Satellite Grouping and Routing Protocol for LEO/MEO Satellite IP Networks *

Chao Chen
Broadband & Wireless Networking Laboratory
School of Elec. & Comp. Eng.
Georgia Inst. of Technology
Atlanta, GA 30332
cchen@ece.gatech.edu

Eylem Ekici *
Dept. of Elec. Eng.
The Ohio State University
Columbus, OH 43210
ekici@ee.eng.ohio-state.edu

Ian F. Akyildiz
Broadband & Wireless Networking Laboratory
School of Elec. & Comp. Eng.
Georgia Inst. of Technology
Atlanta, GA 30332
ian@ece.gatech.edu

ABSTRACT

The rapid growth of Internet-based applications pushes broadband satellite networks to carry on IP traffic. In previously proposed connectionless routing schemes in satellite networks, the metrics used to calculate the paths do not reflect the total delay a packet may experience. In this paper, a new *Satellite Grouping and Routing Protocol (SGRP)* is developed. It divides Low Earth Orbit (LEO) satellites into groups according to the the footprint area of the Medium Earth Orbit (MEO) satellites in each snapshot period. Based on the delay reports sent by LEO satellites, MEO satellite managers compute the minimum-delay paths for their LEO members. The snapshot and group decision method is detailed, the performance of SGRP is evaluated through simulations and analysis.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing Protocols*

General Terms

Algorithms

Keywords

satellite networks, connectionless routing, Low Earth Orbit (LEO), Medium Earth Orbit (MEO)

*This work is supported by the National Science Foundation under Grant ANI-0087762 and NASA Glenn Research Center under Grant NAG3-2580.

*Eylem Ekici was with the Broadband & Wireless Networking Laboratory, School of Electrical & Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 when this work was performed.

1. INTRODUCTION

Satellite systems have the advantage of global coverage and inherent broadcast capability, and offer a solution for providing broadband access to end users. Compared to Geostationary (GEO) satellites, Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite networks have shorter round trip delays and lower transmission power requirements. In many constellations direct inter-satellite links (ISLs) provide communication paths among satellites. They can be used to carry signaling and network management traffic as well as data packets [12].

Most of the routing schemes developed for LEO satellite networks assume a connection-oriented network structure. In [3] and [11] the dynamic routing problem is tackled by a discrete time network model. In each equal-length interval, the satellite network is regarded as having a fixed topology. In [7], a satellite over satellite (SOS) network architecture is proposed, which is composed of LEO and MEO satellite layers. With the rapid growth of Internet-based applications, proposed broadband satellite networks will be required to transport IP traffic [13]. Recently, routing protocols for IP-based LEO satellite networks have also been introduced. The Datagram Routing Algorithm [4] aims to forward the packets on minimum propagation delay paths. The mobility of the satellites is captured using the logical location concept. In [5], a link state packet is flooded only as far as the routing radius for a given satellite. Shortest path routing is used in the near vicinity of the destination while data packets are routed based on the destination satellite's position when they are far away. The basic shortcoming of both schemes for connectionless routing is that the metrics used to calculate the paths do not reflect the total delay a packet may experience in the network. The delay, which is composed of propagation, processing, queuing, and transmission delays, can vary in the satellite network greatly due to the positions of the individual satellites and network load. Therefore, it is necessary to develop a routing scheme that forwards the packets on minimum delay paths in the LEO satellite network.

In this paper, we propose a new routing protocol: *Satellite Grouping and Routing Protocol (SGRP)*, which operates on a two-layered satellite network consisting of LEO and MEO satellites. The main idea of the SGRP is to transmit packets in minimum-delay path and distribute the routing table calculation for the LEO satellites to multiple MEO satellites. LEO satellites are divided into groups according to the footprint area of the MEO satellites in each snapshot period. Snapshot periods are determined according to the predictable MEO trajectory and the changes in the LEO group memberships. The MEO satellite that covers a set of LEO satellites becomes the manager of that LEO group. Group managers are in charge of collecting and exchanging the link delay information of the LEO layer, and calculating the routing tables for their LEO members. SGRP enables the collaboration between the separate satellite network constellations. The calculation of the routing tables is shifted to MEO satellites, which effectively distributes the power consumption between LEO and MEO satellites. Besides the management functions, MEO satellites can be used for other purposes as well, such as packets routing and forwarding, etc.

The remainder of this paper is organized as follows: In Section 2, the two-layer satellite network architecture is presented. The methods to determine LEO satellite groups and snapshot periods are detailed in Section 3. Section 4 introduces the definitions used in the paper. In Section 5, the new routing algorithm called Satellite Grouping and Routing Protocol (SGRP) is described in detail. The performance evaluation of SGRP is presented in Section 6. Finally, Section 7 concludes this paper.

2. SATELLITE NETWORK ARCHITECTURE

We consider a two-layer satellite network and the terrestrial gateway stations. The mobility and dynamics of LEO and MEO satellites is captured by the logical location and the snapshot concepts respectively. In a snapshot period, LEO satellites are grouped according to the footprint areas of MEO satellites. LEO satellites have direct links to their MEO group managers. Terrestrial gateways are fixed on the earth, they have direct links to the LEO satellites within sight. They are in charge of address translation and the communication between the terrestrial autonomous systems and the satellite network. Terrestrial gateways, together with LEO and MEO satellites, form an autonomous system.

2.1 Satellite Layers

The satellite network is composed of a LEO satellite layer and a MEO satellite layer. We assume that both satellite layers provide global coverage individually.

1. **MEO layer:** The MEO layer is composed of all MEO satellites in the network. It has a total number of $N_M \times M_M$ satellites, where N_M is the number of planes in MEO constellation, M_M is the number of satellites in a plane. MEO satellite is denoted by $M_{i,j}$, where $i = 1, ..., N_M, j = 1, ..., M_M$.

