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Citation:

Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, Naoko Yoshimura, and Naoto Kadowaki, " Packet Transfer Delay Minimization by Network-Wide Equalization of Unbalanced TrafficLoad in Multi-Layered Satellite Networks," IEEE 77th Vehicular Technology Conference (VTC2013 Spring), Dresden, Germany, Jun. 2013.

URL:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6692690

Packet Transfer Delay Minimization by Network-Wide Equalization of Unbalanced Traffic Load in Multi-Layered Satellite Networks

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***Abstract*—Multi-Layered Satellite Networks (MLSNs) have many advantages such as extensive coverage, lower delay performance, and disaster resistance. Moreover, the networks permit load distribution by bypassing traffic efficiently from lower layers to upper layers. In the future, the MLSNs should play an important role to provide global communication services. However, sometimes traffic congestion happens in these networks since the distribution of users is unbalanced heavily depending on geographical restrictions, which causes bad effects on the networks such as increasing delay. Therefore, we focus on network design to avoid traffic congestion. There are many constitution elements to design these networks. One of the most significant elements is the altitude of satellites because it affects propagation distance and number of links between layers in MLSNs, and thus the packet transfer delay of the networks. Therefore, we analyze the relationship between the altitude of satellites and the packet transfer delay with network-wide equalization. Furthermore, the existence of the optimal altitude of satellites is denoted in this paper. Our analyses are validated by simulation experiments.**

I. Introduction

Satellite networks provide worldwide communication environments since they have wide coverage and advantage of simultaneous transmissive communication. Additionally, they can set up network environments to the areas having inadequate infrastructure such as islands or mountainous areas. Moreover, during the time of disaster, we can use them instead of the destroyed ground network systems. Hence, expanding network capacity and having an efficient communication scheme are needed.

There are some types of satellite networks classified in terms of satellite orbit. Recently, the networks using Non-Geostationary Earth Orbit (NGEO) satellites have attracted attention for their usability [1]. Especially, Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites show advantages of lower delay and electric power saving performance while comparing to Geostationary Earth Orbit (GEO) satellites which were often used in the past. LEO and MEO satellites compose constellations by more than one satellite and cover all over the world. However, traffic congestion might occur at specific satellites in NGEO satellite networks with elevation of the network users because the user distributions of sources and destinations on the surface of the earth are nonhomogeneous. The traffic load tends to converge to the satellites which cover the areas of large cities. It causes the loss of packets and the increase of delay which are serious problems. In order to resolve such kind of situation of traffic congestion, realizing Multi-Layered Satellite Networks (MLSNs) attracts a great deal of interest in late years [2].

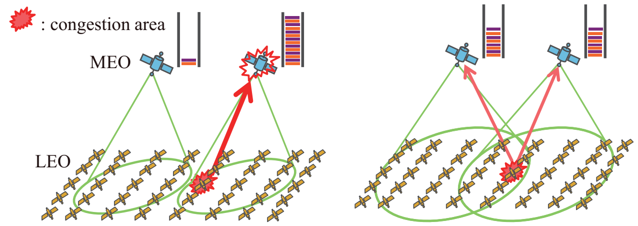
MLSNs consist of hierarchically layered networks, which increase the network capacity and make it possible to bypass traffic from lower layer to upper layer. Therefore, they avoid traffic congestion and provide large capacity and high speed networks all over the world. In this paper, we focus on MLSNs consisting of LEO and MEO satellites since they are superior in terms of lower delay and thrifty power consumption [3]. It is needed to design the constellation to delivery traffic efficiently in MLSNs. There are many components to construct MLSNs such as number, orbit, and altitude of each layer satellites [4]. Among them, we mainly focus on the altitude of satellites because it is strongly related to the transfer delay of the networks. The altitude of satellites in each layer affects the propagation distance and the coverage of upper satellites to lower layer satellites which determine the number of links between the two layers. The propagation distance and the number of links affects the propagation delay and the queuing delay, respectively. Hence, we analyze the relationship between the altitude of satellites and the packet transfer delay in MLSNs with mathematical approach. Accordingly, we show the existence of the optimal satellite altitude for minimizing the packet transfer delay in MLSNs.

