A Traffic Distribution Technique to Minimize Packet Delivery Delay in Multi-Layered Satellite Networks

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Yuichi Kawamoto, *Member, IEEE,* Hiroki Nishiyama, *Senior Member, IEEE,* Nei Kato, *Fellow, IEEE,* abd Naoto Kadowaki, *Member, IEEE*

Abstract—**Multi-Layered Satellite Networks (MLSNs) have an enormous potential to provide a ubiquitous wireless environment due to their advantages, such as extensive coverage, high network capacity, and lower delay performance. Since MLSNs are flexible and can be expanded easily to construct useful communication networks, researchers have paid a great deal of attention to find out how to use them efficiently. However, traffic congestions may occur in such networks since the distribution of MLSN-users is heavily influenced by geographical restrictions, and they may often lead to severe communication delay and throughput degradation. Traditional research works propose a counter-measure for avoiding traffic congestion caused by traffic flow on each layer. However, they do not consider the congestions due to the inter-layer traffic that may, indeed, occur in MLSNs. Therefore, to effectively resolve the problem of traffic congestion, we propose a new MLSNs model by envisioning a method to distribute the flow of packets between the two layers of the considered MLSNs for minimizing the packet delivery delay of the network. Moreover, we analyze the effect of the method on the packet delivery delay by considering propagation and queuing latencies. The analysis clearly shows the advantage of our proposed model. Furthermore, computer-based simulation results validate our analysis and demonstrate the effectiveness of our proposed model.**

Index Terms—**NGEO satellite networks, multi-layered satellite networks, traffic distribution, packet delivery delay, and queuing theory.**

I. Introduction

SATELLITE networks are able to provide worldwide communication environments since they have a significantly wide coverage and are effective in facilitating simultaneous transmissive communications. In addition, satellite networks can be used to set up communication in areas such as islands and isolated mountainous areas where adequate infrastructure may not be easily deployed. Moreover, it is possible to utilize them for the destroyed ground network systems during/after disasters. Satellite networks are classified in terms of the orbit of the corresponding satellite. Recently, the networks using Non-Geostationary Earth Orbit (NGEO) satellites have attracted attention for their usability [1], [2]. In particular, Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) satellites exhibit advantages of lower delay and electric power saving performance in contrast with the Geostationary Earth Orbit (GEO) satellites, which have been heavily used to date [3]-[5]. LEO and MEO satellites compose constellations by more than one satellite and cover the entire earth. Furthermore, the latest studies also focused upon satellite laser communications and they achieved significantly high transmission speed [6]. This research trend indicates that a tremendously high capacity global communication coverage facilitated by satellites is expected to appear in the near future.

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

N. Kadowaki works for the National Institute of Information and Communications Technology (NICT) in Tokyo, Japan. He may be contacted at naoto@nict.go.jp.

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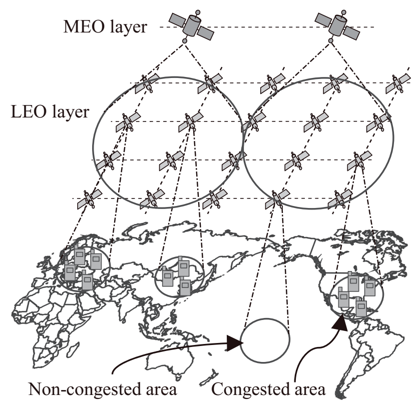


Fig. 1. An example of a MLSN constructed by LEO and MEO satellites, and the nonhomogeneous traffic distribution.

Moreover, realizing Multi-Layered Satellite Networks (MLSNs) have attracted a great deal of interest amongst researchers in recent years [7]-[9]. MLSNs consist of hierarchically layered networks, which increase the network capacity and make it possible to bypass traffic from the lower to upper layers [10], [11]. Therefore, they avoid traffic congestion and provide large capacity and high speed networks all over the world. In this paper, we focus on the MLSNs consisting of LEO and MEO satellites as depicted in Fig. 1 since they exhibit, in contrast with other satellites networks, superior performance in terms of low delay and significantly low power consumption [12], [13].

MLSNs are, however, not without their shortcoming, particularly when it comes to congestion. Some satellites in a MLSN may experience traffic congestion as the number of users in the network increases. This may happen as an effect of the non-homogeneous distribution of source and destination users on the ground. For instance, heavy traffic load tends to overwhelm a satellite, which covers the area of a relatively large city. It may eventually lead to loss of packets and increase of end-to-end delay, which pose serious problems to the communication. Fig. 1 demonstrates an example of a typical MLSN constructed by LEO and MEO satellites, and the nonhomogeneous traffic distribution. As depicted in this figure, the distribution of the MLSN users on the ground tends to converge in specific areas (such as North America and Europe) in contrast with the sea areas. As a consequence, some LEO satellites covering the highly dense populations receive much higher volume of traffic. Moreover, the non-homogeneous traffic distribution in the LEO layer causes the biased converging of traffic at the MEO satellites.

In order to solve the serious problem of the above-mentioned traffic congestion, we propose, in this paper, a new MLSNs model with a method to distribute packet flows between the LEO and MEO layers. In this model, we focus upon expanding the coverage of the satellite on the upper layer to increase the number of links between the LEO and MEO satellites that enables bypassing of more traffic flows. In addition, we analyze the overall communication delay (which includes both the propagation and queuing latencies within the considered MLSN) and the number of the afore-mentioned bypassing links.

The remainder of this paper is organized as follows. Section II describes a general MLSNs model and the existing MLSNs model considered by traditional research works. Our new model of MLSNs with traffic distribution technique is presented in Section III. Section IV contains an analysis of the queuing and propagation delays with the change of the number of links between the LEO and MEO layers, and explains how to decide an optimal number of links in the considered MLSN. Computer-based simulation results are presented in Section V to validate our proposed method. We apply our proposed model to a real environment in Section VI. Finally, the paper is concluded in Section VII.