2. **LEO Layer:** The LEO layer consists of all LEO satellites in the network. The total number of satellites in this layer is $N_L \times M_L$, where N_L is the number of planes in LEO constellation, M_L is the number of satellites in a plane. The LEO satellites are organized into a Walker constellation [10].

The *logical location* concept is used for the LEO layer to hide the mobility of LEO satellites. Logical locations are equally spaced points in the grid of the LEO satellite constellation and are embodied by the nearest LEO satellites. A logical location is referred to as (n, m), where n is the plane number, $1 \leq n \leq N_L$, and m is the satellite position in the plane, $1 \leq m \leq M_L$. The LEO satellite representing the logical location (n, m) at time t is referred to as $L_{n,m}$.

The MEO satellite topology is captured by a series of *snapshots*. In every snapshot period, the logical locations covered by a MEO satellite are considered to be fixed although the LEO satellites that embody the logical locations may change. The snapshot period is determined according to the predictable MEO trajectories and the positions of the logical locations. The snapshot concept hides the mobility of the MEO satellites and is independent of the properties of the MEO constellation.

2.2 Links in the Network

There are three types of duplex links in the network:

1. **Inter-Satellite Links (ISLs):** Satellites are connected to their immediate neighbors in the same layer via duplex ISLs. There are two kinds of ISLs in the network: *intra-plane ISL* and *inter-plane ISL*. Intra-plane ISLs can be maintained permanently whereas inter-plane ISLs are operated only outside the polar regions and can be temporarily switched off due to changes in distance and viewing angle between satellites. $\text{ISL}_{s \to d}$ or $\text{ISL}_{d \to s}$ denotes an ISL that connects two satellites s and d in the same layer.

2. **Inter-Orbital Links (IOLs):** The communication between MEO and LEO satellites occurs over IOLs. If a LEO satellite s lies in the coverage area of a MEO satellite d, then they are connected by an IOL, which is referred to as $\text{IOL}_{s \to d}$ or $\text{IOL}_{d \to s}$.

3. **User Data Links (UDLs):** Terrestrial gateways are directly connected to LEO satellites that cover them via UDLs. The UDL between a LEO satellite s and a terrestrial gateway G is denoted by $\text{UDL}_{s \to G}$ or $\text{UDL}_{G \to s}$.

2.3 Satellite Groups

A LEO group is defined as a set of logical locations that reside in the coverage area of the same MEO satellite. The members and the number of a LEO group changes as MEO satellites move. Hence, the groups must be redefined in each snapshot period. In a snapshot period, the MEO satellite that covers a set of logical locations becomes the group manager. A LEO group $\mathcal{L}_{i,j}$ is the collection of all LEO satellites that lie in the coverage area of the MEO satellite $M_{i,j}$, $\mathcal{L}_{i,j} = \{\mathcal{L}_{i,j}(k) \mid k = 1, ..., K_{i,j}\}$, where $K_{i,j}$ is the number of LEO members in group $\mathcal{L}_{i,j}$. The members of a LEO group are connected to the manager MEO satellite via IOLs. For example, in Figure 1, the LEO group of MEO satellite $M_{i,j}$ is $\mathcal{L}_{i,j}$, which has six members $\mathcal{L}_{i,j}(1)$ through $\mathcal{L}_{i,j}(6)$.

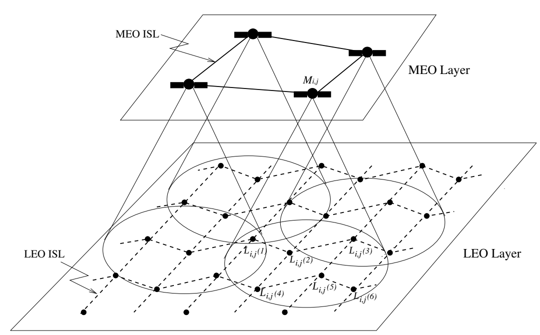


Figure 1: LEO/MEO joint constellation.

3. LEO SATELLITE GROUPS AND SNAPSHOT PERIODS

Since the satellite orbits are well designed beforehand, the exact position of any LEO and MEO satellite can be calculated. Based on the positions of LEO and MEO satellites, and the footprints of all MEO satellites, we can create the LEO satellite groups and determine the length of the snapshot periods at any time t.

3.1 MEO Footprints on the LEO Layer

The MEO footprints on the LEO layer are needed to determine the group membership of LEO satellites. The half-sided center angle of the LEO footprint on LEO the layer ψ is calculated as:

$$\psi = 90 - \epsilon_{min} - \arcsin(\frac{R_E + h_L}{R_E + h_M} \cdot \cos \epsilon_{min}), \quad (1)$$

where R_E is the radius of the Earth, h_L and h_M are the plane altitude of LEO layer and MEO layer, respectively, ϵ_{min} is the minimum elevation angle of MEO satellites from the LEO layer.

Suppose that a LEO satellite $L_{n,m}$ is at (ϕ, θ), where ϕ is the latitude and θ is the longitude of the satellite $L_{n,m}$, and a MEO satellite $M_{i,j}$ is at (Φ, Θ). For $L_{n,m}$ to lie in the footprint of $M_{i,j}$, the following condition must be satisfied:

$$\angle \text{A'OB} = 2 \arcsin \frac{|\text{A'B}|}{2(R_E + h_L)} \leq \psi \quad (2)$$

In Figure 2, O is the center of the Earth, A and B represent the positions of $M_{i,j}$ and $L_{n,m}$, respectively. A' is the crossing point of line OA and the sphere with the radius $(R_E + h_L)$.

