MLSR: A Novel Routing Algorithm for Multilayered Satellite IP Networks

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Abstract—**Several IP-based routing algorithms have been developed for low-Earth orbit (LEO) satellite networks in recent years. The performance of the satellite IP networks can be improved drastically if multiple satellite constellations are used in the architecture. In this work, a multilayered satellite IP network is introduced that consists of LEO, medium-Earth orbit (MEO), and geostationary Earth orbit (GEO) satellites. A new multilayered satellite routing algorithm (MLSR) is developed that calculates routing tables efficiently using the collected delay measurements. The performance of the multilayered satellite network and MLSR is evaluated through simulations and analysis.**

Index Terms—**GEOs, IP routing, LEOs, MEOs, satellite networks.**

I. INTRODUCTION

SATELLITE networks provide global coverage, are capable of consistently sustaining high bandwidth levels, and support flexible and scalable network configurations. Currently, more than half of the world lacks a wired network infrastructure. Locally built networks and individual hosts can easily be connected to the rest of the world by installing satellite interfaces. They also constitute alternatives to terrestrial links. In case of link failures and congestions, traffic can be routed through satellites.

One of the challenges of satellite networks is the development of specialized routing algorithms. The routing algorithms for satellite networks should compute paths with low communication and computational overhead, and adapt the routing decisions to the dynamic satellite network topology in real time. Connection-oriented routing has been the focus of the research for the low-Earth orbit (LEO) satellite networks in recent years. Connection-oriented routing proposals assume ATM-like switches in the satellites. The connections must be established and maintained in the satellite network, which is

a very dynamic environment. There are different approaches to solve connection-oriented routing problem. The heuristic routing algorithm proposed in [1], [2] aims to reduce the number of path handovers due to the satellite mobility. The algorithm presented in [3] uses the snapshots of the constellation to optimize the paths. A quality-of-service (QoS)-based LEO satellite network is described in [4], which includes a routing scheme that resembles minimum hop routing in Manhattan Street Networks [5]. The probabilistic routing protocol (PRP) introduced in [6] aims to maintain the initial paths as long as possible to minimize the signaling overhead. In [7], a two-layered satellite network architecture consisting of LEO and medium-Earth orbit (MEO) satellite networks and a routing algorithm are proposed.

With the explosive growth of the Internet, connectionless routing is being pushed to satellite networks. To realize this, satellites carry IP switches that forward packets independently. These IP switches are connected to each other as well as to ground stations. There are several proposals regarding the IP-based routing in satellite networks. The so-called *Darting* algorithm delays the exchange of topology update information until it is necessary to send data packets [8]. However, it is shown in [9] that the Darting algorithm does not reduce the protocol overhead. The datagram routing algorithm [10] aims to route the packets on minimum propagation delay paths using a distributed routing protocol. The routing protocol presented in [11] uses a hybrid approach that uses geographic-based routing and shortest path routing with limited scope.

The existing routing algorithms described above for satellite IP networks are based on the LEO satellites architectures only. However, we believe that a combination of different layers of satellites, such as LEO, MEO, and geostationary Earth orbit (GEO) satellites, would yield a much better performance than these layers individually. Therefore, we propose a satellite network architecture that consists of satellites in three layers, and introduce the multilayered satellite routing algorithm (MLSR) that calculates shortest delay paths efficiently between the satellites in the satellite network and the gateways on the Earth. With MLSR, the routing tables are updated regularly to cope with the satellite mobility and the changes in the network load.

The paper is organized as follows. In Section II, the multilayered satellite network architecture is presented. The definitions used in the paper are given in Section III. In Section IV, the new routing algorithm, MLSR, is presented in detail. The performance evaluation of MLSR is presented in Section V. Finally, Section VI concludes the paper.

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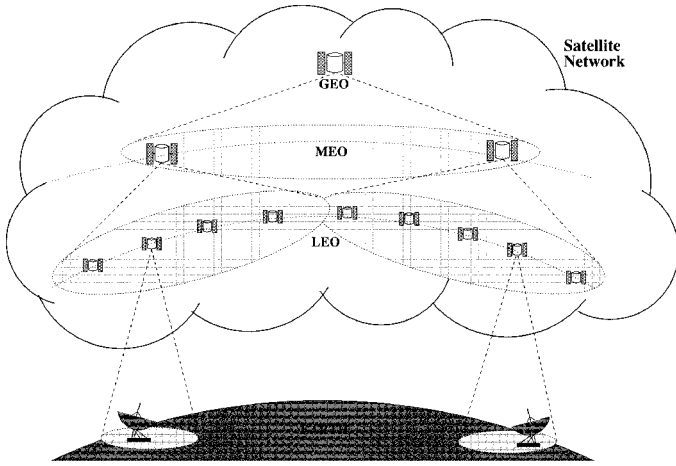
Fig. 1.   Proposed multilayered satellite network.

II. MULTILAYERED SATELLITE NETWORK ARCHITECTURE

A. Satellite Layers

The satellite network architecture is divided into three layers that each cover the entire globe.

1) *GEO Layer:* The GEO layer is composed of all GEO satellites in the satellite network. The GEO satellites, by definition, have the same revolution cycle as the Earth. Consequently, they appear stationary when observed from the Earth. The total number of satellites in the GEO layer is assumed to be N_{G}, and they are organized as a belt above the equator.

2) *MEO Layer:* The MEO layer refers to the collection of all MEO satellites in the network. This layer is positioned at an altitude between the GEO and the LEO layers. We assume that there are N_{M} MEO satellites. The constellation of the MEO satellites can be arbitrary as long as global coverage is achieved at all times.

3) *LEO Layer:* The LEO layer consists of all LEO satellites in the network. This layer has the lowest altitude among the three satellite layers. The LEO layer contains N_{L} satellites. We assume that the LEO satellites form a Walker Star type [12] constellation.

Currently, GEO, MEO, and LEO satellite networks exist individually. As stated before, their collaborative use will increase the capacity, reliability, and performance in global scale communications. A section of the proposed multilayered satellite network is depicted in Fig. 1. The terrestrial gateways are covered by LEO, MEO, and GEO satellites. Once the packets are sent to the satellite network, they are routed to the destination gateway independently over multiple satellite hops in possibly different layers. The routing decisions inside the satellite network is isolated from the terrestrial networks. Note that the number of satellites in a layer decreases with the increasing altitude. Therefore, we assume throughout the paper that $N_{\mathrm{L}} > N_{\mathrm{M}} \gg N_{\mathrm{G}}$.

B. Logical Location Concept and Satellite Notation

In the satellite network, the LEO and MEO satellites move with respect to the Earth. In [10], the *logical location* concept

was introduced to cope with the problems caused by the mobility of LEO satellites. In this approach, the entire LEO constellation is divided into grid points. The grid points are spaced with equal angular distances. The LEO satellite closest to the center of a logical location is assigned to that logical location. When the satellite assigned to a logical location changes, the successor satellite must take the necessary routing information from its predecessor. The links adjacent to the predecessor LEO satellite are also switched to the new LEO satellite.

In our satellite network architecture, we use the logical location concept to isolate the mobility of the LEO satellites from the satellites in upper layers. Unlike the datagram routing algorithm [10], which uses the logical locations to compute paths, our routing algorithm uses the logical location concept to form groups of LEO satellites. The formation of the satellite groups is described in Section II-D. The MEO satellites can be organized in an arbitrary manner as long as global coverage is provided at all times. Similarly, it is assumed that there are enough GEO satellites to provide global coverage.

A satellite in the GEO layer is denoted by G_i. Similarly, $M_{i,j}$ denotes a satellite in the MEO layer which is in the coverage area of the GEO satellite G_i. A LEO satellite $L_{i,j,k}$ is in the coverage area of the GEO satellite G_i and the MEO satellite $M_{i,j}$. In general, the coverage areas of two satellites of the same satellite layer may overlap, e.g., two neighboring MEO satellites may cover the same LEO satellite. In order to keep the notation simple, we will assume that such satellites communicate with only one of the satellites of the same higher layer. The described algorithms can be generalized to include satellites maintaining links to multiple satellites of the same higher layer.

C. Links in the Network

The satellites maintain three types of links.

1) *Inter-Satellite Links (ISLs):* The communication within a layer is accomplished over inter-satellite links (ISLs). The LEO satellites are connected to their four immediate neighbors in the same layer via duplex ISLs. The MEO satellites are always connected to their immediate neighbors in the same orbit. The inter-orbital ISLs between the MEO satellites are maintained whenever possible. Hence, at any given time, every MEO satellite $M_{i,j}$ is connected to $\mathbf{N}(M_{i,j})$ other MEO satellites in the same layer, where $\mathbf{N}()$ is a function that returns the number of neighbors of a satellite in the same layer. The GEO satellites also communicate with their two immediate neighbors through ISLs. $\mathrm{ISL}_{s \rightarrow d}$ denotes an ISL that connects satellites s and d in the same layer.

2) *Inter-Orbital Links (IOLs):* The communication between satellites in different layers occur over inter-orbital links (IOLs). In our architecture, IOLs connect each satellite with other satellites in its coverage area in the lower layers. The satellites in the lower layers maintain IOLs to satellites that cover them, as well. If two satellites s and d are in different layers, and the satellite in the higher layer covers the satellite in the lower layer, then they are connected with two IOLs, which are denoted by $\mathrm{IOL}_{s \rightarrow d}$ and $\mathrm{IOL}_{d \rightarrow s}$. Note that the satellite s may be in the GEO

layer and the satellite d may be in the LEO layer, i.e., the IOLs are not necessarily established between satellites in adjacent layers.

3) *User Data Links (UDLs):* The satellites communicate with the terrestrial gateways over user data links (UDLs). A satellite can maintain UDLs to multiple terrestrial gateways. Similarly, a terrestrial gateway may be directly connected to multiple satellites in different layers. A UDL between a satellite s and a terrestrial gateway T is denoted by $\mathrm{UDL}_{s \rightarrow T}$, where s can be any satellite in any layer, as long as it covers T.

D. Satellite Groups

In order to reduce the computational complexity in the satellites and the communication load on the network, the satellite network is organized hierarchically. In this hierarchy, satellites are grouped and their management is given to a satellite in the upper layer. The hierarchical organization is used for routing table calculations. The data packets are forwarded independent of this hierarchy. There are two types of satellite groups in our architecture.

1) *LEO Groups:* A LEO group $\mathcal{L}_{i,j}$ is the collection of all LEO satellites that are in the coverage area of the MEO satellite $M_{i,j}$, i.e., $\mathcal{L}_{i,j} = \{L_{i,j,k} \,|\, k = 0, \dots, \mathbf{S}(\mathcal{L}_{i,j}) - 1\}$, where $\mathbf{S}()$ is a function that calculates the size of a satellite group. All satellites in a LEO group $\mathcal{L}_{i,j}$ are connected to the MEO satellite $M_{i,j}$, which is the manager of that LEO group. The LEO groups may be composed of different number of satellites. There is a one-to-one correspondence between LEO groups and their managers.

