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A Delay-Based Traffic Distribution Technique for Multi-Layered Satellite Networks

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***Abstract*—Recently, Non-Geostationary Earth Orbit (NGEO) satellite networks have gained research attention. Since they offer many features, e.g., extensive coverage, disaster-resistance, and efficient power consumption, they are considered as a good candidate for providing global communication services. Moreover, Multi-Layered Satellite Networks (MLSNs), which consist of layered NGEO satellite networks, have attracted much attention since they achieve excellent load distribution through bypassing traffic from the lower layer to upper layer. However, there is a possibility that traffic congestion may exist at a satellite on the upper layer because each satellite on the upper layer usually covers more than one satellite on lower layers in MLSNs. In this paper, we focus on traffic control in two-layered networks, especially on distributing the packet flow between the two layers in order to minimize the transfer delay of the network. Simulation results demonstrate the correctness of our analyses about delay in the network.**

I. INTRODUCTION

In recent years, due to the widespread use of compact yet high performance mobile terminals, realizing a ubiquitous wireless environment have attracted attention. However, since improving the network infrastructure on the ground is costly, service providers have a strong tendency to limit their coverage to urban areas. This results in a digital division between urban and rural areas which has become a serious problem. To cope with this problem, satellite networks have gained much attention.

Satellite networks are classified according to their altitude. One of those classifications is the Non-Geostationary Earth Orbit (NGEO) satellite networks, such as Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite networks, which are expected to solve the digital division problem [1], [2]. NGEO networks consist of a number of satellites and cover all over the world. Additionally, the risk of breakdown due to a natural disaster is quite low, which emphasize NGEO's potential to become a robust networks.

Furthermore, Multi-Layered Satellite Networks (MLSNs) have attracted researchers in recent years [3]-[4]. In this paper, we particularly focus on two-layered satellite networks which consist of LEO and MEO satellites. They allow bypassing packets between the lower layer and the upper layer to avoid traffic congestion while keeping the advantages of NGEO satellite networks [5], [6]. However, there is a possibility that a satellite on the upper layer may get congested since each satellite on upper layer usually covers more than one satellite on the lower layer in MLSNs.

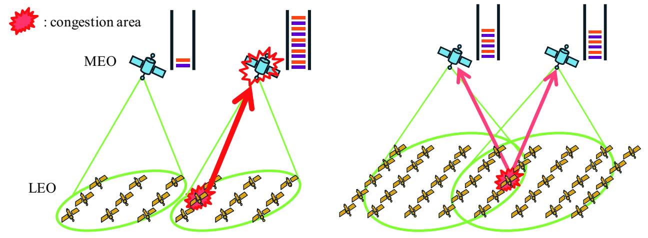
In order to handle such kind of congestion situation, we propose a method to control traffic flow, especially from LEO satellites to MEO satellites, in order to minimize the transfer delay. In this paper, we analyze the relationship between the traffic distribution and the delay in MLSNs. Particularly we focus on the optimal number of links between LEO satellites and MEO satellites. In other words, how many MEO satellites should one LEO satellite communicate with. For discussing the above mentioned argument, we formulate the queuing delay and the propagation delay in the system and study the relationship between each delay and the optimal number of MEO satellites which one LEO satellite should communicate with in order to minimize the transfer delay in MLSNs.

The remainder of this paper is organized as follows. Section II briefly describes a general MLSN model and states one of its shortcomings. In addition, a new method to distribute traffic is introduced. Section III studies, using mathematical analyses, the optimal number of MEO satellites which one LEO satellite should communicate with. Simulation results are presented in Section IV. Finally, concluding remarks are provided in Section V.

II. SYSTEM MODEL

A. A general MLSN model and its shortcoming

In this section, we introduce one of the most typical MLSN models which is the two-layered satellite network composing of LEO and MEO satellites. This model uses hierarchically layered networks where each layer constructs a mesh topology network [7], [8]. The satellites on the same layer usually communicate with four adjacent satellites via Inter-Satellite Links (ISLs). Moreover, the satellites on different layers are connected with each other via Inter-Layer Links (ILLs). Furthermore, one MEO satellite communicates with more than one LEO satellite because almost all LEO satellite constellations have a larger number of satellites than MEO satellite constellations do. For example, Iridium [9], which is one of the LEO satellite constellations that have 66 satellites, compared to Spaceway NGSO MEO satellite constellation which consists of 20 satellites [10]. So, in general, the number of satellites, one MEO satellite covers, is determined by the ratio between



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

Fig. 1. An example shows a general MLSN model and the application of traffic distribution method.

