Datagram Routing Algorithm for LEO Satellite Networks

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Abstract - **Satellite networks provide global coverage and support a wide range of services.** *Low Earth Orbit (LEO)* **satellites provide short round trip delays and are becoming increasingly important. One of the challenges in LEO satellite networks is the development of specialized and efficient routing algorithms. In this work, a datagram routing algorithm for LEO satellite networks is introduced. The algorithm generates minimum propagation delay paths. The performance of the algorithm is evaluated through simulations and finally robustness issues are discussed.**

I. INTRODUCTION

Satellite networks can meet a variety of data communication needs of businesses, government, and individuals. Due to their wide-area coverage characteristics and ability to deliver wide bandwidths with a consistent level of service, satellite links are attractive for both developed and developing countries. There is no doubt that satellites (both LEO, GEO) will be an essential part of the Next Generation Internet (NGI). There are several reasons why satellites will play a key role in the NGI [1]:

• Satellite services can be provided over wide geographical areas including urban, rural, remote, and inaccessible areas. It should be noted that the 2/3 of the world still does not have the infrastructure for the Internet.
• Satellite communication systems have very flexible bandwidth-on-demand capabilities.
• Alternative channels can be provided for connections that have unpredictable bandwidth demands and traffic characteristics, which may result in maximum resource utilization.
• New users can easily be added to the system by simply installing the Internet interfaces at customer premises. As a result, network expansions will be a simple task.
• Satellites can act as a safety valve for NGI. Fiber failure, or network congestion problems, can be recovered easily by routing traffic through a satellite channel.
• New applications such as "Digital Earth," as well as Tele-education, Telemedicine, Entertainment etc. can be realized through satellites.

There are many technical obstacles to be overcome to make satellite Internet systems commercially viable. One of the challenges in LEO satellite networks research is the development of specialized and efficient routing algorithms. In particular, the special design of *Low Earth Orbit (LEO)* satellite networks causes the packets to take multiple hops from source to destination. The interconnectivity pattern of LEO satellites forms different shapes depending on their movement. The satellites are connected to each other via *Inter-Satellite Links* (ISL). The so-called *Inter-plane ISLs* connect satellites from different orbits (also called planes). On the other hand, the *Intra-plane ISLs* connect satellites in the same plane. While the distances between the satellites (vertical paths) in the same plane are fixed throughout the connections, the distances between satellites in different planes (horizontal paths) are different and vary with the movement of the satellites, e.g., the horizontal distances are longest when satellites are over Equator and shortest when they are over the polar region boundaries. Although the satellite movements cause changes in the network topology, the established connections must be maintained in the network. This is where efficient routing algorithms are needed not only to establish optimum path between source and destination but also to maintain the path throughout the communication.

In recent years, some routing algorithms for LEO satellite networks have been developed assuming a connection-oriented network structure, e.g., ATM or ATM-type like switches on-board of satellites [2], [3], [4], [5]. The developed algorithms focus mainly on the initial path setup phase. The paths are computed in a ground switch centrally and the routing tables on satellites are configured based on these computations. Satellites then only forward the packets according to their routing tables. As mentioned above, satellite movements cause changes in the network topology and consequently these initial path assignments may also change with time and may not keep its initial optimality. To address this problem the so-called "path handover" solution has been investigated in [6]. The performance of the existing path handovers depends heavily on the optimality of the initial path establishments.

As the Internet is becoming very popular and the efforts regarding NGI are on the way, there is an initiative in the commercial and also in the military world, to push the IP technology also to satellite networks. In other words, the switches on the satellites could be IP switches or IP like switches which means we would have datagram (connectionless) type network structure. Keeping this objective in mind, we introduce a datagram routing algorithm that generates *minimum propagation delay paths* between
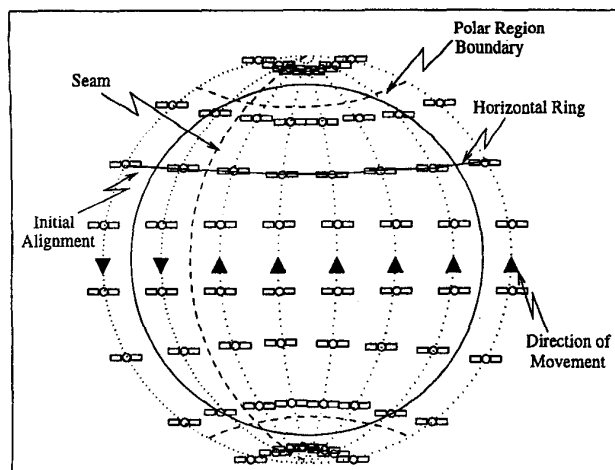
Fig. 1. Orbital Planes around the Earth

Fig. 2. Switching of Left and Right Neighbors in Polar Regions

source and destination. The routing problem becomes especially interesting when we consider the changing distances between satellites in different planes as well as the movements of the satellites which cause a constant change in the network topology. The new routing algorithm is distributed, i.e., the routing decisions are made independently for each packet. Also congestions and failures can easily be avoided with local decisions. Since the algorithm is datagram based, there is no need for handovers of established connection paths as this is the case for algorithms in connection-oriented networks mentioned above.

The paper is organized as follows: In Section II we explain the satellite network architecture and in Section III we describe the new Datagram Routing Algorithm. In Section IV we present performance analysis of the the new algorithm and in Section V we conclude the paper.

II. SATELLITE NETWORK ARCHITECTURE

The satellite network is composed of N separate orbits (planes), each with M satellites at low distances from the Earth as shown in Fig. 1. The planes are separated from each other with the same angular distance of $\frac{360°}{2 \times N}$. They cross each other only over the North and South poles. The satellites in a plane are separated from each other with an angular distance of $\frac{360°}{M}$. Since the planes are circular, the radii of the satellites in the same plane are the same at all times and so are the distances from each other.

