Performance of End-to-End Mobility Management in Satellite IP Networks

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***Abstract*— IETF has developed Mobile IP to support mobility of IP hosts at the network layer. The National Aeronautics and Space Administration has implemented Mobile IP to handle handovers in space networks. Due to a number of limitations of Mobile IP, such as high handover latency, packet loss rate, and conflict with existing network security solutions, a new IP-diversity based mobility management scheme, called SIGMA, has been developed through collaborative efforts of NASA and University of Oklahoma. In this paper, we illustrate the performance of SIGMA for managing handovers in space networks. We show by simulation that SIGMA extends network connectivity from space to ground, and ensures smooth handover between spacecrafts for different space network scenarios.**

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. Satellites can be classified into three types depending on the altitude: 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

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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 diversity refers to having multiple IP addresses in one mobile host. It is important to note that SIGMA can be used with any transport layer protocol that supports IP diversity. For illustration purposes, we use SCTP (Stream Control Transmission Protocol), which supports IP-diversity, as our underlying transport layer protocol. Multihoming is a built-in feature of SCTP, which is convenient to introduce IP diversity in mobile computing environments.

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 in LEO satellite environment. As far as the authors are concerned, there is no such research paper in the literature which demonstrates the performance of transport layer based handover solutions in satellite IP networks. 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) show the performance of SIGMA as a end-to-end mobility management scheme in satellite networks, (2) analyze the throughput and delay characteristics of SIGMA during typical satellite handovers, and (3) compare the performance of handover policies that depend on choosing between LEO and GEO satellites when both options are available.

The rest of the paper is organized as follows: Section II illustrates the SIGMA architecture in satellite environment. Section III describes the simulation scenario and simulation parameters. In Section IV, we present the results and analysis of SIGMA simulations in satellite environment. Finally, concluding remarks are given in Section V.

II. 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. 1, 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 [12].

STEP 1: Obtain new IP address
Refer to Figure 1 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). This can be accomplished through several methods: DHCP, DHCPv6, or IPv6 stateless address auto-configuration (SAA) [13].

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 [14]. This option defines two new chunk types (ASCONF and ASCONF-ACK) and several parameter types (Add IP Address, Delete IP address, and Set Primary Address etc.).

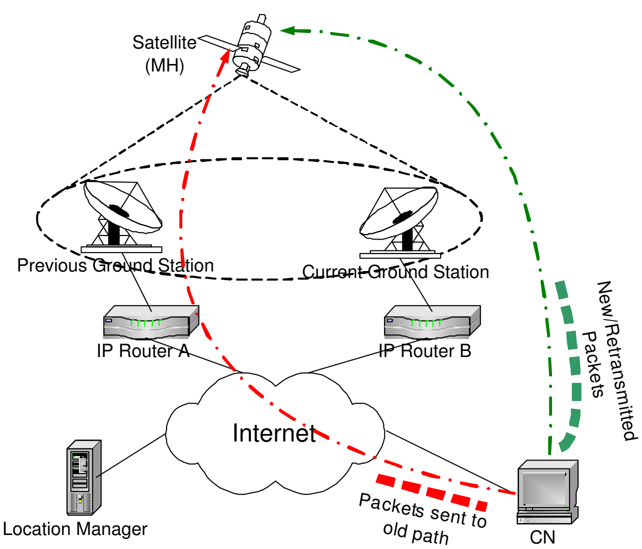

Fig. 1. An SCTP Association with Multi-homed Satellite.

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 ASCONF from satellite to CN, through which CN set its primary destination address to satellites IP2.

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. MH can use any unique information as its identity such as home address like MIP, or domain name, or a public key defined in Public Key Infrastructure (PKI). We can observe an important difference between SIGMA and MIP: the location management and data traffic forwarding functions are coupled together in MIP, while in SIGMA they are decoupled to speedup handover and make the deployment more flexible.

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 by sending an ASCONF chunk to CN to delete IP1 from CN's available destination IP list.

A less aggressive way to prevent CN from sending data to IP1 is MH advertising a zero receiver window (corresponding to IP1) to CN. This will give CN an impression that the interface (on which IP1 is bound) buffer is full and can not receive any more data. By deactivating, instead of deleting the IP address, SIGMA can adapt more gracefully to MHs zigzag (often referred to as ping pong) movement patterns, and reuse the previously obtained IP address (IP1) as long as the lifetime of IP1 has not expired. This will reduce the latency and signalling traffic that would have otherwise been caused by obtaining a new IP address.

