Toward Optimized Traffic Distribution for Efficient Network Capacity Utilization in Two-Layered Satellite Networks

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Toward Optimized Traffic Distribution for Efficient Network Capacity Utilization in Two-Layered Satellite Networks

Hiroki Nishiyama, *Member, IEEE,* Yuta Tada, Nei Kato, *Senior Member, IEEE,* Naoko Yoshimura, Morio Toyoshima, *Member, IEEE,* and Naoto Kadowaki, *Member, IEEE*

***Abstract*—A Multi-Layered Satellite Network (MLSN) appears to be a promising network to provide global, ubiquitous, and broadband communication. In order to utilize the abundant network resources of the MLSNs, fair traffic distribution among its satellites layers is, indeed, important. In this paper, we propose a routing method to optimally distribute traffic load among the layers (i.e., the satellites layers in the MLSN). The load balancing scheme of the proposed routing method is developed by adopting a traffic distribution model, which is based upon network capacity estimation and theoretical analysis of the congestion rate in each layer. The performance of the proposed routing method has been validated through extensive computer simulations, which demonstrate that our traffic distribution model is reliable enough to characterize the traffic behavior in the MLSN. Furthermore, in contrast with the basic routing approach, our proposed routing method is more effective in terms of improved throughput and lower packet drops, which are optimized by the theoretical parameter setting.**

***Index Terms*—Satellite communication, multi-layered satellite networks, traffic distribution, routing, and load balancing.**

I. Introduction

RECENT improvement of technology, particularly in terms of wireless telecommunication, has been outstanding. Nowadays, we can easily procure sophisticated mobile devices, which have become reasonably inexpensive and accessible to a large population. Furthermore, terrestrial wireless networks have been well developed in metropolitan areas all over the world. Due to these technological evolutions in the developed regions, an environment for facilitating ubiquitous communication has been gradually constructed [1], [2]. However, since network facilities are still not widely available in the rural areas, provisioning of adequate network equipment, for establishing easy connections to other networks, is crucial for having ubiquitous communication. To this end, the use of satellite networks appears to be an effective solution. Because, satellite networks have large "footprints", which can cover a lot of terrestrial users. In addition, they need few terrestrial facilities to establish connections with the user-terminals. Therefore, ubiquitous communication may be achieved at low costs by using satellite networks, which would not break down even under a natural disaster.

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H. Nishiyama and N. Kato are with the Graduate School of Information Sciences, Tohoku University, in Sendai, Japan. They maybe contacted at bigtree@it.ecei.tohoku.ac.jp and kato@it.ecei.tohoku.ac.jp, respectively.

Y. Tada works for the NTT Communications Corporation in Tokyo, Japan.

N. Yoshimura, M. Toyoshima, and N. Kadowaki work for the National Institute of Information and Communications Technology (NICT) in Tokyo, Japan. They may be contacted at naoko@nict.go.jp, morio@nict.go.jp, and naoto@nict.go.jp, respectively.

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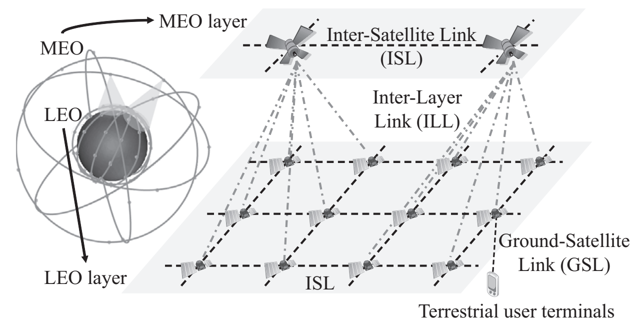


Fig. 1. An example of two layered satellite network consisting of LEO and MEO layers.

Generally, satellite networks are classified into two types, namely Geostationary Earth Orbit (GEO) and Non-GEO (NGEO) satellite networks. A satellite in the GEO satellite network has an altitude of 36,000km, and can cover about one-third of the earth with its huge coverage. A principal feature of a GEO satellite network is that it always covers the same region of the earth, because of its fixed position against the earth's surface. Inmarsat [3], a prime example of GEO satellite networks, provides satellite telecommunication services. Besides, as an experimental GEO satellite network having a large bandwidth, WINDS [4] has flourished in providing high-speed satellite communication. On the other hand, a NGEO satellite network consists of several satellites, which are deployed around the earth with lower altitude than that of a GEO satellite. Although their footprints are smaller than those of the GEO satellites, the NGEO satellites can construct a big network covering the whole earth by communicating with one another. The Iridium network, constructed by 66 satellites, is well known as a NGEO satellite network and in service for providing emergency phone calls [5].

In addition to the above mentioned satellite networks, Multi-Layered Satellite Networks (MLSNs) were proposed in the recent past as a practical architecture of next generation satellite networks. MLSNs are constructed by integrating several satellite networks and have hierarchical structures. An example of a typical MLSN is a two-layered MLSN depicted in Fig. 1, which is composed of a Low Earth Orbit (LEO) constellation and a Medium Earth Orbit (MEO) constellation. MLSNs are constructed by several types of links. First, Inter-Satellite Links (ISLs) connect each satellite within each constellation and form mesh or ring topology. Besides, satellites in different layers are connected by Inter-Layer Links (ILLs) in the MLSN. There, terrestrial users connect to the satellites via Ground-Satellite Links (GSLs) and thus, are able to communicate with each other. Integration of these multiple networks provide various advantages, reinforcement of the network capacity, increase of available paths, possibility of hierarchical network management, and so forth. However, there are also various issues that we have to take into account to effectively utilize MLSNs. Guaranteeing Quality of Service (QoS), handover management, and load balancing among the satellites layers are amongst the significant concerns involving MLSN.

In this work, we focus on the particular problem of load balancing among the layers (i.e., the satellites layers in the MLSN). In the MLSN, it is necessary to utilize satellites in each layer for fulfilling the specific purposes. The existing proposals allocate different roles to the satellites in each layer to reduce the overhead of network management and guarantee users' QoS. However, the traffic from users must increase as broadband satellite communication environments are developed and deployed. This will require the load balancing method to efficiently utilize network resources in the MLSN. For this reason, developing innovative route control schemes to efficiently distribute traffic at each network layer is, indeed, an urgent task.

In this paper, we propose a routing method for fair traffic distribution in a simple two-layered MLSN. This traffic distribution scheme is developed by the traffic generation and detouring model, and also optimized by theoretical analysis. The rest of the paper is structured as follows. In Section II, we introduce several related works. In Section III, we propose a routing method for fair traffic distribution in MLSNs. Additionally, we analyze our method and develop a model to optimize the configurations of our routing method in this section. Then, in Section IV, we demonstrate the effectiveness of our proposed routing method through computer simulations. Finally, concluding remarks are presented in Section V.

II. Related work

Over the years, research works on satellite networks have been conducted from various aspects. In the GEO satellite networks, the GSL bandwidth has been extended to accommodate high-speed communication. As a consequence, gigabit links have become a reality and numerous services can be launched in the near future due to this development. There, sophisticated techniques such as radio resource management, packet scheduling, modulation, and transport protocols are deeply studied to provide more satisfactory QoS [6–10]. On the other hand, regarding the NGEO satellite networks, additional issues such as satellite mobility and connectivity of the constellation need to be addressed. In NGEO satellite networks, as satellites move around the earth in a single orbit, the availability of the ISLs and GSLs changes periodically. This is called "handover" and some problems caused by this phenomenon have to be effectively managed [11–13]. In other words, since packet delivery should be completed without using unavailable links, it is quite important to select suitable paths to carry the packets. In addition, each satellite, which constructs NGEO satellite networks, has the same ability to handle packets. Therefore, all the links should be equally utilized in the entire network to achieve fair and efficient network utilization. For these reasons, routing strategy is one of the most important components in NGEO satellite network management to achieve efficient communication. In fact, several research works on the routing strategy for NGEO satellite networks have been conducted to develop sophisticated routing techniques [14], [15]. Although these works address issues on the single satellite networks, MLSNs also have similar research concerns. In particular, the importance of the routing strategy still remains in case of the MLSNs. In the following, we introduce relevant research works involving the routing issues in the MLSNs.