II. Traffic distribution technique for MLSN

Satellites are generally categorized into LEO, MEO, and GEO satellites according to their orbital altitudes. Each satellite has their respective advantages. Amongst these satellites, we take particular note of LEO and MEO satellites for their comparatively low delay and power saving aspects. They have lower orbital altitude than GEO satellites, and cover the entire earth by constructing satellite constellations. Iridium [14] and Nelstar [15] are prominent examples of LEO satellite constellation. On the other hand, Spaceway-NGSO [16] and ICO [17] are known as MEO satellites constellations. Although MEO satellite constellations require fewer satellites in contrast with their LEO counterparts, they exhibit longer propagational delays. This shortcoming of the MEO satellite constellations can be attributed to their comparatively higher altitude than the LEO satellite constellations.

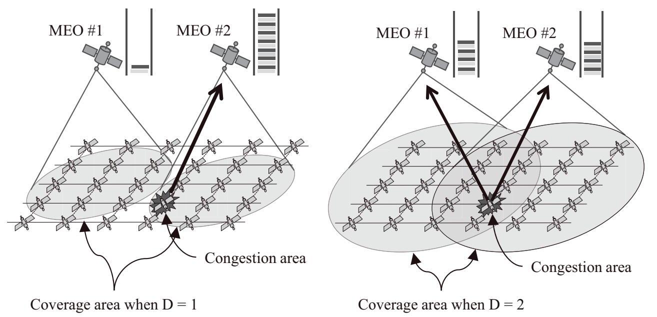
On the other hand, MLSNs are hierarchal networks comprising satellite constellations of different altitudes, such as LEO, MEO, and GEO satellite constellations. In this paper, we focus on MLSNs consisting of mesh type LEO and MEO satellite constellations as depicted in Fig. 1. The MLSNs retain the advantages of NGEO satellite networks and increase the overall network capacity. Additionally, each LEO satellite has a link with the nearest MEO satellites in the general MLSN model. This link is referred to as an Inter Layer Link (ILL). In fact, LEO satellites are divided into the same number of groups as MEO satellites. Moreover, Dijkstra Shortest Path (DSP) is used as a routing method in this paper [18]. The DSP is a scheme that uses Dijkstra's algorithm, which is a well known method to solve the shortest path problem. In the MLSN, the network traffic are transmitted from the earth stations to the LEO satellites, and then flow through other LEO/MEO satellites before reaching the destination ground-user according to the DSP algorithm. By this way, it is possible to bypass traffic from the lower to upper layers. Therefore, MLSNs are considered as an efficient network to provide worldwide wireless communication services.

However, the traffic distribution on the earth is not homogeneous at all, because the users tend to converge in big cities compared to remote areas such as the mountainous regions or the sea [19]. The distribution of the amount of the generated traffic is similar to that of the population distribution. Thus, much traffic gather at some LEO and MEO satellites covering populated areas leading to traffic congestion at those LEO and MEO satellites. Traffic congestion is detrimental to the network performance as it results in a significant level of packets drop, throughput degradation, and increase in the end-to-end communication delay. Therefore, an effective scheme to avoid such kind of traffic congestion is, indeed, urgently required for facilitating effective MLSN communication.

In the research work conducted by Taleb *et al*. [20], a method is proposed to avoid the congestion on LEO satellite networks by exchanging the information on congestion status among the neighboring satellites, and detouring the traffic according to that information. In the work in [21], a scheme is developed to prevent the traffic congestion from affecting the LEO satellites in the MLSN by preliminarily distributing the traffic based upon prediction of the congestion event *a priori*. In summary, these approaches avoid the congestion on the LEO satellites by bypassing traffic flows to neighboring LEO satellites and/or MEO satellites. Although these methods are, to some extent, able to avoid the congestion on individual layers due to heavy traffic, they do not consider the inter-layer traffic. In MLSNs, since the satellites on the upper layer receive the traffic from many satellites on the lower layer, the congestion may also occur at the upper layer satellites. This affects all bypassing traffic from the lower to upper layers, and seriously degrades the network performance. None of the afore-mentioned existing method can solve the problem. Therefore, in this paper, we focus on the congestion caused by the inter-layer traffic, and propose an adequate method to avoid the congestion.

III. MLSN constellation for effective traffic distribution

As mentioned in the previous section, the congestion may also occur at the MEO satellites in MLSNs because the satellites on the upper layer usually communicate with more



(a) A general MLSN model. (b) A MLSN model with traffic distribution.

Fig. 2. An example demonstrating a general MLSN model and the application of traffic distribution method.

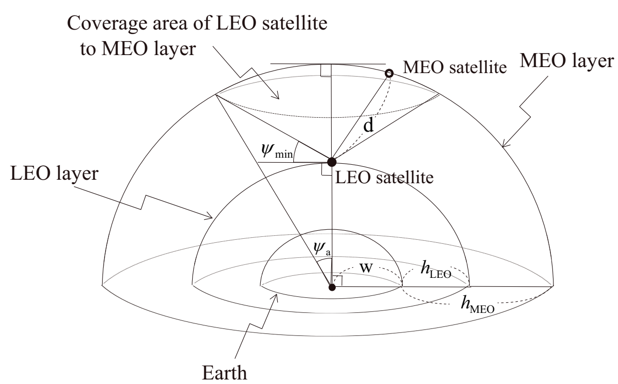


Fig. 3. Illustration of the MEO satellites area, which one LEO satellite can cover.

than one satellite on the lower layer. Fig. 2a demonstrates a general MLSN model and a case where the traffic congestion occurs at a single MEO satellite. For the purpose of illustration, these two MEO satellites are labeled as MEO #1 and MEO #2, respectively. In this figure, although MEO #1 and MEO #2 receive a part of packets from some LEO satellites, only MEO #2 receive the packets from the LEO satellite on the considered congested area. In other words, MEO #2 is assumed to receive more packets than MEO #1. Hence, the load balance on the queue of each MEO satellite is substantially non-homogeneous, which causes increasing delay and packet drop. Although Fig. 2a shows a simple model for ease of explanation, similar phenomena can be encountered in real networks. Therefore, the satellites on the upper layer are significantly affected by the non-homogeneous distribution of the traffic flows.