2) *MEO Groups:* A MEO group $\mathcal{M}_i$ is the collection of all MEO satellites that are in the coverage area of the GEO satellite G_i, i.e., $\mathcal{M}_i = \{M_{i,j} \,|\, j = 0, \dots, \mathbf{S}(\mathcal{M}_i) - 1\}$, where $\mathbf{S}()$ is a function that calculates the size of a satellite group. All satellites in a MEO group $\mathcal{M}_i$ are connected to the GEO satellite G_i, which is the manager of that MEO group. Similar to the LEO groups, the MEO groups may also be composed of different number of satellites. There is a one-to-one correspondence between MEO groups and their managers.

The group membership in the LEO layer is coupled with the logical location of the satellites. Although LEO satellites may move in and out of the coverage area of a MEO satellite, the group membership does not change as long as the MEO satellite covers the same set of logical locations. The membership of MEO groups are tightly coupled with the individual satellites. Hence, the MEO group membership changes when a MEO satellite moves out of the coverage area of a GEO satellite. In case a satellite is in the coverage area of more than one satellite of the same upper layer, its management is given to the closest satellite in the upper layer. Since the movement of the satellites is deterministic, the timing of group membership changes can be calculated in advance.

A sample grouping in the satellite network is shown in Fig. 2, where a GEO satellite G_0 and satellites in its coverage area are illustrated. In this example, the LEO satellites are
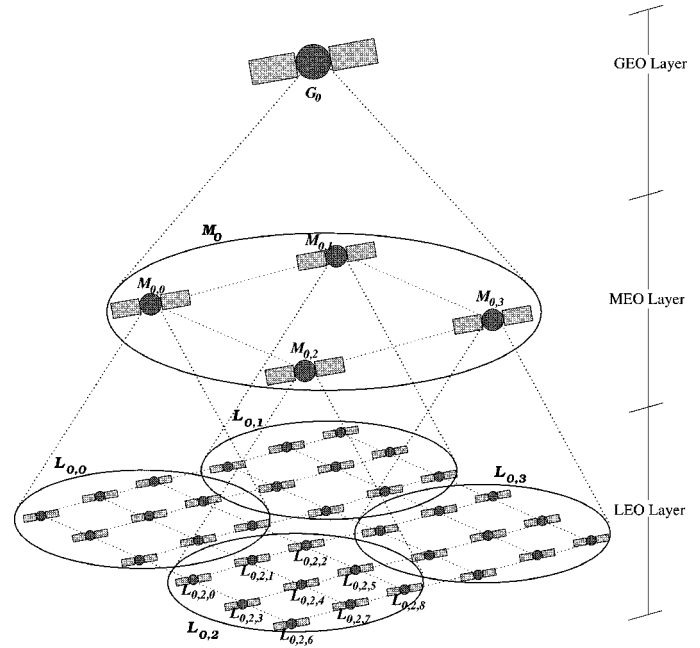

Fig. 2. Hierarchical organization of the satellite network.

organized in four groups of size nine. The LEO and MEO groups have the same subscripts as their manager satellites. The LEO groups $\mathcal{L}_{0,0}, \dots, \mathcal{L}_{0,3}$ are managed by the MEO satellites $M_{0,0}, \dots, M_{0,3}$, respectively. The four MEO satellites $M_{0,0}, \dots, M_{0,3}$ constitute the MEO group $\mathcal{M}_0$, which is managed by the GEO satellite G_0. The IOLs and UDLs are omitted in Fig. 2. Note that the satellites in a given layer actually move in circular orbits at the same altitude, which form an imaginary sphere. The circular orbits of LEO and MEO satellites can also be seen in the snapshot of the multilayered satellite network in Fig. 1. The satellite layers depicted in Fig. 2 are projections of the convex surfaces created by the orbits to planar surfaces.

In the LEO layer, a large number of satellites is needed to achieve global coverage. In order to reduce the computational burden on the GEO satellites that calculate the routing tables, the LEO groups are represented as nodes. Hence, the details of the LEO layer topology are hidden from the GEO satellites, which makes the routing table calculations easier. The part of the satellite network shown in Fig. 2 is reduced to the topology shown in Fig. 3.

III. DEFINITIONS

In the satellite network, the links are associated with delays. The total delay is composed of propagation, processing, and queueing delays, and is measured by the upstream satellites. The upstream satellite calculates the propagation delay to the downstream satellite from their relative positions in the space. The processing delay is approximated by the average time needed to perform routing table lookup. The queueing delay is determined from the length of the queue at the time of the measurement, the average packet size, and the link capacity. The average total delay is the sum of these three delay components. The delay functions $\mathcal{D}$ and $\mathcal{D}^+$ return the average delay between two nodes
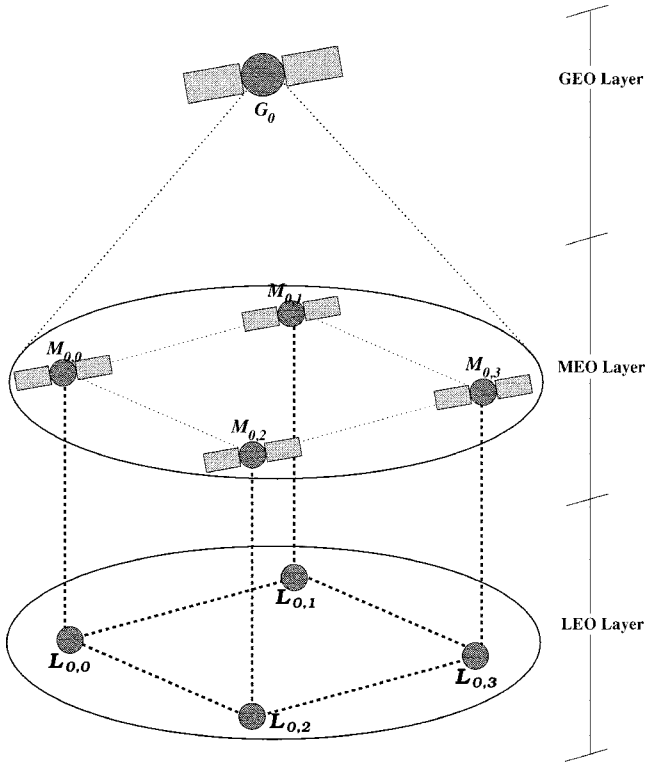
Fig. 3.   GEO view of the multilayered satellite network.

if there exists a direct link between them. If such a link does not exist, then $\mathcal{D}$ returns infinity and $\mathcal{D}^+$ returns zero. The functions $\mathcal{D}$ and $\mathcal{D}^+$ are used to calculate the delay measurement reports (Definition 3) and summary links (Definition 2), respectively.

Definition 1 (Delay Functions $\mathcal{D}$ and $\mathcal{D}^+$): Let $l_{a\to b}$ be a direct link from node a to node b. The delay function $\mathcal{D}(l_{a\to b})$ is defined as

$$\mathcal{D}(l_{a\to b}) = \begin{cases} \text{Delay from } a \text{ to } b, & \exists l_{a\to b} \\ \infty, & \text{otherwise.} \end{cases} \quad (1)$$

The existing delay function $\mathcal{D}^+(l_{a\to b})$ is defined as

$$\mathcal{D}^+(l_{a\to b}) = \begin{cases} \mathcal{D}(l_{a\to b}), & \exists l_{a\to b} \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

In the GEO layer, the individual LEO satellites are not considered for routing table calculations. Instead, every LEO group stands for all its LEO satellite members, and is represented as nodes. The links that connect the nodes that represent LEO groups to any other node in the network are called *summary links*. A summary link is chosen as the link with the longest delay that connects the members of a LEO group with another node in the network. As an example, the LEO group $\mathcal{L}_{0,2}$ and its manager MEO satellite $M_{0,2}$ are illustrated in Fig. 4. The summary link $\text{SL}_{\mathcal{L}_{0,2}\to M_{0,2}}^{Out}$, which represents the link from the LEO group $\mathcal{L}_{0,2}$ to its manager MEO satellite $M_{0,2}$, is chosen as the IOL with the largest delay that connects the members of the LEO group to $M_{0,2}$. If we assume that $\text{IOL}_{L_{0,2,3}\to M_{0,2}}$ has the largest delay, which is marked with a bold dashed line, then it is selected as the summary link SL^{Out} that connects the LEO group to the manager MEO satellite. In Fig. 3, the summary links are also shown as bold dashed lines. The summary links are formally defined as follows.
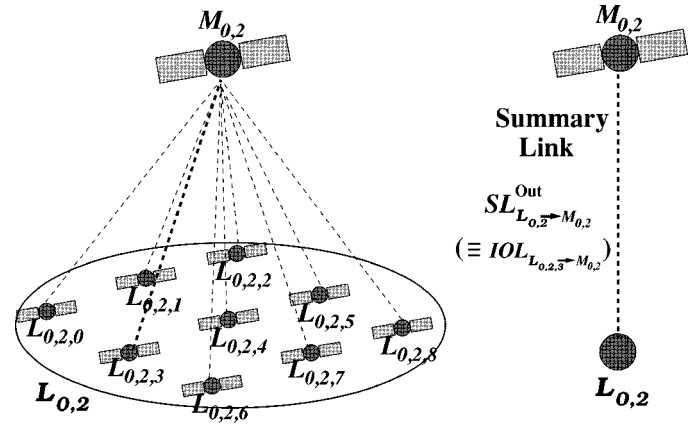

Fig. 4.   Example of summary link selection.

Definition 2 (Summary Link): Let $\mathcal{L}_{i,j}$ be a LEO group in the satellite network. The summary links SL adjacent to $\mathcal{L}_{i,j}$ are defined as follows.

1) The outgoing summary link $\text{SL}_{\mathcal{L}_{i,j}\to A}^{Out}$ from a LEO group $\mathcal{L}_{i,j}$ to any node A is the link with the longest delay that connects the members of $\mathcal{L}_{i,j}$ to the node A, i.e.,

$$\text{SL}_{\mathcal{L}_{i,j}\to A}^{Out} = \begin{cases} \arg\max_{0\le k<\mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}^+\left(\text{UDL}_{L_{i,j,k}\to A}\right), \\ \qquad \text{if } A \text{ is a gateway} \\ \arg\max_{\substack{0\le k<\mathbf{S}(\mathcal{L}_{i,j}) \\ 0\le r<\mathbf{S}(\mathcal{L}_{p,q})}} \mathcal{D}^+\left(\text{ISL}_{L_{i,j,k}\to L_{p,q,r}}\right), \\ \qquad \text{if } A = \mathcal{L}_{p,q}, \ (p,q)\neq(i,j) \\ \arg\max_{0\le k<\mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}^+\left(\text{IOL}_{L_{i,j,k}\to M_{i,j}}\right), \\ \qquad \text{if } A = M_{i,j} \\ \arg\max_{0\le k<\mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}^+\left(\text{IOL}_{L_{i,j,k}\to G_i}\right), \\ \qquad \text{if } A = G_i, \end{cases} \quad (3)$$

where $\arg$ returns the argument passed to the $\mathcal{D}^+$ function, and $\mathbf{S}()$ calculates the number of satellites in a group.

