Logical Topology-Based Routing in LEO Constellations

YURONG HU and VICTOR O. K. LI
Department of Electrical and Electronic Engineering
The University of Hong Kong, Hong Kong
{yrhu,vli}@eee.hku.hk

Abstract— Satellite communication is distinguished by global coverage and the ability to support a wide range of applications. LEO (Low Earth Orbit) satellite systems employing inter-satellite links offer rich connectivity in space and provide direct broadband access and personal communication service. One of the technical challenges for LEO systems is the design of efficient routing strategies tailored to their highly dynamic nature. In this paper, we present a new routing method which solves the routing problem effciently by overlaying a static logical topology over the physical constellation. The algorithm generates near-optimal shortest paths. The performance of our proposed scheme is evaluated through theoretical analysis and simulations.

I. Introduction

In the past decade, there has been renewed interests in satellite communication systems, thanks to continuous and rapid progress in communication, electronic, and space technology. Distinguished by its global coverage, inherent broadcast capability, bandwidth-on-demand flexibility, and the ability to support mobility, satellite communication is an excellent candidate to provide broadband integrated Internet services to globally scattered users. State-of-art satellite technologies, such as multi-beam antennas, on-board processing/switching, high bandwidth radio, and laser inter-satellite links (ISLs) are deployed in complicated LEO constellation networks.

Although inter-satellite links (ISLs) between satellites within line-of-sight of each other in the LEO satellite constellation enhance the system autonomy, they complicate the routing issue. In LEO constellations, there are two types of ISLs: fixed intra-plane ISLs connecting adjacent satellites in the same orbit and dynamic inter-plane ISLs connecting neighboring satellites in adjoining orbits. Inter-plane ISLs, due to the relative movements of satellites, suffer from continuously changing lengths. Furthermore, they are forced to switch off temporarily when the viewing angles or distances between two satellites change too fast for the steerable antennas to follow. This may occur between satellites in two counter-rotating orbits separated by seam regions (the shaded areas in Fig. 1) or when satellites enter polar regions where satellite orbits swap (Fig. 2). Therefore, the satellite network is highly dynamic and routing algorithms are required to handle frequent topological variations efficiently.

In recent years, some routing schemes proposed for LEO constellations have focused on connection-oriented scenarios [1], [2], [3], [4]. The main problem with connection-oriented routing is that an initial connection may experience link handovers (i.e., when any ISL along the connection is temporarily switched off), and/or connection handovers (i.e., when the connection is no longer valid for delivering packet to the destination) due to satellite movements. To maintain the connection in this highly dynamic environment, rerouting is necessary and will introduce

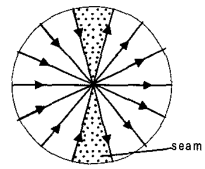

Fig. 1. LEO constellation

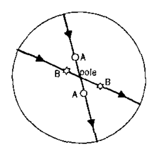

Fig. 2. Orbits swap

large overhead. With the increasing interests in providing Internet service via satellite systems, connectionless datagram routing has received much attention. [5] investigated IP routing in LEO constellations. In [6], a distributed routing algorithm, which routes packets with the goal of reducing the geographic distance to a packet's destination and by using a locally scoped shortest path algorithm, is studied. But its lack of robustness limits its usage.

To handle the dynamic nature of the network, two different concepts deserve attention. Chang et al. [7] modeled a LEO system as a Finite State Automaton (FSA) by dividing the system period[1] into a set of fixed length time intervals so that the topology can be regarded as static during each time interval which is referred to as a state. A number of consecutive routing tables for all states are then saved onboard and retrieved when the state changes. The algorithm requires large storage space. Another method [8] defined a virtual topology composed of virtual nodes, and packets are routed on this superimposed virtual network. Each virtual node (VN) is associated with a fixed portion of the Earth's surface. Within a period, a VN is represented by a nearest physical satellite. However, the fixed relation between a VN and terminals within a ground area can not be maintained because of satellite movements. Furthermore, careful investigation reveals that the virtual topology itself is dynamic. Routing over the virtual topology still has to handle dynamic topological changes.