3.2 Group Definition and Snapshot Determination

Assume that the satellite network topology is periodic with T, where T is the least common multiple of the revolution periods of the Earth and the MEO satellites, and the time needed for any two satellites to be exactly on a given logical location. T is referred to as *system cycle*. The satellite topology can be considered as a periodically repeating series of P topology snapshots in the system cycle T. Over the interval $[t_i, t_{i+1}], i = 0, 1, ..., P - 1$, the LEO satellites' group membership is constant. Snapshot periods may have different lengths.

The snapshots and the LEO satellite groups are created according to the following criteria:

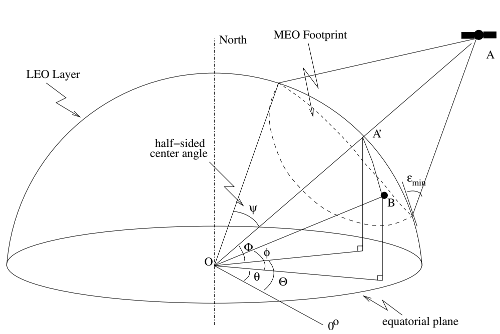


Figure 2: A MEO footprint.

1. A LEO group is created according to the footprint of the MEO satellites on the LEO layer. Generally, the LEO satellites that lie in the same footprint of a MEO satellite form a group, and this MEO satellite becomes the group manager.
2. If a LEO satellite lies in an overlapping region covered by several MEO satellites, the one called *primary manager* is chosen among them. Primary manager takes care of the routing table calculation of the LEO satellite in a snapshot period. Since the trajectory of the MEO satellites is predictable, a LEO satellite chooses the MEO satellite with the longest predicted coverage time as its primary manager.
3. The snapshot period is further determined according to the changes in the LEO group memberships. Assume that at time $t = t_i$, at least one of the LEO satellites is no longer covered by its primary manager in snapshot i. In such a case, a new snapshot of the system must be created. Every LEO satellite chooses the group manager with the maximum predicted service time as the primary manager for snapshot $i + 1$. According to this criteria, new snapshots are created at times $t_1, t_2, ..., t_P$, where $t_P = T$, the system cycle. The snapshots repeat themselves with a period of T.

4. DEFINITIONS

Definition 1. [Primary Manager] Let $\mathcal{H}(x)$ refer to the MEO manager set of LEO satellite x, then $\mathcal{H}(x) = \{M_{i,j} \mid x \in \mathcal{L}_{i,j}\}$ includes all MEO satellites whose footprint covers x. The primary manager of x is written as $\mathcal{PH}(x)$. It is selected from $\mathcal{H}(x)$ and has the longest predicted coverage time for x, i.e, within all MEO satellites that currently cover x, $\mathcal{PH}(x)$ still covers x after all others exclude x in their footprints.

$$\mathcal{PH}(x) = \arg\max_{M_{i,j}} \{\text{predicted coverage time of } M_{i,j}, \text{w.r.t } x \mid M_{i,j} \in \mathcal{H}(x)\}. \quad (3)$$

Definition 2. [Care-of Member List] Every MEO satellite has a "care-of member" list in each snapshot period. The care-of member list $\mathcal{CM}(M_{i,j})$ of a MEO satellite $M_{i,j}$ is defined as

$$\mathcal{CM}(M_{i,j}) = \{x \mid \mathcal{PH}(x) = M_{i,j}\}. \quad (4)$$

Hence $M_{i,j}$ is the primary manager of every LEO satellite in $\mathcal{CM}(M_{i,j})$.

Definition 3. [Delay Function $\mathcal{D}$] Let $l_{x \to y}$ be a direct ISL from node x to node y in LEO layer. The delay function $\mathcal{D}(l_{x \to y})$ is defined as follows:

$$\mathcal{D}(l_{x \to y}) = \begin{cases} \text{Delay from } x \text{ to } y, & \exists\, l_{x \to y} \\ \infty \quad , & \text{otherwise} \end{cases}. \quad (5)$$

Definition 4. [Delay Report] Delay report $\mathcal{DR}(x)$ of LEO satellite x is a set of tuples $\{y, \mathcal{D}(l_{x \to y})\}$, where y is a LEO satellite such that $\text{ISL}_{x \to y}$ exists between x and y. Delay report $\mathcal{DR}(M_{i,j})$ of MEO satellite $M_{i,j}$ is a collection of the delay report of $M_{i,j}$'s care-of members.

$$\mathcal{DR}(M_{i,j}) = \{\mathcal{DR}(x) \mid x \in \mathcal{CM}(M_{i,j})\}. \quad (6)$$

Delay report $\mathcal{DR}(M_i)$ of MEO plane i is a collection of the delay report of $M_{i,j}$ in plane i.

$$\mathcal{DR}(M_i) = \{\mathcal{DR}(M_{i,j}), j = 1, ..., M_M\}. \quad (7)$$

Definition 5. [Plane Crossing Point] Crossing points of plane i and plane l are referred to as $\mathcal{CP}(i, l)$, indicating where the two planes cross each other. There are two crossing points for each pair of i and l.

Definition 6. [Remote Group] A remote group of LEO satellite x is a LEO group which is not covered by any satellite in $\mathcal{H}(x)$. The set of x's remote group is written as

$$\mathcal{RM}(x) = \{\mathcal{L}_{i,j} \mid M_{i,j} \overline{\in} \mathcal{H}(x)\}. \quad (8)$$

MEO group managers prepare different routing tables for each of their care-of members. In our algorithm, two types of routing tables are needed: the *original routing table* and the *simplified routing table*.

Definition 7. [Path $\mathcal{P}_{x \to y}$] $\mathcal{P}_{x \to y}$ is defined as the minimum delay path associated with source x and destination y. It is a sequential list of satellites on the path.