2) The incoming summary link $\text{SL}_{A\to\mathcal{L}_{i,j}}^{In}$ from a node A to a LEO group $\mathcal{L}_{i,j}$ is the link with the longest delay that connects the node A to the members of $\mathcal{L}_{i,j}$, i.e.,

$$\text{SL}_{A\to\mathcal{L}_{i,j}}^{In} = \begin{cases} \arg\max_{0\le k<\mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}^+\left(\text{UDL}_{A\to L_{i,j,k}}\right), \\ \qquad \text{if } A \text{ is a gateway} \\ \arg\max_{\substack{0\le k<\mathbf{S}(\mathcal{L}_{i,j}) \\ 0\le r<\mathbf{S}(\mathcal{L}_{p,q})}} \mathcal{D}^+\left(\text{ISL}_{L_{p,q,r}\to L_{i,j,k}}\right), \\ \qquad \text{if } A = \mathcal{L}_{p,q}, \ (p,q)\neq(i,j) \\ \arg\max_{0\le k<\mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}^+\left(\text{IOL}_{M_{i,j}\to L_{i,j,k}}\right), \\ \qquad \text{if } A = M_{i,j} \\ \arg\max_{0\le k<\mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}^+\left(\text{IOL}_{G_i\to L_{i,j,k}}\right), \\ \qquad \text{if } A = G_i, \end{cases} \quad (4)$$

where $\arg$ returns the argument passed to the $\mathcal{D}^+$ function, and $\mathbf{S}()$ calculates the number of satellites in a group.

To calculate the routing tables, satellites need to measure the delay of the links adjacent to them. These measurements are then exchanged between the satellites. The delay measurements of a satellite are contained in a data unit called the *delay measurement report*. The definitions of the delay measurement reports in three satellite layers and in LEO groups are given below.

Definition 3 (Delay Measurement Report): A delay measurement report $\mathcal{DMR}(X)$ of a node X is a set of tuples $\{Y, \mathcal{D}(l_{X \rightarrow Y})\}$, where Y is a node such that there exists a link $l_{X \rightarrow Y}$ from X to Y. The delay measurement reports of LEO, MEO, and GEO satellites, and the LEO groups are computed as follows.

1) Let a LEO satellite $L_{i,j,k}$ be connected to terrestrial gateways $T_{L_{i,j,k}}^t$, $0 \le t < \mathbf{N}_T(L_{i,j,k})$ over $\text{UDL}_{L_{i,j,k} \rightarrow T_{L_{i,j,k}}^t}$, where $\mathbf{N}_T(L_{i,j,k})$ is the number of terrestrial gateways in $L_{i,j,k}$s coverage area. Let $L_{i,j,k}$ be also connected to four other LEO satellites L_{i_s,j_s,k_s}, $0 \le s < 4$, with $\text{ISL}_{L_{i,j,k} \rightarrow L_{i_s,j_s,k_s}}$. The connection of $L_{i,j,k}$ to its MEO manager $M_{i,j}$ and the GEO satellite G_i is accomplished over $\text{IOL}_{L_{i,j,k} \rightarrow M_{i,j}}$ and $\text{IOL}_{L_{i,j,k} \rightarrow G_i}$, respectively. The delay measurement report $\mathcal{DMR}(L_{i,j,k})$ of the LEO satellite $L_{i,j,k}$ is given by

$$
\begin{aligned}
\mathcal{DMR}&(L_{i,j,k}) \\
&= \left\{ (A, \mathcal{D}(\text{UDL}_{L_{i,j,k} \rightarrow A})) \Big| A = T_{L_{i,j,k}}^0, \ldots, T_{L_{i,j,k}}^{\mathbf{N}_T(L_{i,j,k})-1} \right\} \\
&\quad \bigcup \left\{ (B, \mathcal{D}(\text{ISL}_{L_{i,j,k} \rightarrow B})) \big| B = L_{i_0,j_0,k_0}, \ldots, L_{i_3,j_3,k_3} \right\} \\
&\quad \bigcup \left\{ (C, \mathcal{D}(\text{IOL}_{L_{i,j,k} \rightarrow C})) \big| C = M_{i,j}, G_i \right\} \quad (5)
\end{aligned}
$$

i.e., $\mathcal{DMR}(L_{i,j,k})$ is a list that consists of all nodes (LEO, MEO, GEO satellites, and terrestrial gateways) $L_{i,j,k}$ is directly connected to and the measured link delays to these nodes.

2) Let a MEO satellite $M_{i,j}$ be connected to terrestrial gateways $T_{M_{i,j}}^t$, for $t = 0, \ldots, \mathbf{N}_T(M_{i,j}) - 1$ over $\text{UDL}_{M_{i,j} \rightarrow T_{M_{i,j}}^t}$, where $\mathbf{N}_T(M_{i,j})$ is the number of terrestrial gateways in its coverage area. Let $M_{i,j}$ be also connected to other MEO satellites M_{i_s,j_s}, for $s = 0, \ldots, \mathbf{N}(M_{i,j})$, with $\text{ISL}_{M_{i,j} \rightarrow M_{i_s,j_s}}$, where $\mathbf{N}(M_{i,j})$ is the number of MEO neighbors of $M_{i,j}$. The connection of $M_{i,j}$ to the GEO satellite G_i is accomplished over $\text{IOL}_{M_{i,j} \rightarrow G_i}$. $M_{i,j}$ also manages the LEO group $\mathcal{L}_{i,j}$. The delay measurement report $\mathcal{DMR}(M_{i,j})$ of the MEO satellite $M_{i,j}$ is given by

$$
\begin{aligned}
\mathcal{DMR}&(M_{i,j}) \\
&= \left\{ (A, \mathcal{D}(\text{UDL}_{M_{i,j} \rightarrow A})) \Big| A = T_{M_{i,j}}^0, \ldots, T_{M_{i,j}}^{\mathbf{N}_T(M_{i,j})-1} \right\} \\
&\quad \bigcup \Big\{ (B, \mathcal{D}(\text{ISL}_{M_{i,j} \rightarrow B})) \big| B = M_{i_s,j_s}, s = 0, \ldots, \\
&\qquad\qquad \mathbf{N}(M_{i,j}) - 1 \Big\} \\
&\quad \bigcup \left\{ \left(\mathcal{L}_{i,j}, \mathcal{D}\left(\text{SL}_{M_{i,j} \rightarrow \mathcal{L}_{i,j}}^{In} \right) \right) \right\} \\
&\quad \bigcup \left\{ (G_i, \mathcal{D}(\text{IOL}_{M_{i,j} \rightarrow G_i})) \right\} \quad (6)
\end{aligned}
$$

i.e., $\mathcal{DMR}(M_{i,j})$ is a list that consists of all nodes (LEO groups, MEO, and GEO satellites, and terrestrial gateways) $M_{i,j}$ is directly connected to, and the measured link delays to these nodes.

3) Let a GEO satellite G_i be connected to terrestrial gateways $T_{G_i}^t$, for $t = 0, \ldots, \mathbf{N}_T(G_i) - 1$ over $\text{UDL}_{G_i \rightarrow T_{G_i}^t}$, where $\mathbf{N}_T(G_i)$ is the number of terrestrial gateways in G_is coverage area. Let G_i be also connected to two other GEO satellites G_{i_0} and G_{i_1} over $\text{ISL}_{G_i \rightarrow G_{i_0}}$ and $\text{ISL}_{G_i \rightarrow G_{i_1}}$, respectively. The connections of G_i to the MEO satellites $M_{i,j}$, $j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1$ are accomplished over $\text{IOL}_{G_i \rightarrow M_{i,j}}$, where $\mathbf{S}(\mathcal{M}_i)$ is the number of MEO satellites in group $\mathcal{M}_i$. Let the LEO groups $\mathcal{L}_{i,j}$, for $j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1$, be also in the coverage area of G_i. The delay measurement report $\mathcal{DMR}(G_i)$ of the GEO satellite G_i is given by

$$
\begin{aligned}
\mathcal{DMR}&(G_i) \\
&= \left\{ (A, \mathcal{D}(\text{UDL}_{G_i \rightarrow A})) \Big| A = T_{G_i}^t, \ldots, T_{G_i}^{\mathbf{N}_T(G_i)-1} \right\} \\
&\quad \bigcup \left\{ (B, \mathcal{D}(\text{ISL}_{G_i \rightarrow B})) | B = G_{i_0}, G_{i_1} \right\} \\
&\quad \bigcup \left\{ (C, \mathcal{D}(\text{IOL}_{G_i \rightarrow C})) \big| C = M_{i,0}, \ldots, M_{i,\mathbf{S}(\mathcal{M}_i)-1} \right\} \\
&\quad \bigcup \left\{ \left(D, \mathcal{D}\left(\text{SL}_{G_i \rightarrow D}^{In} \right) \right) \big| D = \mathcal{L}_{i,0}, \ldots, \mathcal{L}_{i,\mathbf{S}(\mathcal{M}_i)-1} \right\} \quad (7)
\end{aligned}
$$

i.e., $\mathcal{DMR}(G_i)$ is a list that consists of all nodes (LEO groups, MEO and GEO satellites, and terrestrial gateways) G_i is directly connected to, and the measured link delays to these nodes.

4) Let a LEO group $\mathcal{L}_{i,j}$ be managed by the MEO satellite $M_{i,j}$. The delay measurement report $\mathcal{DMR}(\mathcal{L}_{i,j})$ of the LEO group $\mathcal{L}_{i,j}$ is given by

$$
\begin{aligned}
\mathcal{DMR}&(\mathcal{L}_{i,j}) \\
&= \left\{ \left(A, \mathcal{D}\left(\text{SL}_{\mathcal{L}_{i,j} \rightarrow A}^{Out} \right) \right) \Big| A \text{ is a terrestrial gateway} \right\} \\
&\quad \bigcup \left\{ \left(B, \mathcal{D}\left(\text{SL}_{\mathcal{L}_{i,j} \rightarrow B}^{Out} \right) \right) \Big| B = \mathcal{L}_{i_s,j_s}, s = 0, \ldots, \mathbf{S}(\mathcal{M}_i) \right\} \\
&\quad \bigcup \left\{ \left(M_{i,j}, \mathcal{D}\left(\text{SL}_{\mathcal{L}_{i,j} \rightarrow M_{i,j}}^{Out} \right) \right) \right\}. \quad (8)
\end{aligned}
$$

In other words, $\mathcal{DMR}(\mathcal{L}_{i,j})$ is the list of all direct neighbors of the LEO group $\mathcal{L}_{i,j}$ and the delays on the summary links to these neighbors.