In order to avoid the issue of traffic congestion on MEO satellites mentioned earlier, we propose a new network model to distribute the traffic load of MEO satellites. We assume the use of larger MEO satellites coverage in this model as depicted in Fig. 2b. Expanding the area of MEO satellites coverage leads to increased number of links between the LEO and MEO satellites since each LEO satellite is covered by more than one MEO satellites. In Fig. 2b, the LEO satellite on the congested area can send their packets to both MEO #1 and MEO #2. Thus, the amount of the received packets become the same between MEO #1 and MEO #2. As a consequence, the traffic converging at a single MEO satellite are distributed to some MEO satellites, and the traffic distribution on the MEO satellite layer becomes near-uniform. This results in preventing the scenario which might have generated traffic congestion.

In the above mentioned MLSNs model, the number of links between the LEO and MEO satellites is equal to the number of MEO satellites covering a LEO satellite. We define this number as D. In other terms, each LEO satellite can distribute traffic to the same number of MEO satellites as D. The value of D is proportional to the largeness of the coverage area of a LEO satellite to the MEO layer as shown in Fig. 3, and the upper limit of the largeness is determined by the difference of the altitude between the LEO and MEO satellites, and the elevation angle of the antenna of the LEO satellites. We define the maximum value of D as D_{max}. To formulate the value of D_{max}, we refer to the altitude of the LEO and MEO satellites, and the minimum elevation angle of the antenna of LEO satellites as h_{LEO}, h_{MEO}, and ψ_{min}, respectively. In addition, we refer to the number of all the MEO satellites as N_{MEO}. Moreover, the angle ψ_{a} is defined as shown in Fig. 3 with the radius of the earth, w. Thus, the value of D_{max} is formulated as follows.

$$D_{\mathrm{max}} = \frac{1-\cos\psi_{\mathrm{a}}}{2} \cdot N_{\mathrm{MEO}}, \tag{1}$$

where

$$\psi_{\mathrm{a}} = \arctan \frac{B \pm AB\sqrt{1+B^2-A^2B^2}}{1-A^2B^2}, \tag{2}$$

and A and B in the above equation are represented as follows.

$$A = \frac{\mathrm{w}+h_{\mathrm{LEO}}}{\mathrm{w}+h_{\mathrm{MEO}}}, \tag{3}$$

$$B = \frac{1}{\tan\psi_{\mathrm{min}}}. \tag{4}$$

The number of LEO satellites covered by a MEO satellite, R, is expressed by using the value of D. Each MEO satellite receives traffic from the same number (as many as R) of LEO satellites. We refer to the number of all LEO satellites as N_{LEO}. Thus, the value of R is described as follows.

$$R = \frac{N_{\mathrm{LEO}}}{N_{\mathrm{MEO}}} \cdot D. \tag{5}$$

To demonstrate the relationship between the value of D_{max}, R_{max}, which is the maximum value of R, and the distance between each layer, we set some parameters for the LEO and MEO satellite constellations (with reference to Iridium and Spaceway-NGSO, respectively). Fig. 4 demonstrates the value of D_{max} and R_{max} when the altitude of the MEO satellites change. In this demonstration, we fix the altitude of LEO satellites as 780 km and vary the altitude of the MEO satellites from 1,000km to 36,000km to evaluate the effect of the distance between each layer. Additionally, the minimum elevation angle of the antenna of the LEO satellites and the number of the LEO and MEO satellites, ψ_{min}, N_{LEO}, and N_{MEO}, are set to 10°, 66, and 20, respectively. Moreover, we use 6,400km for the value of the radius of the earth, w. As it is

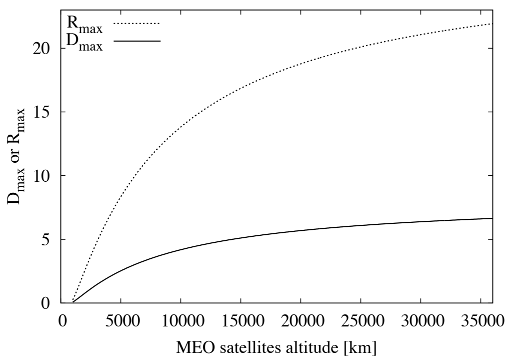


Fig. 4. The relationship between the MEO satellites altitude and the value of $D_{\max}$ and $R_{\max}$.

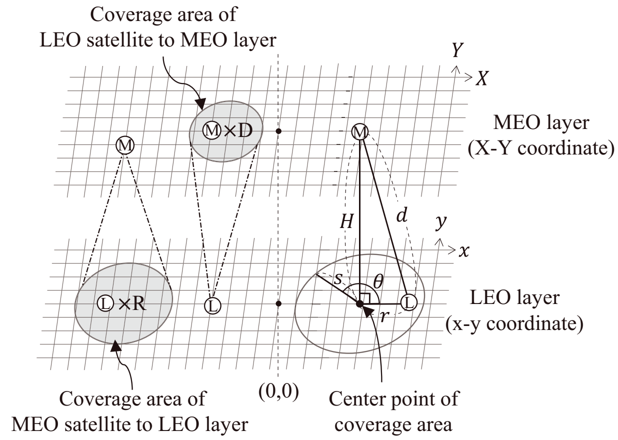


Fig. 5. Local model of MLSNs for analysis.

evident from the Fig. 4, the value of $D_{\max}$ and $R_{\max}$ increase with increasing of the altitude of MEO satellites. Furthermore, $R_{\max}$ has about three times the value of $D_{\max}$ since the number of LEO satellites is approximately three times more than that of the MEO satellites. Since the parameter of the satellites' antenna is a fixed value depending on the satellites architectures, $D_{\max}$ and $R_{\max}$ depend on the distance between each layer of the MLSNs while the number of the satellites of each layer remains fixed.

