Assessing Packet Delivery Delay in Multi-Layered Satellite Networks

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***Abstract*—Non-Geostationary satellite networks have many advantages to enable ubiquitous wireless environments such as, extensive coverage, disaster-resistance, and efficient power consumption. Furthermore, to use these networks more efficiently, multi-layered satellite networks are a promising approach, due to their ability to achieve increases in network capacity and to detour traffic efficiently, while maintaining the advantages of each layer. However, they suffer from high delay. In this paper, we focus on constellation design of two-layered satellite networks, in particular on the satellite altitude that minimizes the total packet delivery delay of the network. We express the relationship between the total packet delivery delay and the satellite altitude in mathematical form and develop an expression for determining the altitude to minimize total packet delivery delay. Simulation results validate our analyses.**

I. Introduction

The wide spread of wireless devices such as mobile phones and smartphones have made ubiquitous wireless environments ever more important [1]. However, it is difficult to provide this kind of service over the entire world by using existing infrastructure. Especially in islands and mountainous areas, where it is very hard for economic reasons. Thus, satellite networks are expected to eliminate the need of building infrastructure support.

Currently, there are many satellites orbiting earth. Among them, Non-Geostationary Earth Orbit (NGEO) satellite networks that have Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) have attracted attention [2], due to their ability in providing worldwide wireless environments. They cover the earth with more than one satellite and have many advantages such as efficient power consumption and low delay, as compared with Geostationary Earth Orbit (GEO), because of their low orbit. Moreover, Multi-Layered Satellite Networks (MLSNs) have been heavily researched in recent years [3],[4]. MLSNs consist of hierarchically layered networks. In this research we focus on two-layered satellite networks constructed by LEO and MEO satellite constellations. These networks provide high capacity and have low traffic congestion.

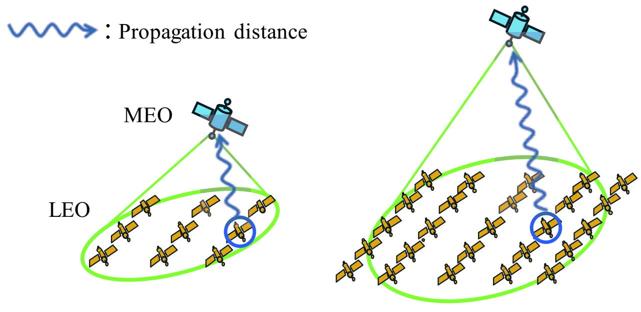
Researches in [5],[6] aim at increasing network capacity while decreasing the delay of lower orbit satellites. Additionally, by routing some packets from the lower layer to the upper layer, it is possible to avoid traffic congestion as in [7]. However, such strategies increase the propagation delay due to longer communication distances. Since, delays in satellite networks are higher than grand terrestrial networks, it is very important to reduce delays in MLSNs.

Therefore, we focus on the constellation designs of two-layered MLSNs to reduce these delays. In particular, we consider the constellation's altitude, intuitively, the total packet delivery delay is closely related to it. In MLSNs that consist of LEO and MEO satellites, the difference of their altitudes changes the distance between the LEO and the MEO satellites, and also the number of LEO satellites that an MEO satellite can cover. Consequently, the propagation delay and queueing delay can dramatically change. Thus, we conclude that the altitude of satellites has a big effect on total packet delivery delay. Thus, we analyze the relationship between the satellites altitude and the total packet delivery delay, and consider a method to decide the optimal satellites altitude to minimize the total packet delivery delay.

The remainder of this paper is organized as follows. Section II describes the constellations of MLSN and how they affect total packet delivery delay. Section III describes the relationship between the altitude of satellites and delay of the network via mathematical analyses. Simulation results are presented in Section IV. Finally, this paper is concluded in Section V.