The geographical location of a satellite S is given by $[lon_S, lat_S]$ indicating the longitude and latitude of the location of S, respectively. We assume that the entire Earth is covered by logical locations of satellites. These logical locations are filled by the nearest satellite. Hence, the identity S of the satellite is not permanently coupled with its logical location, which is taken over by the successor satellite in the same plane. The logical location of a satel-
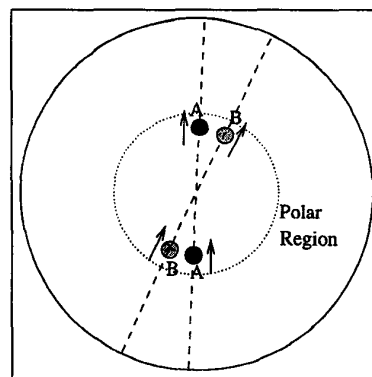
lite S is given by $\langle p, s \rangle$ where p for $p = 0, ..., N - 1$, is the plane number and s, for $s = 0, ..., M - 1$, is the satellite number. The routing is performed basically by considering these logical locations as hops. By this way, we do not need to be concerned with the satellite movements.

Each satellite has four neighboring satellites: two in the same plane and two in the left and right planes. The links between satellites in the same plane are called intra-plane ISLs. The links between satellites in different planes are called inter-plane ISLs. On intra- and inter-plane ISLs, the communication is bidirectional.

The intra-plane ISLs are maintained at all times, i.e., each satellite is always connected to the rest of the network through its up and down neighbors. The propagation delay on the intra-plane links is always fixed. All satellites are moving in the same circular direction within the same plane. As a consequence, any satellite that is observed from the Earth moving from South to North will be observed to start moving from North to South when it crosses the North pole. Hence, the 0th and N^{th} planes rotate in opposite directions. The borders of counter-rotating satellites are called seams as shown in Fig. 1.

The inter-plane ISLs are operated only outside the polar regions. When the satellites move towards the polar regions, the inter-plane ISLs become shorter. When two satellites in adjacent planes cross the poles, they switch their positions. In order to allow this switching, the inter-plane ISLs are shut down in polar regions and re-established outside of the polar regions as shown in Fig. 2.

The length L_v of all intra-plane ISLs is fixed and is computed by:

$$L_v = \sqrt{2} \, R \sqrt{1 - \cos(\frac{360°}{M})} \qquad (1)$$

where R is the radius of the plane.

The length L_h of inter-plane ISLs is variable and is calculated by:

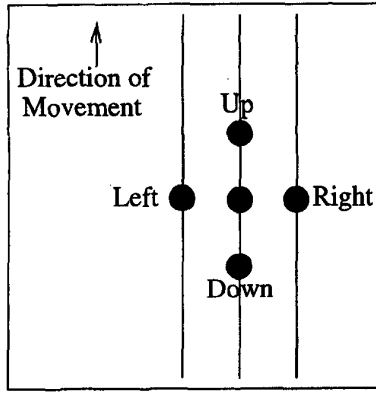$$L_h = \alpha \times \cos(lat) \qquad (2)$$

Fig. 3. Neighbor Concept

where

$$\alpha = \sqrt{2}\,R\sqrt{1 - \cos\left(\frac{360^{\circ}}{2 \times N}\right)}$$

with *lat* as the latitude at which the inter-plane ISL resides.

III. DATAGRAM ROUTING ALGORITHM

The connection structure of the satellites and their deterministic movements around the Earth simplifies the design of efficient and robust routing algorithms for datagram traffic. First we give definitions and theorems which will be used for the new routing algorithm.

A. Definitions

Definition 1. **Neighbor Concept.** Each satellite has two neighbors in the same plane and two neighbors in adjacent planes as shown in Fig. 3. The neighbors in the direction of orbital movement is labeled as *up* and in the opposite direction as *down*. The satellites in adjacent planes are called *left* and *right* neighbors.

Definition 2. **Initial Alignment.** The satellite network is said to be in *initial alignment* if all satellites with satellite number k (satellites on one side of the seam) and satellite number $(M - k - 1)$ (satellites on the other side of the seam) are positioned at the same latitude as shown in Fig. 1. In this case all inter-plane ISLs become parallel to the Equator and all satellites are exactly in the centers of their logical locations.

Definition 3. **Horizontal Ring.** The satellites on the same latitude with the initial alignment and the ISLs connecting them constitute a *horizontal ring* as shown in Fig. 1. The two horizontal rings closest to the polar regions are positioned at the latitude lat_{min}. Note that the difference between the horizontal rings and latitudes is that the horizontal rings may have different latitude values as the satellites move.

Definition 4. **Multihop Path.** Any source-destination satellite pair in the network can be connected by using *multihop paths*. Let a multihop path $P_{S_0 \rightarrow S_n}$ be defined as the ordered list of links $\{l_{SS'}\}$ such that

$$P_{S_0 \rightarrow S_n} = \{l_{S_0 S_1}, l_{S_1 S_2}, \cdots, l_{S_{n-1} S_n}\} \qquad (3)$$

forms an n-hop path from source satellite S_0 to destination satellite S_n.

Definition 5. **Total Propagation Delay.** The *total propagation delay* D_P on the path P is simply the sum of all individual propagation delays on each hop of the same path:

$$D_P = \sum_{i=0}^{n-1} \mathcal{D}(l_{S_i S_{i+1}}) \qquad (4)$$

where $\mathcal{D}(l_{SS'})$ is the propagation delay on each hop, i.e., from satellite S to satellite S'.