In this paper, we propose a new algorithm, logical topology-based routing scheme, to overlay a static logical topology (LT)

[1] The system period is the least common multiple of the orbit period and the Earth's rotation period.

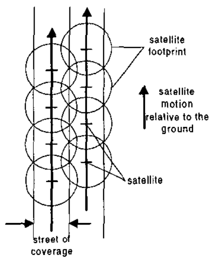

Fig. 3. Street of coverage

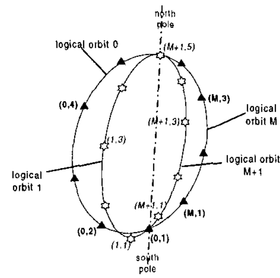

Fig. 4. Logical nodes

over the LEO constellation and hide the dynamic topology from the routing procedure executed on the logical topology. The rest of the paper is organized as follows. In Section II, we explain the construction of the static logical topology and routing method used. Section III presents performance analysis and related simulation results for our new scheme. The last section concludes the paper.

II. Logical topology-based routing

A. Logical topology

We first neglect the effect of the Earth's rotation. In the constellation, we assume the orbits are pure polar and circular and the Earth is perfectly spherical. Suppose there are M orbits evenly spaced apart. The inter-plane separation is $\beta = \frac{\pi}{M}$ in radians. The orbits are sequentially numbered from 0 to $M-1$ from west to east, to allow orbit 0 and $M-1$ to be two neighboring counter-rotating orbits. In each orbit, N satellites are distributed evenly with angular separation of $\alpha = \frac{2\pi}{N}$ and move at constant speed along the orbit forming a street coverage pattern, as illustrated in Fig. 3. Satellites in adjacent orbits are staggered at an angular distance of $\frac{\alpha}{2}$ for maximum ground coverage. Each satellite is connected to its eight nearest neighbors by ISLs: the four closest in the same orbit, the closest one in each adjacent orbit, and the closest one in each orbit next to the adjacent orbits. The satellite on the edge of the seam keeps only one inter-plane ISL active across the seam. Besides, the inter-plane ISLs are switched off temporarily near the polar regions. The geographical location of each satellite is given by (p_{lon}, p_{lat}) indicating the longitude and latitude, with positive value for longitude east and latitude north, and negative value for longitude west and latitude south.

Our static logical topology is set up as follows. We put N evenly spaced, fixed logical nodes (LNs) in every orbit, and then divide a physical circular orbit i $(i = 0, 1, ..., M-1)$ into two half-circle logical orbits (LOs) i and $i+M$, separated by the north and south poles. The distributions of logical nodes in the two half-circle LOs are guaranteed to be symmetric. In each LO, LNs are sequentially numbered with increasing latitude values from 1 to $\lfloor\frac{N}{2}\rfloor$ or $\lceil\frac{N}{2}\rceil$ (when N is an odd number, two half-circle logical orbits may contain $\lfloor\frac{N}{2}\rfloor$ and $\lceil\frac{N}{2}\rceil$ nodes respectively). To break the tie when an LN is put on the south or north pole where the two half-circle LOs separate, we define the LN on the south pole as belonging to LO i $(i = 1, 2, ..., M-1)$, while an LN on the north pole is in LO j $(j = M, ..., 2M-1)$. Thus, each LN is identified by (o, s), where $o = 0, 1, ..., 2M-1$ is the logical orbit number and $s = 1, 2, ..., \lfloor\frac{N}{2}\rfloor$ or $\lceil\frac{N}{2}\rceil$ is the logical satellite number in LO o. We also stagger the LNs in adjacent logical orbits for $\frac{\alpha}{2}$ radians. A simple example with $N = 9$ is illustrated in Fig. 4. To simplify the analysis, we put LN 1 in LO 0 at the south pole.