Definition 8. [Original Routing Table] The Original routing table $\mathcal{ORT}_{M_{i,j}}$ is kept in the MEO satellite $M_{i,j}$. It provides an entry for each of its care-of members, and registers paths from $\mathcal{CM}(M_{i,j})$ to all destinations. The path from satellite x to a destination satellite y is defined as:

$$\mathcal{ORT}_{M_{i,j}}(x, y) = \mathcal{P}_{x \to y}, \text{ where } x \in \mathcal{CM}(M_{i,j}). \quad (9)$$

Definition 9. [Simplified Routing Table] The Simplified Routing Table $\mathcal{SRT}_x$ of LEO satellite x is created based on original routing table $\mathcal{ORT}_{M_{i,j}}$ if $x \in \mathcal{L}_{i,j}$, and the group membership of destination satellites. Each entry of this routing table has a destination field and a next-hop field, where *next-hop* is the second node on $\mathcal{P}_{x \to Dest}$, and written as $\mathcal{SRT}_x(Dest)$. Here *Dest* can be any of the LEO satellites or a remote group. If the paths to all satellites in a remote group $\mathcal{L}_{i,j}$ have the same next-hop, then the entries to all those LEO satellite destinations are replaced by a single entry in the simplified routing table. The destination field of this entry is set as $\mathcal{L}_{i,j}$.

Definition 10. [Congestion Area] The congestion area of a congested link $l_{x_1 \to x_2}$ is defined as:

$$\mathcal{CA}(l_{x_1 \to x_2}) = \cup\{l_{y_1 \to y_2} \mid \mathcal{P}_{x_k \to y_i} \leq r, k = 1 \text{or } 2\}. \quad (10)$$

r is the radius in number of hops of the congestion area.

5. SATELLITE GROUPING AND ROUTING PROTOCOL

The goal of our new *Satellite Routing and Routing Protocol (SGRP)* is to forward the packets on minimum delay paths in spite of the satellite mobility, and to distribute the routing table calculation for the LEO satellites to multiple MEO satellites. The delay metric used in the route computation is the sum of the processing, queuing, and transmission delays in the satellites and the propagation delays on the ISLs. Routing tables are calculated by MEO satellite group managers, transmitted to and stored in the individual LEO satellites.

In this section, the detailed design of SGRP is presented. It includes three phases:

- Delay report from LEO satellite to MEO layer,
- Delay exchange in MEO layer,
- Routing table calculation.

The SGRP protocol also has mechanisms to resolve congestion and satellite failures to avoid dropping packets.

5.1 Delay Report

Delay information of LEO links is reported to MEO satellites every T_c period, it is done as follows:
Initialization: At the beginning of a new snapshot period, MEO satellite $M_{i,j}$'s care-of member list $\mathcal{CM}(M_{i,j})$ is initialized as empty.
Step 1. Delay Reporting: A LEO satellite x continuously measures the delay on its outgoing links. Every T_c period it creates delay report $\mathcal{DR}(x)$, and sends it to its primary manager $M_{i,j} = \mathcal{PH}(x)$ via $\text{IOL}_{x \to M_{i,j}}$.
Step 2. Delay Reception: After receiving a delay report $\mathcal{DR}(x)$, $M_{i,j}$ adds x into its own delay report $\mathcal{CM}(M_{i,j})$.
Step 3. Delay Transfer: After a fixed period of time, $M_{i,j}$ assumes that its members have finished the reporting, and its delay report $\mathcal{DR}(M_{i,j})$ is formed and ready to be exchanged as well.

5.2 Delay Exchange

After collecting link delay measurements from their group members, MEO group managers exchange the measurements inside the MEO layer to obtain the common picture of the LEO network topology. Our proposed exchange method includes two steps: *intra-plane exchange* and *inter-plane exchange*.
Step 1: Intra-plane Exchange
In MEO layer, the delay reports are first circulated in the same MEO plane.
1. MEO satellite $M_{i,j}$ sends its delay report $\mathcal{DR}(M_{i,j})$ to its two adjacent neighbors, $M_{i,p}$, in the same plane through $\text{ISL}_{M_{i,j} \to M_{i,p}}$, where $p = j-1, j+1$.
2. After receiving delay reports $\mathcal{DR}(M_{i,j})$, $M_{i,p}$ checks to see if it has been received before. If so, it is discarded.
3. $M_{i,p}$ forwards the new report $\mathcal{DR}(M_{i,j})$ on the other intra-plane ISL which is different from the incoming one, i.e. $\text{ISL}_{M_{i,p} \to M_{i,p+1}}$ or $\text{ISL}_{M_{i,p} \to M_{i,p-1}}$.

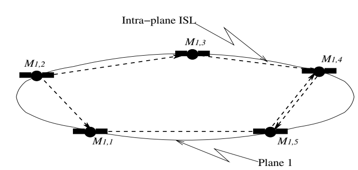


Figure 3: Intra-plane exchange.

Figure 3 shows the circulation of delay reports in the MEO plane 1. $M_{1,2}$ sends out $\mathcal{DR}(M_{1,2})$ to its neighbors $M_{1,1}$ and $M_{1,3}$. At the end, $M_{1,4}$ and $M_{1,5}$ each receive a duplicate report, upon which the circulation of $\mathcal{DR}(M_{1,2})$ is terminated.
Step 2: Inter-plane Exchange
After the LEO delay information is exchanged within plane i, a copy of the same information must be sent out to plane $l, l = 1, ..., N_M, l \neq i$, and circulated there as well. The steps of the inter-plane delay report exchanging are as follows:
1. The two satellites on plane i nearest to plane crossing points $\mathcal{CP}(i, l)$ are chosen to be plane i's starting points. The two satellites nearest to $\mathcal{CP}(i, l)$ on plane l are selected as their reception satellites respectively. $\mathcal{DR}(M_i)$ is sent from plane i to plane l via the inter-plane ISLs.
2. The two reception satellites on plane l forward $\mathcal{DR}(M_i)$ clockwise via their intra-plane ISLs to the neighboring MEO satellites.