From the definition of the maximum value of D in the above expressions, we can choose the value of D between 1 and $D_{\max}$. The larger values of D cause the traffic flow from the LEO satellites to the MEO satellites, and the traffic distribution on the MEO satellite layer becomes almost uniform. Hence, the queuing delay decreases with the increasing value of D. However, the distribution of the traffic from the LEO satellites to the MEO satellites causes the increase of the propagation distance because the MEO satellites, which are not the nearest from the LEO satellite are also needed to receive packets flow from the LEO satellite to distribute the traffic from the LEO satellites to the MEO ones. For example, even though the LEO satellites on the congested area send their packets to only MEO #2, which is the nearest MEO satellite from the LEO satellite in the general MLSNs model as shown in Fig. 2a, the LEO satellites send their packets to not only MEO #2 but also MEO #1, which is farther from the LEO satellite than MEO #2 in our proposed model as shown in Fig. 2b. Therefore, the propagation delay increases with the increase of the value of D. Thus, since there is a trade-off between propagation delay and queuing delay when determining the value of D, the optimal value of D exists that minimizes the sum of the queuing delay and propagation delay.

IV. Delay Analysis

At the beginning of this section, we analyze the relationship between the queuing delay at the MEO satellite and the value of D. We show that traffic distribution from the LEO to MEO satellites leads to decreasing queuing delay through the delay formulation technique based on the queuing theory. Then, we express the propagation delay mathematically. Furthermore, we analyze how our method can decide the optimal value of D to minimize the packet delivery delay.

A. Local MLSNs model for analysis

For the sake of analysis, Fig. 5 shows a local model of MLSNs where the position of each LEO satellite and that of each MEO satellite are represented by the $x-y$ and $X-Y$ coordinate systems, respectively. The size of each cell on each layer is considered to be the same and the center points of both layers are defined as (0,0) (i.e., as the same position). Although the positions of the satellites are expressed as discrete values typically since satellites are deployed at regular intervals, we consider them to be continuous values for considering the time average of the traffic distribution of the NGEO satellites, which always move on the same layer. Thus, due to similar reasons, D and R are also considered to have continuous values. We assume that the number of MEO satellites equals to D are in the coverage area of the LEO satellites to MEO layer. In addition, the number of MEO satellites in the coverage area of the MEO satellites to the LEO layer equals to R.

Furthermore, we assume Gaussian distribution, which is expressed as Eq. 6 by using $x-y$ coordinates which show the positions of the LEO satellites as the traffic distribution, which is from the LEO to the MEO satellites, where σ_x, σ_y, μ_x, μ_y, and ρ_{xy} are standard deviations of x and y, means of x and y, and correlation coefficient , respectively. The center point of the traffic distribution is the same as that of the LEO layer. Moreover, the interval of the traffic generation from the LEO to MEO satellites is assumed to comply with Poisson arrival.

$$f(x,y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho_{xy}^2}} \cdot \exp\left[-\frac{1}{2(1-\rho_{xy}^2)}\left\{\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2\ \rho_{xy}(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right\}\right]. \tag{6}$$

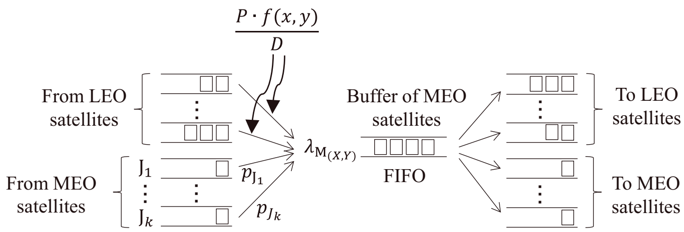


Fig. 6. Packet switching in each MEO satellite.

B. Modeling of the queuing delay

We use queuing theory to formulate the queuing delay at the MEO satellites. To construct the queuing model at a MEO satellite, we consider the simple satellite system circuit shown in Fig. 6. This circuit consists of one packet arrival and one packet sending architecture, which is basically a First In First Out (FIFO) system. By supposing the circuit with Poison arrival of traffic, the queuing model is assumed as an M/M/1 queuing model. In this system, the congestion rate is expressed by ρ, which represents how congested the system is. The value of ρ takes the value from 0 to 1, and a higher value of ρ reflects a more congested system. ρ is defined by two other parameters, namely λ and μ, as $\rho = \lambda/\mu$. The value of λ denotes the average packet arrival rate, and μ refers to the average packet sending rate. Thus, the queuing delay of this system is formulated as the following expression with the above parameters.

$$\Delta_{\mathrm{q}} = \frac{\rho}{1-\rho} \cdot \frac{1}{\mu} = \frac{\lambda}{(\mu - \lambda) \cdot \mu}. \tag{7}$$

Since the value of μ determined by the distribution of packet size and the processing rate of the circuit embedded on the satellites, it does not depend on the value of D. Thus, we evaluate the change of the value of λ when the value of D changes to assess the queuing delay at the MEO satellites.

The packets arriving at each MEO satellite is separated to two categories according to if the sending satellite is a LEO satellites or an adjacent MEO satellite as shown in Fig. 6. We define the total amount of packets which is transferred to the MEO layer from the LEO one as P. Since the packets arriving to a MEO satellite from the LEO satellites is the sum of the arriving packets from each LEO satellite, it is expressed as the sum of $(P \cdot f(x,y))/D$ of each LEO satellite, which lies in the coverage area of a MEO satellite to the LEO layer. Moreover, we refer to the average packet sending rate of an adjacent MEO satellites as p_{J_k}, where the number of k indicates the identification number of each adjacent MEO satellite. Thus, the average packet arrival rate of the MEO satellite from each adjacent MEO satellite is expressed as p_{J_k}/J, where J denotes the number of adjacent MEO satellites.

