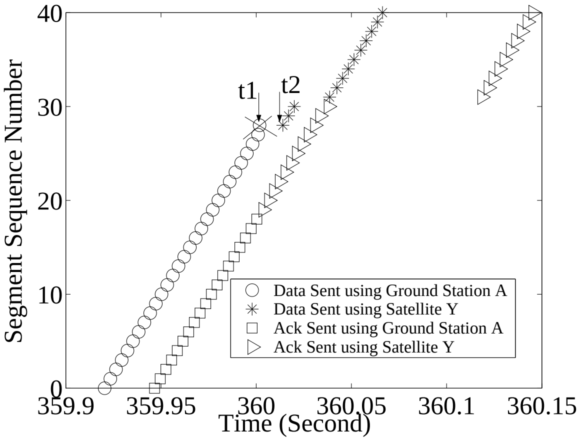

Fig. 9. Packet Trace during First Handover in TGSC Scenario.

B. Throughput

In this section, we examine the throughput of SIGMA in different satellite simulation scenarios. *Throughput* is defined as the number of total useful bytes that is received by the CN during a time unit (granularity), which gives us an estimate of average transmission speed that can be achieved.

TGSC Scenario: Fig. 10 shows the throughput of an SCTP connection between satellite X (MH) and CN versus simulation time for the TGSC scenario. We plot both the throughput curves for simulations with and without SIGMA. With SIGMA, when ground station A goes outside the coverage of satellite X (at around 360 sec), satellite X hands over all its connections with ground station A to satellite Y. Satellite Y communicates with ground station A to keep the ongoing connection alive. Without SIGMA, there is a distinct throughput drop when both of the ground stations are out of coverage of satellite X between 360 to 423.032 sec. With SIGMA enabled during simulation, there is no drop in throughput during this period. Later at 423.032 sec., when ground station B comes into the visibility area of satellite X, SIGMA hands over all the connections of satellite X through ISL to satellite Y onto ground station B. During both handovers, there is a slight drop of throughput at the correspondent node. This is due to the fact that for long RTT in satellite environment, SIGMA takes more time during handover procedure (first two steps of SIGMA handover in Sec. V) and increment of congestion window to a stable level at the MH, which in turn drops the throughput a little bit. Figures in Sec. VII-C will show the results to support this claim.

OGSCI Scenario: Fig. 11 shows the throughput versus time of OGSCI scenario. As can be seen in the figure, in simulation without SIGMA, the connectivity between the satellite (MH) and the CN is lost at around 90 sec. On the other hand, with SIGMA, all ongoing connections from satellite X to CN are handed over to satellite Y using the ISL. This extends the connectivity till around 380 seconds. As in TGSC scenario, slight drop in throughput occurs during handover at around 90 sec. The reason is same as before, handover latency and the time needed to increment the congestion window at the satellite after handover are increased due to increased RTT in satellite networks.

MLGC Scenario: In mixed constellation scenario (Fig. 8), ground station A goes out of coverage of satellite X at around 90 sec. SIGMA then hands over all the connections of satellite X with ground station A to the GEO satellite. The throughput of this scenario is shown in Fig. 12. When the connection between the MH (satellite) and CN is transferred through the GEO satellite, the throughput significantly decreases, but the connectivity still exists. Throughput decreases due to the fact that when SIGMA transfers the connection to the GEO satellite, Smoothed Round Trip Time (SRTT) increases to around .030 sec from 0.006 sec (standard for LEO satellites). Drop in throughput is not related to handover; it is only due to increased RTT [34]. On the other hand, if SIGMA hands over the ongoing connections to the neighboring satellite using ISL (as seen in OGSCI scenario), SRTT remains at around 0.006 sec even after handover. This concludes that, whenever possible, *it is better to hand over to the neighboring satellites instead of handing over the connections to the GEO satellite*. Also for all these scenarios, during handover throughput remains almost constant, implying a *smooth handover with SIGMA*.

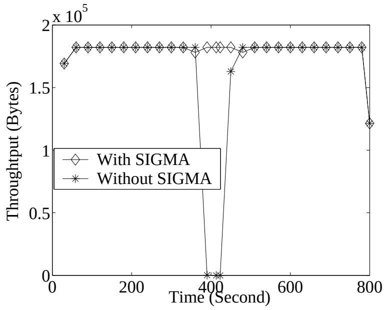

Fig. 10. Throughput in TGSC Scenario.

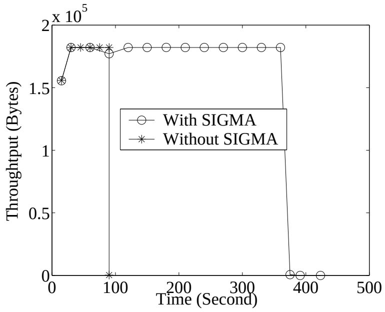

Fig. 11. Throughput in OGSCI Scenario.