During the calculation of the routing tables, the MEO satellites use the topology of the LEO satellites in its near vicinity. This information is called *neighboring LEO topology*. A MEO satellite needs the neighboring LEO topology to refine the routing decisions for itself and the LEO satellites in its coverage area. The neighboring LEO topology is constructed by a MEO satellite using the delay measurement reports from the LEO group it manages, and the reports obtained from the neighboring MEO satellites.

Definition 4 (Neighboring LEO Topology): Let a MEO satellite $M_{i,j}$ be connected to $\mathbf{N}(M_{i,j})$ other MEO satellites M_{i_s,j_s}, for $s = 0, \ldots, \mathbf{N}(M_{i,j})$. The neighboring LEO topology $\text{NLT}(M_{i,j})$ of the MEO satellite $M_{i,j}$ is the set

of delay measurement reports obtained from the LEO satellites managed by the MEO satellites $M_{i,j}$ and its neighbors M_{i_s, j_s}, $s = 0, \ldots, \mathbf{N}(M_{i,j})$

$$\text{NLT}(M_{i,j}) = \{\mathcal{DMR}(L_{i,j,k}) | k = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1\}$$
$$\bigcup \{\mathcal{DMR}(L_{i_s, j_s, k}) | k = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1$$
$$\text{and } s = 0, \ldots, \mathbf{N}(M_{i,j})\} \qquad (9)$$

where $\mathbf{S}(\mathcal{L}_{i,j})$ is the number of LEO satellites in group $\mathcal{L}_{i,j}$, and $\mathbf{N}(M_{i,j})$ is the number of neighboring MEO satellites of $M_{i,j}$, which manages $\mathcal{L}_{i,j}$. In other words, $\text{NLT}(M_{i,j})$ is the topology of the LEO satellites in the LEO groups $\mathcal{L}_{i,j}$ and $\mathcal{L}_{i_s, j_s}$, $s = 0, \ldots, \mathbf{N}(M_{i,j})$.

The GEO satellites collect the topology and link delay information from the satellites in their coverage area. The set of delay measurement reports collected by a GEO satellite from the satellites in its coverage area is called the *partial topology* (PT). The *total topology* (TT) is created by combining all partial topologies in the GEO satellites.

Definition 5 (Partial and Total Topologies): Let the GEO satellite G_i have the delay measurement reports $\mathcal{DMR}(G_i)$, $\{\mathcal{DMR}(M_{i,j}) | j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1\}$, and $\{\mathcal{DMR}(\mathcal{L}_{i,j}) | j = 0, \ldots, \mathbf{S}(\mathcal{M}_i)\}$. The partial topology PT_i of the satellite network seen by the GEO satellite G_i is defined as

$$\text{PT}_i = \mathcal{DMR}(G_i) \bigcup \{\mathcal{DMR}(M_{i,j}) | j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1\}$$
$$\bigcup \{\mathcal{DMR}(\mathcal{L}_{i,j}) | j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1\}. \quad (10)$$

The TT is the union of all recorded partial topologies, i.e.,

$$\text{TT} = \{\text{PT}_i | i = 0, \ldots, N_G - 1\}. \qquad (11)$$

In our satellite network architecture, the *routing tables* are created by GEO and MEO satellites using the topology information they have. A routing table is a function that takes a destination as an argument and returns the next hop on the path to that destination. The formal definition of a routing table is given below.

Definition 6 (Routing Table): Let $\mathcal{S}$ be the set of all satellites and LEO groups, and $X, Y \in \mathcal{S}$. Also, let $\mathcal{S}^+$ be the set of all satellites, LEO groups, and the terrestrial gateways. The routing table $\text{RT}_Y^X : \{D \longmapsto N\}$ is a function created by X to be used by Y, where $D, N \subset \mathcal{S}^+$, such that $\text{RT}_Y^X(\text{Dest}) = \text{Next}$ returns the next hop Next to reach the destination Dest. RT_Y^X is created such that Y must be connected to all return values Dest with an ISL, IOL, UDL, or SL. The destinations and next hops are maintained as a table of tuples $\{\text{Dest}, \text{Next}\}$.

IV. MULTILAYERED SATELLITE ROUTING ALGORITHM (MLSR)

The packets in the multilayered satellite network are processed and forwarded individually in every satellite on their paths. The routing decisions are stored in routing tables onboard the satellites. These tables must be updated to reflect the changes in the network topology and in the traffic load carried by the network. The following issues were considered when designing the MLSR algorithm.

- **Computational Complexity:** The multilayered satellite network consists of a large number of nodes. The periodic routing table calculations are performed in the satellite network and require high processing power in a power-limited environment. To cope with this problem, MLSR reduces the number of vertices to be considered in the GEO satellites and decentralizes routing table computations.
- **Communication Overhead:** In order to reflect the current condition of the satellite network to the routing decisions, the up-to-date link delays must be used while calculating the routing tables. The collection of the delay measurements puts additional communication load on the satellite network. In MLSR, LEO groups are abstracted as nodes and only summary link delays are sent to the GEO satellites, which reduces the communication overhead of the routing algorithm.
- **Delay Measurements:** Although the propagation delay is a major part of the link delays, the processing and queueing delays can become larger than the propagation delay on the congested links. In MLSR, the satellites measure the average delay on their outgoing links. The measured link delays used in MLSR include the propagation, processing, and queueing delays.

In the following section, the steps of routing table calculation in the MLSR algorithm are presented in detail.

A. Routing Table Calculation

The routing table calculations are performed under two conditions.

- **Changes in the Group Memberships:** The changes in the satellite group memberships indicate the changes in the satellite interconnection structure. In order to reflect the changes in the topology to the routing decisions, the routing tables must be recalculated. The timing of satellite group membership changes can be precalculated and stored onboard the satellites.
- **Periodic Calculations:** Between the two consecutive changes in the group memberships, the interconnection of the satellites remain the same. However, the delays on the links are dynamic due to changes in the traffic load as well as the movements of the satellites. Periodic routing table calculations aim to reflect the changes in the link delays. The period of recalculations should be shorter than the average time between group membership changes.

The routing table calculations involve a series of computations and communication events that trigger each other. In Fig. 5, the steps of routing table calculation in MLSR is shown. The arrows indicate communication events and ellipses correspond to events involving computations. The satellites are represented by filled circles. Satellites in the same layer are contained in the same dashed rectangle. The LEO and MEO groups are marked with solid rectangles. The details of the routing algorithm are presented next.

Step 1: Creation of Delay Measurement Reports for LEO Satellites: The LEO satellites measure the delays on their out-
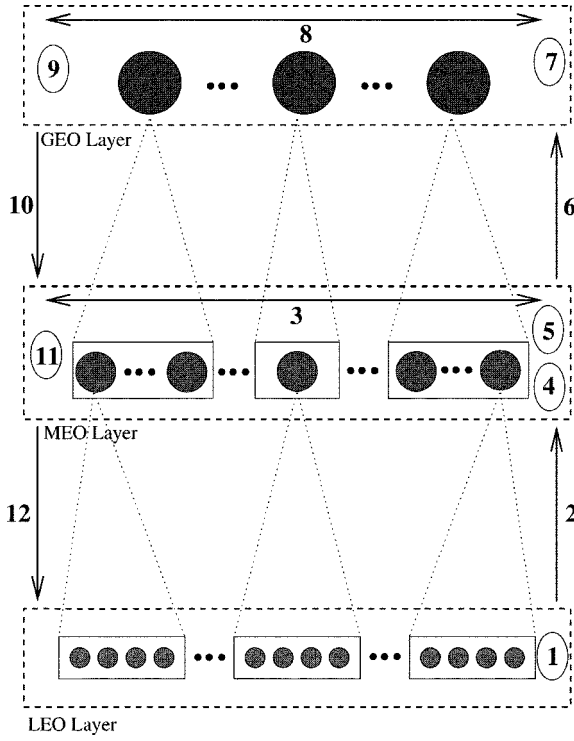
Fig. 5. Steps of MLSR routing table calculation.

going links. All LEO satellites $L_{i,j,k}$ create the delay measurement reports $\mathcal{DMR}(L_{i,j,k})$ (Definition 3) using (5).

Step 2: Reporting the Delay Measurement Reports to MEO Layer: The link delay measurements of LEO satellites are sent to the manager MEO satellites. Each LEO satellite $L_{i,j,k}$ sends its delay measurement report $\mathcal{DMR}(L_{i,j,k})$ to its manager MEO satellite $M_{i,j}$ over $IOL_{L_{i,j,k} \to M_{i,j}}$.

Step 3: Delay Measurement Report Exchange for MEO Layer: The MEO satellites send the delay measurement reports they obtained from the LEO satellites to their immediate neighbors.

Let a MEO satellite $M_{i,j}$ be connected to $\mathbf{N}(M_{i,j})$ other MEO satellites M_{i_s,j_s}, $s = 0, \ldots, \mathbf{N}(M_{i,j}) - 1$, via $ISL_{M_{i,j} \to M_{i_s,j_s}}$. After $M_{i,j}$ receives delay measurement reports $\{\mathcal{DMR}(L_{i,j,k}) | k = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1\}$ from the LEO satellites, it sends these measurement reports to its MEO neighbors M_{i_s,j_s}, $s = 0, \ldots, \mathbf{N}(M_{i,j}) - 1$, on $ISL_{M_{i,j} \to M_{i_s,j_s}}$. $M_{i,j}$ also forms the neighboring LEO topology $NLT(M_{i,j})$ (Definition 4) and stores it to be used later.

Step 4: Creation of Delay Measurement Reports for LEO Groups: The MEO satellites create the summary links (Definition 2) for the LEO groups they manage. All MEO satellites $M_{i,j}$ that manage the LEO satellite groups $\mathcal{L}_{i,j}$, create the delay measurement reports $\mathcal{DMR}(\mathcal{L}_{i,j})$ (Definition 3) using (8).

Step 5: Creation of Delay Measurement Reports for MEO Layer: In this step, MEO satellites measure the delays on their outgoing links and create the summary link to their LEO groups. With these measurements, MEO satellites create delay measurement reports. All MEO satellites $M_{i,j}$ create their own delay measurement reports $\mathcal{DMR}(M_{i,j})$ (Definition 3) using (6).