Satellite over Satellite (SOS) Network [16] developed by J. Lee *et.al.* in 2000 is referred to as the oldest proposal about the multi-layered architecture of satellite networks. In SOS, in-depth analysis on multi-layered topology such as footprint and orbit are given in terms of MLSN composed of a LEO layer and a MEO layer. In addition, Hierarchical QoS Routing Protocol (HQRP), a routing protocol specifically designed for MLSN, is proposed in that work. Mainly two resolutions are stressed upon in HQRP, the first resolution is about hierarchical network management, and the second one is about routing strategy for QoS satisfaction. Regarding the former suggestion, MEO satellites build the global routing table and distribute it to LEO satellites. This operation aims at achieving faster convergence of routing information. On the other hand, the second suggestion on routing implies that the traffic, which experience large hop counts, are transferred via the MEO layer. End-to-end delay can be kept low by sending the traffic via the upper layer because queuing and computational delays can be decreased due to the hop count reduction when compared with sending via the lower layer. This protocol is validated by computer simulations under three types of MLSNs that vary with the number of LEO satellites. As represented by HQRP, researches on MLSNs can be mainly classified into two types in terms of strategy involving the MEO layer utilization, i.e., intelligent network management and path for distant traffic. From hereon, we introduce other relevant research works based on these classifications.

First, we introduce research works focusing on the network management by the MEO layer. By integrating GEO satellite networks in the earlier mentioned SOS network, a three-layered MLSN architecture has been proposed by Ian F. Akyildiz *et.al.* in 2002 [17]. This work indicated that computational complexities involving topology control and route decision could be reduced by introducing a concept of satellite groups. The satellite groups are defined based on the footprints of satellites in the upper layer. According to the procedure of hierarchical management, the GEO satellite collects information about transmission delays of available links and calculates suitable routes instead of LEO and MEO satellites. Therefore, overheads caused by route calculation are effectively eliminated. As a similar protocol, Satellite Grouping and Routing Protocol (SGRP) was proposed by C. Chen *et.al.* [18]. SGRP is adopted to two layered MLSN constructed by a LEO layer and a MEO layer, and it makes groups of the LEO satellite on the basis of footprint of MEO satellites. In the group, LEO satellites report delay information of their adjacent links to the group manager, i.e., the MEO satellite. The MEO satellite calculates routing table for the LEO satellites.

Second, we introduce researches focusing on the MEO layer utilization of detouring path. In this type of protocol, traffic are usually differentiated based on the distance between the source and destination nodes. Hierarchical and Distributed QoS Routing Protocol (HDRP) proposed by Y. Zhou *et.al.* in [19] is an example of such a routing protocol. In HDRP, LEO satellites covered by a MEO satellite belong to the same domain. For the intra-domain communication, packets are transferred only through the links between LEO satellites. On the other hand, for the inter-domain communication, packets are transferred via MEO layer. In this way, LEO and MEO links are differently utilized according to the distance of communication. Adaptive Routing Protocol for QoS (ARPQ) proposed by S. Bayhan *et.al.* [20] differentiates traffic based on not only distance but also on the traffic type. ARPQ sorts out voice packets by consulting estimated transmission delay of each packet. Voice packets, estimated transmission delay of which is within a threshold time, are marked as Short Distance Voice (SDV) and transmitted via the minimum delay path. On the other hand, if the estimated transmission delay of the packets exceeds the threshold time, the packets are marked as Long Distance Voice (LDV) packets and transferred through the MEO layer.

Regarding the protocol proposed in [21], QoS class of traffic is adopted as a provision for detouring the packets to the MEO layer. This routing scheme is based on Explicit Load Balancing (ELB) protocol, which aims at fair traffic distribution among LEO constellations [22–24]. The basic concept of ELB is that traffic are detoured to the secondary path when the primary shortest path experiences traffic congestion. By adapting ELB to MLSNs, secondary path selection including the links in the MEO layer is only possible for the best-effort traffic.

As introduced above, existing proposals give different roles for satellites in each layer. However, none of them achieves optimized traffic distribution among layers. In the near future, the amount of traffic is expected to increase much as mobile communication devices and infrastructures continue to become more sophisticated. Then, in spite of huge network resources that the MLSNs have, traffic congestion is expected to occur. Therefore, efficient load distribution schemes need to be designed in order to solve such problems. In particular, fair load distribution among the layers is already a problem, which researchers have not yet addressed, i.e., how traffic distribution can be optimized. By achieving an optimized load distribution, packet drop reduction and throughput increase can be attained due to efficient utilization of network resources. To solve this problem, we propose a routing scheme for load distribution optimization among the satellite layers for the most common type of MLSNs, i.e., two-layered LEO/MEO satellite networks.

III. Optimized traffic distribution to evenly utilize capacities in each layer in MLSN

While there are various types of MLSN architectures proposed in literature, e.g., LEO/MEO, LEO/GEO, LEO/MEO/GEO, and so on, as mentioned in the previous section, we assume the two-layered LEO/MEO MLSN here. The reason behind this assumption is due to the fact that a large propagation delay is caused by using GEO satellite networks. We propose the following load balancing scheme to distribute traffic among the LEO and MEO layers in order to make efficient use of the MLSN's network resources.

A. Threshold based traffic distribution scheme

In our routing method, traffic are basically transmitted through the shortest path within the LEO layer. This condition enables each traffic flow to reach its destination as fast as possible. Therefore, the total communication delay can be kept at a reasonably low level. We assume that the transmission delay of the link i is denoted by d_{l_i}. Then, provided that a path, $\boldsymbol{r}$, is composed of links $\{l_1, l_2, \cdots, l_i, \cdots, l_n\}$, the total end-to-end delay of the path, $d(\boldsymbol{r})$, is defined by the summation of the delay at each link, i.e., $d(\boldsymbol{r}) = \sum_{l_i \in \boldsymbol{r}} d_{l_i}$, where $\boldsymbol{r} = \{l_1, l_2, \cdots l_n\}$. When using the shortest path routing, the path having the smallest communication delay in the LEO layer is selected. The path calculation is conducted when hand-off of link occurs anywhere in the network.

However, since congestion easily occurs at the LEO layer if the amount of the traffic increases, a proper amount of traffic should be diverted to the MEO layer to avoid this congestion. Long Distance Traffic (LDT), distance of which between the source and destination nodes are larger than other traffic, are suitable to be detoured because LDT pass through a lot of links and have a large possibility to share the capacity of specific links with other traffic in contrast with Short Distance Traffic (SDT). In order to distribute LDT to the MEO layer, we introduce the time scale threshold, denoted by θ_d, in our route calculation. Suppose that the packets of a traffic flow are transferred via path $\boldsymbol{r}$. When the total communication delay, $d(\boldsymbol{r})$, exceeds the value of θ_d, the traffic are classified as LDT and detoured to the MEO layer through the first LEO satellite. On the other hand, when $d(\boldsymbol{r})$ is within the value of θ_d, the traffic are classified as SDT and transferred via path $\boldsymbol{r}$. After detouring the traffic to each layer according to the threshold θ_d, traffic are delivered only through that layer until it reaches the satellite just above the destined terrestrial user terminal. These conditions are summarized in Fig. 2. The value of this threshold, θ_d, is fixed regardless of any incident, such as time elapse or fluctuation in generation of traffic. In terms of this routing strategy, we evaluated its performance in our earlier works in [25] and [26]. There, we verified the possibility to achieve an efficient traffic distribution, in other words, to minimize packet drops in the entire MLSN with an optimal threshold value. However, the method to find the optimal value has not been addressed to date, and remains an open research issue.