We define the average packet arrival rate of the MEO satellite which has the position (X, Y) from all LEO satellites which the MEO satellite covers and from the adjacent MEO satellites as $\lambda_{\mathrm{M}(X,Y)}$. Since the average packet arrival rate of each MEO satellite is formulated as the sum of packet arrival rate from the above two categories, $\lambda_{\mathrm{M}(X,Y)}$ is expressed as follows:

$$\lambda_{\mathrm{M}(X,Y)} = \iint_{r<s} \frac{P \cdot f(x,y)}{D}\, dxdy + \sum_{k=1}^{J} \frac{p_{\mathrm{J}_k}}{J}, \tag{8}$$

where

$$r = \sqrt{(x-X)^2 + (y-Y)^2}. \tag{9}$$

In these expressions, r expresses the distance between the center point of the coverage area of a MEO satellite to the LEO layer and the LEO satellite, and s is defined as the radius of the coverage area of a MEO satellites to the LEO layer as shown in Fig. 5. Additionally, from its definition, R is obtained for the product of the number of LEO satellites and the ratio between the dimension of LEO layer and coverage area of MEO satellite to LEO layer. Thus, the next expression holds.

$$R = \frac{\pi s^2}{4\pi(\mathrm{w} + h_{\mathrm{LEO}})^2} \cdot N_{\mathrm{LEO}}. \tag{10}$$

By equating Eq. 5 and Eq. 10, we get

$$\frac{N_{\mathrm{LEO}}}{N_{\mathrm{MEO}}} \cdot D = \frac{\pi s^2}{4\pi(\mathrm{w} + h_{\mathrm{LEO}})^2} \cdot N_{\mathrm{LEO}}. \tag{11}$$

We solve Eq. 11 for s to get the following equation,

$$s = 2(\mathrm{w} + h_{\mathrm{LEO}})\sqrt{\frac{D}{N_{\mathrm{MEO}}}}. \tag{12}$$

C. Formulation of the propagation delay

The propagation delay is calculated from the distance between the satellites in the MLSN. When the value of D is 1, each LEO satellite sends packets only to the nearest MEO satellite. On the other hand, when the value of D is set to more than 1, each LEO satellite sends packets to the farther MEO satellites. Thus, the average propagation distance increases with the increase in the value of D. The distance between the LEO and MEO satellites is formulated as d with the altitude of each layer, h_{LEO} and h_{MEO}, by following the expression below.

$$d = \sqrt{r^2 + H^2}, \tag{13}$$

where,

$$H \equiv h_{\mathrm{MEO}} - h_{\mathrm{LEO}}. \tag{14}$$

Hence, the average propagation delay is represented as the following expression since it is equal to the ratio of the distance to the light speed, c.

$$\Delta_{\mathrm{p}} = \frac{1}{\pi s^2} \iint_{r<s} \frac{d}{c}\, dxdy. \tag{15}$$

In order to assess the behavior of Δ_{p} when the value of D changes, we convert Eq. 15 from the rectangular coordinates to polar coordinates while we assume $X = Y = 0$ as follows.

$$\begin{aligned} \Delta_{\mathrm{p}} &= \frac{1}{\pi s^2} \int_0^{2\pi} \int_0^{s} \frac{\sqrt{r^2 + H^2}}{c}\, r dr d\theta \\ &= \frac{2}{3 s^2 c} \left\{ (s^2 + H^2)^{\frac{3}{2}} - H^3 \right\}. \end{aligned} \tag{16}$$

When the value of D is set to 1, the value of s becomes the smallest. Thus, the value of s increases with D and it leads to an increase in the propagation delay from the above expression, because it is clear that $\Delta_{\rm p}$ is an increasing function of the value of s. Therefore, the lager the value of D, the bigger the average propagation delay between the LEO and MEO satellites.

On the other hand, the change of the value of D causes the change of the number of MEO satellites, which receive the traffic from a LEO satellite. Thus, the propagation distance of the traffic on the MEO layer changes. However, it can be considered as a negligible value because the traffic are distributed equally between receiving MEO satellites in our proposed model and it causes both increasing and decreasing of propagation distances in almost an even fashion. In other words, distributing the traffic originating from a LEO satellite to multiple MEO satellites, does not change the the average hop count of routes in the MEO layer. This is due to the fact that traffic flows through multiple paths in the MEO layer, and all paths have an equal probability of becoming short or long, $Pr(Distance)$, thus the arithmetic mean of these multiple paths is equal to $Pr(Distance)$. Therefore, the average change of the propagation distance on the MEO layer caused by the envisioned traffic distribution is considered negligible in our proposed model.

D. Effect of the value of D to packet delivery delay in MLSN

The total packet delivery delay, $\Delta_{\rm t}$, which is the sum of queuing and propagation delays is expressed as follows.