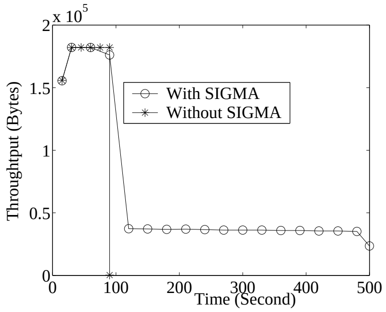

Fig. 12. Throughput in MLGC Scenario.

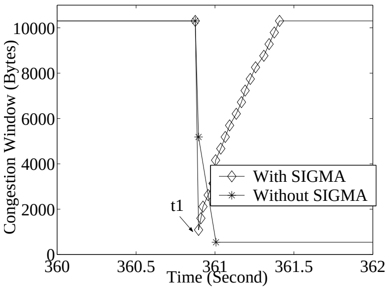

Fig. 13. Congestion Window Evolution in TGSC Scenario.

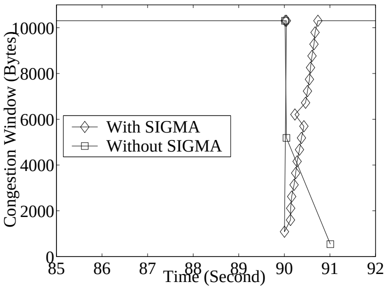

Fig. 14. Congestion Window Evolution in OGSCI Scenario.

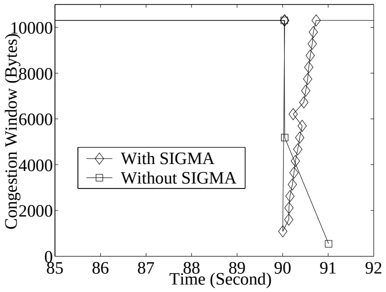

Fig. 15. Congestion Window Evolution in MLGC Scenario.

C. Congestion Window

In this section, we analyze the effect of congestion window evolution time on throughput during handover. We show congestion window evolution at satellite X for all the three scenarios. During SIGMA handovers, two congestion windows are maintained at the MH. One is related to the old communication path, while the other is for the new communication path that is set up after handover. This is because MH is handed over to a new transport address, which has different set of congestion control parameters compared to the old one. In SIGMA, the sender always probes the new communication path after a handover, regardless of segment drops, i.e., the sender (in our simulations, satellite X) automatically begins a slow start sequence of the congestion window to avoid possible congestion. The congestion window traces in this section show only important part of congestion window evolution during handover.

TGSC Scenario: Fig. 13 shows the evolution of the new congestion window (belonging to new communication path) at the sender MH (satellite) during first handover for TGSC scenario. The second handover during 423 sec. also exhibits the same congestion window evolution. The graph depicts congestion window evolution versus simulation time. At time t_1, the SCTP connection between satellite X and ground station A is handed over to satellite Y, resulting in a new congestion window (*cwnd*) and slow start sequence of *cwnd* at the MH. Similar adjustment happens during second handover, when the ISL between satellites X and Y is handed over to ground station B to keep the connection between satellite X and CN alive.

As shown in Fig 13, the new network path after the first handover (at t_1) begins a slow start sequence of congestion window to avoid any possible congestion. Due to large RTT in satellite networks, the new congestion window at the sender MH (satellite) takes around 0.5 sec to adjust to a stable level. This level is almost equal to the old congestion window if both old and new communication path parameters (delay, loss, bandwidth, etc.) are equal. In our experiment, MH's old and new $cwnd$ remains constant after handovers at around 360 (t_1) and 423 sec. Thus, there is a delay for adjusting the new congestion window belonging to the new communication path. RTT also increases the handover latency which along with time needed for new congestion window adjustment results in a slight drop in throughput during handovers (Fig. 10).

OGSCI Scenario: The new congestion window evolution at the MH for OGSCI scenario is presented in Fig. 14. It shows that at around 90 sec, the old congestion window drops due to handover. After a small handover latency, the new congestion window starts a slow sequence and the same $cwnd$ level is reinstated as before handover. As shown in Fig. 14, MH experiences a slight delay of 0.5 sec to adjust congestion window due to increased RTT. RTT also increases the delay during handover procedure (first two steps of SIGMA handover procedure in Sec. V), which consequently, drops throughput. In simulation without SIGMA, the congestion window drops to zero at around 90 sec., as the connection is lost after that time.