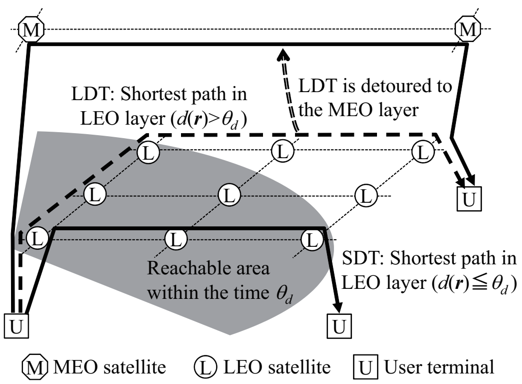


Fig. 2. Definitions of Long Distance Traffic (LDT) and Short Distance Traffic (SDT), and traffic detouring.

Although the concept of our routing method is partially similar to the previous researches such as [16] or [20], our method is different from the existing works for the following reasons. First, our purpose is to distribute the traffic fairly among the satellites layers and eliminate congestion. ARPQ appeared in [20] uses the satellites in the upper layers to mitigate the end-to-end delay of LDT, especially regarding only real-time traffic such as Voice over Internet Protocol (VoIP). But, our concern lies in the fact that the amount of real-time traffic is too small compared with other categories of traffic [27]. Hence, controlling only the real-time traffic is not enough to achieve traffic distribution that utilizes entire network resources of the MLSN. Second, in HQRP appeared in [16], the way to decide the suitable distribution balance is not declared. In our proposed method, traffic distribution is fairly balanced by deciding the detouring threshold, θ_d, with theoretical reason, which is discussed in following subsections.

B. Definition of the optimal threshold

We consider the definition of the optimal threshold with the following assumptions for simplicity. First, users and flows are uniformly deployed on the earth. Second, we assume a two-layered MLSN, each layer of which is a constellation with lattice-connected ISLs due to its similarity on the link connectivity. Third, we assume that packet drops occur only at the ISL, i.e., ILLs and GSLs do not experience any congestion due to their sufficiently large capacities. With these assumptions, each layer in the considered two-layered MLSN can be regarded as an integration of single systems, each of which consists of four incoming and four outgoing links as depicted in Fig. 3 due to the symmetric properties of the network. Therefore, in the followings, we address the traffic distribution at the single system in each layer.

In our study, the optimal traffic detouring threshold is defined so that the ratio of the amount of traffic between the LEO and the MEO layers is equivalent to the ratio of the system capacity. In other words, the following equation is satisfied,

$$\frac{ATS_{LEO}(\theta_d)}{ATS_{MEO}(\theta_d)} = \frac{C_{LEO}}{C_{MEO}}, \tag{1}$$

where ATS_{LEO} and ATS_{MEO} denote the amount of traffic in the system in each layer. C_{LEO} and C_{MEO} are the capacity

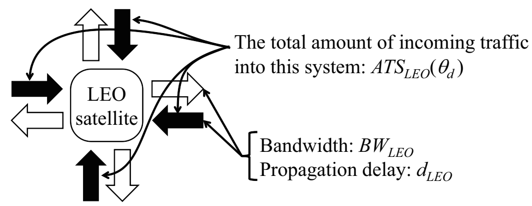


Fig. 3. Parameters of the network considering a specific system (in this example, a system including a LEO satellite has been considered).

of the system, which can be defined as a summation of the Bandwidth Delay Product (BDP) of their inter-satellite links as follows,

$$C_{layer} = 4 \times BDP_{layer} = 4 \times BW_{layer} \cdot d_{layer}, \tag{2}$$

where BW_{layer} and d_{layer} indicate the bandwidth and the propagation delay of the inter-satellite link in the layer, respectively.

We explain the reason why we set out Eq. 1 as the objective function from the theoretical point of view, i.e., the queuing theory. The utilization ratio, ρ, can be expressed by the average packet arrival rate, λ, divided by the average service rate, μ, according to the queuing theory. Here, the average service rate at the system in each layer can be defined as,

$$\mu_{LEO} = 4 \times BW_{LEO}, \tag{3}$$
$$\mu_{MEO} = 4 \times BW_{MEO}. \tag{4}$$

On the other hand, the average packet arrival rate at the system in each layer can be expressed as follows,

$$\lambda_{LEO} = ATS_{LEO}(\theta_d)/d_{LEO}, \tag{5}$$
$$\lambda_{MEO} = ATS_{MEO}(\theta_d)/d_{MEO}. \tag{6}$$

Therefore, the utilization ratio can be derived as,

$$\rho_{LEO} = ATS_{LEO}(\theta_d)/(4 \cdot BW_{LEO} \cdot d_{LEO}), \tag{7}$$
$$\rho_{MEO} = ATS_{MEO}(\theta_d)/(4 \cdot BW_{MEO} \cdot d_{MEO}). \tag{8}$$

In our research, we aim to efficiently distribute traffic between LEO and MEO layer so that the packet drop occurrence due to traffic overload becomes even. In other words, the utilization ratio must be equal between both layers according to the well-known fundamental queuing analysis, which results in the derivation of Eq. 1.

In the above discussion, the assumptions about traffic and network allow us to use the same system model for all satellites in the same layer. Although it is possible to extend our formulation for modeling of actual network environments by introducing different system models for each satellite, i.e., different detouring thresholds for different satellites, the calculation process of ATS_{layer} becomes complex, which is beyond the scope of this paper.

C. Formulation of the optimal value of the threshold

It is evident from Eqs. 1 and 2 that the optimal detouring threshold value can be derived by formulating the amount of traffic in the system in each layer, which is achieved by three steps, i.e., modeling of traffic generation and distribution, quantifying traffic arrival ratio, and calculation of the amount of traffic in the system.

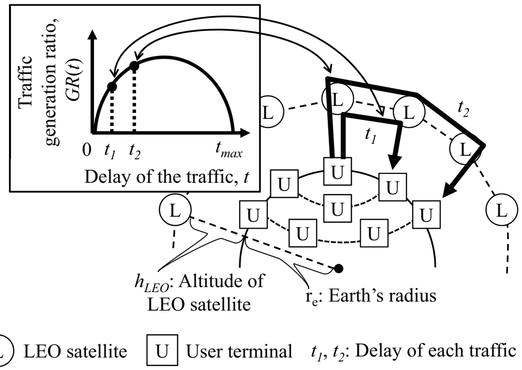
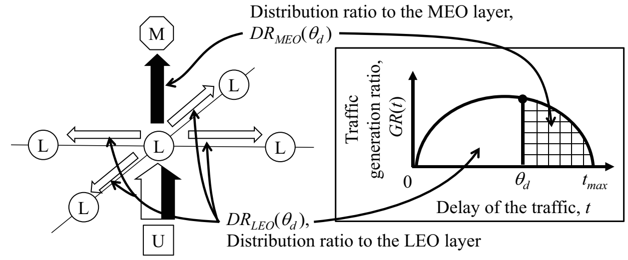
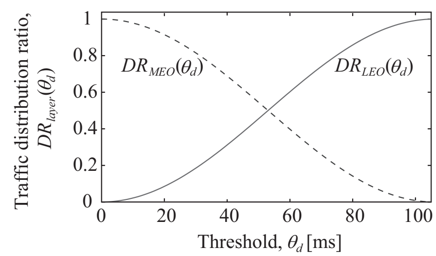


Fig. 4. Modeling of traffic generation.