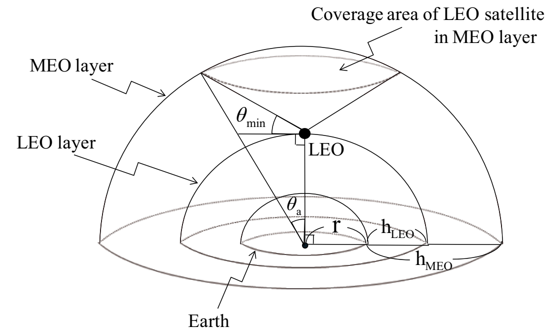


Fig. 2. The MEO satellites area in the coverage of one LEO satellite.

the number of MEO satellites and the number of LEO satellites in the system.

The above mentioned general MLSN model has a problem, which is that traffic congestion may occur at upper layer satellites due to the inhomogeneous traffic distribution resulting from the non-uniform placement of network users due to geographical features and population distribution. In such a situation, more traffic is gathered at the LEO satellites which covers urban areas in contrast with the satellites over the sea or mountain areas [11]. As a result, many packets flow may converge to the MEO satellite servicing those congested LEO satellites. This leads to traffic congestion and affects the communication performance. Fig. 1(a) shows an example of such a situation where the traffic congestion occurs at one MEO satellite. In such a model, where each LEO satellite is allowed to communicate with only one MEO satellite, the queue on the MEO satellite is filled up quickly, and thus increases the queuing delay.

B. Introduction of a traffic distribution method

To cope with the above mentioned issue, we consider a method to distribute packets flow in a MLSN model in which the coverage areas of some MEO satellites are overlapped. In literature, the overlapped coverage area of MEO satellites is utilized for efficient handover between satellites and some researches tend to reduce such kind of overlaps. In this paper, we consider the utilization of such overlapped areas in our traffic distribution method. Fig. 1(b) describes a simple example to show our method for utilizing the overlapped coverage area made by two MEO satellites. In this figure, LEO satellites, lie on the overlapped area, are able to communicate with more than one MEO satellite. Therefore, traffic from a congested LEO satellite can be distributed to more than one MEO satellite in order to avoid traffic congestion.

III. MATHEMATICAL ANALYSES

In this section, by defining the number of MEO satellites which one LEO satellite can communicate with as D, we formulate the maximum value of D by considering the altitude difference between the two layers. We also study the relationship between the value of D and the delay in the network. It is worth noting that the considered delay consists of queuing delay and propagation delay. Additionally, we define the optimal value of D which can be used to minimize the transfer delay in the network.

A. Maximum number of MEO satellites covered by a LEO satellite ($D_{\max}$)

The newly proposed LEO satellites in MLSNs can send packets to a maximum number of MEO satellites equals to the value of $D_{\max}$. The value of $D_{\max}$ depends on (i) altitude difference between LEO and MEO satellites, (ii) elevation angle of the antenna of LEO satellites, and (iii) the total number of MEO satellites.

Fig. 2 demonstrates a simple example. The value of $D_{\max}$ is considered to be proportionally related to the range which one LEO satellite covers in the MEO satellites orbit (represented by the top arc in the figure). The number of MEO satellites on this range equals to the value of $D_{\max}$. To formulate $D_{\max}$, we refer to the altitude of MEO and LEO satellites, and the minimum elevation angle of LEO satellite's antenna as h_{MEO}, h_{LEO}, and $\theta_{\min}$, respectively. Additionally, we refer to the radius of the earth as r. The angle θ_a is defined as shown in Fig. 2. Moreover, N_{MEO} represents the total number of MEO satellites. The expression for the value of $D_{\max}$ is developed as follows:

$$D_{\max} = \frac{1-\cos\theta_a}{2} \cdot N_{\text{MEO}}, \tag{1}$$

where,

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

and the value of A and B in the above expression are described as follows:

$$A = \frac{\text{r} + h_{\text{LEO}}}{\text{r} + h_{\text{MEO}}}, \tag{3}$$

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

In order to study the relationship between the value of $D_{\max}$ and the altitude difference between the two layers, we fix some parameters according to the implementation of Iridium and Spaceway NGSO as LEO and MEO constellations, respectively. The altitude of LEO satellites is fixed to 780 km while

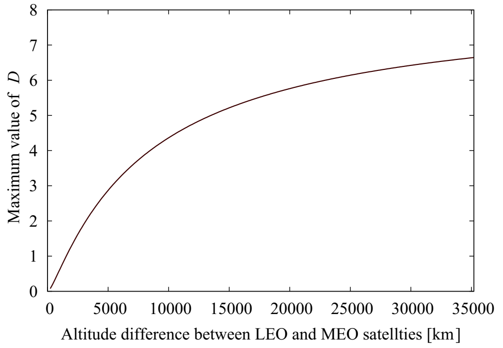


Fig. 3. The maximum value of D with varying the altitude difference.