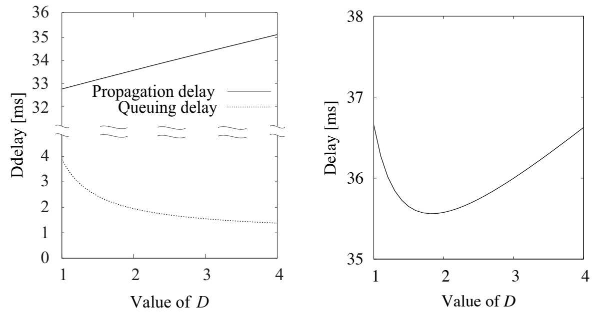
$$\Delta_{\rm t} = \Delta_{\rm q} + \Delta_{\rm p}. \tag{17}$$

In order to validate the packet delivery delay when the value of D changes, we assess the queuing delay, propagation delay, and packet delivery delay with numerical analysis in this subsection. In this analysis, we set $\sigma_{xy} = 0$, $\mu_x = \mu_y = 0$, and $\sigma_x = \sigma_y$ to assess the queuing delay with a simple Gaussian distribution model. Thus, Eq. 6 is transformed as follows.

$$F(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \cdot \exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)\right\}, \tag{18}$$

where $F(x,y)$ expresses the simple Gaussian distribution model. Thus, the packet arrival rate of each MEO satellite from all LEO satellites which the MEO satellite covers and from the adjacent MEO satellites, $\lambda_{{\rm M}(X,Y)}$, is expressed as Eq. 19, and it is converted from the rectangular to polar coordinates as Eq. 20. Therefore, the queuing delay of each MEO satellite can be calculated by using Eqs. 7 and 20. On the other hand, the propagation delay is computed from Eq. 16.

In this calculation, we assume that the number of MEO satellites is 9, and the coordinate of these MEO satellites follows -1$\leq X, Y \geq$1. Additionally, LEO satellites are assumed to exist on the coverage area of the MEO satellites uniformly. The altitudes of LEO and MEO satellites are set to 780km and 10,352km, and the distance between LEO satellites and that between the MEO satellites are set to 5,000km and 20,000km, respectively. Moreover, both σ_x and σ_y are set to 0.7, and P is set to 4kbps. The average packet sending rate of MEO satellite, μ, is set to 500bps. The packet sending rate of adjacent MEO satellites and the number of adjacent MEO satellites are set to 1kbps and 4, respectively. In this numerical analysis, we calculate the average queuing delay of each MEO satellite and the average propagation delay by changing the value of D from 1 to 4 in the local MLSN model.



(a) Average queuing delay and propagation delay with varying the value of D.

(b) Average packet delivery delay with varying the value of D.

Fig. 7. Calculation results of each type of delay.

The average queuing and propagation delays are shown in Fig. 7a. It is understood that the queuing delay decreases and the propagation delay increases as the value of D rises. Moreover, the packet delivery delay which is the sum of these delays is shown in Fig. 7b. It shows that the packet delivery delay is a convex function and there is an optimal value of D to minimize $\Delta_{\rm t}$. It is because the queuing and propagation delays have a trade-off relationship. Since the propagation delay is calculated from the architecture of the MLSN constellation, the optimal value of D depends on the queuing delay. Therefore, the optimal value of D is determined by how the network is congested. All the notations used in our analysis are summarized in Table I.

V. SIMULATION

In this section, we verify the relationship between the packet delivery delay in the MLSNs and the traffic rate to confirm the effectiveness of our proposed model of MLSNs. Additionally, the packet drop rate in MEO satellites and throughput in the MEO layer are measured to evaluate the advantage of proposed model. Network Simulator version 2 (NS-2) [22] is used to evaluate this. In the remainder of this section, the simulation environment is first described, followed by the simulation results.

A. Simulation setup

We assume that the considered network consists of an MLSN and ground terminals. The MLSN comprises a two-layered satellite network with a number LEO satellites and MEO satellites. We refer to Iridium and Spaceway NGSO as the LEO and MEO satellite constellations, respectively, to set the relevant parameters of the network. Accordingly, the number of satellites in the LEO layer and that in the MEO layer are set to 66 and 20, respectively. These satellites in each

TABLE I

A LIST OF NOTATIONS DEFINED AND USED IN OUR ANALYSIS.

D	Number of MEO satellites which each LEO satellite can distribute traffic to.
R	Number of LEO satellites which each MEO satellite receive traffic from.
$D_{\max}, R_{\max}$	Maximum value of D or R.
$N_{\mathrm{LEO}}, N_{\mathrm{MEO}}$	Number of LEO or MEO satellites.
$h_{\mathrm{LEO}}, h_{\mathrm{MEO}}$	Altitude of LEO or MEO satellites.
w	Radius of the earth.
ψ_{a}	Angle which is defined as shown in Fig. 3.
$\psi_{\min}$	Minimum elevation angle of antenna of LEO satellites.
x, y	Position of LEO satellites in x-y coordinate.
X, Y	Position of MEO satellites in X-Y coordinate.
σ_x, σ_y	Standard deviations of x or y.
ρ_{xy}	Coefficient of correlation.
μ_x, μ_y	Means of x or y.
ρ	Congestion rate.
λ	Average packet arrival rate.
μ	Average packet sending rate.
P	Total amount of packets which is generated from all LEO satellites to MEO satellites.
p_{J_k}	Average packet sending rate of adjacent MEO satellites.
k	Identification number of each adjacent MEO satellite.
J	Number of adjacent MEO satellites.
$\lambda_{\mathrm{M}(X,Y)}$	Average packet arrival rate of each MEO satellite.
r	Distance between the center point of the coverage area of an MEO satellites to LEO layer and LEO satellite.
s	Radius of the coverage area of an MEO satellites to LEO layer.
d	Distance between LEO and MEO satellites.
c	Light speed.
Δ_{q}	Queuing delay.
Δ_{p}	Propagation delay.
Δ_{t}	Packet delivery delay.

layer are connected with one other via Inter Satellite Links (ISLs), and they form a mesh type topology. Each layer is also connected via Inter Layer Links (ILLs). The bandwidth of each of these links is set to 15Mbps. In addition, we refer to [23] and [24] in order to establish the non-homogeneous distribution of the traffic-flows. Among these, 30 traffic-flows going through more than one MEO satellite are chosen to evaluate the effectiveness of our proposed model, which distributes the traffic-flows from the LEO to MEO satellites. Thus, 30 ground terminals are distributed as source and destination nodes all over the earth. These ground terminals generate traffic-flows and send packets to the LEO satellites. The traffic-flow is modeled as a non-persistent “On/Off” flow. The “On/Off” periods of the connections are assumed to follow a Pareto distribution with a shape equal to 1.2. Both the average idle time and the burst time are set to 200ms. The packet size is set to 1KB. The traffic generation lasts for 30 seconds. Moreover, we use the DSP algorithm as the routing method in our conducted simulations. In the above mentioned network environment, we verify the packet delivery delay, packet drop rate, and throughput in the network by varying the value of D. The value of D in the proposed model is set to the optimal value according to the traffic rate. On the other hand, the general MLSN model uses the value of D equal to 1.