(a) Conceptual picture of traffic distribution ratio.



(b) Traffic distribution ratio in each LEO satellite for different threshold values.

Fig. 5. Modeling of traffic detouring.

1) Modeling of traffic generation and distribution: At first, we quantify the amount of generated traffic as a function of its communication delay, t. Let us denote the traffic generation ratio, which is defined by relation between the amount of traffic and its communication delay t in each LEO satellite as $GR(t)$. $GR(t)$ is proportional to the number of reachable users from the source node within the communication delay, t. In addition, the communication delay t is, in turn, proportional to the distance between the source and destination nodes. Furthermore, while traffic are sent via satellite networks, the propagation delay between the terrestrial user terminals and LEO satellite is affected by not only the altitude of the LEO satellite but also the lattice-shaped link connections of the LEO layer. For these reasons, $GR(t)$ can be expressed by the following equation,

$$GR(t) = \frac{\mathrm{c}}{2\sqrt{2}(\mathrm{r_e} + h_{LEO})} \sin\left(\frac{\mathrm{c}t}{\sqrt{2}(\mathrm{r_e} + h_{LEO})}\right), \quad (9)$$

where c denotes light speed, $\mathrm{r_e}$ denotes the radius of the earth, and h_{LEO} refers to the altitude of the LEO satellites. Note that $GR(t)$ is normalized as the integral of $GR(t)$ from zero to the maximum value of t, t_{max}, to be one. Here, t_{max} is derived by the following equation,

$$t_{max} = \frac{\sqrt{2}\pi(\mathrm{r_e} + h_{LEO})}{\mathrm{c}}. \quad (10)$$

The above equation means that the maximum delay of the traffic can be estimated from the farthest situation of the distance between the source and destination nodes. In terms of this derivation of $GR(t)$, the conceptual picture of the traffic model is depicted in Fig. 4.

In our routing method, traffic with communication delay exceeding the value of θ_d are detoured to the MEO layer. Therefore, the ratio of the amount of traffic distributed at the MEO layer in each LEO satellite, $DR_{MEO}(\theta_d)$, can be expressed as a function of $GR(t)$ as follows,

$$DR_{MEO}(\theta_d) = \int_{\theta_d}^{t_{max}} GR(t)dt. \quad (11)$$

Similarly, the remaining traffic are transferred via the LEO layer. Thus, the ratio of the amount of traffic distributed at the LEO layer, $DR_{LEO}(\theta_d)$, can be expressed by the following equation,

$$DR_{LEO}(\theta_d) = \int_{0}^{\theta_d} GR(t)dt. \quad (12)$$

Conceptual picture of traffic distribution ratio is depicted in Fig. 5a. In addition, the above equations are depicted as a graph in Fig. 5b. This graph was plotted by adopting the parameters of the Iridium constellation as an example. In other words, h_{LEO} is assumed to be 780km. In Fig. 5b, the vertical axis demonstrates the normalized amount of the traffic distributed at each layer. From this figure, we can observe that the ratio of traffic distribution is dominated by the value of θ_d.

2) Quantifying the traffic arrival ratio at each layer: The traffic assigned to each layer keep flowing through the layer until they arrive at the satellite above the destination user terminal for certain durations. During the transmission, the traffic affect all the satellites, through which they flow. The impact level of the traffic (that originate from other satellites) at a specific satellite depends on the distance between both the satellites. In other words, each satellite gains stronger impact by traffic from nearer satellites than those from farther satellites because of the traffic transit. In this subsection, we quantify this relationship, namely the distance from other satellites and the strength of impact, by clarifying the traffic arrival ratio, which is defined by the amount of traffic from all the other satellites as a function of the number of hops from other satellites. As depicted in Fig. 6, we consider an example of the environment around a specific satellite X in the LEO layer by looking down on a quarter of the earth. We derive the arrival ratio of the traffic arriving at the satellite X from other satellites in this situation. Here, we assume that the amount of traffic newly flown into each satellite at the unit of time is equal to one.

In Fig. 6a, each term of ${}_n\mathrm{C}_k$ indicates the prospective number of the shortest paths to the satellite X from the satellite, which is n hops away from the satellite X. k is an integer value determined based on the relative position of each satellite to the satellite X. For example, the shortest path candidates in case of the 3-hop arrival are depicted in Fig. 6b. The range of k can be expressed by $(1 \leq k \leq n)$ with $(0 < n \leq n_{max}/2)$, $(n - n_{max}/2 + 1 \leq k \leq n_{max}/2)$ with $(n_{max}/2 < n < n_{max})$, and $(k = n_{max}/2)$ with $(n = n_{max})$. Here, it should be noted that there are four satellites, which have ${}_n\mathrm{C}_k$ of the shortest path candidates in the whole network except the case of $n = n_{max}$, i.e., the satellite Y in Fig. 6a, due to symmetry. In each path destined to the satellite X, we need to take into account the effect of traffic diffusion as shown in Fig. 6b. With the assumption that the traffic originated from a satellite evenly diffuse to all directions, as the number of hops increases more, the more is the reduction in traffic arrival at the satellite X. The traffic arrival reduction can be expressed as $(4 \cdot 3^{n-1})^{-1}$. Note that when $n = 0$, $AR_{layer}(0) = 1$. This is because only the traffic newly flown into each satellite from its coverage area needs to be considered.

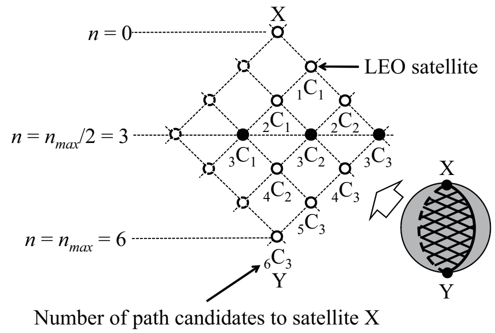
From these considerations, we can derive the traffic arrival ratio in a unit of time at a specific satellite from all the other distant satellites in the same layer, $AR_{layer}(t)$, as follows,

$$
AR_{layer}(t) =
\begin{cases}
1, \quad \text{for } n = 0, \\
\displaystyle\sum_{k=1}^{n} \left({}_n\mathrm{C}_k \times 4 \times \frac{1}{4} \cdot \frac{1}{3^{n-1}} \right) \\
\displaystyle\qquad = \sum_{k=1}^{n} \frac{{}_n\mathrm{C}_k}{3^{n-1}}, \quad \text{for } 0 < n \leq \frac{n_{max}}{2}, \\
\displaystyle\sum_{k=n-\frac{n_{max}}{2}+1}^{n_{max}/2} \left({}_n\mathrm{C}_k \times 4 \times \frac{1}{4} \cdot \frac{1}{3^{n-1}} \right) \\
\displaystyle\qquad = \sum_{k=n-\frac{n_{max}}{2}+1}^{n_{max}/2} \frac{{}_n\mathrm{C}_k}{3^{n-1}}, \quad \text{for } \frac{n_{max}}{2} < n < n_{max}, \\
\displaystyle {}_n\mathrm{C}_{n_{max}/2} \times 4 \times \frac{1}{4} \cdot \frac{1}{3^{n-1}} \\
\displaystyle\qquad = \frac{{}_n\mathrm{C}_{n_{max}/2}}{3^{n-1}}, \quad \text{for } n = n_{max},
\end{cases}
\tag{13}
$$