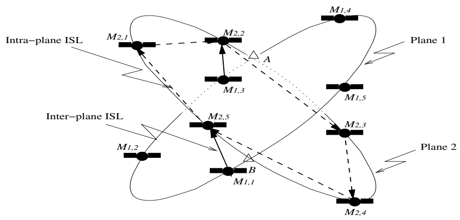


Figure 4: Inter-plane exchange.

3. After receiving $\mathcal{DR}(M_i)$, MEO satellite $M_{l,m}$ first checks to see whether it has been received before. If so, the delay report is discarded, otherwise, it is forwarded clockwise to the next neighboring MEO satellite.

Figure 4 shows the transfer of $\mathcal{DR}(M_1)$ from plane 1 to plane 2. $\mathcal{CP}(1,2) = \{A, B\}$. $M_{1,1}$ and $M_{1,3}$ are chosen as the starting points, their reception satellites are $M_{2,5}$ and $M_{2,2}$, respectively. Starting from $M_{2,5}$ and $M_{2,2}$, the report is circulated clockwise over the dashed lines. Note that the circulation of different plane's delay reports are processed in a parallel way, i.e, the delay report of one plane can be sent to different planes simultaneously.

5.3 Routing Table Calculation

Routing tables are prepared by the MEO satellites for their care-of members. Original routing tables register the detailed path and are kept in MEO satellites. Simplified routing tables are sent to the LEO satellites.

Step 1: Original Routing Table Calculation

The routing table calculations are performed by the MEO satellites after they received all the delay reports. A MEO satellite $M_{i,j}$ computes the minimum delay paths from the LEO satellites in $\mathcal{CM}(M_{i,j})$ to all LEO destinations, and adds them into original routing table $\mathcal{ORT}_{M_{i,j}}$.

Step 2: Simplified Routing Table Calculation

Based on $\mathcal{ORT}_{M_{i,j}}$, MEO group managers arrange the paths into destination and next-hop pairs for each of its care-of members. Before sending routing tables to LEO layer, $M_{i,j}$ tries to aggregate the destinations in remote groups to reduce the size of routing tables.

The entry of $\mathcal{SRT}_x(Dest)$ =*next-hop* in a simplified routing table is formed for a LEO satellite x by $\mathcal{PH}(x)$. When $\mathcal{SRT}_x$ is ready, it is sent from $\mathcal{PH}(x)$ to x via $\text{IOL}_{\mathcal{PH}(x)\to x}$. The path aggregation is done as follows:

Let $\mathcal{S}$ = all satellites in LEO layer
for $\mathcal{L}_{i,j} \in \mathcal{RM}(x)$
    if the second node on $\mathcal{P}_{x\to y} = t$, for all $y \in \mathcal{L}_{i,j}$
        $\mathcal{SRT}_x(\mathcal{L}_{i,j}) = t$
        $\mathcal{S} = \mathcal{S} - \mathcal{L}_{i,j}$
    end
end
for $y \in \mathcal{S}$
    $\mathcal{SRT}_x(y)$ = the second node on $\mathcal{P}_{x\to y}$
end

5.4 Congestion Avoidance

In our algorithm, data packets are routed according to the delay information which LEO satellites gather every T_c period. If traffic load changes fast, as the delay variation can only be noticed in the next reporting period, the routing decision cannot reflect the fluctuation of the real-time delay and congestion may occur. We introduce a congestion avoidance phase to deal with this problem. It consists of three steps:

Step 1: Congestion Detection

To avoid congestion in the LEO network, every LEO satellite continuously monitors the queue lengths of the output buffers of their adjacent links. If the queue length associated with $l_{x_1\to x_2}$ is more than ξ packets, then "congestion" is said to have occurred on link $l_{x_1\to x_2}$. x_1 reports $\mathcal{D}(l_{x_1\to x_2}) = \infty$ to all its MEO managers in $\mathcal{H}(x_1)$ promptly.

Step 2: Information Propagation

Upon receiving a congestion warning of link $l_{x_1\to x_2}$, $M_{i,j}$ sets $\mathcal{D}(l_{x_1\to x_2}) = \infty$. Then, it propagates $\mathcal{D}(l_{x_1\to x_2}) = \infty$ in MEO layer using the same intra- and inter-plane exchange methods as in Section 5.2.

Step 3: Path Recalculation

To reduce the computation overhead, MEO group managers only recalculate those paths affected by the congestion. Meanwhile they try to lead the long routes away from entering the congestion area.

A MEO satellite M checks all paths in $\mathcal{ORT}_M$, and searches those affected by the congested link. If a path is either originated or destined within the congestion area $\mathcal{CA}(l_{x_1\to x_2})$, it will be kept. If a path goes through the $\mathcal{CA}(l_{x_1\to x_2})$, then M "cuts" congestion area from re-computation of this path, i.e, set all delays associated with links in $\mathcal{CA}(l_{x_1\to x_2})$ to infinity, thus leads these paths away from entering the congestion area. The path recalculation in MEO satellite M for $x \in \mathcal{CM}(M)$ is summarized below:

Let $\mathcal{S}$ = all satellites in LEO layer
for $y \in S$
    if $l_{x_1\to x_2}$ is on $\mathcal{ORT}_M(x,y) = \mathcal{P}_{x\to y}$
        if $l \in \mathcal{CA}(l_{x_1\to x_2})$, for all $l \in \mathcal{P}_{x\to y}$
            keep $\mathcal{P}_{x\to y}$, search next y
        else if $l \notin \mathcal{CA}(l_{x_1\to x_2})$, where l is the first and last link on path $\mathcal{P}_{x\to y}$
            set $\mathcal{D}(l_{y_1\to y_2}) = \infty$, for all $l_{y_1\to y_2}$ in $\mathcal{CA}(l_{x_1\to x_2})$
        end
        M recalculates $\mathcal{P}_{x\to y}$
        $\mathcal{ORT}_M(x,y) = \mathcal{P}_{x\to y}$
    end
end

After the calculation, M updates affected parts in $\mathcal{ORT}_M$, aggregates the new paths, and send packets to update the affected entries in simplified routing table $\mathcal{SRT}_x$ of its member x accordingly.