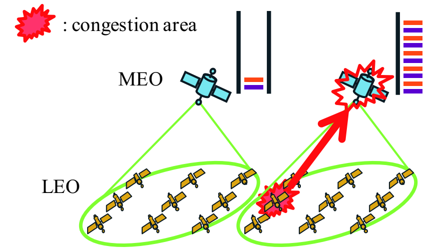
II. Constellations and Total packet delivery delay

The constellation of satellite's type is determined by a number of factors. For example, the number and the orbiting of satellites, their communication capacity, and altitude they orbit from [8]. In the case of single layer satellite networks, Iridium [9] is a prominent example of a network consisting of LEO satellites used now to cover the world. It consists of 66 LEO satellites having an altitude of about 780 kilometers high, each satellite has four links to communicate with adjacent satellites. Another example is Nelstar [10], consists of 120 LEO satellites having an altitude of 1367 kilometers, and have an orbit that passes only over low latitude regions, to cover the populated areas. Different kinds are MEO satellite constellations. For example, the Spaceway NGSO [11] consists of 20 MEO satellites, and their altitude is 10352 kilometers. In this MEO satellite constellation, each satellite has the four links, similar to Iridium. Similarly, MLSNs can also be categorized according to the above mentioned factors. When paying attention to their impact on total packet delivery delay,



(a) An MEO satellite having low altitude. (b) An MEO satellite having high altitude.

Fig. 1. The relationship between MEO satellite's altitude and propagation delay in LEO/MEO satellite networks.



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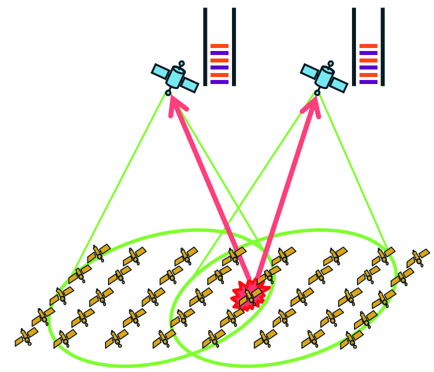

(b) An MEO satellite having high altitude.

Fig. 2. The relationship between MEO satellite's altitude and queueing delay in LEO/MEO satellite networks.

how high the satellites are deployed is a very important factor. In the upcoming section, the relationship between the satellites altitude and delay, especially propagation delay and queueing delay, will be discussed. In this paper, we consider changing the MEO constellation's altitude while fixing the LEO's altitude to focus on the distance between MEO and LEO satellites.

A. The relationship between satellite altitude and propagation delay

Fig. 1 shows a simple topology of an MLSN to demonstrate the effect of the MEO satellite's altitude on propagation delay. The case where the MEO satellite's altitude is low is illustrated in Fig. 1(a), and Fig. 1(b) shows the case where this altitude is high. If an MEO satellite's altitude is high as in Fig. 1(b), compared with the case where it is low like Fig. 1(a), the distance between LEO and MEO satellites is long. Thus, the propagation delay grows with higher altitudes because it is proportional to the distance between the satellites.

B. The effect of MEO satellite's altitude on queueing delay

Fig. 2 illustrates how the queueing delay changes with the MEO satellites altitude. As can be seen, the number of LEO satellites an MEO satellite can cover changes with its altitude. In Fig. 2(a), LEO satellites deliver their packets to only one MEO, because there is no more than one MEO satellite that covers a single LEO satellite. In contrast, if the altitude of an MEO satellites is high as demonstrated in Fig. 2(b), the coverage of MEO satellites becomes large. The large coverage enables multiple MEO satellites to receive packets from LEO satellites at congested areas. Thus, making it possible for the congested LEO satellites to be able to distribute traffic to more than one MEO satellite. As a result, balancing the number of packets in the queue of each MEO satellite, and decreasing the queueing delay, compared to the case that a LEO satellite is covered by only one MEO satellite.

Although Fig. 2 shows a simple topology for explanation, similar phenomena can occur in real networks. Due to the fact that crowds in a specific region cause traffic congestion, following from the distribution of crowds on earth [12]. If the altitude of an MEO satellite is low at a crowded time, traffic will be routed to only one MEO satellite and the queueing delay will increase. In conclusion, we observe that there is a trade-off between propagation delay and queueing delay when deciding the MEO satellites altitude.