For each of the MN logical nodes, there is a one-to-one mapping to an actual satellite, together with the mapping from ISLs to logical links (LLs) with the same capacity. Due to satellite movements, a particular satellite is not coupled with an LN permanently. A subsequent satellite in the same physical circular orbit approaching the LN will take over the responsibility. A logical node is represented by a satellite for a certain period. We define this period as $T_c = \frac{T_o}{N}$, where T_o is the orbital period for the satellite to rotate around the Earth once. The one-to-one mapping refreshes synchronously every T_c. Each satellite will repeatedly represent N logical nodes pertaining to two LOs.

While the mapping between physical and logical topology remains unchanged during T_c, their relative positions deviate slightly while the satellites move. The fixed logical topology overlaps exactly with a snapshot of the physical topology once every T_c. If the connectivity pattern in the physical topology does not change within T_c, the LT is static. Even if the link connectivity changes, the variations in each T_c are identical because of LEO constellation symmetry. Within each T_c, the following two events may trigger a topological change:

- Satellites embodying LNs in polar regions cross polar region boundary and all its ISLs are temporarily switched off.
- Two satellites, as two ends of a seam-crossing ISL, move too far apart and each has to handover the seam-crossing ISL to another satellite.

Since the satellites in different orbits move synchronously, each of the above two events can occur at most once within each T_c. Therefore, in the worst case, there will be three different static topologies within each T_c.

So far, we have neglected the effect of Earth's rotation and the LT is fixed under this assumption. Note that, for stationary users on the Earth's surface, the LT moves at the same speed but

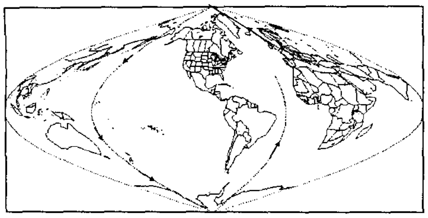

Fig. 5. A satellite's track on the Earth's surface

in the reverse direction of the Earth's self-rotation. The whole LT drifts over the Earth from east to west. Let us project a satellite's track over a period on the Earth's surface (see Fig. 5). The movements can be decomposed into two components: one along the longitude and the other along the latitude. A satellite's orbital behavior causes its movement along the longitude, while the effect of Earth's self-rotation accounts for the horizontal shift of the satellite's track. By deploying the LT, the former factor is concealed by the mapping from actual satellites to LNs, and the shift of the whole LT itself reflects the latter element.

B. Routing scheme

Since the logical topology is static, we can simply use static routing over the logical topology. The minimum-hop or shortest paths from an LN to any other nodes are precalculated, stored in LNs, and retrieved when necessary. Each node keeps routing entries containing information {destination node, next hop ID, ISL ID} for all other LNs and hop-by-hop forwarding is performed when packets arrive. We assume packets carry information of the egress node, either explicit identities of destination LNs or geographic locations of destination terminals. If the packet header only contains geographic position of the destination terminal as (D_{log}, D_{lat}), the ingress node (o_{in}, s_{in}), knowing its own geographic position $(p_{lon}^{in}, p_{lat}^{in})$ (in fact, the position of the satellite representing it), will determine the egress point (o_e, s_e) with the following formula[2]:

$$o_e = \left\lceil o_{in} + \frac{(D_{lon} - p_{lon}^{in})2M}{360^o} - 1 \right\rceil \bmod 2M \qquad (1)$$

$$s_e = \begin{cases} \left\lceil s_{in} + \frac{(D_{lat} - p_{lat}^{in})N}{360^o} - 1 \right\rceil, \\ \quad |o_e - o_{in}| \ is\ even \\ \left\lceil s_{in} + \frac{(D_{lat} - p_{lat}^{in})N}{360^o} + \frac{(-1)^{o_{in}}}{2} - 1 \right\rceil, \\ \quad |o_e - o_{in}| \ is\ odd \end{cases}$$

Due to LT shifting, a user will be served by different LNs as time passes. If the user session persists for a long time, packets would traverse the LEO constellation through different ingress and egress nodes, thus taking totally different paths. The decision on the egress node is made in a timely manner on a per-packet basis. Therefore, the effect of complicated rerouting and path modification in connection-oriented schemes is automatically provided by our simple calculation.