5.5 Satellite Failure

A satellite may fail, or be shut down temporarily for some reason such as maintenance and testing, or when crossing oceans or polar regions to save energy, etc. When failure occurs, all minimum delay paths passing through this satellite must be rerouted so that, the packets that normally pass through the failed satellite would not be dropped. In our algorithm, the rerouting is done in the following way: When a satellite fails, its immediate neighbors are the first to sense this occurrence. They send reports to MEO group managers immediately. Upon receiving failure notification of a LEO satellite s, $M_{i,j}$ sets all link delays associated with s to infinity. Then $M_{i,j}$ propagates the update delay report

Table 1: LEO/MEO constellation parameters.

	MEO	LEO
Altitude	h_M=10390 km	h_L=700 km
Number of planes	N_M=2	N_L=12
Number of satellite per plane	M_M=5	M_L=24
Angular velocity	w_M=1^o/min	w_L=3.6^o/min
Orbit inclination angle	45^o	90^o
Minimum elevation angle	$\epsilon_{min} = 10^o$	-

Table 2: Continental traffic flow shares in %.

	Destination					
Source	N.A.	Eur.	Asia	S.A.	Afr.	Ocea.
N. A.	85.08	7.26	4.63	1.87	0.46	0.70
Europe	23.46	57.00	14.18	1.64	2.74	0.98
Asia	22.28	21.12	49.62	1.15	1.68	4.14
S. A.	50.37	13.66	6.42	26.10	1.84	1.61
Africa	24.03	44.36	18.23	3.58	7.69	2.11
Oceania	25.21	11.00	31.21	2.18	1.46	28.95

in the MEO layer.

To reduce the computation overhead, MEO group managers only recalculate those paths affected by the failure. A MEO satellite M checks the paths in $\mathcal{ORT}_M$, finds those affected by the failed satellite s. If the failed satellite lies on a path, M recalculates the path, update the corresponding entry in $\mathcal{ORT}_M$, and performs group aggregation.

6. PERFORMANCE EVALUATION

Our simulation consists of two major parts: First, find the snapshot period and group membership information in each snapshot period according to the parameters of LEO and MEO satellite constellations; and secondly, using SGRP algorithm, keep track of the end-to-end delay between some terrestrial source-destination pairs, with the background traffic changing dynamically.

6.1 Snapshot Periods Identification

In our two-layer satellite networks, the ICO network is chosen as the MEO satellite constellation, the LEO satellite constellation is a slightly modified version of the Teledesic network, where the orbital inclination is 90^o instead of 98.2^o. The system parameters are given in Table 1. The system cycle for these parameters is T = 1440 minutes, i.e., one day.

Using our computation method in Section 3, there are a total of 93 snapshot periods in a system cycle. As expected, the snapshots repeat themselves after time T. The mean duration time for all 93 snapshots is 15.5 minutes. The length distribution of the snapshot duration is given in Figure 5.

6.2 Traffic Modeling

In our satellite network, every link is associated with an instantaneous delay. The links are modeled as finite capacity queues, the traffic requirements between satellites are mapped to the ISLs according to the shortest path the packets will take. They provide the arrival rates in the queuing model. We assume Poisson arrival rate and exponentially distributed service time, then the queuing delay of each link can be deduced by the $M/M/1/K$ queuing model.

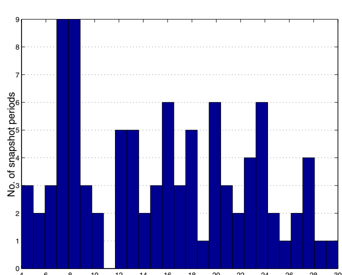


Figure 5: Distribution of snapshot duration.

According to our protocol, the routing tables are recalculated at snapshot periods and every T_c minutes in between, which corresponds to the beginning of a calculation period. The delays are assumed to be the same throughout a calculation period, and are changed when the delay information is collected once again.

We divide the Earth into $15^o \times 15^o$ geographical zones, and map each zone with a LEO logical location. Because of the asymmetry of the IP traffic, the user behavior and host behavior are different for each zone. Hence we build two database for the user density level and host density level for each zone. Together with a traffic matrix model, the global background traffic can be generated.

1) *User Density Level*

The forecasted voice traffic over LEO satellite systems for the year 2005 in [9] is referred to determine the user density levels. Here we assume that the potential requirement for satellite network IP traffic from each geographical zone is proportional to the expected volume of voice traffic. As users show different activities during different times of the day, we take the daily evolution of user density [8] into consideration.

2) *Host Density Level*

The statistics on [1] give the number of Internet hosts on each continent. The statistics are used to get the host density level for different terrestrial zones. According to the data, we adjust the user density level to get the host density level of each zone by the following equation:

$$h_j = u_j \cdot N_h(k) / \sum_i u(i) \tag{11}$$

where h_j is the host density level of zone j, of which the user density level is u_j; $N_h(k)$ and $\sum_i u(i)$ is the number of hosts and the sum of user density level of zones in continent k, zone j is located within continent k.

3) *Traffic Matrix*

Similar to the method in [2], the inter-satellite traffic requirement between satellites i and j, i.e, T^{ij}, depends on the user density level u_i, the host density level h_j, and the distance $d(i,j)$ between the satellites.

$$T^{ij} = \frac{(u_i \cdot h_j)^\alpha}{(d(i,j))^\beta} \tag{12}$$

Here i corresponds to the LEO logical location (n, m), where $n = \lceil i/M_L \rceil$, $m = i$ MOD M_L. Setting $\alpha = 0.5, \beta = 1.5$, we can get the traffic flow shares among the continents in Table 2.