III. Analyses of Relationship Between Delay and MEO Satellite Altitude

We considered the effect of MEO satellite's altitude on the propagation delay and the queueing delay in the preceding section. According to the above discussion, increasing the distance between LEO and MEO satellites increases propagation delay, and decreasing MEO satellites altitude decreases queueing delay. In fact, changing the altitude of MEO produces contradicting affects in each kind of delay.

In this section, we analyze the above relationships between each delay and the MEO satellites altitude using mathematical expressions. After these analyses, we consider the optimal MEO satellites altitude to minimize the packet delivery by taking account of the above mentioned trade-off.

A. Formulating propagation delay

Firstly, we analyze the relationship between the MEO satellites altitude and propagation delay. The distance between MEO satellites and LEO satellite, d, can be formulated from the MEO satellite's altitude, h_{MEO}, and that of a LEO satellite, h_{LEO}, as follows:

$$d = \frac{h_{\mathrm{MEO}} - h_{\mathrm{LEO}}}{\sin\theta}, \qquad (1)$$

where θ denotes the angle of elevation from the lower layer to the upper layer. The propagation delay is proportional to the displacement between the LEO layer to the MEO layer. Since the propagation delay, $Delay_{\mathrm{prop}}$, equals the ratio between distance, d, to the light speed, c, thus

$$Delay_{\mathrm{prop}} = \frac{d}{c} = \frac{h_{\mathrm{MEO}} - h_{\mathrm{LEO}}}{c{\cdot}\sin\theta}. \tag{2}$$

The above expression implies that $Delay_{\mathrm{prop}}$ is determined by the distance between the altitudes of LEO and MEO satellites i.e., ($h_{\mathrm{MEO}} - h_{\mathrm{LEO}}$), because the parameters c and θ are fixed values. Furthermore, since we consider the case where h_{LEO} is fixed, the propagation delay is dependent on the MEO satellites altitude. If the MEO satellite's altitude increases, the delay will increase according to the above expression. Thus, the $Delay_{\mathrm{prop}}$ is a monotonically increasing function of h_{MEO}.

B. Formulating queueing delay

Secondly, we formulate the queueing delay of MEO satellites based on queueing theory, which is the mathematical study of waiting lines. It allows analyzing the average waiting time in a queue. We propose the satellite system queueing model shown in Fig. 3, here each satellite has one packet arrival rate and one sending packets rate. This system is known as a M/M/1 model. The congestion rate of the system, here ρ is, it shows how congested the system is, and takes the values from 0 to 1. The higher its value is the more congested the system is. ρ is defined by two parameters, namely, λ and μ, which denote the average packet arrival rate, and the average packet sending rate, respectively. Thus, ρ is formulated as λ/μ. Since the considered system is an M/M/1 model, from queueing theory the queueing delay of this system can be expressed as follows:

$$Delay_{\mathrm{queue}} = \frac{\rho}{1-\rho}{\cdot}\frac{1}{\mu}. \tag{3}$$

As indicated in the preceding section, the queueing delay changes with the number of MEO satellites that one LEO satellite is covered by, D. λ of an MEO satellite changes with D since the amount of packets arriving to an MEO satellite changes with the number of satellites a LEO satellite is covered by. If the number of D is more than one, traffic will be distributed to more than one MEO satellite. So, in order to formulate λ, we separate satellites which send packets to the MEO into three groups depending on which area they reside in, as illustrated in Fig. 3. The first of these is the area where the LEO satellites that generate a lot of traffic are positioned. We define the number of LEO satellites in this area as C, and the average arrival rate of the packets from the LEO satellites in this congested area to an MEO satellite is represented as λ_c. The second of these three areas is the area of LEO satellites that have LEO satellites which do not send many packets to MEO satellites, i.e, in non-congested areas. F is the number of LEO satellites in this area, and λ_f denotes the average rate of packets from this area. The third area is where adjacent MEO satellites reside. In MEO satellite constellations, satellites communicate with neighboring satellites by using the links available in the system, and the number of MEO satellites which one MEO satellite can communicate with is a fixed