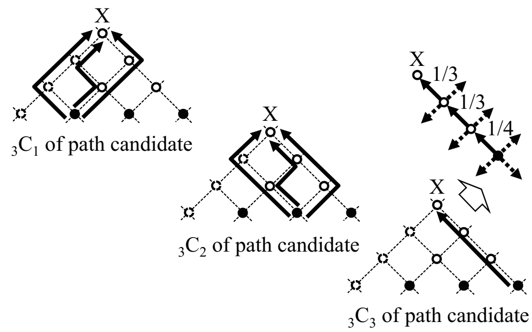
where the number of hops, n, is different in each layer when we express it with delay of the traffic in the LEO layer, t, as follows,

$$
n(t) =
\begin{cases}
\mathrm{round}\left(\dfrac{t}{d_{LEO}} \right), \quad \text{in LEO layer}, \\
\mathrm{round}\left(t \cdot \dfrac{\mathrm{r_e} + h_{MEO}}{\mathrm{r_e} + h_{LEO}} \cdot \dfrac{1}{d_{MEO}} \right), \quad \text{in MEO layer},
\end{cases}
\tag{14}
$$

where d_{LEO} and d_{MEO} denote an average transmission delay in the LEO layer and that in the MEO layer, respectively, and h_{MEO} denotes the altitude of the MEO satellite. n_{max} can be given by $n(t = t_{max})$.



(a) The number of hops and paths to the satellite X.



(b) Shortest paths in case of 3-hop arrival, and traffic diffusion effect.

Fig. 6. Examples of traffic flows surrounding a specific satellite.

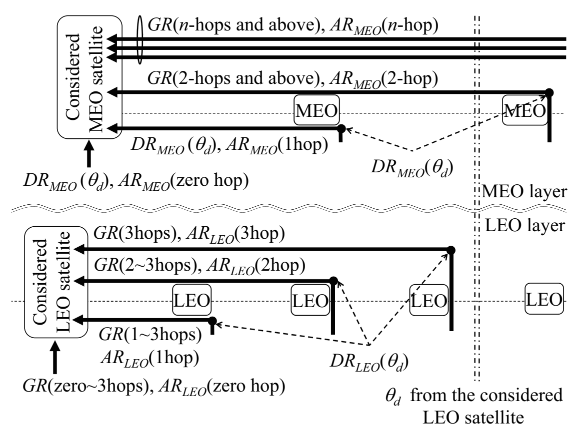


Fig. 7. Parameters of the network considering a specific satellite.

3) Calculation of the amount of traffic in the system: In Fig. 7, we depict the conceptual picture of how we derive the amount of traffic in each system. The amount of traffic in the system involving the LEO layer can be calculated by integrating the traffic from close satellites according to our strategy of traffic distribution. The traffic from the farthest satellites have an end-to-end delay equal to θ_d. Therefore, such traffic arrive at the satellite in the considered system with the generation ratio of $GR(\theta_d)$ with respect to the distribution ratio of $DR_{LEO}(\theta_d)$ and the arrival ratio of $AR(\theta_d)$. In Fig. 7, since traffic with delay of θ_d experience three hops in the LEO layer, the generation ratio and arrival ratio of the traffic with the three hops are taken into account. In addition, the traffic having the generation ratio of two and three hops arrive from closer satellites to the considered LEO system such as satellites

TABLE I
PARAMETERS OF SATELLITE CONSTELLATIONS.

	LEO	MEO
Model	Iridium	Spaceway NGSO
Number of satellites	66	20
Number of planes	6	4
Number of satellites per plane	11	5
Altitude	780km	10,352km
Eccentricity	0	0
Inclination	86.4degree	55.0degree

TABLE II
PARAMETERS OF THE NETWORK.

Number of users	100
Bandwidth of ISL	5Mbps
Queue length of ISL	20packets
Queue type	Drop-tail
Maximum interval of route calculation	300s
Number of flows	300
Simulation time	6027s
Traffic type	On/Off traffic
On/Off distribution	Pareto distribution
Average On/Off interval	200ms
Packet size	1KByte

with the distance of two hops with the arrival ratio of two hops. In this way, the amount of traffic in the single LEO system, $ATS_{LEO}(\theta_d)$, can be expressed as Eq. 15 by considering all the places where the traffic can arrive at the system. In Eq. 15, I denotes the total amount of traffic in the whole network, and N_{LEO} denotes the number of the LEO satellites. Note that $(I \cdot DR_{LEO}(\theta_d)/N_{LEO})$ refers to the amount of newly assigned traffic to each LEO satellite.

On the other hand, in terms of the system in the MEO layer, all the traffic distributed in the close sphere (i.e., inside the distance within the delay of threshold time in Fig. 7) arrives at the considered MEO system because such traffic have longer end-to-end delay than θ_d. Nevertheless, it cannot be said that all the traffic arrive at the considered MEO system from farther spheres, i.e., some traffic arrive at the destination before arriving at the considered MEO system. In this case, the traffic from the satellites, with the distance of n hops and above, arrive at the considered MEO system. Therefore, we have to take into account the generation ratio of n hops and above, and the arrival ratio of n hops. For these reasons, the amount of traffic in the single MEO system, $ATS_{MEO}(\theta_d)$, can be expressed by Eq. 16 where N_{MEO} denotes the number of the MEO satellites. Note that $(I \cdot DR_{MEO}(\theta_d)/N_{MEO})$ means the amount of traffic newly assigned to each MEO satellite.

Finally, we calculate the optimal detouring threshold, θ_d, from Eq. 1 with Eqs. 2, 15, and 16.

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed routing method, we conducted extensive simulations by using Network Simulator version 2 (NS2) [28].

A. Simulation setup

We constructed a simulation topology featuring a typical MLSN by integrating Iridium constellation [5] for the LEO layer and Spaceway NGSO constellation [29] for the MEO layer. As mentioned earlier, Iridium is one of the most famous NGEO satellite networks in operation. In our simulation, Iridium constellation, which has cross-seam links, is adopted from the view point of symmetric property of the network. Spaceway NGSO network is not in operation now, but it is known to be a sophisticated MEO constellation. Detailed configurations of these constellations are summarized in Table I. In addition, other configurations of the network are listed in Table II. We differentiate the capacities of the intra-layer links from those of the inter-layer links in order not to drop packets at the inter-layer links. We deploy 100 terrestrial user-terminals on the earth in a random manner. Then, 300 pairs of source and destination nodes are also randomly selected, i.e., 300 flows are transmitted through the MLSN. To suppose general scenario with the existence of real-time and non-real-time traffic, it is assumed that each flow is produced by an On/Off traffic, in which the average interval between the “On” and “Off” events is 200ms. In the evaluation of the modeling accuracy, the average transmission rate of the terrestrial users is set to be 500kbps when traffic are generated. We repeated the simulation 20 times and considered the average values of all the simulation runs as result. By referring to Eq. 2, the capacity of the Spaceway constellation can be estimated about 1.5 times larger than that of the Iridium constellation. According to our strategy of the threshold determination, the optimal threshold θ_d for this MLSN is equal to 60ms.