The remainder of this paper is organized as follows. Section II describes constellations of MLSN and the network assumption in this research. Section III describes the analyses regarding the alteration of queuing delay and propagation delay with the change of satellites' altitude and shows the way to decide the optimal altitude of satellites in MLSNs. Simulation results are presented in Section IV. Finally, this paper is concluded in Section V.

II. Satellite constellation and network models

A. General satellite constellation model and its shortcoming

Satellites are generally categorized into LEO, MEO, and GEO satellites according to their altitude. Each satellite constellation has different advantages. In these constellations, we



(a) An 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.

take particular note of LEO and MEO satellite constellations for their lower delay and electric power saving aspects. They have lower altitude orbit than GEO satellites and cover all over the world by more than one satellite. Especially Iridium [5] is a famous LEO satellites constellation which is a system to provide worldwide communication environment. It consists of 66 satellites orbiting 780km high, has a mesh type topology which constructs 6 orbits, and has 4 Inter Satellite Links (ISLs) with adjacent satellites. On the other hand, Spaceway-NGSO is known as an MEO satellites constellation. Spaceway-NGSO is also mesh type constellation which is consists of 20 satellites orbiting 10352km high and has 4 orbit and 4 ISLs. Since MEO satellite constellations have higher altitude than LEO's ones, propagation delay is larger, but they can cover all over the world with smaller number of satellites.

In this paper, we focus attention on MLSNs consisting of mesh type LEO and MEO satellite constellations. MLSNs keep advantages of NGEO satellite networks and increase network capacity. Additionally, each LEO satellite has a link with the nearest MEO satellites in general MLSN model. In fact, LEO satellites are divided into the same number of groups as MEO satellites. In these networks, traffic is sent from satellite earth stations to LEO satellites, and go through other LEO satellites or MEO satellites to destination. Hence, they make it possible to bypass traffic from lower layer to upper layer. [6] shows an example of using each layer for efficiently routing of the network. Therefore, MLSNs are considered as an efficient network for providing worldwide wireless communication services.

However, traffic distribution on the earth is very inhomogeneous because users of the network tend to converge to big cities against sea or mountain area [7]. The distribution of the amount of generated traffic is similar to that of population. Thus, much traffic gathers to some LEO satellites covering populated area, and sometimes they send a part of their traffic to a MEO satellite as shown Fig. 1(a). MEO satellites usually receive traffics from more than one LEO satellites at the same time. Then, it is considered that traffic congestion usually happens at the MEO satellite. Fig. 1(a) shows a simple model for explanation, but similar phenomena can happen in real networks. Traffic congestion causes a decrease in the performance of the network such as packet drop, throughput degradation, and the increase of delay.

B. The new network model to distribute traffic load

In order to avoid above mentioned issue of traffic congestion at MEO satellites, we propose a new network model to distribute traffic load of MEO satellites. We assume to use MEO satellites at a maximum coverage in this model as shown in Fig. 1(b). Expanding of using area of MEO satellites coverage leads to the increases of the number of links between LEO and MEO satellites since each LEO satellite is covered by more than one MEO satellite. Hence, the traffic gathering at one MEO satellite is distributed to some MEO satellites, and the traffic distribution on the MEO satellite layer becomes almost uniform. It causes the decrease of generating traffic congestion.