The packet arrival rate of each pair of satellites (packets/sec) is computed by:

$$\lambda_{ij} = \frac{T^{ij}}{\sum_{k=0}^{N_L \times M_L} \sum_{l=0}^{N_L \times M_L} T^{kl}} \times (\text{Total offered traffic}) \quad (13)$$

Here "Total offered traffic" represents the total traffic generated worldwide.

6.3 Simulation Results

To evaluate the performance of the Satellite Grouping and Routing Protocol (SGRP) on the LEO/MEO satellite architecture, we conducted three sets of experiments:

- **Path Optimality:** The first set of the simulations shows the differences of end-to-end delay among the Datagram Routing Algorithm(DRA) [4], SGRP, and the Bellman's shortest path algorithm [6].
- **Effect of Link Congestion:** Our routing algorithm SGRP has reaction mechanism when congestion occur. This set of simulations shows the performance difference among SGRP, DRA and shortest path algorithms in case of link congestion.
- **Effect of Satellite Failure:** This set of simulations shows the effect of satellite failures on the performance of SGRP, with comparison with DRA and shortest path algorithm.

In all simulations, the capacity of all UDLs and ISLs are chosen as 160 Mbps, and each outgoing link has been allocated a buffer size of 5 MB. If we assume an average packet size of 1000 bytes, the link capacity becomes 20000 packets per second and the buffer size becomes 5000 packets. The shortest-path algorithm is performed centrally based on the overall knowledge of link-state informations. The recalculation period T_c in SGRP is 4 minutes. In all three schemes, the delay characteristics are monitored every 1 minute.

1) *Path Optimality*

The first set of experiments are based on the observation of the end-to-end delay between a terrestrial source-destination pair. The source node is located at (112.5^oE, 37.5^oN) in China, Asia and the destination is at (277.5^oW, 33.75^oN) in United States, North America. The sender generates an average of 8 Mbps (1000 packets per second) for 100 minutes.

To compare the delays of different schemes under different link load, we increase the ISL utilization in the LEO layer gradually. It is done as follows: First, the packet arrival rate is generated by Equation (13), it gives the average traffic rates of flows between the source-destination pair. Flows are generated with exponentially distributed rates with fixed means λ_{ij}. Then the rates are mapped to ISLs according to the minimum propagation delay paths the packets will take. The load of a link is the sum of all the rates of flows that pass through this link.

In our simulation, every time the "Total offered traffic" is chosen, the routes and end-to-end delays of certain flows are monitored for 100 minutes. The satellite link loads are changing dynamically with fixed nominal means. The average end-to-end delay performance of the DRA, SGRP, and the shortest-path routing algorithm with respect to the average link load are depicted in Figure 6(a).

It can be seen that when average link load is as low as 3%, the end-to-end delay performance of the three algorithms are similar. This is reasonable because when the traffic load is light, the propagation delay is the dominant factor in the end-to-end delay. However, as average link load increases, DRA and SGRP cause longer delays than shortest-path routing algorithm. The end-to-end delay of the path calculated by DRA increases dramatically when the average link load is greater than 3%. This is because when average link load increases, ISLs in areas with higher traffic density are tend to be congested. DRA reflects packets only when they approach or enter into the congestion areas, whereas the routing scheme based on SGRP can lead paths away based on the big picture of traffic distribution in LEO networks, , thus reduce the traffic entering into the congested areas. However, as SGRP leads long paths away to avoid even the vicinity of the congested links, these routes experience longer delay compared to the paths calculated by shortest path algorithm.

2) *Effect of Link Congestion*

In the following two sets of experiments, we compare the end-to-end delay of three different routing schemes mentioned previously under link congestion and satellite failures. To reflect the effect of real-time changes on delay performance, the background traffic is adjusted every hour according to the time of the day. All paths and link loads are updated after recalculation.

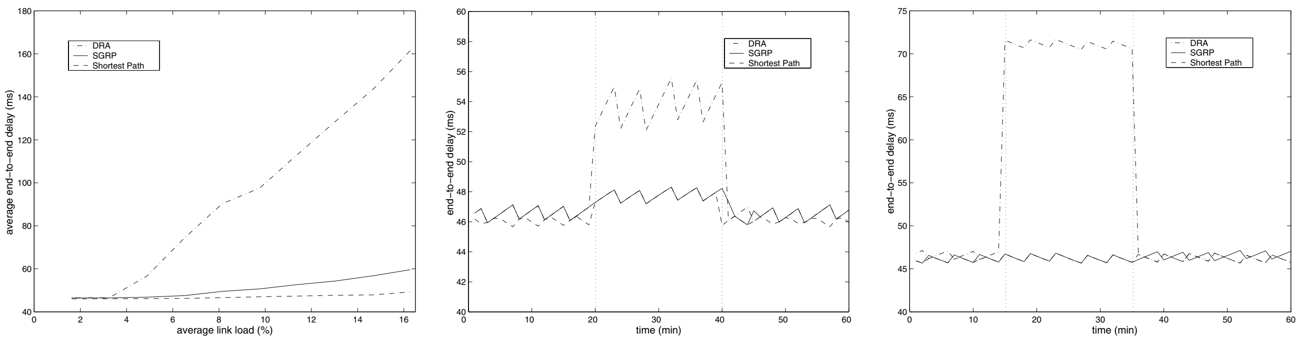
We first keep track of the end-to-end delay of the same source-destination pair under satellite link congestion. In our experiments, the sender generates traffic of 1000 packets per second for 60 minutes in a peak hour from 10am to 11am. The congestion occurs at the link from LEO logical location $(277.5^oW, 63.75^oN)$ to $(277.5^oW, 48.75^oN)$ between 10:20am and 10:40am. To simplify the simulation, we confine the congestion to this link, and setting the load on this path to 100% of the link capacity.