Definition 6. **Minimum Propagation Delay Path.** The *minimum propagation delay path* $P^*_{S_0 \rightarrow S_n}$ between S_0 and S_n is defined as:

$$P^*_{S_0 \rightarrow S_n} = \arg \min_{P \in \{P_{S_0 \rightarrow S_n}\}} \{D_P\} \qquad (5)$$

where $\{P_{S_0 \rightarrow S_n}\}$ is the set of all multihop paths from S_0 to S_n.

$P^V_{S_0 \rightarrow S_n}$ is defined as the minimum propagation delay path among the set of paths from S_0 to S_n that cross any polar region. Similarly, $P^H_{S_0 \rightarrow S_n}$ is the minimum propagation delay path among the set of paths that do not cross a polar region. Note that $P^*_{S_0 \rightarrow S_n} = \arg \min\{D_{P^V_{S_0 \rightarrow S_n}}, D_{P^H_{S_0 \rightarrow S_n}}\}$.

B. Decision Maps

The decision map is used by each satellite to decide on the outgoing link for each packet such that the generated path has the minimum propagation delay. To create the decision map we derived the following lemmas and theorems where we used the assumption that the satellites are in the initial alignment (*Definition 2*).

At this point we point out the grid structure of the satellites which cover the entire Earth. This grid structure could be regarded as a type of Manhattan Street Network [7] which have been researched extensively in the last decade. However, there is a major difference here. The distances between the satellites in different latitudes are changing, e.g., they become shorter in the latitudes closer to Poles and longer in the latitudes closer to Equator, (2). Keeping this fact in mind, we need to design our new routing algorithm in such a way that the shortest end-to-end delay path between source and destination will be determined. Since we assume very minimal processing in the on-board switches, the delay caused by these events can be assumed to be negligible and the end-to-end delay will involve only the propagation delays between the satellites.

Lemma 1: Assume the source satellite S_0 resides at $\langle p_{S_0}, s_{S_0}\rangle$ and the destination satellite S_n at $\langle p_{S_n}, s_{S_n}\rangle$. Also assume that both satellites are outside of the polar regions. Further assume that S_0 resides at a latitude higher than the latitude of S_n, i.e., $|lat_{S_0}| > |lat_{S_n}|$.

1. If S_0 and S_n are on the same side of the seam, then the *minimum propagation delay path* from S_0 to S_n $(P^*_{S_0 \to S_n})$ passes through the satellite at $\langle p_{S_n}, s_{S_0}\rangle$, i.e., this satellite is in the same horizontal ring *(Definition 3)* as the source satellite S_0 and is in the same plane as the destination satellite S_n.

2. If S_0 and S_n are on different sides of the seam, then $P^*_{S_0 \to S_n}$ passes through the satellite $\langle p_{S_n}, (N-1-s_{S_0})\rangle$, i.e., this satellite is in the same horizontal ring *(Definition 3)* as the source satellite S_0 but on the other side of the seam and is on the same plane as the destination satellite S_n.

Proof:

1. Suppose $P^*_{S_0 \to S_n}$ does not pass the polar region. Then the horizontal hops of this path are either in the same ring as the source or in rings at higher latitudes. Taking these horizontal hops, eventually a satellite at $\langle p_{S_n}, s_{S_0}\rangle$ in the same ring as S_0 and in the same plane as S_n will be reached. From this satellite at $\langle p_{S_n}, s_{S_0}\rangle$ the vertical hops will then lead to S_n.

Suppose $P^*_{S_0 \to S_n}$ crosses the polar region. Then the horizontal hops are taken in the ring closest to the polar region until the plane of S_n is reached. Then the vertical hops takes the packets through the polar region directly to S_n. Since S_n is at a lower latitude, the vertical hops would pass through the satellite at $\langle p_{S_n}, s_{S_0}\rangle$, which is in the same horizontal ring as S_0 and in the same plane as S_n.

2. Again here $P^*_{S_0 \to S_n}$ would pass through the satellite located in $\langle p_{S_n}, (N-1-s_{S_0})\rangle$ which is in the same ring as S_0 and in the same plane as S_n.

From Lemma 1 it follows that all source-destination satellite pairs must pass through a satellite that is in the same ring as the source and in the same plane as the destination. The path from that satellite to the destination only involves vertical hops.

Lemma 2: Assume S_0 and S_n are in the same horizontal ring outside of the polar regions. Also assume that the polar regions will not be crossed. Then $P^H_{S_0 \to S_n}$ *(Definition 6)* involves all horizontal hops on any ring between S_0 and the polar region.

Proof: Since the polar regions are not crossed, the horizontal hops are taken on any ring between S_0 and the polar regions because the inter-plane ISLs are longer in rings at lower latitudes than S_0. Consequently, the propagation delay is shorter in the rings at higher latitudes. Assume there is a path shown as dashed line in Fig. 4. We can find a shorter propagation delay path (solid line) by taking vertical hops in the same plane to the ring at the highest latitude close to the polar region, then take the horizontal hops in that ring, reaching the plane of S_n
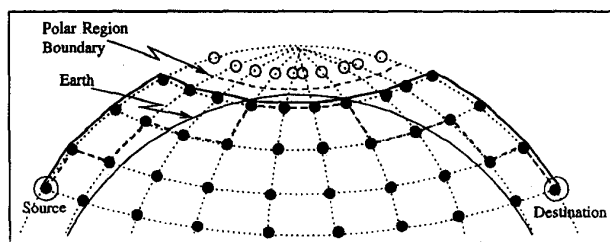

Fig. 4. Example for Lemma 2

and take vertical hops to reach S_n. It is easy to see that the solid path is shorter than the dashed one because the horizontal hops are shorter. The lengths of vertical hops are equal for both paths.