[2] $x \bmod y$ is the positive remainder after dividing x by y.

When an LN receives a packet with egress LN in the header, it simply forwards the packet onto the desired ISL or transmits it downlink according to the routing table. We summarize the forwarding operation in the following pseudo-program.

small *At a logical node* (o, s) *embodied by a satellite whose current position is* (p_{lon}, p_{lat})*:*

```
while(new packet arrives)
{ check the header
  if(header contains destination terminal position (D_lon, D_lat))
  {   determine egress node ID by (1);
      add egress node ID (o_e, s_e) to the header;
  }
  search the routing table for entry (o_e, s_e),
  forward packet to next hop accordingly;
}
```

III. Performance Evaluation

We now evaluate the performance of our proposed routing algorithm using analytical and simulation models. In all simulations, we use a Teledesic-like LEO constellation which consists of $M = 12$ orbital planes and $N = 24$ satellites per orbit with an orbital altitude of 1375 km. Thus, the orbital period is roughly $T_o = 113\, min$. We set the polar region boundary at latitude 70^o in the Northern and Southern hemispheres. Satellites entering these polar regions will switch off all their inter-plane ISLs.

A. Implementation complexity

The implementation complexity comprises mainly onboard computational and storage requirements. In our logical topology-based static routing scheme, shortest path calculation is completed offline. The implementation complexity is only due to the storage requirement of routing tables. We will compare our strategy with FSA [7] which also employs offline static routing scheme. In our scheme, each satellite will sequentially represent N logical nodes. Considering the periodical connectivity pattern discussed in Section II, each logical node needs to carry at most three sets of routing tables. Therefore, at most $3N$ routing tables are maintained by each satellite. However, in Chang et al.'s algorithm, in order to obtain performance comparable to our scheme, the system should be modeled as an FSA with $\frac{3T_E}{T_c} = \frac{3NT_E}{T_o}$ states. Each satellite has to store up to $\frac{3NT_E}{T_o}$ routing tables. Its implementation complexity is $\frac{T_E}{T_o}$ times that of our proposal. For the simulated constellation where $T_o = 113\, min$, our scheme reduces the onboard storage requirement by a factor of 12. The low implementation complexity is achieved by the mapping of physical and logical topology in which the periodical nature of the satellite constellation is fully utilized to reduce redundant information onboard the satellites as much as possible.

B. Path length variation

When the routing table is calculated over the static logical topology, the shortest path between any two logical nodes is generated with static lengths. However, because of the deviation

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in position between logical nodes and agent satellites, static path lengths are not the actual distances the packets have to travel. In LT, static lengths of horizontal LLs are incapable of reflecting the varying lengths of inter-plane ISLs. The general formula to calculate the actual distance of an inter-plane ISL between two satellites positioned at (p^1_{lon}, p^1_{lat}) and (p^2_{lon}, p^2_{lat}) is given as follows:

$$l = H\left\{2 - cos(p^1_{lat} - p^2_{lat})[1 + cos(p^1_{lon} - p^2_{lon})] + [1 - cos(p^1_{lon} - p^2_{lon})]cos(p^1_{lat} + p^2_{lat})\right\}^{\frac{1}{2}}$$

where $H = R_E + h$, R_E is the radius of the Earth, and h is the orbit altitude. According to different patterns of the associated inter-plane ISLs, we classify horizontal LLs into three categories: LLs between adjacent non-counterrotating LOs, LLs connecting nodes in LOs next to the neighboring LOs, and seam-crossing LLs. We will next investigate the actual length variations for each of them. The length variation here refers to the difference between actual distance (in fact, the length of ISLs) and the static length of LLs.