B. Simulation results

By using the simulation results, we verify the change in packet delivery delay, packet drop rate, and throughput. First, Fig. 8 demonstrates the change of the packet delivery delay with the variation of the traffic rate in the network. From Fig. 8, we can confirm that our proposed model achieves a lower packet delivery delay than that of the general model. Especially, when the traffic rate is high, the amount of decreased delay becomes large. Secondly, we verify the packet

$$\lambda_{\mathrm{M}(X,Y)} = \iint_{r<s} \frac{P \cdot F(x,y)}{D}\, dxdy + \sum_{k=1}^{J} \frac{p_{\mathrm{J}_k}}{J} \tag{19}$$

$$= \int_0^{2\pi}\int_0^{s} \frac{P}{D} \cdot \frac{r}{2\pi\sigma_x\sigma_y} \cdot \exp\left[-\frac{1}{2}\left\{\frac{(X + r\cdot\cos\theta)^2}{\sigma_x^2} + \frac{(Y + r\cdot\sin\theta)}{\sigma_y^2}\right\}\right] drd\theta + \sum_{k=1}^{J}\frac{p_{\mathrm{J}_k}}{J}. \tag{20}$$

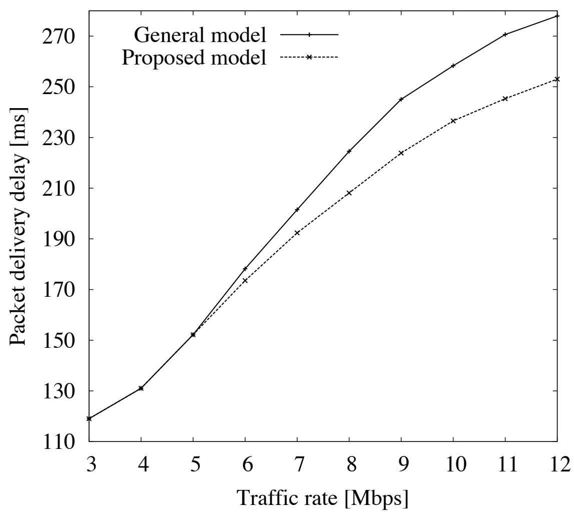


Fig. 8. Packet delivery delay vs. traffic rate.

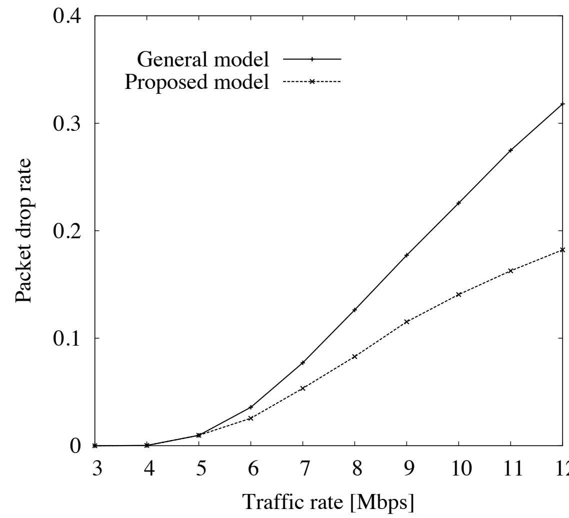


Fig. 9. Packet drop rate at MEO satellite vs. traffic rate.

drop rate in MEO satellites and the throughput of the MEO layer in our proposed model by comparing it to the general MLSN model. Fig. 9 shows the change of packet drop rate that occurs at MEO satellites caused by traffic congestion in packets flow in the MEO layer. From Fig. 9, it is evident that the packet drop rate in our proposed model is drastically lower than that of the general model. This is because the traffic distribution of our method avoids traffic congestion in MEO satellites. The throughput in the MEO layer is shown in Fig. 10. This figure shows the change of amount of traffic that the MEO layer can deliver per unit of time in the MLSN. We can see that our proposed model achieves higher throughput than the general model when the traffic rate is over 6Mbps. If the traffic rate is between 3Mbps and 5Mbps, the optimal value of D in the proposed model is 1. Therefore, it achieves the same performance of the general MLSN model. Additionally, throughput increases when the traffic rate changes from 5Mbps to 6Mbps and from 9Mbps to 10Mbps. This is because the optimal value of D changes at these traffic rates. From the above results, we confirm the effectiveness of our proposed model.

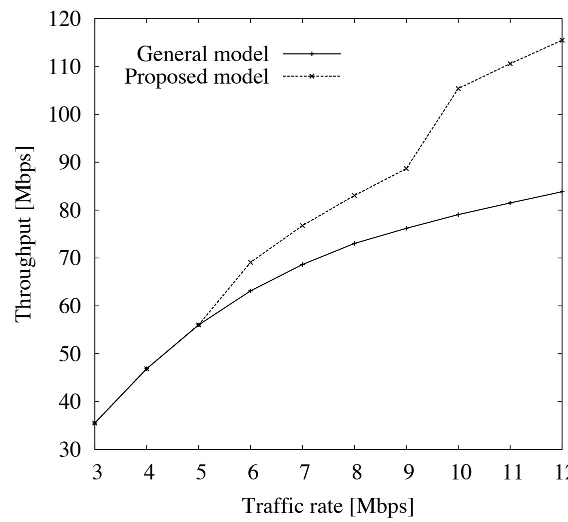


Fig. 10. Throughput in the MEO layer vs. traffic rate.