According to Lemma 2, $P^*_{S_0 \to S_n}$ that does not cross the polar region $(P^H_{S_0 \to S_n})$ takes horizontal hops in a ring between the polar region and the ring of S_0. If there are A rings between the source satellite and the polar regions, then there are $A + 1$ candidates for $P^H_{S_0 \to S_n}$. If the polar regions are crossed, the $P^*_{S_0 \to S_n}$ can easily be determined. In this case, the number of vertical hops is fixed and the horizontal hops are taken in the ring closest to the polar region where the inter-plane ISLs are the shortest. Comparing the lengths of the paths crossing the polar region and all other paths not crossing it, we can decide on the final path. The following Theorems help us with these decisions.

Theorem 1: Let S_0 and S_n be outside of the polar regions and S_0 be at a higher latitude, lat, than S_n. Assume that S_0 is A $(A \geq 0)$ hops away from the horizontal ring closest to the polar region and that the ring of S_0 is the kth $(k > 0)$ horizontal ring when counted from the closest pole. $P^*_{S_0 \to S_n}$ crosses the polar region if the number of horizontal hops n_h between S_0 and S_n satisfies:

$$n_h > \max_{0 \leq a \leq A} \left\{ \frac{N\cos(lat_{min}) + \frac{L_v}{\alpha}(2(k-a)+1)}{\cos(lat + a\frac{360°}{M}) + \cos(lat_{min})} \right\} \quad (6)$$

where L_v and α are given in (1) and (2), respectively and lat_{min} is the latitude of the ring closest to the polar region. **Proof:** We compare the propagation delays of paths from S_0 to S_n with and without crossing the polar region. The path over polar region takes the necessary $(N - n_h)$ horizontal hops in the ring closest to the polar region at latitude lat_{min} and has a propagation delay D_v. The path without the polar region takes the horizontal hops in a ring which is a hops closer to the polar region, for $a = 0, ..., A$, with the propagation delay D_{h+a}. The path crossing the polar region is shorter if if D_v is less than D_{h+a} for all possible values of a.

$$D_v < D_{h+a}$$
$$(N - n_h)\,\alpha\cos(lat) + L_v(2k+1)$$
$$< n\alpha\cos(lat_{min} + a\frac{360°}{M}) + 2aL_v \quad (7)$$

To guarantee that the path over polar regions is $P^*_{S_0 \to S_n}$, the Inequality (7) must hold for all possible values of a. Solving the equation above for n_h, the statement in Theorem 1 can be reached. If S_n is at a higher latitude lat than S_0, then a similar argumentation leads us to the same result.

In Theorem 2 below we present a decision criterion for staying in the same horizontal ring or going to another ring at a higher latitude.

Theorem 2: Let S_0 and S_n be outside of the polar regions and S_0 be at a higher latitude lat than S_n. Assume that S_0 is A ($A \geq 0$) hops away from the horizontal ring closest to the polar region and that the ring of S_0 is the kth ($k > 0$) horizontal ring when counted from the closest pole. $P^*_{S_0 \to S_n}$ has all horizontal hops in the same ring as S_0 if the condition in Theorem 1 is not satisfied and if the number of horizontal hops, n_h, between S_0 and S_n satisfies:

$$n_h < \min_{1 \leq a \leq A} \left\{ \frac{2aL_v}{\alpha} \frac{1}{\cos(lat) - \cos(lat + a\frac{360°}{M})} \right\} \quad (8)$$

Proof: Since we assumed that the condition in Theorem 1 is not satisfied, the path should not cross the polar regions. In order to take the horizontal hops in the same ring of S_0, any path with horizontal hops at a higher latitude must have a longer propagation delay. If we denote the propagation delay of the path in the ring of S_0 as D_h and the propagation delay of a path that takes the horizontal hops in a ring a hops away from the kth ring as D_{h+a}, then the following must be satisfied for all values of a, $1 \leq a \leq A$:

$$D_h < D_{h+a}$$
$$n_h \alpha \cos(lat) < n_h \alpha \cos(lat + a\frac{360°}{M}) + 2aL_v \quad (9)$$

Solving Inequality (9) for n_h, the statement in Theorem 2 can be reached.

The criteria presented in Theorems 1 and 2 help us to decide on the next hop such that the packet is forwarded on $P^*_{S_0 \to S_n}$. For this purpose, we created a decision map for the satellite network. In Fig. 5 we show the decision map for a particular network with $N = 12$ planes, each containing $M = 24$ satellites. The latitudes of the rings are indicated by "$\wedge$" in the x-axis. The latitude of the current satellite S_c and the remaining horizontal hop count to S_n identifies a point on the decision map. The area above the solid line is the region where (6) is satisfied. The area below the dashed line is the region where (8) is satisfied.

C. The Routing Algorithm

For any set of parameters that describes the satellite network, it is possible to find minimum propagation delay paths between any source-destination pair that are outside of the polar regions. A careful consideration would
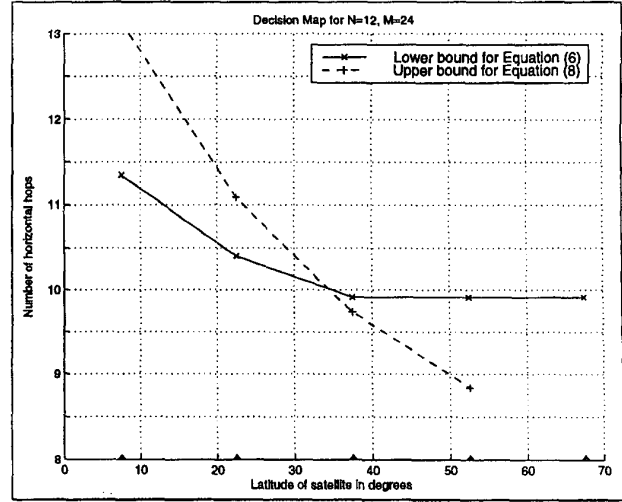

Fig. 5. Decision Map for a Constellation with 12 Planes, 24 Satellites

lead to more generalized paths that would also include the satellites in the polar regions.