Step 6: Reporting the Delay Measurement Reports to GEO Layer: The MEO satellites send their own delay measurement

reports and the delay measurement reports of their LEO groups to the GEO satellites they are connected to. All MEO satellites $M_{i,j}$ send the delay measurement reports $\mathcal{DMR}(M_{i,j})$ and $\mathcal{DMR}(\mathcal{L}_{i,j})$ to the GEO satellites G_i over $IOL_{M_{i,j} \to G_i}$.

Step 7: Creation of Delay Measurement Reports for GEO Layer: In this step, GEO satellites measure the delays on their outgoing links and create the summary links to the LEO groups in their coverage area. GEO satellites create delay measurement reports to be used for the route calculations. All GEO satellites G_i create their own delay measurement reports $\mathcal{DMR}(G_i)$ (Definition 3) using (7).

Step 8: Delay Measurement Report Exchange in GEO Layer: GEO satellites exchange the delay measurement reports to create the total topology of the network before starting the path calculations. To accomplish this, every GEO satellite multicasts the partial topology information they collect from the satellites in its coverage to all other GEO satellites.

Let the GEO satellite G_i have the delay measurement reports $\mathcal{DMR}(G_i)$, $\{\mathcal{DMR}(M_{i,j}) | j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1\}$, and $\{\mathcal{DMR}(\mathcal{L}_{i,j}) | j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1\}$. G_i creates a partial topology message (TTL_i, PT_i), where TTL_i is the "time to live" of the message and PT_i is the partial topology (Definition 5) in G_i. The initial value of TL_i is N_G. Every partial topology message created or received is first recorded. Then, TTL_i is decremented by one. The partial topology message with the updated TTL_i is sent to the GEO neighbor to the east if $TTL_i > 0$. With the collected partial topologies, the total topology TT (Definition 5) is formed. Note that the direction the partial topology messages are forwarded can be chosen as either east or west, as long as it is consistent in all GEO satellites.

Step 9: Routing Table Calculation in GEO Satellites: After creating the TT, each GEO satellite calculates the routing tables for all MEO satellites and LEO groups in their coverage area. The routing tables show the next hops for a packet destined to a GEO or MEO satellite, LEO group, or terrestrial gateway when the packet is in a particular satellite. The routing table calculations are performed using Bellman's shortest path algorithm and the total satellite topology (TT). Note that the individual LEO satellites do not appear as destinations or as next hops in a routing table calculated by a GEO satellite.

Let the GEO satellite G_i contain in its coverage area the MEO satellites $M_{i,j}$ and the LEO groups $\mathcal{L}_{i,j}$, $j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1$. Using the TT and Bellman's algorithm, G_i creates routing tables $RT_A^{G_i}$ (Definition 6) for all satellites A, where

$$A \in \left\{ G_i, M_{i,0}, \ldots, M_{i,\mathbf{S}(\mathcal{M}_i)-1}, \mathcal{L}_{i,0}, \ldots, \mathcal{L}_{i,\mathbf{S}(\mathcal{M}_i)-1} \right\}$$

i.e., for all terrestrial gateways, LEO groups, and MEO satellites in its coverage area and the GEO satellite G_i itself. $RT_A^{G_i}$ returns the next hops to reach all GEO and MEO satellites, LEO groups, and terrestrial gateways.

Step 10: Distribution of Routing Tables to MEO Satellites: The routing tables calculated in the GEO layer are first sent to the MEO satellites. Every MEO satellite receives two routing tables, one for itself and another one for the LEO group it manages.

Let a GEO satellite G_i be connected to the MEO satellites $M_{i,j}$, $j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1$, over $IOL_{G_i \to M_{i,j}}$. G_i sends the

routing tables $\text{RT}^{G_i}_{M_{i,j}}$ and $\text{RT}^{G_i}_{\mathcal{L}_{i,j}}$ to the MEO satellites $M_{i,j}$, $j = 0, \ldots, \mathbf{S}(\mathcal{M}_i) - 1$.

Step 11: Routing Table Calculation in MEO Satellites: MEO satellites modify the routing tables they received according their neighboring LEO topology information (Definition 4). The purpose of these modifications is to refine the routing tables such that the entries for the LEO groups they manage are replaced by actual LEO satellites. The MEO satellites also create individual routing tables for the LEO satellites in their LEO groups.

Let the MEO satellite $M_{i,j}$ have $\mathbf{N}(M_{i,j})$ MEO neighbors M_{i_s, i_s}, $s = 0, \ldots, \mathbf{N}(M_{i,j}) - 1$, and manage the LEO group $\mathcal{L}_{i,j}$.

1) $M_{i,j}$ first calculates the partial routing tables $\text{PRT}^{M_{i,j}}_A$, $A \in \{M_{i,j}, L_{i,j,0}, \ldots, L_{i,j,\mathbf{S}(\mathcal{L}_{i,j})-1}\}$, using its delay measurements created in Step 5 and the neighboring LEO topology $\text{NLT}_{i,j}$. The destinations in $\text{PRT}^{M_{i,j}}_A$ are the nodes is $\text{NLT}_{i,j}$ and the nodes that $M_{i,j}$ is connected through an IOL, ISL, or UDL.

2) $M_{i,j}$ creates for its own use a new routing table $\text{RT}^{M_{i,j}}_{M_{i,j}}$ using $\text{RT}^{G_i}_{M_{i,j}}$ and $\text{PRT}^{M_{i,j}}_{M_{i,j}}$ as follows:

   a) Copy all entries from $\text{PRT}^{M_{i,j}}_{M_{i,j}}$ to $\text{RT}^{M_{i,j}}_{M_{i,j}}$.

   b) Copy from $\text{RT}^{G_i}_{M_{i,j}}$ to $\text{RT}^{M_{i,j}}_{M_{i,j}}$ the entries for the destinations d, $d \notin \{\mathcal{L}_{i,j}\} \bigcup \{\mathcal{L}_{i_s,j_s} | s = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1\}$.

3) $M_{i,j}$ creates new routing tables $\text{RT}^{M_{i,j}}_{L_{i,j,k}}$, $k = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1$, for the LEO satellites in its coverage area using $\text{RT}^{G_i}_{\mathcal{L}_{i,j}}$ and $\text{PRT}^{M_{i,j}}_{M_{i,j,k}}$ as follows:

   a) Copy all entries from $\text{PRT}^{M_{i,j}}_{L_{i,j,k}}$ to $\text{RT}^{M_{i,j}}_{L_{i,j,k}}$.

   b) Copy from $\text{RT}^{G_i}_{\mathcal{L}_{i,j}}$ to $\text{RT}^{M_{i,j}}_{M_{i,j}}$ the entries for the destinations d, $d \notin \{\mathcal{L}_{i_s,j_s} | s = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1\}$.

   c) Replace in $\text{RT}^{M_{i,j}}_{L_{i,j,k}}$ all destinations $\text{RT}^{M_{i,j}}_{L_{i,j,k}}(x) = \mathcal{L}_{i_s,j_s}$ by $\text{PRT}^{M_{i,j}}_{L_{i,j,k}}(L_{i_s,j_s,0})$.

Step 12: Distribution of Routing Tables to LEO Satellites: After the routing table calculations, MEO satellites transfer the specialized routing tables to the LEO satellites in their coverage area.

Let the MEO satellite $M_{i,j}$ be connected to the LEO satellites $L_{i,j,k}$, $k = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1$ over $\text{ISL}_{M_{i,j} \to L_{i,j,k}}$. $M_{i,j}$ sends the routing table $\text{RT}^{M_{i,j}}_{L_{i,j,k}}$ to the LEO satellite $L_{i,j,k}$ over $\text{ISL}_{M_{i,j} \to L_{i,j,k}}$, $k = 0, \ldots, \mathbf{S}(\mathcal{L}_{i,j}) - 1$.

B. Packet Forwarding

In each satellite, the packets are processed individually. Every satellite stores a customized routing table for its own use. When a satellite receives a packet, its next hop is looked up from the routing table stored onboard the satellite. The packet is then placed into the buffer of the link (ISL, IOL, or UDL) that leads directly to the next hop. The satellites in the GEO, MEO, and LEO layers use the routing tables $\text{RT}^{G_i}_{G_i}$, $\text{RT}^{M_{i,j}}_{M_{i,j}}$, and $\text{RT}^{M_{i,j}}_{L_{i,j,k}}$, respectively.

Assume a satellite S receives a packet destined to D. Using the routing table RT_S, the next hop N for the packet is found as follows:

1) If D appears as a destination in RT_S, then the next hop is looked up from the routing table directly, i.e., $\text{Next} = \text{RT}_S(D)$.

2) If D is a LEO satellite $L_{i,j,k}$, which does not appear in the routing table RT_S, then the next hop to reach its LEO group is used instead, i.e., $\text{Next} = \text{RT}_S(\mathcal{L}_{i,j})$.

3) If the next hop is a LEO group, then the packet is sent to the LEO satellite, to which the delay is minimum. In other words, if Next is a LEO group $\mathcal{L}_{i,j}$, then the Next is updated as $\text{Next} = \text{Next}^*$ such that

$$\text{IOL}_{S \to \text{Next}^*} = \arg \min_{0 \leq k < \mathbf{S}(\mathcal{L}_{i,j})} \mathcal{D}(\text{IOL}_{S \to L_{i,j,k}})$$

where $\arg$ returns the argument passed to the $\mathcal{D}$ function.

C. Satellite Failures

When satellites fail, the network topology changes. The paths that go through the failing satellites can no longer be used. In a multilayered satellite network, it is very difficult to resolve satellite failures locally. Therefore, the neighbors of the failing satellite initiate a new routing table calculation. The calculated paths do not go through the failing satellite, and the routing tables are created accordingly. The steps of the forced routing table calculation can be outlined as follows.

1) The satellites that lose the direct connection to their manager satellites try to find themselves new managers. For that purpose, the satellites in the lower layer send broadcast discovery packets to the satellites in one higher layer.

2) The satellite in the upper layer whose reply arrives first is chosen as the new manager satellite and a tunnel over multiple hops is created. The information to create the tunnel to the new manager satellite is contained in the reply packet. The new tunnels are used only to relay delay measurement reports and routing tables.

3) The failure information is broadcast in the GEO layer. The GEO satellite sends the forced routing table calculation request to the MEO satellites they manage.

4) Similarly, the MEO satellites forward the forced routing table calculation request to the LEO satellites.

5) Once the MEO satellites receive this request, the steps described in Section IV-A are followed to calculate and distribute the routing tables. Note that the delay measurement reports do not include the links that lead to the failing satellite.

V. PERFORMANCE EVALUATION

For performance evaluation of the multilayered satellite architecture and MLSR, we conducted four sets of experiments.

- **Path Optimality:** The first set of the simulations show the delay difference between the shortest paths and the paths created by our routing algorithm MLSR. We also present the packet loss probabilities in both cases.