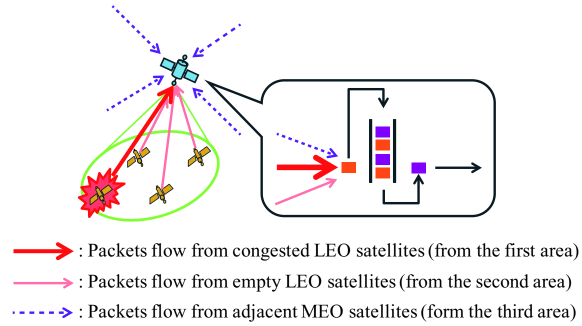

Fig. 3. Packet sources and queueing system.

value depending on the constellation type. We denote this number as M and the average packet arrival rate from these MEO satellites arrival rate as λ_m.

The value of D effects λ of the first and second areas, because the packets from LEO satellites are distributed to a number of MEO satellites equal to the value of D. In other words, the amount of packets flowing from LEO satellites in the first and second areas differs according to the value of D. Therefore, λ is formulated as follows:

$$\lambda = \frac{C{\cdot}\lambda_c}{D} + \frac{F{\cdot}.\lambda_f}{D} + M{\cdot}\lambda_m, \tag{4}$$

where, the value of the F reflects the number of non-congested LEO satellites which one MEO satellite covers. F can be derived from D as follows:

$$F = \frac{N_{\mathrm{LEO}}}{N_{\mathrm{MEO}}}{\cdot}D - C. \tag{5}$$

Here, we define N_{MEO} and N_{LEO}, as the number of MEO and LEO satellites, respectively. Thus, the value of λ can be derived by substituting Eq. (5) into Eq. (4), as follows:

$$\lambda = \frac{C{\cdot}(\lambda_c - \lambda_f)}{D} + \frac{N_{\mathrm{LEO}}}{N_{\mathrm{MEO}}}{\cdot}\lambda_f + M \cdot \lambda_m. \tag{6}$$

The value of λ_c is much larger than λ_f, since the bias of population is very dramatic and a lot of traffic flows to a specific satellite. Thus, the first term in the above formula, the value of the λ_c has predominant influence. In addition, the value of this term is in inversely proportion to D. On the other hand, the second and third terms do not change with D, but rather they are constants. Therefore, if the value of the D increases, λ will decrease. On the other hand, the average packet sending rate, μ, is not influenced by other parameters. Since, the processing performance of satellites is constant, and the processing time depends on the packet length. Thus, the average packet sending rate is determined by the average packet length.

According to Eq. (3), the queueing delay increases with the growth of ρ, and ρ is proportional to λ. So, if D increases, $Delay_{\mathrm{queu}}$ is reduced by the decrease of λ. That is because the packets from LEO satellites in the congested area are distributed to a number of MEO satellites equal to the value of D.

C. The number of MEO satellites covering a LEO satellite

Herein, we aim to formulate the number of MEO satellites which one LEO satellite can communicate with, D. That is the number of MEO satellites in the ambit one LEO satellite. Hence, D can be derived from the ratio between area where MEO satellites exist and area one LEO satellite covers. Fig. 4 illustrates this ratio. The above area in this figure is one that a LEO satellite covers. The square footage of this area is determined by the minimal elevation angle from a LEO satellite to an MEO satellite, $\theta_{\min}$ shown Fig. 4, N_{MEO}, N_{LEO}, and the radius of the earth, r. Thus, the value of D is formulated as follows:

$$D = \frac{1 - \cos\theta_a}{2} \cdot N_{\mathrm{MEO}}, \tag{7}$$

where

$$\theta_a = \arctan \frac{B \pm AB\sqrt{1 + B^2 - A^2B^2}}{1 - A^2B^2}, \tag{8}$$