the MEO satellites altitude is varied from 1000 km to 36000 km to study the effect of the altitude difference between the two layers on the value of $D_{\max}$. Moreover, we set the N_{MEO} to 20 and $\theta_{\min}$ to 10°. We also use 6400 km for the value of r. Using the above values, the relationship between the calculated value of $D_{\max}$ and the satellites altitude difference is plotted in Fig. 3. As it is evident from the figure, the value of $D_{\max}$ increases with the increase of the altitude difference while the rate of this increase decays. Therefore, the maximum number of MEO satellites which one LEO satellite is able to communicate with, $D_{\max}$, is determined by the altitude difference between the two layers in MLSN.

B. Queuing delay

Now, we study the relationship between the queuing delay and the value of D. We apply queuing theory to formulate the queuing delay in MLSN, particularly at MEO satellites, as demonstrated by the simple satellite system model provided in Fig. 4. The system consists of one packet arrival and one packet sending architecture known as M/M/1 model, which is one of the simplest systems for modeling a queue. In this system, the congestion rate is represented as ρ where the value of ρ lies in the range of 0 to 1, where higher values reflect that the system has higher congestion. ρ can be expressed by using the two parameters, λ and μ, as λ/μ. Where λ refers to the average packet arrival rate and μ reflects to the average packet sending rate.

The queuing delay in the system can be formulated using the above parameters as follows:

$$Delay_{\text{queue}} = \frac{\rho}{1-\rho} \cdot \frac{1}{\mu}. \tag{5}$$

As it is evident from the above expressions, the queuing delay depends on the values of λ and μ. With the assumption that the processing rate of the satellites is constant, the average packet sending rate, μ, can be determined by the average packet size which each satellite involve. Therefore, we use the value of λ to evaluate the queuing delay of MEO satellites.

To formulate λ of a MEO satellite, we separate the packet flows reaching the MEO satellite into three categories according to the sending satellite as shown in Fig. 4. The first packet flow category is coming from congested LEO satellites. We refer to the number of congested LEO satellites as C. The average packet arrival rate of the MEO satellite from each flow of this category is referred to as λ_c. The second packet flow category is made up by the flows coming from LEO satellites other than the above-mentioned congested LEO satellites. In fact, this category packet flows are not so congested. The number of these non-congested LEO satellites is expressed as F. Moreover, the average packet arrival rate from each flow of this category is represented by λ_f. The flows from adjacent MEO satellites which send traffic to the targeted MEO satellite is categorized to be the third group. Since we assume the MEO satellite constellation to be a mesh topology, each MEO satellite have some adjacent satellites. We refer to the number of these adjacent MEO satellites as M and the average packet arrival rate coming from each flow of this category is expressed as λ_m.

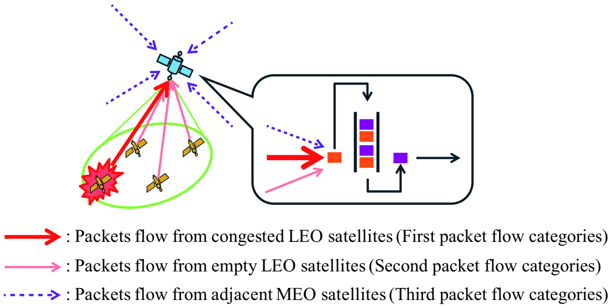


Fig. 4. Categorized flow and queuing system.

From the above description, λ is separated into three parts, first part made by congested LEO satellites and represented by λ_c multiplied by C, second part made by non-congested LEO satellites and represented by λ_f multiplied by F, and third part made by adjacent MEO satellites and represented by λ_m multiplied by M. Furthermore, we believe that the value of D plays a key role in the evaluation of λ. For example, if D increases, a LEO satellite will be able to distribute its traffic to more MEO satellites, which decreases the amount of traffic reaching each MEO satellite and therefore reduces the average packet arrival rate λ. Since the value of D affects the traffic from LEO satellites only, λ can be expressed as follows:

$$\lambda = \frac{C \cdot \lambda_c}{D} + \frac{F \cdot \lambda_f}{D} + M \cdot \lambda_m. \tag{6}$$

The number of non-congested LEO satellites, F, can be formulated using the difference between the total number of LEO satellites and the the number of congested LEO satellites which are covered by the targeted MEO satellite.

$$F = \frac{N_{\text{LEO}}}{N_{\text{MEO}}} \cdot D - C, \tag{7}$$

where N_{LEO} refers to the total number of LEO satellites in the network.