- **Effect of Satellite Altitudes:** This set of simulations show the effect of the relative positions of the three satellite layers on the end-to-end delays and the packet loss probabilities.

- **Comparison With Other Architectures:** We demonstrated performance difference of the multilayered satellite network and other satellite network architectures with fewer layers. The focus of these experiments is again the end-to-end delays and the packet loss probabilities.
- **Protocol Overhead:** We analytically compare the communication and computational overhead of routing table calculations in MLSR with the central and fully distributed routing table calculation approaches, which calculate the shortest paths using Bellman's algorithm.

In all simulations, the LEO satellites are located at an altitude of 1375 km, with $30°$ angular distance from each other. The $N_L = 72$ LEO satellites move in circular polar orbits. The MEO satellites reside at 12 000 km, separated from each other with $60°$ angular distance. The number of MEO satellites is $N_M = 18$, and they also move in polar orbits. We further assume three equally spaced GEO satellites above the equator. The capacity of all UDLs, ISLs, and IOLs are chosen as 200 Mb/s, and each outgoing link has been allocated a buffer space of 5 MB. If we assume an average packet size of 1000 bytes, the link capacity becomes 25 000 packets/s and the buffer space becomes 5000 packets.

The experiments are based on the observation of the average end-to-end delay and the packet loss probability between two terrestrial source–destination pairs. Both pairs have the same source node, which is located at (105°W, 45°N). The destination of the first pair is located at (15°W, 15°N), and the destination of the second pair is located at (−105°W, −45°N). All terrestrial nodes are connected to the closest LEO, MEO, and GEO satellites. In the first pair, the source and the destination are connected to LEO satellites that belong to neighboring LEO groups. The second pair is separated by a longer distance. In all experiments, the sender generates an average of 8 Mb/s (1000 packets/s) for 400 s. The routing table calculations are performed every 100 s. These assumptions are used in all experiments unless otherwise stated.

A. Path Optimality of MLSR

The first set of experiments compares the end-to-end delays and the packet loss probabilities between the shortest paths calculated by the Bellman's shortest path algorithm and the paths created by our routing algorithm MLSR. In both schemes, the routing tables are updated every 100 s.

In Fig. 6, the delay performance and the packet loss probability of the MLSR algorithm and the shortest path routing algorithm are depicted. In these experiments, the ISL utilization in the LEO layer is increased gradually, and the delay and loss probabilities are recorded. The ISL utilization is modified by adjusting the background traffic carried by all LEO ISLs.

Fig. 6(a) and (b) shows the performance for the two source–destination pairs, respectively. The source and the destination of the first pair are located in the coverage areas of neighboring LEO groups, and therefore, the MLSR algorithm routes the packets on the optimal paths. Consequently, both curves are overlapped in Fig. 6(a). The propagation delay is the determining factor for the end-to-end delay until LEO ISL utilization reaches 95.8%. When the ISL utilization reaches this threshold, the paths going through MEO satellites become
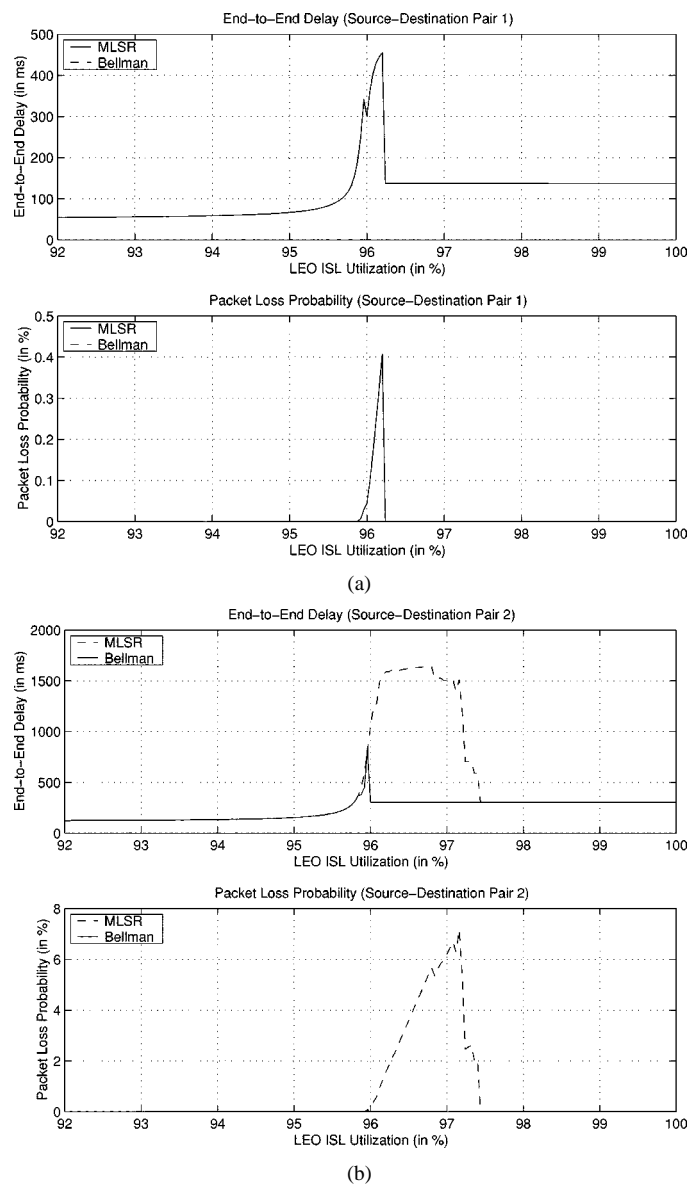

Fig. 6. Delay and packet loss probability performance of the MLSR and shortest path routing algorithms. (a) Source–destination pair 1. (b) Source–destination pair 2.

shorter. After the next routing table calculation, the packets are forwarded over the MEO satellites. Since the packets no longer take LEO hops and the load on LEO ISLs are reduced, the paths that go through LEO satellites become shorter. Hence, in the next routing table calculation cycle, the routing tables are set up such that the packets are forwarded over LEO satellites. This switching of paths continues until the LEO ISL utilization reaches another threshold, for which the paths that go over MEO satellites are permanently shorter than the paths that go over LEO satellites. From this point on, the packets are always forwarded over the MEO satellites, and the end-to-end delay stabilizes around 130 ms. This transition phase, in which paths constantly change, is called the *oscillatory phase*. During the oscillatory phase, the end-to-end delay is higher than the level that is reached after this phase is over. Furthermore, the packet loss probability is also increased in this phase. Note that the packet loss probability is much lower (very close to zero)
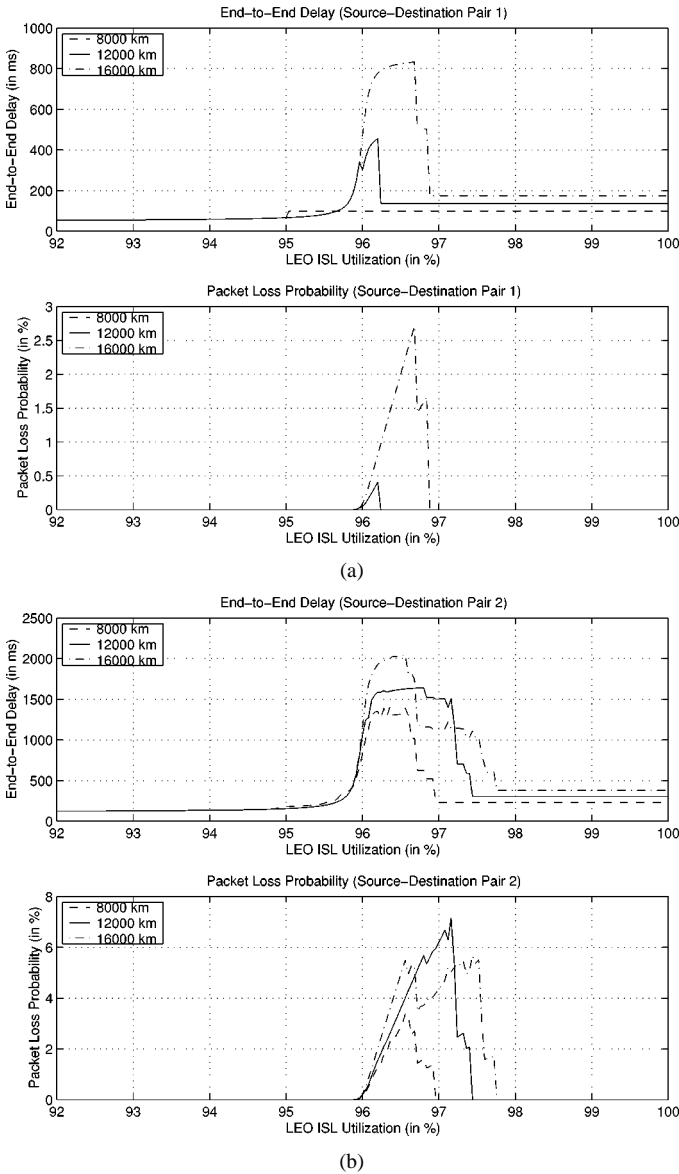
Fig. 7. Delay and packet loss probability performance of MLSR for different MEO altitudes versus LEO ISL utilization. (a) Source–destination pair 1. (b) Source–destination pair 2.

Fig. 8. Delay and packet loss probability performance of MLSR for different MEO altitudes versus MEO ISL utilization. (a) Source–destination pair 1. (b) Source–destination pair 2.

outside the oscillatory region and it cannot be seen in Fig. 6(a). In our simulations, we observed that the path oscillations only occur during the oscillatory phase, which is at most 2% of the entire link utilization spectrum. This means that the system does not suffer from path oscillations unless most of the link utilizations stabilize in oscillatory phases.