The performance evaluation is conducted from two aspects. First, in order to verify the accuracy of the proposed theoretical model of the network and traffic generation, we confirm the relationship between the threshold value and the traffic detouring ratio. There, we compare our traffic detouring model and the optimal value of detouring threshold theoretically calculated with the simulated traffic behavior. Second, we compare our routing method with other routing schemes. As a countermeasure, we chose Dijkstra’s Shortest Path (DSP) [30] routing method because this method is one of the most popular routing methods in NGEO satellite networks. Besides, since

$$ATS_{LEO}(\theta_d) = \frac{I \cdot DR_{LEO}(\theta_d)}{N_{LEO}} \times \int_0^{\theta_d} \frac{\int_t^{\theta_d} GR(s)ds}{DR_{LEO}(\theta_d)} \cdot AR_{LEO}(t)\ dt \tag{15}$$

$$ATS_{MEO}(\theta_d) = \frac{I \cdot DR_{MEO}(\theta_d)}{N_{MEO}} \times \left(\int_{\theta_d}^{t_{max}} AR_{MEO}(t)\ dt + \int_{\theta_d}^{t_{max}} \frac{\int_t^{t_{max}} GR(s)ds}{DR_{MEO}(\theta_d)} \cdot AR_{MEO}(t)\ dt \right) \tag{16}$$

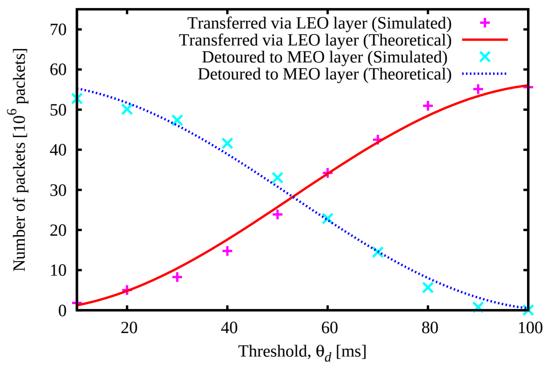
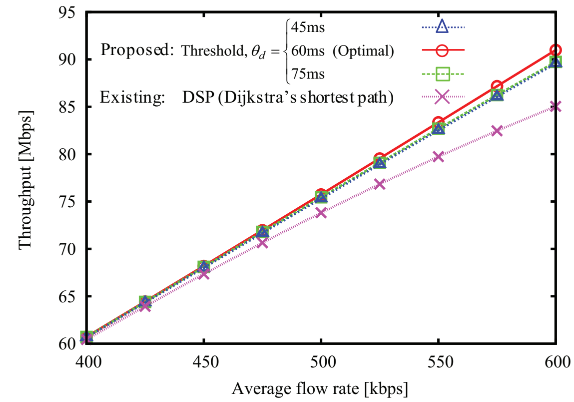
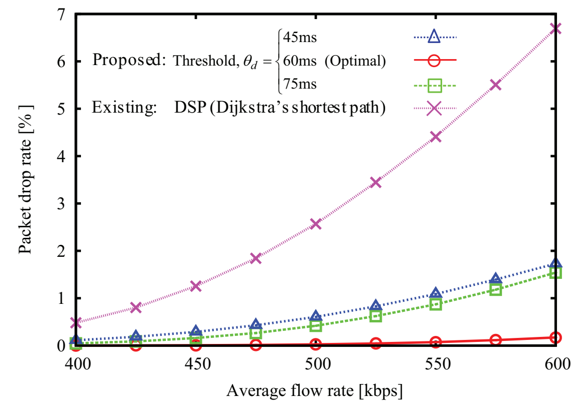


Fig. 8. Effect of the threshold (θ_d) on the traffic detouring ratio in terms of number of detoured packets.



(a) Comparison in throughput between the proposed scheme and DSP.



(b) Comparison in packet drop ratio between the proposed scheme and DSP.

Fig. 9. Performance comparison between the proposed scheme and DSP in terms of throughput and packet drop ratio.

DSP is a basis of our routing method, the effectiveness of the proposed method can be obviously verified by comparing with this method. At the same time, we compare the proposed routing method with different threshold values to confirm that routing with the optimal threshold value demonstrates the best performance in contrast with routing with other threshold values.

B. Validation of the traffic distribution performance

Fig. 8 demonstrates the comparison of the detouring ratios obtained through simulations and derived from the mathematical model. While the simulation results are plotted with points, the theoretical values are represented by lines. It is evident that the proposed scheme successfully controls the traffic detouring ratio between the LEO and MEO layers by adjusting the threshold as similar as expected from the analytical model. Therefore, it can be concluded that the optimal threshold value decided by using this analytical approach is, indeed, reliable enough.

C. Performance comparison

Fig. 9 demonstrates the result of the comparison between the proposed routing method and DSP. Note that the optimal value of the threshold, computed theoretically from the proposed model, is 60ms. In order to simulate our proposed method, we use two other threshold values in addition to the optimum one, and their values are set to $\pm$15ms with respect to the optimal threshold value. In other words, the three threshold values, used for comparison in our simulation, are 45ms, 60ms, and 75ms, respectively. In this comparison, the average flow rate varies from 400kbps to 600kbps.

Figs. 9a and 9b demonstrate the comparison in the total network throughput and packet drop ratio, respectively. As evident from the results in these figures, although the performances of DSP become worse as the average flow rate increases, the performance of the proposed routing method maintains its effectiveness. This can be confirmed from Fig. 10, which shows the behavior of the traffic distribution. The vertical axis indicates the number of packets, which are distributed to the layer in each routing method. As shown in this figure, in terms of DSP, the MEO layer is not utilized at all. On the other hand, in terms of the proposed routing, the distributed traffic ratio between the LEO and MEO layers is strictly controlled according to the routing strategy. Actually, it can be confirmed that each LEO satellite distributes only about 40% of traffic to the MEO layer, while the network capacity of the MEO layer is 1.5 times as much as that of the LEO layer. This is because the proposed scheme adequately takes into consideration that the traffic detoured to the MEO layer are long distance traffic, which occupy the network capacity for a longer time. Thus, the fair utilization of network capacity between layers can be eventually achieved, which leads to the increased throughput and decreased packet drops as demonstrated in Fig. 9.

In addition, it can be confirmed by comparing the results of the different thresholds that the proposed traffic distribution using our calculation scheme of optimal threshold value is quite reasonable. When the threshold value is configured to be the optimal value, the network throughput retains the highest value of any other configuration of the threshold θ_d. At the same time, the packet drop rate remains the minimum as the average flow rate increases. To summarize these evaluations, we confirmed that our proposed method is, indeed, effective in terms of throughput and packet drops by efficiently distributing the traffic load to each layer of satellites in the considered

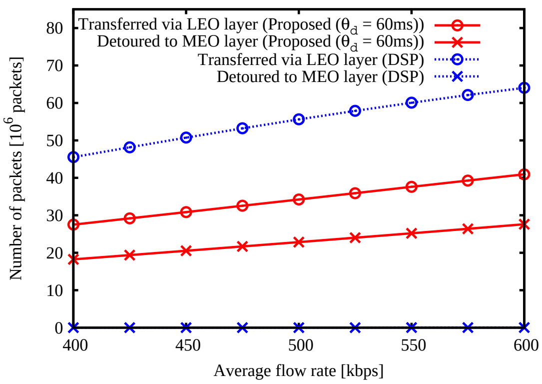


Fig. 10. Comparison in traffic distribution between the proposed scheme and DSP.

MLSN.