Using the above expression of F in Eq. 6, λ can be represented as follows:

$$\lambda = \frac{C \cdot (\lambda_c - \lambda_f)}{D} + \frac{N_{\text{LEO}}}{N_{\text{MEO}}} \cdot \lambda_f + M \cdot \lambda_m. \tag{8}$$

From the first part of the above expression, it is evident that the value of λ decreases with the increase of the value of D. Additionally, λ_c is expected to be much larger than λ_f since the amount of the traffic coming from congested LEO satellites is much larger than other traffic flows considering the non-uniform distribution of the users. Therefore, the value of D strongly affects the value of λ. Recalling the formulation of ρ, the decrease in the value of λ causes the value of ρ to be decreased. This also decreases the queuing delay as per Eq. 5. As a result of this, in order to reduce the queuing delay of the network, it is recommended to use a higher value of D.

C. Propagation delay

Hereon, we study the relationship between the value of D and the propagation delay of the network. In order to consider the propagation delay, we separate each traffic route into two parts. The first part represents the link from the source LEO satellite to the corresponding MEO satellites. The second part represents the route from those MEO satellites to the destination LEO satellite.

First, to study the difference in propagation delay between each route in the first part of the flow, we express the distance and propagation delay between the source LEO satellite and its corresponding MEO satellites. The distance between a LEO satellite and a MEO satellite is described using the altitude of each satellite and the angle θ which represents the elevation angle from the LEO satellite to the MEO satellite and takes a value from 0° to 90°.

$$d = \frac{h_{\mathrm{MEO}} - h_{\mathrm{LEO}}}{\sin\theta}. \tag{9}$$

The propagation delay between a LEO satellite and a MEO satellite, referred to as $Delay_{\mathrm{LtoM}}$, can be represented by dividing the distance by the speed of light (referred to as c).

$$Delay_{\mathrm{LtoM}} = \frac{d}{c} = \frac{h_{\mathrm{MEO}} - h_{\mathrm{LEO}}}{c \cdot \sin\theta}. \tag{10}$$

Hence, if the constellation of the network is fixed, the value of $Delay_{\mathrm{LtoM}}$ will depend only on the value of θ. When the value of D is set to 1, each LEO satellite will have a link with the nearest MEO satellite which gives the largest θ. But if the value of D becomes larger, each LEO satellite will get more links, which results in longer distance from the LEO satellite to the MEO satellite. From the above discussion, we believe that more routes results in increasing the propagation distance between LEO satellites and MEO satellites which means that $Delay_{\mathrm{LtoM}}$ increases.

Second, we consider the propagation delay of the flow after arriving at the corresponding MEO satellite. The traffic flow in this part is done according to the routing strategy used, which means that the propagation delay of each route depends on the routing policy used in the network. For this reason, we refer to the propagation delay of this part of the route as K.

The total propagation delay of both parts of the whole route, referred to as $Delay_{\mathrm{prop}}$, is represented as follows:

$$Delay_{\mathrm{prop}} = \frac{h_{\mathrm{MEO}} - h_{\mathrm{LEO}}}{c \cdot \sin\theta} + K. \tag{11}$$

All the parameters in the above expression, except θ, depend on the constellation design and the routing policy of the network. On the other hand, the value of θ depends on the value of D. As a result, the propagation delay depends on the value of D, which means that in order to decrease the propagation delay, the value of D should be decreased.

D. Optimal value of D

From the above discussion, starting from studying the value of $D_{\max}$ to the effect of the value of D on both the queuing and propagation delays, we need to find an optimal value of D, since increasing D decreases the queuing delay while simultaneously increasing the propagation delay. Thus, we define the transfer delay as the sum of queuing delay and propagation delay, and define the optimal D as the value that minimizes the transfer delay.

IV. SIMULATION

Network Simulator Version 2 (NS-2) [12] is used to evaluate the above-mentioned analyses. First, we verify the existence of an optimal value of D by simulation. Second, the relationship between the optimal value of D and the traffic condition in the network is described. The simulation environment is shown in following section.