MLGC Scenario: When the connections from the satellite are handed over to the GEO satellite in MLGC scenario, the congestion window is also adjusted as shown in Fig. 15. This figure shows the congestion window evolution versus simulation time for MLGC scenario.The congestion is reinstated after handover with a slight delay of 0.5 sec during handover procedure. As explained before, this delay in handover and congestion window adjustment in MH decreases the throughput during handover.

During all these scenarios, handover latency is small enough to prevent CN from encountering a time out due to a drop in congestion window at the MH. It means that CN assumes the new link to have the same capacity as the old one. Thus, CN increases the congestion window to the previous level instantly, although MH follows a slow start sequence.

VIII. CONCLUSION

This paper presents a survey of satellite handover schemes for LEO satellite networks. It also shows the performance of SIGMA as an end-to-end mobility management scheme in satellite environment. Our results indicate that for typical satellite scenarios and parameters, SIGMA increases connectivity of Internet nodes by seamless handover between satellites, and exhibits low handover latency and extremely low packet loss rate. We also conclude that in case of an option to handover a connection to either a LEO or a GEO satellite using ISL, the connection should always be handed over to the neighboring LEO satellite to maximize the throughput.

REFERENCES

[1] I. F. Akyildiz, H. Uzunalioglu, and M. D. Bender, “Handover management in low earth orbit (LEO) satellite networks,” *Mobile Networks and Applications*, vol. 4, no. 4, pp. 301–310, December 1999.

[2] V. Santos, R. Silva, M. Dinis, and J. Neves, “Performance evaluation of channel assignment strategies and handover policies for satellite mobile networks,” *Annual International Conference on Universal Personal Communications*, Tokyo, Japan, pp. 86–90, 6-10 November 1995.

[3] E. Papapetrou, S. Karapantazis, G. Dimitriadis, and F.-N. Pavlidou, “Satellite handover techniques for LEO networks,” *International Journal of Satellite Communications and Networking*, vol. 22, no. 2, pp. 231–245, March/April 2004.

[4] E. Del Re, R. Fantacci, and G. Giambene, “Efficient dynamic channel allocation techniques with handover queuing for mobile satellite networks,” *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 2, pp. 397–405, February 1995.

[5] K. Bhasin and J. L. Hayden, “Space Internet architectures and technologies for NASA enterprises,” *International Journal of Satellite Communications*, vol. 20, no. 5, pp. 311–332, September/October 2002.

[6] K. Leung, D. Shell, W. Ivancic, D. H. Stewart, T. L. Bell, and B. A. Kachmar, “Application of mobile-IP to space and aeronautical networks,” *IEEE Aerospace Conference*, Big Sky, MT, USA, pp. 1027–33, 10-17 March 2001.

[7] C. Perkins, “Mobile networking through mobile IP,” *IEEE Internet Computing*, vol. 2, no. 1, pp. 58–69, January/February 1998.

[8] W.D. Ivancic, “Secure, network-centric operations of a space-based asset: Cisco router in Low-Earth Orbit (CLEO) and Virtual Mission Operations Center (VMOC).” Presentation, Net-Centric Operations 2005, Washington, DC, 10-11 May 2005.

[9] R. C’aceres and V. N. Padmanabhan, “Fast and scalable handover for wireless internetworks,” *Mobicom 96*, Rye, New York, USA, pp. 56–66, 10-12 November 1996.

[10] S. Fu, L. Ma, M. Atiquzzaman, and Y. Lee, “Architecture and performance of SIGMA: A seamless handover scheme for data networks,” *IEEE ICC*, Seoul, South Korea, pp. 3249–3253, 16-20 May 2005.

[11] S. Fu and M. Atiquzzaman, “SIGMA: A transport layer mobility management scheme for terrestrial and space networks.” book chapter to be published by Kluwer Academic Publishers, 2005. www.cs.ou.edu/~netlab.

[12] S. Cho, I. F. Akyildiz, M. D. Bender, and H. Uzunalioglu, “New spotbeam handover management technique for LEO satellite networks,” *IEEE Global Telecommunications Conference*, San Francisco, CA, USA, pp. 1156–1160, 27 November - 1 December 2000.

[13] N. Efthymiou, Y.E. Hu, R.E. Sheriff, and A. Properzi, “Inter-segment handover algorithm for an integrated terrestrial/satellite-UMTS environment,” *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, Boston, Massachusetts, USA, pp. 993–998, 8-11 September 1998.

[14] S. Cho, I. F. Akyildiz, M. D. Bender, and H. Uzunalioglu, “A new connection admission control for spotbeam handover in LEO satellite networks,” *Wireless Networks*, vol. 8, no. 4, pp. 403–415, July 2002.