The new routing algorithm generates the paths in a different way, i.e., the satellites process every incoming packet independently, assuring that the packets will be forwarded on $P^*_{S_0 \to S_n}$ as the result of their collective behavior. The next hop on the path is determined in two phases. In the *Direction Estimation Phase*, possible next hops on the minimum hop path is determined assuming that all ISLs have equal length. With this assumption, a minimum hop path becomes also a minimum propagation delay path. However, this is not exactly what we are interested in because the lengths of ISLs are different in these networks as we mentioned before. Thus, we have the *Direction Enhancement Phase*, where we consider that the inter-plane ISLs have different lengths, (2), and refine our decision made in the first phase about the next hop accordingly. These two phases are explained in detail in the following two subsections.

C.1 Direction Estimation

The *direction estimation phase* deals with the determination of the next hop on the minimum hop path. The number and direction of hops on a minimum hop path are called *minimum hop metrics*, which consist of a pair of direction indicators, d_v and d_h, and a pair of number of hops for each direction, $n_v \in \{0, 1, ..., M\}$ and $n_h \in \{0, 1, ..., N\}$. The vertical movements are described by:

$$d_v = \begin{cases} +1 & \text{upward} \\ 0 & \text{no vertical movement} \\ -1 & \text{downward} \end{cases} \quad (10)$$

The horizontal movements are described by:

$$d_h = \begin{cases} +1 & \text{right} \\ 0 & \text{no horizontal movement} \\ -1 & \text{left} \end{cases} \quad (11)$$

To determine minimum hop metrics, we use the logical locations of the current satellite S_c and destination satellite S_n. Let S_c be at $\langle ps_{S_c}, ss_{S_c}\rangle$ on $P^*_{S_0 \to S_n}$ and S_n at $\langle ps_{S_n}, ss_{S_n}\rangle$.

• If $ss_{S_c} < \frac{M}{2}$ and $ss_{S_n} < \frac{M}{2}$ with M as the number of the satellites in a plane, then the S_c and S_n are in the Eastern Hemisphere, i.e., on the same side of the seam.
• If $ss_{S_c} \geq \frac{M}{2}$ and $ss_{S_n} \geq \frac{M}{2}$, then they both are in the Western Hemisphere, on the other side of the seam.
• Otherwise, S_c and S_n are on different sides of the seam. After determining the respective locations of S_c and S_n, the numbers of hops for $P^V_{S_c \to S_n}$ and $P^H_{S_c \to S_n}$ (Definition 6) are calculated by assuming that all ISLs have the same length. The path with minimum number of hops is chosen as the minimum hop metrics. The procedure is as follows:
• If S_c and S_n are on the same side of the seam:
  – The number of vertical hops for $P^H_{S_c \to S_n}$ is $n_v = |ss_{S_c} - ss_{S_n}|$ and the number of horizontal hops is $n_h = |ps_{S_c} - ps_{S_n}|$. Their sum gives the total hop number for $P^H_{S_c \to S_n}$.
  – The number of horizontal hops for $P^V_{S_c \to S_n}$ is $n_h = (N - |ps_{S_c} - ps_{S_n}|)$. If S_c and S_n are in the Eastern Hemisphere, then number of vertical hops is $n_v = \min\{(ss_{S_c} + ss_{S_n} + 1), M - (ss_{S_c} + ss_{S_n} + 1)\}$. If S_c and S_n are both in the Western Hemisphere, then the number of vertical hops is $n_v = \min\{2 \times M - (ss_{S_c} + ss_{S_n} + 1), (ss_{S_c} + ss_{S_n} + 1) - M\}$. The sum of the number of vertical and horizontal hops gives the total hop number for $P^V_{S_c \to S_n}$.
• If S_c and S_n are on different sides of the seam:
  – For $P^H_{S_c \to S_n}$, the number of vertical hops is $n_v = |M - ss_{S_c} - ss_{S_n} - 1|$ and the number of horizontal hops is $n_h = (M + |ps_{S_c} - ps_{S_n}|)$. Their sum gives the total hop number for $P^H_{S_c \to S_n}$.
  – For $P^V_{S_c \to S_n}$, the number of horizontal hops is $n_h = |ps_{S_c} - ps_{S_n}|$. The number of vertical hops is given by $n_v = \min\{|ss_{S_n} - ss_{S_c}|, M - |ss_{S_n} - ss_{S_c}|\}$. The sum of vertical and horizontal hop numbers gives the total hop number for $P^V_{S_c \to S_n}$.

Among $P^H_{S_c \to S_n}$ and $P^V_{S_c \to S_n}$, the one with minimum total hop number is chosen and their horizontal n_h and vertical hop numbers n_v are recorded. If $P^H_{S_c \to S_n}$ is the minimum hop path, then the directions for horizontal d_h and vertical hops d_v are determined using Table I. If $P^V_{S_c \to S_n}$ is the minimum hop path, then the directions, d_h and d_v, are determined using Table II.