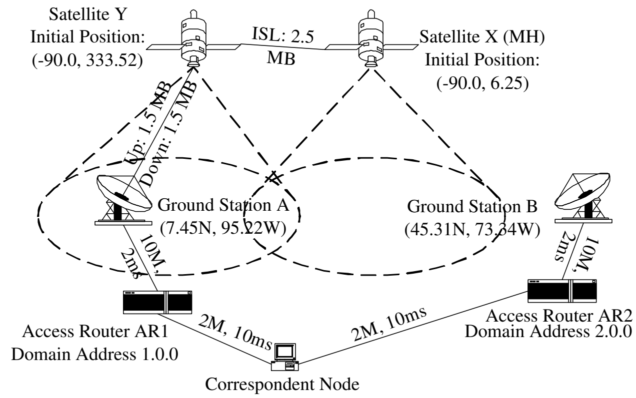

Fig. 2. Two-Ground Station Constellation (TGSC) Scenario.

III. 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) [15] 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. 2, 3 and 4. 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. 2 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.

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. 3). 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 [16]. As shown in Fig. 3, 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.

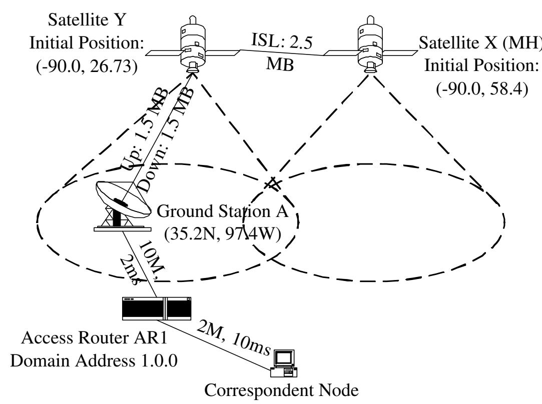

Fig. 3. One-Ground Station Constellation with ISL (OGSCI) Scenario.

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. 4 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.

B. Simulation Parameters

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

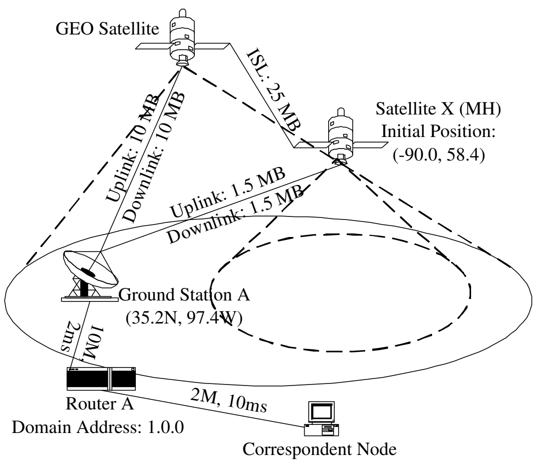

Fig. 4. Mixed LEO-GEO Constellation (MLGC) Scenario.

- Iridium like satellite constellation is assumed.
- Standard Iridium parameters [17] are used:
  1) Satellite Altitude = 780 km
  2) Orbital Period = 6026.9 sec
  3) Intersatellite Separation = $360°/11$
  4) Interplane Separation = $31.6°$
  5) Seam Separation = $22°$
  6) Inclination = 86.4
  7) Eccentricity = 0.002 (not modelled)
  8) Minimum Elevation Angle (at the edge of coverage) = $8.2°$
  9) ISL cross-link pattern: 2 intraplane to nearest neighbor in plane, 2 interplane except at seam where only 1 interplane exists.
- 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.

IV. Results and Analysis

In this section, we show packet trace, throughput and congestion window traces for the three SIGMA simulation scenarios described in Section III. 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. 5 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. 5, 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. II). 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. 2). 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. 5, 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.

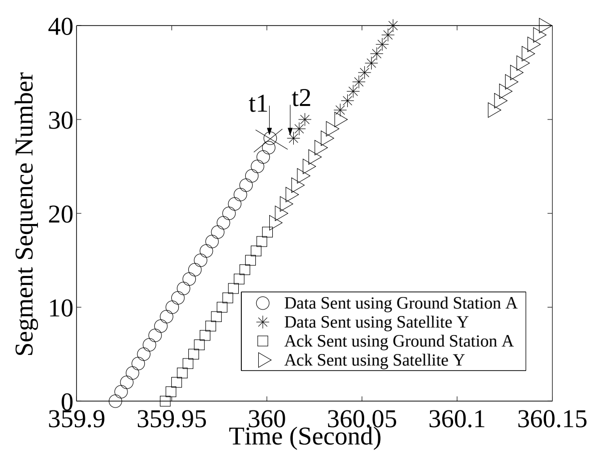

Fig. 5. Packet Trace during First Handover in TGSC Scenario.