V. Conclusion

In this paper, we proposed a route control method aiming at minimizing packet drops by fairly distributing the traffic load among satellites layers in a two-layered MLSN. This method is based on the shortest path routing, and traffic are detoured to the upper layer according to the introduced threshold to avoid traffic concentration at the lower layer. We presented the analytical model to derive the optimal value of the traffic detouring threshold. By using this model, the threshold can be appropriately adjusted to balance the load between layers based on the network capacity of each layer. We evaluated our routing scheme with computer simulations and confirmed effective reduction in packet drops due to appropriate load distribution. Since the analytical model presented in this paper is designed with generalized conditions, it is applicable for different types of MLSN with further enhancements.

References

[1] I. Bisio, F. Lavagetto, M. Marchese, and A. Sciarrone, "Smartphone-based User Activity Recognition Method for Health Remote Monitoring Applications," in *Proc. of 2nd Intl. Conf. on Pervasive and Embedded Computing and Communication Systems*, Feb. 2012, pp. 200-205.

[2] M. Cheng, X. Gong, and L. Cai, "Joint Routing and Link Rate Allocation under Bandwidth and Energy Constraints in Sensor Networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3770–3779, Jul. 2009.

[3] J. Evans, "Satellite systems for personal communications," *IEEE Antennas and Propagation Magazine*, vol. 39, no. 3, pp. 7–20, Jun. 1997.

[4] N. Kadowaki and R. Suzuki, "Overview of the wideband internetworking engineering test and demonstration satellite project," *Journal of the National Institute of Information and Communications Technology*, vol. 54, no. 4, pp. 3–10, Dec. 2007.

[5] P. Lemme, S. Glenister, and A. Miller, "Iridium(R) aeronautical satellite communications," *Aerospace and Electronic Systems Magazine, IEEE*, vol. 14, no. 11, pp. 11–16, Nov. 1999.

[6] I. Bisio and M. Marchese, "Power Saving Bandwidth Allocation over GEO Satellite Networks," *IEEE Communications Letters*, vol. 16, no. 5, pp. 596–599, May 2012.

[7] T. Cola, H. Ernst, and M. Marchese, "Performance analysis of CCSDS File Delivery Protocol and erasure coding techniques in deep space environments," *Computer Networks*, vol. 51, no. 14, pp. 4032–4049, Oct. 2007.

[8] C. Caini, R. Firrincieli, M. Marchese, T. Cola, M. Luglio, C. Roseti, N. Celandroni, and F. Potort, "Transport layer protocols and architectures for satellite networks," *Int. J. Satellite Communications and Networking*, vol. 25, no. 1, pp. 1–26, Jan./Feb. 2007.

[9] I. Bisio and M. Marchese, "Analytical expression and performance evaluation of TCP packet loss probability over geostationary satellite," *IEEE Communications Letters*, vol. 8, no. 4, pp. 232–234, Apr. 2004.

[10] S. Kota and M. Marchese, "Quality of service for satellite IP networks: a survey," *Int. J. of Satellite Communications and Networking*, vol. 21, no. 4-5, pp. 303–349, Jul.-Oct. 2003.

[11] H. Tsunoda, K. Ohta, N. Kato, and Y. Nemoto, "Supporting IP/LEO satellite networks by handover-independent IP mobility management," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 2, pp. 300–307, Feb. 2004.

[12] P. K. Chowdhury, M. Atiquzzaman, and W. Ivancic, "Handover schemes in satellite networks: state-of-the-art and future research directions," *IEEE Communications Surveys & Tutorials*, vol. 8, no. 4, pp. 2–14, Dec. 2006.

[13] A. Z. Shahriar, M. Atiquzzaman, and S. Rahman, "Mobility management protocols for next-generation all-IP satellite networks," *IEEE Wireless Communications*, vol. 15, no. 2, pp. 46–54, Apr. 2008.

[14] E. Ekici, I. F. Akyildiz, and M. D. Bender, "A distributed routing algorithm for datagram traffic in LEO satellite networks," *IEEE/ACM Transactions on Networking*, vol. 9, no. 2, pp. 137–147, Apr. 2001.

[15] E. Papapetrou, S. Karapantazis, and F. N. Pavlidou, "Distributed on-demand routing for LEO satellite systems," *Computer Networks*, vol. 51, no. 15, pp. 4356–4376, Oct. 2007.

[16] J. Lee and S. Kang, "Satellite over satellite (SOS) network: A novel architecture for satellite network," in *Proc. of IEEE INFOCOM*, Tel-Aviv, Israel, Mar. 2000.

[17] I. F. Akyildiz, E. Ekici, and M. D. Bender, "Mlsr: A novel routing algorithm for multilayered satellite IP networks," *IEEE/ACM Transactions on Networking*, vol. 10, no. 3, pp. 411–420, Jun. 2002.

[18] C. Chen and E. Ekici, "A routing protocol for hierarchical LEO/MEO satellite IP networks," *Wireless Networks*, vol. 11, no. 4, pp. 507–521, Jul. 2005.

[19] Z. Yunhui, S. Fuchun, and Z. Bo, "A novel QoS routing protocol for LEO and MEO satellite networks," *Intl. J. of Satellite Communications and Networking*, vol. 25, no. 6, pp. 603–617, Nov. 2007.

[20] S. Bayhan, G. Gur, and F. Alagoz, "Performance of delay-sensitive traffic in multi-layered satellite IP networks with on-board processing capability," *International Journal of Communication Systems*, vol. 20, no. 12, pp. 1367–1389, Jan. 2007.

[21] H. Nishiyama, D. Kudoh, N. Kato, and N. Kadowaki, "Load balancing and QoS provisioning based on congestion prediction for GEO/LEO hybrid satellite networks," in *Proc. of the IEEE*, vol. 99, no. 11, pp. 1998–2007, Nov. 2011.

[22] T. Taleb, D. Mashimo, A. Jamalipour, K. Hashimoto, Y. Nemoto, and N. Kato, "ELB: An explicit load balancing routing protocol for multi-hop NGEO satellite constellations," in *Proc. of IEEE GLOBECOM*, San Francisco, USA, Nov. 2006.

[23] T. Taleb, D. Mashimo, A. Jamalipour, N. Kato, and Y. Nemoto, "Explicit load balancing technique for NGEO satellite IP networks with on-board processing capabilities," *IEEE/ACM Transactions on Networking*, vol. 17, no. 1, pp. 281–293, Feb. 2008.

[24] T. Takahashi, T. Taleb, K. Hashimoto, and N. Kato, "Improving ELB in multi-hop satellite constellations with short ISL delays," in *Proc. of 25th AIAA Int'l Communications Satellite Systems Conference (ICSSC)*, Seoul, Korea, Apr. 2007.

[25] Y. Tada, H. Nishiyama, N. Yoshimura, and N. Kato, "An effective route control method on multi-layered satellite networks," in *Proc. of 61st International Astronautical Congress 2010 (IAC 2010)*, Prague, Czech Republic, Sep. 2010.

[26] Y. Tada, H. Nishiyama, N. Yoshimura, and N. Kato, "Characterization of packet losses and delays in multi-layered satellite networks over an efficient routing scheme," in *IEICE Technical Report*, vol. 110, no. 256, pp. 107–111, Oct. 2010.

[27] "Cisco visual networking index: Forecast and methodology, 2010-2015," [Online]. Available: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360_ns827_Networking_Solutions_White_Paper.html

[28] "The network simulater – ns-2." [Online]. Available: http://isi.edu/nsnam/ns/

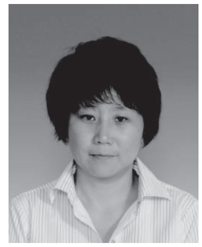
[29] L. Wood, "Satellite constellation networks," *Internetworking and Computing over Satellite Networks*, pp. 13–34, Mar. 2003.