and the parameters A and B in above equation are defined as:

$$A = \frac{\mathrm{r} + h_{\mathrm{LEO}}}{\mathrm{r} + h_{\mathrm{MEO}}}, \tag{9}$$

$$B = \frac{1}{\tan\theta_{\min}}. \tag{10}$$

If the LEO satellites altitude is fixed, all parameter that do not include h_{MEO} of D are constants. Hence, D depends solely on the altitude of MEO satellites. Fig. 5 shows the theoretical value of D, it demonstrates the relationship between D and altitude of MEO satellites, h_{MEO}, with N_{MEO} equal to 66, N_{MEO} to 20, and h_{LEO} to 780 kilometers. The altitude of MEO satellites, h_{MEO}, is varied from 1000 kilometers to 36000 kilometers. Moreover, r and $\theta_{\min}$ are set to 6400 kilometers and $\pi/18$, respectively. These parameters are set because we assume the LEO satellites constellation is Iridium and the MEO satellites constellation is Spaceway NGSO. It is clearly evident from this graph that the value of D increases with the growth of h_{MEO}. Therefore, if the MEO satellites altitude is higher, LEO satellites can distribute packets to a larger number of MEO satellites. Moreover, the rate of change in D saturates and reaches its maximum value between six and seven. Because the highest altitude of an MEO satellite is less than 36000 kilometers due to the gravitational force of earth.

D. Optimal MEO satellites altitude

In the previous sections, we have analyzed the effect of MEO satellites altitude on each delay. From these analyses, it is understood that the propagation delay is a monotonically increasing function of MEO satellite altitude, and the queueing delay decreases with the increase of the MEO satellites altitude, because the value of D increases with the growth of MEO satellites altitude and then the packets from the congested LEO satellites are distributed to a number of MEO satellites equal to the value of D. Consequently, we expect that the total of these delay is a convex up function of MEO satellites altitude. Therefore, there exists a value of MEO satellite altitude that minimize total packet delivery delay.

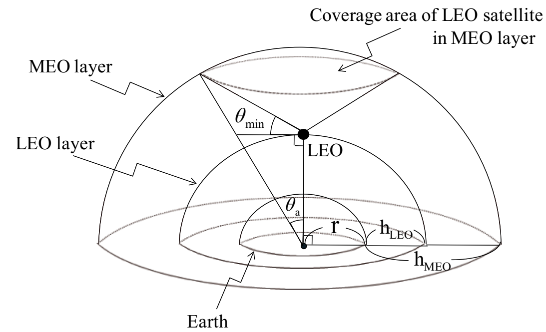

Fig. 4. The MEO satellites area that one LEO satellite can cover.

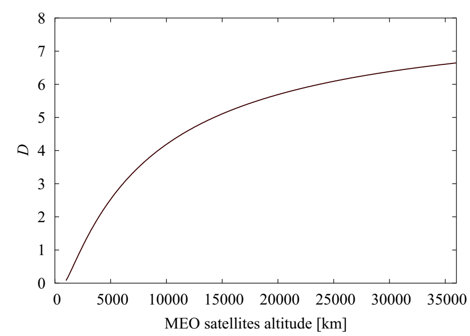

Fig. 5. The relationship between the MEO satellites altitude and the value of D.

IV. SIMULATIONS

In this section, we aim to verify the relationship between the occurring delays in the MLSN and the MEO satellites altitude in the network. This experiment is conducted by computer simulations using Network Simulator version 2 (NS-2). First, we show how the MEO satellites altitude affects the propagation delay and queueing delay. Secondly, the relationship between the total packet delivery delay and the MEO satellites altitude is examined. The parameter settings of this experiment are set to create a situation that causes traffic congestion is created on a specific satellite and the queueing delay increases. They are discussed in detail below.