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. 6 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

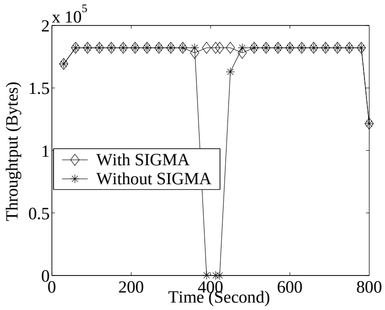

Fig. 6. Throughput in TGSC Scenario.

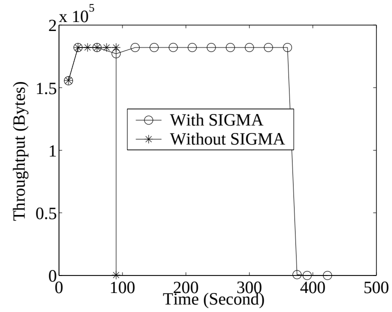

Fig. 7. Throughput in OGSCI Scenario.

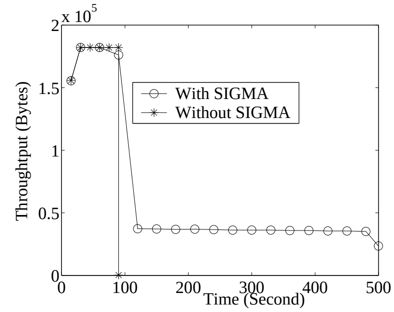

Fig. 8. Throughput in MLGC Scenario.

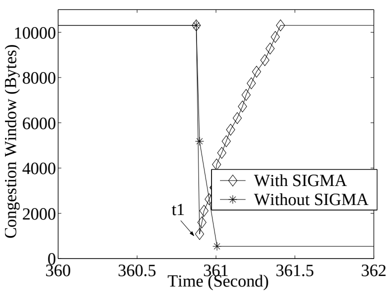

Fig. 9. Congestion Window Evolution in TGSC Scenario.

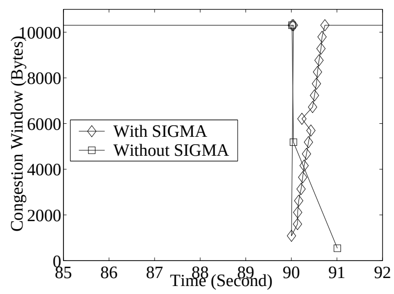

Fig. 10. Congestion Window Evolution in OGSCI Scenario.

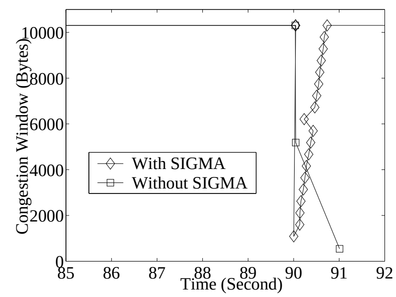

Fig. 11. Congestion Window Evolution in MLGC Scenario.

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. II) and increment of congestion window to a stable level at the MH, which in turn drops the throughput a little bit. Figures in Sec. IV-C will show the results to support this claim.

OGSCI Scenario: Fig. 7 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. 4), 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. 8. 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 [18]. 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*.

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. 9 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 9, 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. 6).

OGSCI Scenario: The new congestion window evolution at the MH for OGSCI scenario is presented in Fig. 10. 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. 10, 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. II), 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. 11. 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.

V. Conclusion

This paper presents 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, "IP mobility support." IETF RFC 3344, August 2002.

[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. 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.

[13] S. Thomson and T. Narten, "IPv6 stateless address autoconfiguration." IETF RFC 2462, December 1998.

[14] 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.

[15] "The Network Simulator- ns-2." available at: http://www.isi.edu/nsnam/ns/.

[16] 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 Proceedings*, Piscataway, NJ, USA, pp. 2/1027–33, 10-17 March 2001.

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

[18] 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.