[15] E. Del Re, R. Fantacci, and G. Giambene, “Handover queuing strategies with dynamic and fixed channel allocation techniques in low earth orbit mobile satellite systems,” *IEEE Transactions on Communications*, vol. 47, no. 1, pp. 89–102, January 1999.

[16] S. Kalyanasundaram, E.K.P Chong, and N.B. Shroff, “An efficient scheme to reduce handoff dropping in LEO satellite systems,” *Wireless Networks*, vol. 7, no. 1, pp. 75–85, January 2001.

[17] G. Maral, J. Restrepo, E. Del Re, Romano Fantacci, and Giovanni Giambene, “Performance analysis for a guaranteed handover service in an LEO constellation with a ‘satellite-fixed cell’ system,” *IEEE Transactions on Vehicular Technology*, vol. 47, no. 4, pp. 1200–1214, November 1998.

[18] Y. Xu, Q. Ding, and C. Ko, “Elastic handover scheme for LEO satellite mobile communication systems,” *IEEE Global Telecommunications Conference*, San Francisco, CA, USA, pp. 1161–1165, 27 November - 1 December 2000.

[19] L. Boukhatem, A.L. Beylot, D. Gaiti, and G. Pujolle, “TCRA: A time-based channel reservation scheme for handover requests in leo satellite systems,” *International Journal of Satellite Communications and Networking*, vol. 21, no. 3, pp. 227–240, May/June 2003.

[20] E. Papapetrou and F.-N. Pavlidou, “QoS handover management in LEO/MEO satellite systems,” *Wireless Personal Communications*, vol. 24, no. 2, pp. 189–204, February 2003.

[21] D. Hong and S. Rappaport, “Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures,” *IEEE Transactions on Vehicular Technology*, vol. 35, no. 3, pp. 77–92, August 1986.

[22] R.A. Guerin, “Channel occupancy time distribution in a cellular radio system,” *IEEE Transactions on Vehicular Technology*, vol. 35, no. 3, pp. 89–99, August 1987.

[23] E. Del Re, R. Fantacci, and G. Giambene, “Different queuing policies for handover requests in low earth orbit mobile satellite systems,” *IEEE Transactions on Vehicular Technology*, vol. 48, no. 2, pp. 448–458, March 1999.

[24] Y.B. Lin, S. Mohan, and A. Noerpel, “Queueing priority channel assignment strategies for PCS hand-off and initial access,” *IEEE Transactions on Vehicular Technology*, vol. 43, pp. 704–712, August 1994.

[25] E. Del Re, R. Fantacci, and G. Giambene, “Performance comparison of different dynamic channel allocation techniques for mobile satellite systems,” *European Transactions on Telecommunications*, vol. 8, no. 6, pp. 609–621, November/December 1997.

[26] Consultative Committee for Space Data Systems, “Next generation space Internet (NGSI- supporting spacecraft IP mobility),” Experimental Specification CCSDS 733.0-O-1, CCSDS Secretariat, Washington DC, USA, April 2003.

[27] H. Matsuoka, T. Yoshimura, and T. Ohya, “End-to-end robust IP soft handover,” *IEEE ICC*, Anchorage, Alaska, p. 532 536, 11-15 May 2003.

[28] S.J. Koh, M. J. Chang, and M. Lee, “mSCTP for soft handover in transport layer,” *IEEE Communications Letters*, vol. 8, no. 3, p. 189 191, March 2004.

[29] S. Fu, M. Atiquzzaman, L. Ma, and Y. Lee, “Signaling cost and performance of SIGMA: A seamless handover scheme for data networks,” *Journal of Wireless Communications and Mobile Computing*, vol. 5, no. 7, pp. 825–845, November 2005.

[30] R. Stewart, M. Ramalho, and Q. Xie, “Stream control transmission protocol (SCTP) dynamic address reconfiguration.” Internet Draft, draft-ietf-tsvwg-addip-sctp-08.txt, June 2004.

[31] “The Network Simulator- ns-2.” available at: http://www.isi.edu/nsnam/ns/.

[32] K. Leung, D. Shell, W.D. Ivancic, D.H. Stewart, T.L. Bell, and B.A. Kachmar, “Application of mobile-IP to space and aeronautical networks,” *IEEE Aerospace Conference*, Piscataway, NJ, USA, pp. 2/1027–33, 10-17 March 2001.

[33] B. Pattan, *Satellite-Based Global Cellular Communications*, McGraw-Hill Telecommunications, McGraw-Hill, 1997.

[34] M. Mathis, J. Semke, and J. Mahdavi, “The macroscopic behavior of the TCP congestion avoidance algorithm,” *ACM SIGCOMM, Computer Communication Review*, vol. 27, no. 3, pp. 67–82, July 1997.