A. Network & traffic settings

The assumed network consists of an MLSN and terrestrial users. The MLSN consists of two-layered satellite constellation with LEO and MEO satellites. To set the parameters of the network, we refer to Iridium and Spaceway NGSO as the constellation of the two layers. The LEO satellite constellation has 66 satellites with an altitude of 780 km measured from the surface of the earth. Meanwhile, 20 satellites are deployed in the MEO layer in the MLSN. The altitude of MEO satellites is set to 10000 km. Both constellations of each layer have a mesh type topology where each satellite has four ISLs to communicate with adjacent satellites. Also, both layers are connected with each other via ILLs. The bandwidth of any link is set to 15 Mbps. Moreover, 80 terrestrial users are uniformly distributed on the ground. Each terrestrial user behaves as a source node as well as a destination node, i.e., it sends and receives packets through the network. Among these terrestrial users, four users are set as congested nodes in order to create a non-uniform distribution of traffic. The congested nodes are assigned a larger traffic rate than other users. The traffic flow is modeled as a non-persistent On/Off flow and is generated at each source node. The On/Off periods are derived from a Pareto distribution with a shape parameter equals to 1.2. We set both the average idle time and the burst time to 200 ms. A packet size of 2 kB is used in this simulation. The above mentioned settings for links and traffic are made up to create a situation where specific satellites are congested and the queuing delay increases. The traffic generation lasts for 30 seconds. Furthermore, we used the Dijkstra Shortest Path algorithm [13] to decide the route for traffic.

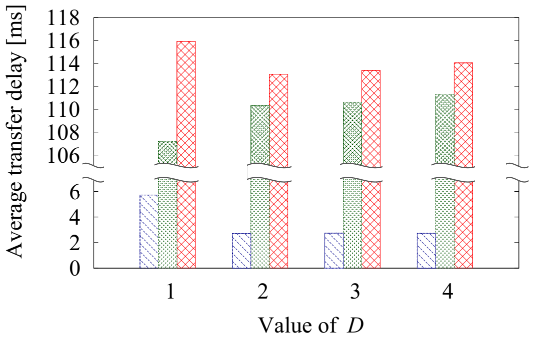
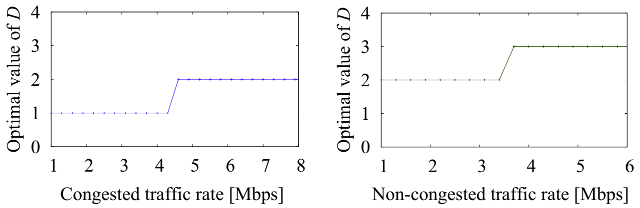


Fig. 5. Queuing delay, propagation delay, and transfer delay with varying the value of D.



(a) Optimal value of D with varying the congested traffic rate.

(b) Optimal value of D with varying the non-congested traffic rate.

Fig. 6. Optimal value of D with varying the congested and non-congested traffic rate.

B. Simulation results

First, by setting the traffic rate of the congested and non-congested users to 8.0 Mbps and 3.2 Mbps, respectively, we evaluate the relationship between D and the different types of delays when D varies from 1 to 4, as shown in Fig. 5. The blue bar in Fig. 5 shows the average queuing delay in the network. As clearing shown, the queuing delay decreases when D changes from 1 to 2, and then almost keeps the same value even if D is increased. This happens due to the distribution of the traffic sent from LEO satellites to more MEO satellites and at one point when the arrival rate at the MEO satellites becomes lower than the sending rate, the queuing delay keeps almost the same value. From the green bar in Fig. 5, it can be seen that the average propagation delay increases with the increase of D as described earlier. Also, the average transfer delay, consists of the sum of the queuing delay and the propagation delay, is shown as a red bar. From this figure, the optimal value of D which achieves the minimum transfer delay in the network is determined to be 2 according to this simulation.

Second, we study the relationship between the optimal D and the traffic rate. In Fig. 6(a), we vary the congested traffic rate from 1.0 Mbps to 8.0 Mbps while setting the non-congested traffic rate at 1.0 Mbps. On the other hand, in Fig. 6(b), we vary the non-congested traffic rate from 1.0 Mbps to 6.0 Mbps while setting the congested traffic rate at 8.0 Mbps. From Fig. 6, it is evident that the optimal value of D increases with the increase of the non-congested and/or congested traffic rates in the network.

From the results of the simulations, we confirm the correctness of our analyses. Also, the optimal value of D is obtained by evaluating the transfer delay in the MLSN.

V. CONCLUSION

In this paper, we proposed a simple technique for distributing the traffic from LEO satellites to MEO satellites. The main target of our technique is to minimize the transfer delay in MLSNs. We analyzed the relationship between the delay and the number of links which one LEO satellite is able to use for sending packets to MEO satellites and also we defined a way to decide the optimal number of those links. The simulation results verified the existence of an optimal number for those links. Furthermore, it has been shown that the optimal number of those links varies with the change of the traffic conditions in the network.

ACKNOWLEDGMENT

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