VI. Applying the Proposed Model to a Real Environment

In this section, we apply our proposed model to satellite networks in a real environment. In the past sections, an analysis of traffic distribution in MLSN was presented. However, when the proposed model is applied to a real satellite network, an algorithm to decide the optimal value of D according to the traffic load in MEO satellites is needed. In our proposed model, all MEO satellites set the same value of D to minimize the packet delivery delay in the whole network according to the traffic distribution in the MEO layer. We propose deploying an operation center to calculate the optimal value of D. The operation center collects information on the amount of traffic that each MEO satellite receives and calculates the optimal value of D at regular time intervals. After the calculation, the operation center broadcast an message that includes the decided value of D to MEO satellites and each MEO satellite changes its coverage area by changing its antenna's angle of depression according to the value of D in the message.

Additionally, the use of other types of satellite constellations should be considered in order to apply our proposed model to a real environment. If other types of satellite constellations are utilized to construct MLSNs, the number of satellites and their altitude are changed. This affects the optimal value of D in the proposed model. In above mentioned simulation, we use Iridium and Spaceway NGSO as the constellation of LEO and MEO satellites, respectively. Thus, here, we discuss the case where other constellations are used to construct the MLSN. For example, Nelstar is a LEO satellite constellation and ICO is a MEO satellite constellation which were introduced in Section II. Nelstar consists of 120 LEO satellites with an altitude of 1200km and ICO is constructed by 10 MEO satellites orbiting a 10354km. We consider the MLSN constructed by these constellations as a comparison to the MLSN that we assumed in the simulation.

Although the number of LEO satellites changes, it does not affect the coverage area size of each MEO satellite. In contrast, changing the number of MEO satellites changes the number of LEO satellites within the MEO satellite coverage area. Since the number of MEO satellites in ICO is less than in Spaceway NGSO, the above mentioned coverage area should be increased. Thus, the amount of traffic that each MEO satellite receives increases and the queuing delay occurring at the MEO layer also increases. Therefore, the value of D should be larger. On the other hand, since the distance between Nelstar and ICO is shorter than the distance between Iridium and Spaceway NGSO, the propagation delay between LEO satellites and MEO satellites becomes small. Thus, the difference in propagation delay between the MLSN constructed by Iridium and Spaceway NGSO and the MLSN constructed by Nelstar and ICO when the value of D change also becomes small. This means that increasing the amount of propagation delay when the value of D increases is smaller in the MLSN constructed by Nelstar and ICO. This causes the optimal value of D that minimizes the sum of queuing delay and propagation delay to become larger. Therefore, in the MLSN constructed by Nelstar and ICO, the optimal value of D tends to be larger than the value in the MLSN constructed by Iridium and Spaceway NGSO.

VII. Conclusion

In this paper, we proposed a new model of MLSNs with an effective traffic distribution technique to avoid traffic congestion scenarios. Our proposed method achieves in avoiding traffic congestions caused by the biased traffic flow from the LEO to MEO layers. The queuing and propagation delays in the network are analyzed in depth. In our presented analysis, it is demonstrated that the queuing delay decreases with the increase in the number of the links between the two layers in the MLSN since the distribution of the packets in the MEO layer is nearly uniform in our approach. On the other hand, it is clearly shown that the propagation delay increases with the increase in the number of links between the two layers. Therefore, it can be concluded that the queuing and propagation delays have a trade-off relationship, and that an optimal number of links between the two layers of the MLSN exists. From the simulation results, the effectiveness of our proposal model is investigated in our work.

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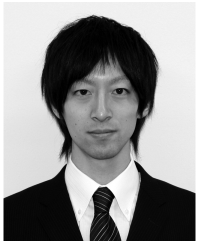
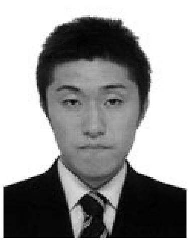
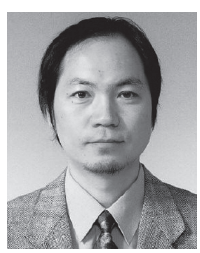


Yuichi Kawamoto received his B.E. in Information Engineering from Tohoku University, Japan, in 2011. Currently, he is pursuing M.S. degree in the Graduate School of Information Science (GSIS) at Tohoku University. He was awarded the Satellite Communications Research Award in the fiscal year of 2011 from the Institute of Electronics, Information and Communication Engineers (IEICE). He is recipient of Japan Society for the Promotion of Science (JSPS) in 2013. His research interests are in the areas of satellite networks and sensor networks. He is a student member of IEEE.



Hiroki Nishiyama 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), and he is also an IEEE senior member.

Nei Kato received his Bachelor Degree from Polytechnic University, Japan in 1986, 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 pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He currently serves as the Vice Chair of IEEE Ad Hoc & Sensor Networks Technical Committee, the Chair of IEEE ComSoc Sendai Chapter, the steering committee member of WCNC and voting member of GITC, an editor of IEEE Wireless Communications(2006-), IEEE Wireless Communications(2006-), IEEE Network Magazine(2012-), IEEE Transactions on Wireless Communications(2008-), IEEE Transactions on Vehicular Technology(2010-), IEEE Trans. on Parallel and Distributed Systems. He has served as the Chair of IEEE Satellite and Space Communications Technical Committee(2010-2012), a co-guest-editor of several Special Issues of IEEE Wireless Communications Magazine, 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, ICC ' 14, 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 IEICE Satellite Communications Research Award(2011), the KDDI Foundation Excellent Research Award(2012), IEICE Communications Society Distinguished Service 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 co-PI of A3 Foresight Program(2011-2014) funded by Japan Society for the Promotion of Sciences(JSPS), NSFC of China, and NRF of Korea. He is a fellow of IEEE and IEICE.



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.