The number of links between LEO and MEO satellites is equal to the number of MEO satellites covering a LEO satellite. We assume that each LEO satellite can distribute traffic to the same number of MEO satellites, which is defined as D. The value of D is proportional to the largeness of the area where one MEO satellite covers, and the largeness is determined by the difference of altitude between LEO and MEO satellites and the elevation angle of LEO satellites' antenna. To formulate the value of D, we refer to the altitude of LEO and MEO satellites, and the minimum elevation angle of LEO satellites' antenna as h_{LEO}, h_{MEO}, and $\theta_{\min}$, respectively. Additionally, we refer to the number of all MEO satellites as N_{MEO}. Moreover, the angle θ_{a} is defined as the angle of elevation from the center of the earth to the edge of coverage area of LEO satellite in MEO layer as shown in [8], with the radius of the earth, namely r. Thus, the value of D is formulated as follows:

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

where

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

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

$$A = \frac{\mathrm{r} + h_{\mathrm{LEO}}}{\mathrm{r} + h_{\mathrm{MEO}}},\ B = \frac{1}{\tan\theta_{\min}}. \tag{3}$$

The number of LEO satellites which an MEO satellite covers, namely R, is expressed by using the value of D. Each MEO satellite receives traffic from the same number of LEO satellites, R . We refer to the number of all LEO satellites as N_{LEO}. Thus, the value of R is described as $(N_{\mathrm{LEO}}/N_{\mathrm{MEO}}) \cdot D$.

Since the values of D and R increase with the increase of MEO satellites' altitude, if the distance between layers is long, the number of links between LEO and MEO satellites increases and the traffic from each LEO satellite is distributed to some MEO satellites. The distribution of traffic is considered to cause the homogenization of traffic load and the decrease of queuing delay at each MEO satellite. However, increasing the distance between two layers raise the increase of propagation delay. Hence, there is a trade-off between queuing delay and propagation delay which needs to be concerned when we decide the altitude of each layer in MLSNs.

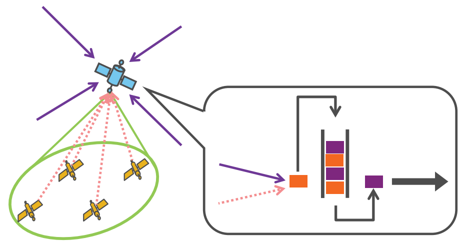


Fig. 2. Packet sources and queueing system.

III. Analyses

In this section, we firstly analyze the relationship between queuing delay at MEO satellite and altitude of satellites. By using the model of queuing theory, we show that distribution of traffic which is from LEO satellites to MEO satellites causes the decrease of queuing delay. Secondly, the propagation delay is described with mathematical expressions. At last, we refer to the method to decide the optimal altitude of satellites in order to minimize the transfer delay.

A. The introduction of queuing theory and a simple model to analyze queuing delay

We use queuing theory to formulate the queuing delay at MEO satellite as presented by the simple satellite system model shown in Fig. 2. This circuit consists of one packet arriving and one packet sending architecture, which is a first in first out system. By supposing the circuit with Poison arrival of traffic, the queuing model is assumed as M/M/1 model in queuing theory. In this model, the queuing delay of this system is formulated as follows:

$$Delay_{\text{queue}} = \frac{\lambda}{(\mu - \lambda)\cdot\mu}, \tag{4}$$

where λ and μ refer to as the average packet arrival rate and the average packet sending rate, respectively. Since the value of μ is determined by the distribution of packet size and the processing rate of the satellites, it does not depend on the altitude of satellites. Thus, we evaluate the change of λ when the altitude of satellites changes in order to assess queuing delay at MEO satellites.

The packets arriving to each MEO satellite are separated to two categories according to whether the sending satellite is LEO or MEO satellite as shown in Fig. 2. We define the packet sending rate of each LEO satellite as p_{L_i}, where the prefix of i shows the identification of each LEO satellite. Since each LEO satellite distributes packets to MEO satellites equally by D, the average packet arrival rate at a MEO satellite from each LEO satellite is expressed as p_{L_i}/D. On the other hand, the average packet sending rate of each MEO satellite is represented as p_{M_k}, where the prefix of k shows the identification of each adjacent MEO satellite. Therefore, the average packet arrival rate of MEO satellite from each adjacent MEO satellite is expressed as p_{M_k}/M.