For the second source–destination pair, a similar behavior can be observed, as shown in Fig. 6(b). However, in this case, the source and destination are not located in the coverage area of neighboring LEO groups. Therefore, the routing tables can forward the packets on suboptimal paths. The oscillatory phase stretches a larger LEO ISL utilization range. The reason for a longer oscillatory phase is the larger number of hops between the source and the destination, which creates a larger number of alternative paths, among which the oscillation can occur. Note that the loss probability under the Bellman algorithm is negligible when compared with the loss probabilities obtained by our
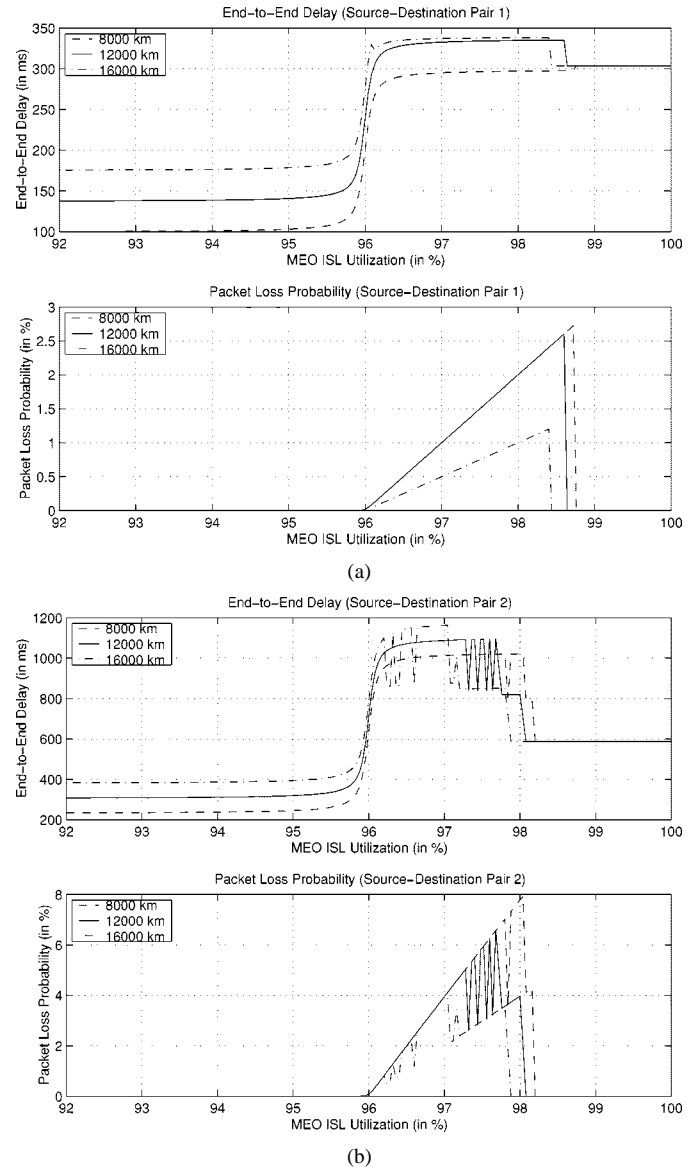
algorithm during the oscillatory phase. Outside the oscillatory phase, both algorithms produce the same end-to-end delay and packet loss probabilities.

B. Effect of Satellite Altitudes

The relative positions of the satellite layers also change the behavior of the MLSR algorithm. To show the effect of the relative positions of the satellites, we performed experiments that show the end-to-end delay and loss probability performance of the MLSR algorithm running in multilayered satellite networks with MEO satellites at 8000, 12 000, and 16 000 km above the Earth's surface. The results are presented in Figs. 7 and 8 for different values of the LEO and MEO ISL utilizations, respectively.

Fig. 7(a) shows the end-to-end delay and packet loss probability performance for the first source–destination pair. When
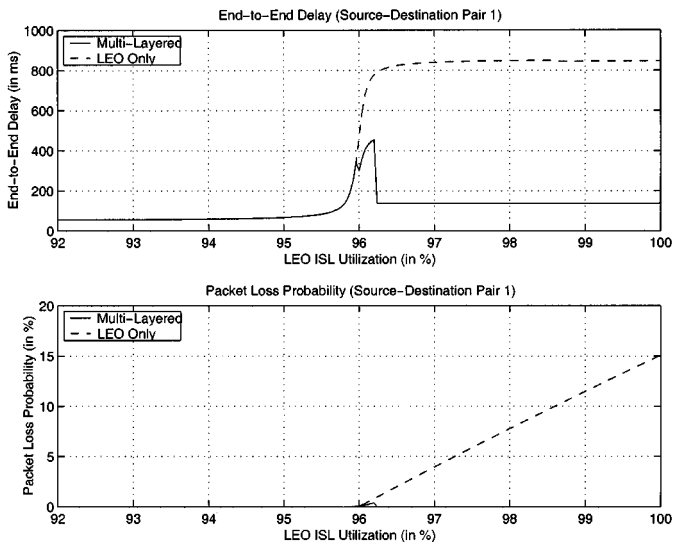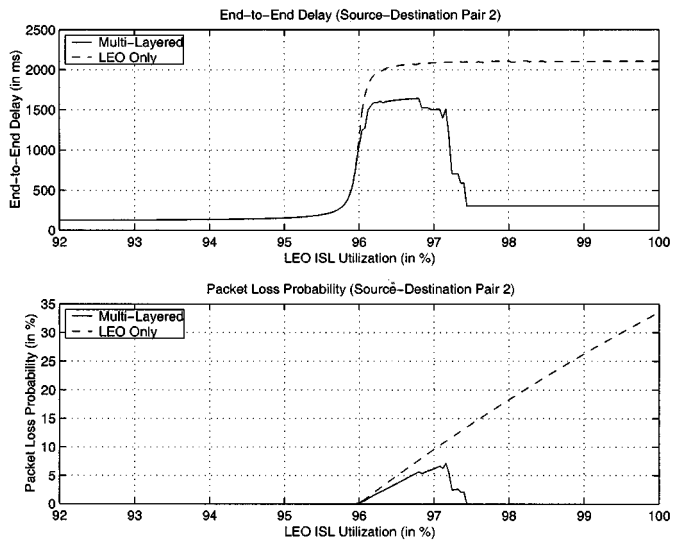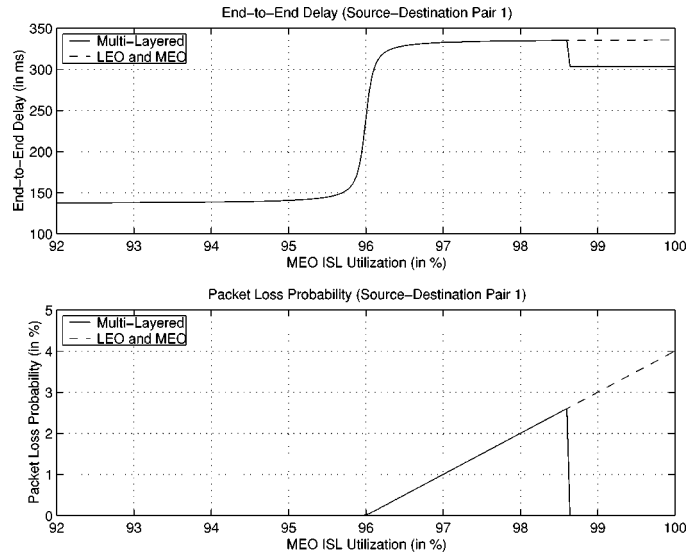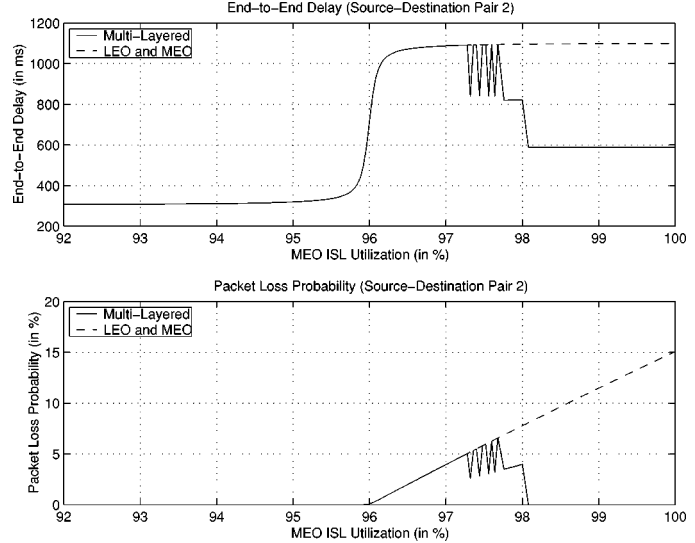
Fig. 9. Delay and packet loss probability performance of multilayered satellite network and a LEO satellite network. (a) Source–destination pair 1. (b) Source–destination pair 2.

Fig. 10. Delay and packet loss probability performance of multilayered and LEO–MEO satellite networks. (a) Source–destination pair 1. (b) Source–destination pair 2.

the MEO satellites are located at 8000 km above the Earth's surface, the paths switch from the LEO satellites to MEO satellites without going into an oscillatory phase. Therefore, its loss probability curve is almost overlapped with the x axis. However, as the altitude of the MEO satellites increase, the oscillatory region and its effect on the end-to-end delay and loss probability increases. The delay after the oscillatory region is smaller for lower MEO altitudes since the LEO and MEO layers are closer to each other and the propagation delay difference of the paths that go over LEO and MEO satellites is smaller. For the second source–destination pair, the oscillatory phase is longer for all MEO altitudes, as shown in Fig. 7(b). The longer distance and higher number of hops between the source and destination increase the number of paths, among which the oscillations may occur. Also in this case, the oscillatory phase lasts longer for higher MEO altitudes since the propagation delay difference between the paths is larger.

In the second set of experiments, the LEO ISL utilization is set to 100% and the MEO ISL utilization is increased. In Fig. 8(a), the end-to-end delay and the packet loss probabilities for the first source–destination pair are shown under this scenario. For all three MEO altitudes, the switching of paths occur without any oscillations. The increase in the end-to-end delay and the loss probability occur for the same path; the paths do not oscillate. After the paths switch over to GEO satellites, the end-to-end delays become the same and the loss rates also drop to negligible values. For the second source–destination pair, however, the switching of paths occur after a long oscillatory phase, as shown in Fig. 8(b). This phase lasts longest for the network with MEO satellites at 8000 km, and shortest for 16 000 km. The sawtooth-shaped portions of the end-to-end delay and loss probabilities correspond to regions where the oscillations occur between two paths. The parts of the curves with smaller changes correspond to oscillations between paths

of smaller delay differences. The curves in this plot are very close to each other compared with the curves in Fig. 8. This phenomenon stems from the fact that the ratio of the MEO and LEO altitudes $(8000/1375, 12000/1375, 16000/1375)$ are much larger than the ratio of the MEO and GEO altitudes $(8000/35786, 12000/35786, 16000/35786)$.