[30] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numerische Mathematik*, vol. 1, no. 1, pp. 269–271, Dec. 1959.

Hiroki Nishiyama (M'08) received his M.S. and Ph.D. in Information Science from Tohoku University, Japan, in 2007 and 2008, respectively. He was a Research Fellow of the prestigious Japan Society for the Promotion of Science (JSPS) until the completion of his PhD, following which he went on to become an Assistant Professor at the Graduate School of Information Sciences (GSIS) at Tohoku University. He was promoted to his current position of an Associate Professor at GSIS in 2012, when he was just 29 years old. He was acclaimed with the Best Paper Awards in many international conferences including IEEE's flagship events, namely the IEEE Wireless Communications and Networking Conference in 2012 (WCNC'12) and the IEEE Global Communications Conference in 2010 (GLOBECOM'10). He is a young yet already prominent researcher in his field as evident from his valuable contributions in terms of many quality publications in prestigious IEEE journals and conferences. He was also a recipient of the IEICE Communications Society Academic Encouragement Award 2011 and the 2009 FUNAI Foundation's Research Incentive Award for Information Technology. He received the Best Student Award and Excellent Research Award from Tohoku University for his phenomenal performance during the undergraduate and master course study, respectively. His research covers a wide range of areas including traffic engineering, congestion control, satellite communications, ad hoc and sensor networks, and network security. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

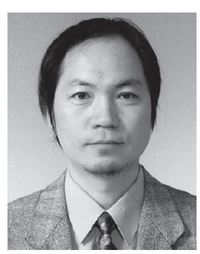
Yuta Tada received his B.E. degree in Communication Engineering from the School of Engineering at Tohoku University, Japan, in March 2010, and the M.S. degree in Applied Information Science from the Graduate School of Information Sciences (GSIS), at the same university, in March 2012. His research interests were in the area of satellite networking, specifically routing and load distribution technologies for multi-layered satellite networks. He is now working at the NTT Communications Corporation.

Nei Kato (A'03-M'04-SM'05) received his M.S. and Ph.D. Degrees in information engineering from Tohoku University, Japan, in 1988 and 1991, respectively. He joined Computer Center of Tohoku University at 1991, and has been a full professor with the Graduate School of Information Sciences since 2003. He has been engaged in research on satellite communications, computer networking, wireless mobile communications, smart grid, image processing and neural networks. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He serves/served as the Vice Chair of IEEE Ad Hoc & Sensor Networks Technical Committee, the Chair of IEEE Satellite and Space Communications Technical Committee(2010-2012), the Chair of the IEICE Satellite Communications Technical Committee(2010-2011), a technical editor of IEEE Wireless Communications(2006-), an editor of IEEE Transactions on Wireless Communications(2008-), an associate editor of IEEE Transactions on Vehicular Technology(2010-), an editor of IEEE Trans. On Parallel and Distributed Systems, a co- guest-editor of SIs on IEEE Wireless Communications Magazine, IEEE Trans. on TPDS and IEEE Trans. on SG. He has served as a symposium co-chair of GLOBECOM'07, ICC'10, ICC'11, ICC'12, Vice Chair of IEEE WCNC'10, WCNC'11, ChinaCom'08, ChinaCom'09, Symposia co-chair of GLOBECOM'12, and workshop co-chair of VTC2010. His awards include Minoru Ishida Foundation Research Encouragement Prize(2003), Distinguished Contributions to Satellite Communications Award from the IEEE Communications Society, Satellite and Space Communications Technical Committee(2005), the FUNAI information Science Award(2007), the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion(2008), the IEICE Network System Research Award(2009), the KDDI Foundation Excellent Research Award(2012), The IEICE Communication Society Best Paper Award(2012), IEEE GLOBECOM Best Paper Award(twice), IEEE WCNC Best Paper Award, and IEICE Communications Society Best Paper Award(2012). Besides his academic activities, he also serves on the expert committee of Telecommunications Council, Ministry of Internal Affairs and Communications, and as the chairperson of ITU-R SG4 and SG7, Japan. Nei Kato is a Distinguished Lecturer of IEEE Communications Society(2012-2013) and the PI of JSPS A3 Foresight Program(2011-2014). He is a fellow of IEICE.



Naoko Yoshimura received her B.S. and M.S. degree in electronic engineering from Nihon University, Japan in 1991 and 1993, respectively. She joined the Communications Research Laboratory (CRL, Ministry of Posts and Telecommunications) in 1993. She was engaged in the research of mobile and fixed satellite communication systems and high data rate satellite communications for the Engineering Test Satellite VI (ETS-VI) and Communications and Broadcasting Engineering Test Satellite (COMETS). Since 1998 she joined the Wideband InterNetworking test and Demonstration Satellite (WINDS) project and she took charge of development of on-board switching system for WINDS. Currently, she is a senior researcher of Space Communication Systems Laboratory of National Institute of Information and Communications Technology (NICT, former CRL). She is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Morio Toyoshima received the B.S. and M.S. degrees in electronic engineering from Shizuoka University, Shizuoka, Japan, in 1992 and in 1994, and the Ph.D. degree from the University of Tokyo, Tokyo, Japan, in 2003 in electronics engineering, respectively. He joined the Communications Research Laboratory (Ministry of Posts and Telecommunications) in 1994 and soon after was engaged in research for the Engineering Test Satellite VI (ETS-VI) optical communication experiment and later involved in the Ground-to-Orbit Laser-com Demonstration (GOLD) experiment with NASA's Jet Propulsion Laboratory. He joined the Japan Aerospace Exploration Agency (JAXA) (former NASDA), for the development of the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) from 1999 to 2003. In December 2003, he became a Senior Researcher of the Optical Space Communications Group, (NICT, former CRL), Japan. Starting in October 2004, he spent one year as a guest scientist at Vienna University of Technology, Austria, in the field of optical space communications. Since April 2006 he worked again in NICT, with emphasis on laser beam propagation through atmospheric turbulence, space laser communications and quantum cryptography. He is now the Director of the Space Communication Systems Laboratory, the Wireless Network Research Institute in NICT since April, 2011. He has the position of Visiting Associate Professor in the Graduate School of Information Systems, the University of Electro-Communications since 2007. Dr. Toyoshima is a member of the IEEE, the Optical Society of America (OSA), the Institute of Electronics, Information and Communication Engineers (IEICE), and the Japan Society for Aeronautical and Space Science (JSASS).



Naoto Kadowaki received B.S. in Communications Engineering, Masters degree in Information Engineering and Ph.D. in Information Science from the University of Tohoku, Sendai, Japan in 1982, 1984, and 2010, respectively. From April 1984 to March 1986, he was with Mitsubishi Electric Corporation. He joined Communications Research Laboratory (CRL), currently renamed as National Institute of Information and Communications Technology (NICT) in 1986. He has been involved in research and development of high data rate satellite communication systems, mobile and personal satellite communications, computer networks, and communication protocols in NICT. From July 1990 to June 1991, he was a visiting researcher to AUSSAT that was reformed as OPTUS Communications, Sydney, Australia. After he was with Advanced Telecommunications Research (ATR) Institute International as the Head of Department of Autonomous Systems and the Head of Department of Smart Networks from July 2004 to December 2006, he was the Managing Director of Strategic Planning Department in NICT from January 2007 to June 2008. He is currently Executive Director of New Generation Wireless Communications Research Center and Director General of Yokosuka Research Laboratories in NICT. He is a member of the IEEE, AIAA and IEICE of Japan.