- Type 1

For a non-seam-crossing LL between neighboring LOs, we can simplify the above general formula as:

$$l_1 = H\sqrt{2 - cos\frac{\alpha}{2}(1 + cos\beta) + (1 - cos\beta)cos(2x + \frac{\alpha}{2})}$$

in which, x and $x + \frac{\alpha}{2}$ are latitude values of two satellites currently embodying end nodes of this LL ($0 \le x < \delta - \frac{\alpha}{2}$, and $0 < \delta < \frac{\pi}{2}$ is the latitude value of polar region boundary[3]). We define function $f_1(z) = \sqrt{a + bcos(z)}$, where $0 < z < \pi$, a and b are constants. Then, $l_1 = Hf_1(\frac{z - \frac{\alpha}{2}}{2})$, $a = 2 - cos\frac{\alpha}{2}(1 + cos\beta)$, $b = 1 - cos\beta$, and $x = \frac{z - \frac{\alpha}{2}}{2}$. We can prove $f_1(z)$ is monotonously decreasing. The largest possible variation occurs when the position discrepancy between LOs and the agent satellites reaches $\frac{\alpha}{2}$. We use function $g_1(z) = f_1(z) - f_1(z + \alpha)$ to describe it. Therefore, the maximum length variation is $\Delta l_1 = H \cdot max\, g_1(z)$, $0 < z < \pi$. The following conditions hold: $\frac{d f_1^2(z)}{dz}|_{z=z^*} = 0$ and $\frac{d f_1^3(z)}{dz}|_{z=z^*} > 0$ when $z^* = arc\ cos(\frac{\sqrt{a^2 - b^2} - a}{b})$ (it is easy to prove $a > b$ here). Thus, $f_1'(z)$ reaches a minimum at $z^* = -\frac{1}{2}\sqrt{2a - 2\sqrt{a^2 - b^2}}$. We can get Δl_1 as

$$\begin{aligned}\Delta l_1 &= H \cdot max\, g_1(z) = H \cdot max\ (f_1(z) - f_1(z + \alpha)) \\ &\le H\,|f_1'(z^*)|\,\alpha = H\frac{\alpha}{2}\sqrt{2a - 2\sqrt{a^2 - b^2}}\end{aligned}$$

- Type 2

The Type 2 LLs are similar to Type 1, but are parallel to the latitude lines. The length of a Type 2 LL can be calculated by $l_2 = 2Hcosx\, sin\beta$, in which x is the latitude value of two associated agent satellites ($0 \le x < \frac{\pi}{2}$). The maximum possible length variation is obtained when x changes by $\alpha/2$, which is

$$\begin{aligned}\Delta l_2 &= max\left(2\,H\, sin\beta\, \left(cosx - cos(x + \frac{\alpha}{2})\right)\right) \\ &\le 4\,H\, sin\beta\, sin\frac{\alpha}{4}\end{aligned}$$

- Type 3

For a seam-crossing LL, the two satellites representing the LL end nodes change their relative positions when moving along two neighboring counter-rotating orbits. Since their speeds are the same, $(p^1_{lat} + p^2_{lat})$ remains unchanged, but $(p^1_{lat} - p^2_{lat})$ may change by a value varying from $\frac{3\alpha}{2}$ to $-\frac{3\alpha}{2}$. We can formulate the LL length as $l_3 = H\, f_2(z, x)$.