A. Satellite constellations

A two-layered network consisting of MEO and LEO satellite constellations is considered. The MEO constellation comprises of 20 satellites, we vary its altitude from 6000 kilometers to 14000 kilometers. The LEO satellite layer is an Iridium constellation that consists of 66 satellites located at an altitude of 780 kilometers. Every satellite in each layer is connected with four adjacent satellites via Inter Satellite Links (ISL), and both layers can communicate via Inter Layer Links (ILL). The capacity of each ISL and ILL is considered to be 5 megabits per second. We use drop-tail queues. The queue length at each satellite is set to 50000 packets to evaluate the delay of this system without packet drops.

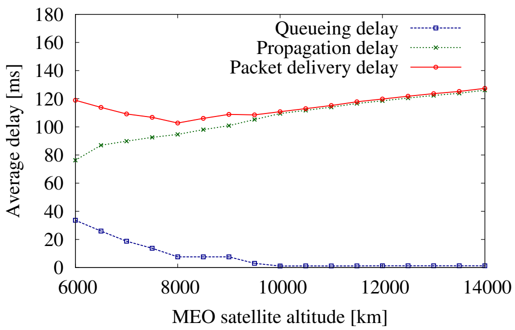

Fig. 6. Propagation delay, queueing delay, and total packet delivery delay for MEO satellite altitude.

B. Traffic settings

On the ground 100 terminals are uniformly deployed, which are the sources and destinations of traffic are deployed all over the world. Traffic is generated in each source node, via 100 non-persistent On/Off flows. The On/Off periods of the connections are following a Pareto distribution with a shape equal to 1.2. The average burst time and the average idle time are both set to 200 milliseconds. The size of each packet is 3 kilobytes in our simulations. The traffic rate of 99 terminals is set to be 0.4 megabits per second and the reminding one is set to 8.0 megabits per second, in order to design two areas, one traffic congested and the other not. The data transmissions last for 30 seconds. In addition, we use the Dijkstra Shortest Path (DSP) [13] as a routing method in this simulation. The DSP is a scheme that uses Dijkstra's algorithm which is well known method to solve the shortest path problem.

C. Experimental result

The propagation delay is demonstrated as the green line in Fig. 6. The figure shows that the propagation delay increases with the growth of MEO satellites altitude. That is because the higher altitude results in farther distance between the MEO and LEO layer, and in turn increasing the propagation delay. The blue line in Fig. 6 shows the queueing delay while the MEO satellites altitude rises from 6000 kilometers to 10000 kilometers high. The queueing delay decreases gradually, and saturates over altitudes higher than 10000 kilometers. This is because if the MEO satellites are positioned higher than a certain value, packets do not fill up the queue of the satellites due to the traffic distribution between different MEO satellites. The red line in Fig. 6 shows the total packet delivery delay, which equals the sume of all delays. The delay decreases for MEO satellite altitudes between 6000 kilometers to 8000 kilometers, and starts rising from 8000 kilometers. From this graph, we can see that the delay is minimized when the altitude is 8000 kilometers high. In conclusion, it is evident that the optimal MEO satellites altitude of the MLSN constructed in this experiment, is 8000 kilometers high.

The result of this experiment suggests the existence of an optimal value for MEO satellite altitude. Also, the trade-off relationship of between the propagation delay and queueing delay has been confirmed, and the optimal MEO satellite altitude can be determined by evaluating the total packet delivery delay in the satellite networks.

V. Conclusion

In this paper, we have analyzed the relationship between the delay and the altitude of satellites in Multi-Layered Satellite Networks (MLSNs). Our analyses showed the existence of an optimal altitude, particular to MEO satellites altitude in two-layered satellite network, that minimizes the total packet delivery delay. The simulation results demonstrate that the total packet delivery delay depends on the satellites altitude. Moreover, we have verified that the propagation delay increases with the increase of the displacement between each layer and the queueing delay decreases with the increase of the MEO satellites altitude. Due to the distribution of packets originating from lower layer to the upper layer. Thus, a trade-off relationship exists with respect to each layer's satellites altitude in MLSNs. Therefore, the optimal altitude of MEO satellites is determined by evaluating the total packet delivery delay in MLSNs.

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