The usage of the Tables I and II can be illustrated with the following example: Assume S_c is at $\langle 2,8\rangle$ and S_n is at $\langle 5,6\rangle$ in a network with $N = 12$ planes, each with $M = 24$ satellites. The portion of the network that contains S_c and S_n are shown in Fig. 6. Following the procedure described

S_c & S_n in the Same Hemisphere					
ps_c ps_n			ss_{S_c} ss_{S_n}		
<	>	=	<	>	=
$d_h=+1$	$d_h=-1$	$d_h=0$	$d_v=-1$	$d_v=+1$	$d_v=0$

S_c & S_n in Different Hemispheres					
ps_c ps_n			$(M-1-ss_{S_c})$ ss_{S_n}		
<	>	=	<	>	=
$d_h=-1$	$d_h=+1$	-	$d_v=+1$	$d_v=-1$	$d_v=0$

TABLE I

CALCULATION OF DIRECTIONS FOR $P^H_{S_c \to S_n}$

S_c & S_n in Eastern Hemisphere					
ps_c ps_n			$2(ss_{S_n}+ss_{S_c}+1)$ M		
<	>	=	<	>	=
$d_h=-1$	$d_h=+1$	$d_h=+1$	$d_v=+1$	$d_v=-1$	$d_v=+1$

S_c & S_n in Western Hemisphere					
ps_c ps_n			$2(ss_{S_c}+ss_{S_n}+1)$ $3M$		
<	>	=	<	>	=
$d_h=-1$	$d_h=+1$	$d_h=+1$	$d_v=+1$	$d_v=-1$	$d_v=-1$

S_c in Eastern & S_n in Western Hemisphere					
ps_c ps_n			$2(ss_{S_n}-ss_{S_c})$ M		
<	>	=	<	>	=
$d_h=+1$	$d_h=-1$	$d_h=0$	$d_v=-1$	$d_v=+1$	$d_v=+1$

S_c in Western & S_n in Eastern Hemisphere					
ps_c ps_n			$2(ss_{S_c}-ss_{S_n})$ M		
<	>	=	<	>	=
$d_h=+1$	$d_h=-1$	$d_h=0$	$d_v=+1$	$d_v=-1$	$d_v=-1$

TABLE II

CALCULATION OF DIRECTIONS FOR $P^V_{S_c \to S_n}$

in this subsection, $P^H_{S_c \to S_n}$ is chosen as the minimum hop path with $n_v = 2$ and $n_h = 3$. Since $P^H_{S_c \to S_n}$ is chosen, we use Table I. S_c and S_n are in the same hemisphere, hence we use the upper part of the table. To determine the direction, the numbers in each cell of the second row is compared. We find that $ps_{S_c} < ps_{S_n}$ ($2 < 5$) and $ss_{S_c} > ss_{S_n}$ ($8 > 6$), and hence the horizontal hops should be taken to right ($d_h = +1$) and the vertical hops should be taken upwards ($d_v = +1$).

The assumption we made for this phase, i.e., that all ISLs have the same length, gives us the flexibility to take either the horizontal or vertical hop indicated by d_v, (10), and d_h, (11). Taking the horizontal and vertical hops in any combination would produce a minimum hop path. In fact, the ISLs have different lengths and the packets can be routed on $P^*_{S_0 \to S_n}$ only if they are taken in a specific order. The next hop on $P^*_{S_0 \to S_n}$ is uniquely determined in the *direction enhancement phase*. Other possible minimum hop paths are used as backup paths in cases of congestion and satellite failure.
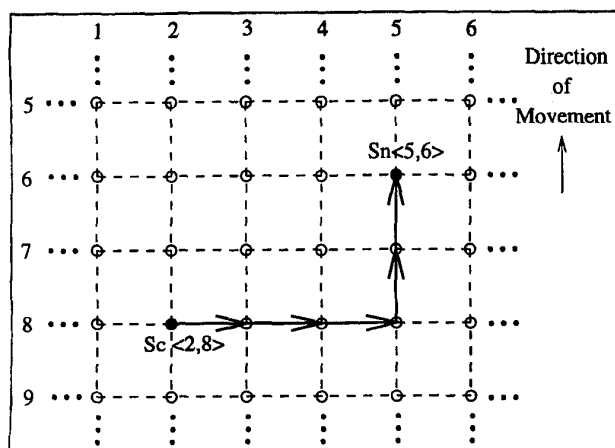
Fig. 6. Example for Calculation of Directions for Minimum Hop Paths

C.2 Direction Enhancement

In the direction enhancement phase, each satellite decides on the neighboring satellite to which it should send the packet next. For this purpose, the minimum hop metrics described in Section III-C.1 and the decision map described in Section III-B are used together. The routing decisions are made as follows:

1. If $S_c = S_n$, i.e., current satellite is the destination satellite, then the packet is not forwarded to neighboring satellites. It is sent to the gateway or any other appropriate receiver on the surface of the Earth.

2. If S_c is in a polar region, then the next hop for the incoming packet leads to a satellite in the same plane. If d_v, (10), is not zero, then the packet is forwarded in the direction indicated by d_v. If d_v equals zero, that means that S_n is also in the same polar region. Thus, the packet has to be forwarded towards the nearest satellite outside of the polar region.

3. If S_c is in the last horizontal ring before the polar region, then the horizontal hops are given priority since the horizontal links are shortest in that ring. If d_h, (11), is non-zero, meaning that the packet has to move horizontally, the packet is forwarded horizontally regardless of the value of d_v, (10). Otherwise, the packet is forwarded considering the value of d_v.