From Figure 6(b), the path calculated by DRA always undergoes higher delay within the congestion period. This delay is about 13% higher than that of the path calculated by SGRP. The average difference between the delays of SGRP and shortest path is about 0.5ms. However, when congestion occurs, their delay performances are about the same. The SGRP recalculate the routing tables right after congestion happens. The recalculation tries to keep the local traffic within the congestion area, but route the long path away from this area. Therefore, the effect of congestion will be compensated by enacting the new routing tables.

3) *Effect of Satellite Failure*

Similarly, we depict the change of instantaneous end-to-end delay for the source-destination pair of the three algorithms when satellite failure happen. The sender generates traffic of 1000 packets per second for 60 minutes from 8am to 9am. The satellite representing the logical location of $(292.5^oW, 67.5^oN)$ is out of service from 8:15am to 8:35am.

In Figure 6(c), the instantaneous end-to-end delays associated with these three algorithms are depicted. The DRA routes packets on the minimum propagation delay path. As the satellites do not send delay reports to others, the satellite failure is known only to the immediate neighbors. When a packet is received by one of these neighbor satellites, and is destined to the failed one, it is deflected to one of the orthogonal directions. In SGRP, the satellite failure is reported to the MEO layer by its neighbors immediately. This failure report is then exchanged among all MEO satellites, causing them to update the routing tables of all the LEO satellites. From the figure, we can see that the failure has



(a) Path optimality. (b) Effect of link congestion. (c) Effect of satellite failure.

Figure 6: Comparison of end-to-end delay performances.

minor effect on SGRP, yet in the satellite failure period, the path calculated by DRA undergoes higher end-to-end delay, which is about 55% higher than SGRP. On the other hand, the delays of SGRP and shortest path are very close either under normal condition or when a satellite fails. Because when satellite failure occurs, the failure report packets are immediately received and passing around in MEO layer. New shortest paths are calculated and begin to take effect after LEO satellites receive the new routing tables. This mechanism compensates the effect of satellite failure.

7. CONCLUSION

In this paper, we introduce a satellite IP network consisting of LEO and MEO layers together with a new routing protocol: Satellite Grouping and Routing Protocol (SGRP). Using this protocol, LEO satellites are dynamicly divided into different groups, for each group a MEO satellite is assigned as the group manager. MEO group managers collect the link delay information from their LEO members, and compute the minimum-delay path for them. The SGRP distributes the computation burden to multiple MEO satellites, thus balances the power consumption between LEO and MEO satellites. The performance of the SGRP algorithm has been assessed with simulations. The performance of SGRP is better than Datagram Routing Algorithm. When satellite failure or link congestion happens, SGRP has mechanism to reduce their effect on routing.

8. REFERENCES

[1] Evaluating the size of the internet. Telcordia Technologies, www.netsizer.com/daily/TopCountry.html.

[2] H. Chang, B. Kim, C. Lee, S. Min, Y. Choi, H. Yang, D. Kim, and C. Kim. Performance Comparison of Optimal Routing and Dynamic Routing in Low-Earth Orbit Satellite Networks. *Proceedings of IEEE 46th Vehicular Technology Conference*, pages 1240–1243, 1996.

[3] H. Chang, B. Kim, C. Lee, S. Min, Y. Choi, H. Yang, D. Kim, and C. Kim. FSA-Based Link Assignment and Routing in Low-Earth Orbit Satellite Networks. *IEEE Transactions on Vehicular Technology*, 47(3):1037–1048, August 1998.

[4] E. Ekici, I. Akyildiz, and M. Bender. A Distributed Routing Algorithm for Datagram Traffic in LEO Satellite Networks. *IEEE/ACM Transaction on Networking*, 9(2):137–147, April 2001.

[5] T. Henderson and R. Katz. On Distributed, Geographic-based Packet Routing for LEO Satellite Networks. *Proceedings of IEEE GLOBECOM 2000*, 2:1119–1123, December 2000.

[6] A. Kerschenbaum. *Telecommunications Network Design Algorithms*. New York: McGraw-Hill, 1993.

[7] J. Lee and S. Kang. Satellite over Satellite (SOS) Network: A Novel Architecture for Satellite Network. *Proceedings of IEEE INFOCOM'2000*, 1:315–321, March 2000.

[8] J. Perdigues, M. Werner, and N. Karafolas. Methodology for Traffic Analysis and ISL Capacity Dimensioning in Broadband Satellite Constellations Using Optical WDM Networking. *Proceedings of 19th AIAA International Communication Satellite Systems Conference (ICSSC'01)*, April 2001.

[9] M. Voilet. The Development and Application of a Cost per Minute Metric of the Evaluation of Mobile Satellite Systems in a Limited-growth Voice Communications Market. *Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, USA*, September 1995.

[10] C. Wang. Structural Properties of a Low Earth Orbit Satellite Constellation - the Walker Delta Network. *Proceedings of MILCOM'93*, 3:968–972, 1993.

[11] W. Werner, G. Berndl, and B. Edmaier. Performance of Optimized Routing in LEO Intersatellite Link Networks. *Proceedings of IEEE 47th Vehicular Technology Conference*, 1:246–250, May 1997.

[12] W. Werner, A. Jahn, E. Lutz, and A. Böttcher. Analysis of System Parameters for LEO/ICO-Satellite Communication Networks. *IEEE Journal on Selected Areas in Communications*, 13(2):371–381, February 1995.

[13] L. Wood, A. Clerget, I. Andrikopoulos, G. Pavlou, and W. Dabbous. IP Routing Issues in Satellite Constellation Networks. *International Journal of Satellite Communications*, 19:69–92, 2001.