C. Comparison With Other Architectures

With this set of experiments, we demonstrated the performance gain obtained by using the multilayered satellite network architecture. First, we compared the end-to-end delay and packet loss probability performance of the multilayered satellite network and a LEO satellite network. The results are shown in Fig. 9 for the same two source–destination pairs. For the LEO satellite network, packets are routed using routing tables created by the Bellman's shortest path algorithm. In both cases, the LEO satellite network provides much worse end-to-end delays and loss probabilities when the LEO ISL utilization goes into the oscillatory region. Although the delay is reduced after the oscillatory phase in the multilayered satellite network, it stabilizes at a much higher level in the LEO satellite network. Since the buffer space allocated for the links are limited, the delay on a path cannot grow indefinitely. However, the packet loss probability increases due to buffer overflows. Therefore, the packet loss probability continues to increase in the LEO satellite network as the LEO ISL utilization increases. The loss probability of the multilayered satellite network is visible as a very small notch at 96.2% in the lower plot of Fig. 9(a). For the second pair, we observe a large oscillatory phase for the multilayered satellite network as shown in Fig. 9(b). The end-to-end delay performance of the LEO satellite network increases up to 2100 ms, and drops down to 350 ms after the oscillatory phase of the multilayered satellite network. In the LEO satellite network, the packet loss probability increases up to 34%, whereas the loss probability is always below 6% in the multilayered satellite network.

We conducted a similar set of experiments for a two-layered satellite network consisting of LEO and MEO satellites only. The routing tables for this network are again calculated with the shortest path algorithm. In order to demonstrate the performance difference, the LEO ISL utilization is adjusted to 100%, and the MEO ISL utilization is increased. As shown in Fig. 10(a), there is no oscillatory phase for the first pair, and the paths switch to GEO UDLs at 98.7% for the multilayered satellite network. However, the two-layered satellite network routes the packets with a larger end-to-end delay, and with increasing packet loss rate. In case of the second source–destination pair, there is an oscillatory phase for the multilayered satellite network between 97.3% and 98.1% MEO ISL utilization [Fig. 10(b)]. The sawtooth-shaped portions correspond to oscillations between two paths only. For the two-layered satellite network, the end-to-end delay stabilizes at a larger value and the packet loss probability increases linearly as the MEO ISL utilization increases.

D. Protocol Overhead

In order to demonstrate the efficiency of the MLSR algorithm, we analytically compare the communication and computational overhead of routing table calculations in MLSR with the central and fully distributed routing table calculation approaches,
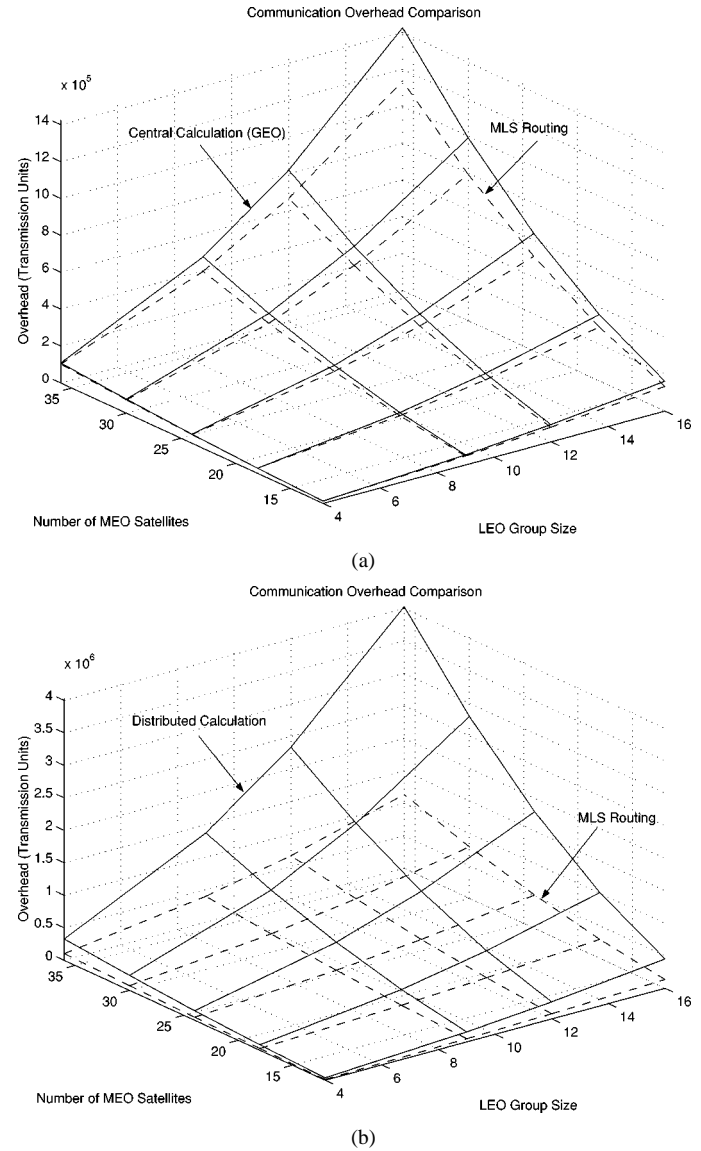

Fig. 11. Communication overhead comparison. (a) MLSR versus centralized calculation. (b) MLSR versus distributed calculation.

which calculate the shortest paths using Bellman's algorithm. In the central routing table calculation scheme, all routing tables are calculated by a designated GEO satellite. The satellites in the network create their delay measurement reports and send them to the GEO satellite over minimum hop paths. The GEO satellite calculates the individual routing tables for all satellites separately using Bellman's shortest path algorithm and sends these routing tables to the corresponding satellites again over minimum hop paths. In the fully distributed routing table calculation approach, every satellite is responsible for calculating its own routing table. The delay measurement reports are broadcast to all satellites. Once a satellite receives all delay measurement reports, it calculates the shortest paths to all other nodes using Bellman's algorithm. Using the shortest paths, every satellite creates its own routing table that contains the next hop to reach all other nodes in the network.

In Fig. 11, the communication overhead of the three routing table calculation schemes are compared for a satellite network with three GEO satellites $(N_G = 3)$, and one terrestrial gateway
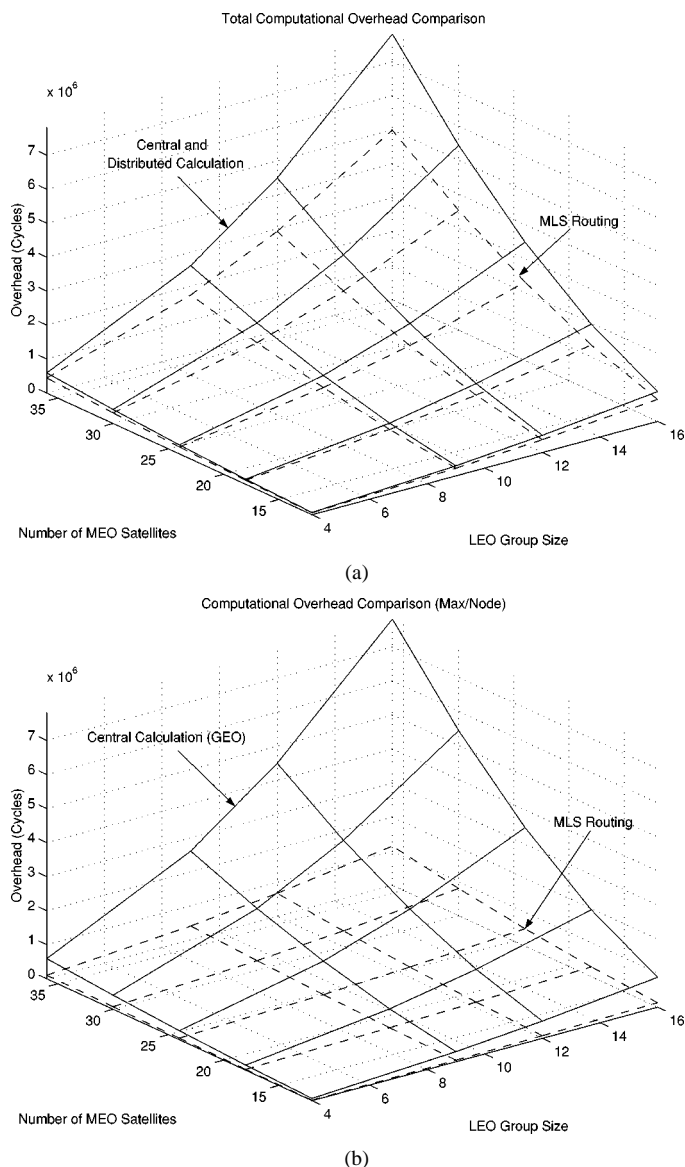
Fig. 12. Computational overhead comparison. (a) Total computational overhead. (b) Maximum computational overhead per node.

We also compared the computational overhead of the three routing table calculation schemes for the same satellite network. The computational overhead is measured in terms of computation cycles and plotted on the z axis in Fig. 12. The total computational overhead to calculate all routing tables is shown in Fig. 12(a). The central and distributed calculation schemes require an equal number of cycles since they use the same link delay and topology information. MLSR has much better computational performance than the other two schemes.

The maximum number of computation cycles in a satellite is depicted in Fig. 12(b). Since the central scheme assigns the routing table calculation to a single satellite, its maximum and total number of computation cycles are the same. In MLSR, the calculations are distributed among the GEO and MEO satellites. Therefore, the maximum number of computation cycles in a satellite under MLSR is much less than in the central case. In the distributed calculation scheme, the computational load is distributed evenly among all satellites. The maximum number of cycles for this case is much less than the maximum number of cycles required by the MLSR algorithm. In the distributed calculation scheme, the maximum number of computation cycles for a satellite is less than 7000, and is not shown in Fig. 12(b).

VI. CONCLUSION

In this work, we introduced a multilayered satellite IP network consisting of LEO, MEO, and GEO satellites. We also a introduced the multilayered satellite routing algorithm (MLSR) that calculates the routing tables for all satellites with low overhead. The performance of the MLSR algorithm has been assessed with simulations. The performance of the MLSR algorithm is the same as the shortest path routing algorithm except for a short oscillatory phase when the hops are switched to a higher satellite layer. We also showed that when the network load is high, our proposed network architecture and the MLSR algorithm perform better than the satellite networks with fewer satellite layers. The MLSR algorithm calculates the routing tables with low communication overhead. It also distributes the computational burden to multiple satellites.

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in every LEO satellite's coverage area. The number of LEO satellites in each LEO group N_L/N_M (x axis) and the number of MEO satellites N_M (y axis) was changed and their effect on the communication overhead was recorded. The total communication overhead is expressed in terms of transmission units (z axis), which is an entry either in the delay measurement report (Definition 3) or in a routing table (Definition 6).

Among these three schemes, MLSR has the least amount of communication overhead. As shown in Fig. 11(a), central routing creates more communication overhead as the number of satellites in the network increases. Since the LEO groups are abstracted to nodes and the links adjacent to the LEO groups are represented by the summary links, MLSR's communication overhead stays below the central calculation scheme's in all cases. The distributed calculation scheme requires broadcasting of delay measurement reports to all satellites, which boosts up its communication overhead, as shown in Fig. 11(b). Note that the distributed scheme also has much higher overhead than the central scheme.

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