4. In other parts of the network, S_c forwards the incoming packets as follows:

(a) If the number of horizontal hops n_h calculated in direction estimation phase satisfies (6), the packet must cross the polar region. Then it is forwarded directly in the vertical direction specified in d_v, (10). This assures that the packet takes the horizontal hops in the smallest ring, i.e., in the ring closest to the polar region.

(b) If n_h does not satisfy (6) and (8) at the same time, then the horizontal hops should be taken in a ring closer

to the polar region. Hence the packet is forwarded to the neighboring satellite at a higher latitude.

(c) In all other cases, the latitudes of S_c and S_n are compared. If S_c is at a higher latitude than S_n, the packet is forwarded horizontally in the same ring as S_c. Otherwise, the packet is forwarded vertically to the horizontal ring of S_n. If d_h, (11), is zero, then the only choice is to forward the packet vertically.

To make the decisions in steps 4.a and 4.b, we can make use of the decision map generated for the network. The decision map of a satellite network can be stored on-board of each satellite since it does not change throughout the lifetime of the network.

C.3 Congestion Resolution and Rerouting in Cases of Satellite Failure

In the Datagram Routing Algorithm, the satellites do not exchange traffic load information. Therefore, congestions are detected using the fill levels of the output buffers. If the next hop of a packet is associated with an overloaded output buffer, i.e., if the output buffer has more than ξ packets, then this situation is interpreted as a congestion occurrence. If the packet has to take both horizontal and vertical hops, then the link in orthogonal direction is checked. If both output buffers contain ξ packets, then the packet is still placed into the output buffer determined in the direction enhancement phase. This scheme ensures that the routing is loop-free. The resulting path is one of the minimum hop paths.

In case of a satellite failure, the neighboring satellites start to deflect the packets in a way similar to the congestion resolution method. Packets destined to the failed satellite are deflected into orthogonal, secondary directions. Unless the current satellite is in a polar region, packets are never sent back to satellites they came from. Assume a packet is destined to the upper neighbor which has failed. If the packet has still to take horizontal hops, it is sent to either left or right neighbor, whichever is specified in d_h, (11). If d_h is zero, then it is sent either to left or right, as long as it is not the previous satellite on the path. The packets may be sent back on the path only if the current satellite is in a polar region. If d_h is non-zero, the resulting path is again one of the minimum hop paths.

IV. PERFORMANCE OF DATAGRAM ROUTING ALGORITHM

For performance evaluation of the datagram routing algorithm we conducted three main experiments.

- **Experiment I:** We compare the length of the paths generated by our new algorithm with the paths generated by Bellman's Shortest Path Algorithm [8].
- **Experiment II:** We discuss the effect of the Direction Enhancement Phase.

- **Experiment III:** We discuss the behavior of our new algorithm in case of satellite failures.

In all experiments we use $M = 12$ planes and $N = 24$ satellites in each plane. The planes as well as the satellites within a plane are separated from each other by 15.0^o. The polar regions are defined as regions between the latitudes 75.0^o and 90.0^o in the Northern and Southern hemispheres. The 0th and 23rd satellites in every plane are at latitude 82.5^o North, inside the polar regions.

A. Path Optimality of Datagram Routing Algorithm

Our new algorithm routes the packets between logical locations in the network. Logical locations in the network are treated as hops for packet routing. Since the satellites move in their planes, they are not always in the centers of their logical locations. Therefore, the optimality of the paths generated by our new algorithm can be affected by the satellite movement. Here we want to demonstrate that this effect is negligible.

In order to obtain minimum propagation delay paths even with the satellite movements, we can apply the Bellman's Shortest Path Algorithm [8]. However, the packet processing time complexity of this algorithm is $O(N \times M \log(N \times M))$ on the average and $O((N \times M)^3)$ in the worst case, where $N \times M$ is the total number of satellites in the network. On the other hand, the packet processing time complexity of our new algorithm is $O(1)$, i.e., it does not depend on the number of satellites. With this property, our new algorithm is more scalable than the Bellman's Shortest Path Algorithm and provides shorter packet processing delays. We use the Bellman's Algorithm only to compare the length of the paths generated by our new algorithm.

When the satellites are not exactly at their logical locations, our new algorithm generates paths that have longer propagation delays than the minimum propagation delay paths created by the Bellman's Shortest Path Algorithm. Within 15°, the satellites take the place at their exact logical locations periodically. This periodic movement of satellites can be captured by $\frac{1}{4}$ of this period. Thus, we examine the satellite movements between 0° and 3.75^o deviations from their logical locations with a step size of 0.5^o.

Then we use our new algorithm and determine the minimum propagation delay path between source and destination satellites. Similarly we apply the Bellman's Shortest Path Algorithm and create optimal paths. If the path obtained by our new algorithm is longer than the optimal path, then we record the differences as a percentage deviation which are given in Fig. 7.

In Fig. 7, it is clear that as the satellites move further away from their logical locations, the average percentage deviation increases. The main cause for the deviations is based on the changing lengths of the ISLs. The length of
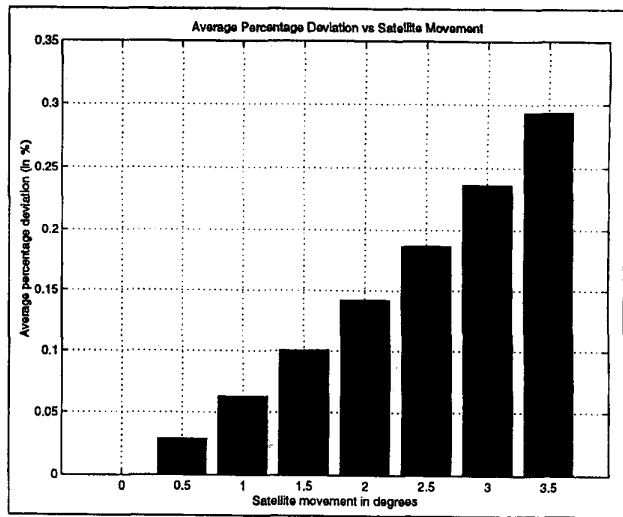

Fig. 7. Average Percentage Deviation vs. Satellite Movement

the inter-plane ISLs within the same horizontal ring deviates from its original value at the initial alignment because half of the satellites move to North and half of them to South, and accordingly the ISL distances will be different. In the worst case (3.5^o) in Fig. 7, the average difference between our algorithm and Bellman's algorithm is less than 0.3%. This clearly shows that our new algorithm provides minimum propagation delay paths with the complexity $O(1)$ and capturing the satellite movements by the logical location concept.