$$f_2(z, x) = \sqrt{2 - cosz\,(1 + cos\beta) + (1 - cos\beta)\, cos(2x)}$$

in which $-\frac{\alpha}{2} \le z \le \frac{\alpha}{2}$, and $0 \le x \le \delta$. $f_2(z, x)$ is monotonously increasing with $|z|$. Thus, the largest length variation will be

$$\begin{aligned}g_2(x) &= f_2(\frac{3\alpha}{2}, x) - f_2(0, x) \\ &= \sqrt{4cos^2\frac{\beta}{2}sin^2\frac{3\alpha}{4} + (2sin\frac{\beta}{2}cosx)^2} - 2sin\frac{\beta}{2}cosx \\ &= \sqrt{c + U^2} - U\end{aligned}$$

We define $c = 4cos^2\frac{\beta}{2}\, sin^2\frac{3\alpha}{4}$ and $U = 2sin\frac{\beta}{2}\, cosx$. Considering that $\frac{d\,g_2(x)}{dx} = \frac{d\,g_2(x)}{dU}\frac{dU}{dx} \ge 0$, the maximum value for $g_2(x)$ is

$$\begin{aligned}\Delta l_3 &\le H\, g_2(\delta) \\ &= 2H\left(\sqrt{cos^2\tfrac{3\beta}{4}sin^2\tfrac{\alpha}{4} + sin^2\tfrac{\beta}{2}cos^2\delta} - 2sin\tfrac{\beta}{2}cos\delta\right)\end{aligned}$$

Between an LN pair (o_o, s_o) and (o_d, s_d), there is a shortest path containing horizontal and vertical LLs obtained by the static algorithm in LT with a static total length of PL_s. However, the actual distance PL of the path varies over time. Length variation of the path is only caused by variation of the horizontal LLs. The maximum number of horizontal hops that may be contained in the path is

$$N_h = \begin{cases} |o_o - o_d| + 1, & |o_o - o_d| \le M \\ 2M - |o_o - o_d| + 1, & |o_o - o_d| > M \end{cases}$$

These horizontal hops may include at most a seam-crossing LL and others are non-seam-crossing LLs. The largest path length variation can then be expressed as

$$\Delta PL \le \begin{cases} (N_h - 1)\,\Delta l_1 + max\,(\Delta l_1, \Delta l_3),\ 2\Delta l_1 \ge \Delta l_2 \\ \lfloor\frac{N_h}{2}\rfloor\,\Delta l_2 + max(\Delta l_1, \Delta l_3),\ 2\,\Delta l_1 < \Delta l_2 \end{cases}$$

[3]We only consider LLs in the North Hemisphere because of the symmetry of the topology.

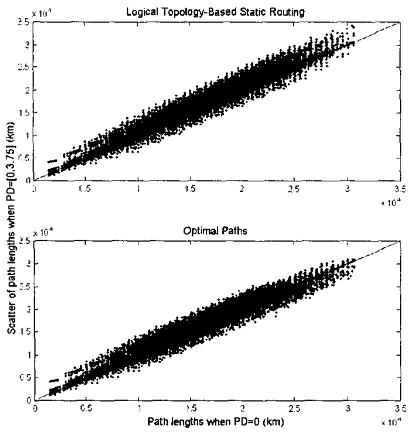

Fig. 6. Scatter of path lengths

Thus, $PL \in [PL_s - \Delta PL, PL_s + \Delta PL]$.

Applying the above analytical formulas to the LEO constellation used in this paper, a set of numerical results are listed below: $\Delta l_1 = 0.0212H$, $\Delta l_2 = 0.0677H$, and $\Delta l_3 = 0.3077H$. By computing the upper bound of the path length variation, we can easily estimate the worst case propagation delay for packets traversing the LEO constellation. In satellite networks where path lengths change dramatically, this kind of estimation is very important, especially for real time traffic with transmission deadlines.

C. Path Optimality

Our new algorithm generates shortest paths based on the superimposed static logical topology. But the precalculated shortest path between two LNs may not be the optimal path between the two corresponding satellites when satellites do not overlap logical nodes exactly. In the simulated constellation, two distinct logical topologies are taken alternatively within each T_c. Therefore, we check the path optimality while the position discrepancy (PD) between physical and logical topology varies within $(0, \frac{\alpha}{4})$. In the simulation, $PD \in [0, 3.75^o]$. We use a step size of 0.375^o.

We use our new algorithm to generate shortest paths for logical node pairs in the logical network. Optimal paths are created between satellite pairs over the physical network when PD takes different values. We calculate the actual distance for each path obtained by our algorithm and that by the optimal algorithm for all 11 different PD values. The scatter of path lengths for both algorithms are depicted in Fig. 6. In each subfigure of Fig. 6, we check those points with the same values on horizontal axis. The horizontal axis reflects the optimal path length for a satellite pair when $PD = 0$. The vertical axes correspond to path lengths between the same satellite pair while $PD \in (0, 3.75^o]$, changing with a step size of 0.375^o, for our algorithm and the optimal scheme, respectively. The pictures reveal that when position discrepancy between logical and physical network exists, the scatter of path lengths of our algorithm is a little wider than that of the optimal paths. Generally, the average path length of our algorithm is larger. But the difference is small. We then compare our path length with that of the optimal path and plot the average deviation percentage versus position discrepancy in Fig. 7. The result shows that even in the worst case ($PD = 3.75^o$), the average path length difference between paths obtained by our algorithm and the optimal paths is less than 6%. The paths generated by our new scheme are near-optimal.

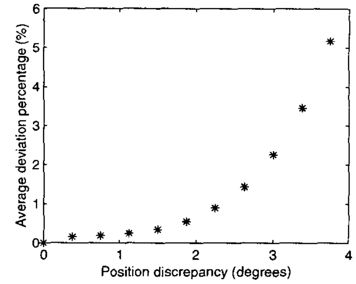

Fig. 7. Average deviation percentage

IV. Conclusion

In this paper, we have introduced a logical topology-based hop-by-hop routing algorithm for LEO constellation networks. By overlaying a static logical topology over LEO constellation and taking full advantage of the periodic and symmetric nature of the satellite network, our new scheme provides an efficient solution to decompose and conceal the complex topology dynamics. It avoids the complicated rerouting and routing modification in connection-oriented schemes and is capable of providing near-optimal paths for satellite pairs with low implementation complexity.

Acknowledgments

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References

[1] M. Werner, "A Dynamic Routing Concept for ATM-based Satellite Personal Communication Networks," *IEEE J. Select. Areas Commun.*, vol. 15, no. 8, Oct. 1997, pp. 1636-1648.

[2] M. Werner, C. Delucchi, H. J. Vogel, G. Maral, and J. D. Ridder, "ATM-based Routing in LEO/MEO Satellite Networks with Intersatellite Links," *IEEE J. Select. Areas Commun.*, vol. 15, no. 1, Jan. 1997, pp. 69-82.

[3] H. Uzunalioglu, M.D. Bender, and I.F. Akyildiz, "A Routing Algorithm for LEO Satellite Networks with Dynamic Connectivity," *ACM-Baltzer Journal of Wireless Networks (WINET)*, vol. 6, no. 3, June 2000.

[4] H. Uzunalioglu, and Y. Wang, "Managing Connection Handover in Satellite Networks," *Proc. IEEE GLOBECOM '97*, pp. 1606-1610.

[5] L. Wood, A. Clerget, I. Andrikopoulos, G. Pavlou and W. Dabbous, "IP Routing Issues in Satellite Constellation Networks," *Int. J. Satellite Commun.*, to appear.

[6] T. Henderson, "Networking over Next-Generation Satellite Systems", Ph.D Dissertation, Univ. of California at Berkeley, 1999.

[7] 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 Trans. Vehicular Tech.*, vol. 47, no. 3, Aug 1998, pp. 1037-1048.

[8] R. Manger and C. Rosenberg, "QoS Guarantees for Multimedia Services on a TDMA-Based Satellite Network," *IEEE Communications Magazine*, July 1997, pp. 56-65.