B. Effect of Enhancement Phase

If we apply only the *Direction Estimation Phase* of our new algorithm, we determine the *minimum hop number* between source and destination satellites. The minimum hop number is determined first by routing packets horizontally until the plane of destination satellite is reached, then taking the vertical hops to reach the destination.

In Fig. 8 we compare the average percentage deviation of the paths generated by our new algorithm with and without the enhancement phase. It is obvious that for any value of satellite movement, the version with enhancement phase results in much lower average deviation values than the version without enhancement phase. The worst average deviation for our new algorithm is less than 0.3%. On the other hand, if we only use the direction estimation phase, the average percentage deviation is always greater than 8.1%. This shows that the direction enhancement phase is an essential part of our algorithm to create minimum propagation delay paths.

C. Effect of Satellite Failures

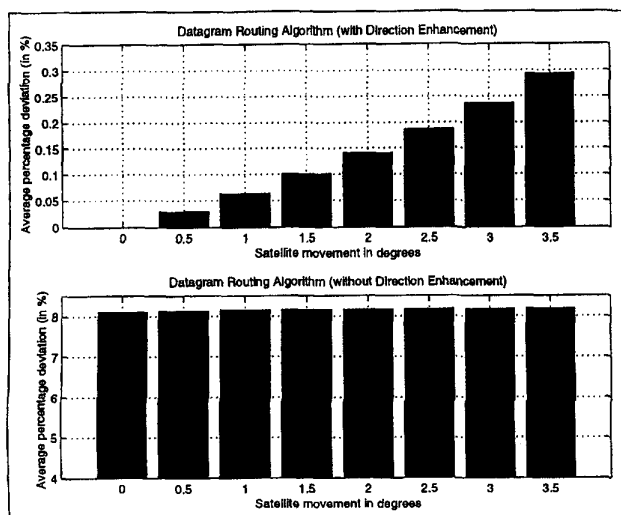When a satellite fails, all minimum propagation delay paths passing through this satellite must be recreated. In

Fig. 8. Average Percentage Deviation vs. Satellite Movement for Datagram Routing Algorithm with and without Enhancement Phase

Fig. 9. Average Percentage Deviation in Case of Satellite Failure versus Latitude of Failing Satellite

our algorithm, the satellite failures are only known to the immediate neighbors. Thus, after the failure, the newly generated paths between all source and destination satellites may not always have minimum propagation delays. In this experiment, we compare all new paths generated by our algorithm with all paths generated by the Bellman's Shortest Path Algorithm after the failed satellite.

In Fig. 9, we present the average percentage difference between the rerouted paths obtained by our algorithm and minimum propagation delay paths by Bellman's Shortest Path Algorithm. The experiments are carried out for different latitudes of the failed satellite. When the failed satellite moves from the Equator ($lat = 0°$) towards the Poles ($lat = 90°$), the average percentage deviation decreases from 6.25% to 4.4%. When the failed satellite is in the ring closest to the polar regions ($lat_{min} = 67.5°$), the average deviation increases to 15%. Similarly, the average deviation is 16% when failure is inside the polar region. The main reason for this behavior is that failures inside or next to the polar regions causes packets to be sent back to the satellites where they entered the polar region. Recall that the inter-plane ISLs are not operational in this region. This increases percentage difference in the propagation delay between the rerouted paths and optimal paths. These increases in the overall average propagation delay are still negligible.

V. Conclusion

In this paper, we introduced a datagram routing algorithm for LEO satellite networks. The algorithm is distributed, and routing decisions are met on a per-packet basis. The generated paths are loop-free and satellite movement have negligible effect on the path optimality.
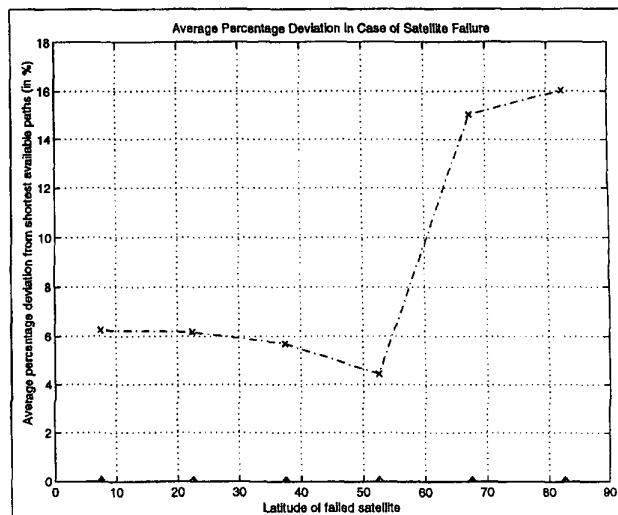
Our new algorithm is capable of avoiding congested regions by making local decisions. In case of satellite failures, the protocol is also capable of routing packets around the location of failure with low degradation in performance.

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