We define the average packet arrival rate of each MEO satellite from all LEO satellites which the MEO satellite covers as λ_{M_j}, where the prefix of j shows the identification of each MEO satellite. Since the average packet arrival rate of each MEO satellite is formulated as the sum of packet arrival rate from above two categories, the value of λ_{M_j} is expressed as follows:

$$\lambda_{M_j} = \sum_{i=1}^{R} \frac{p_{L_i}}{D} + \sum_{k=1}^{M} \frac{p_{M_k}}{M}. \tag{5}$$

B. Assessing the average packet arrival rate at a MEO satellite when the distance between two layers changes

In order to evaluate the change of λ when the distance between two layers changes, we assume two situations where the distance between LEO satellites and MEO satellites is different to each other. One is the situation that each layer's satellites have altitude so that the number of LEO satellites which a MEO satellite covers, namely R, equals to R_1. Additionally, the values of D and λ are set to D_1 and $\lambda_{M_j}(R)$ respectively in this situation. Another situation is that the value of R equals to $R_1 + 1$. In the second situation, the distance between two layers becomes longer and the coverage of MEO satellites expand as they cover one more LEO satellite. In this situation, the value of D and λ are declared as $D_1 + N_{\text{LEO}}/N_{\text{MEO}}$ and $\lambda_{M_j}(R+1)$. The average packet arrival rate of flows from adjacent MEO satellites is the same in both situations because the amount of packet flow in MEO satellite layer is not affected by the altitude of satellites. Therefore, the packet arrival rate at MEO satellites from LEO satellites changes when the distance between two layers changes. We define the change of the rate as $\Delta\lambda_{M_j}$, which is formulated as following expressions by using above-mentioned $\lambda_{M_j}(R)$ and $\lambda_{M_j}(R+1)$.

$$\begin{aligned} \Delta\lambda_{M_j} &= \lambda_{M_j}(R+1) - \lambda_{M_j}(R) \\ &= \sum_{i=1}^{R_1+1} \frac{p_{L_i}}{D + \frac{N_{\text{LEO}}}{N_{\text{MEO}}}} - \sum_{i=1}^{R_1} \frac{p_{L_i}}{D} \\ &= \frac{1}{D + \frac{N_{\text{LEO}}}{N_{\text{MEO}}}} \cdot \left(p_{L_{R_1+1}} - \frac{\sum_{i=1}^{R_1} p_{L_i}}{R_1} \right). \end{aligned} \tag{6}$$

The increase and decrease of packet arrival rate of MEO satellites when the altitude of satellites changes are judged based on above expression. Especially, it is measured by magnitude relationship between $p_{L_{R_1}}$ and $\sum_{i=1}^{R_1} p_{L_i}/R_1$. The value of $p_{L_{R_1}}$ represents that the packet sending rate of the LEO satellite is added to the coverage of the MEO satellite by increasing the distance between two layers. On the other hand, the value of $\sum_{i=1}^{R_1} p_{L_i}/R_1$ expresses the average packet sending rate of LEO satellites which are in the coverage of the MEO satellite before the satellites' altitude changes. If $\Delta\lambda_{M_j}$ has positive value, the packet arrival rate of MEO satellites increases with the increase of distance between two layers. Otherwise, if $\Delta\lambda_{M_j}$ has negative value, the packet arrival rate of MEO satellites decreases with increase of distance between two layers.

Next, in order to estimate the change of the average packet arrival rate distribution of each MEO satellite when the distance between two layers increases, we define Y_{min} and Y_{max} as the minimum and maximum values of $\sum_{i=1}^{R_1} p_{L_i}/R_1$ as following expression.

$$Y_{\text{min}} \leq \frac{\sum_{i=1}^{R_1} p_{L_i}}{R_1} \leq Y_{\text{max}}. \tag{7}$$

If the value of $\sum_{i=1}^{R_1} p_{L_i}/R_1$ equals to the value of Y_{min}, $\Delta\lambda_{M_j}$ has always positive value. Thus, the average packet arrival rate of MEO satellite increases with the increase of distance between two layers. Since the amount of arrival packet of the MEO satellite increases, the value of $\sum_{i=1}^{R_1} p_{L_i}/R_1$ becomes larger, $\sum_{i=1}^{R_1} p_{L_i} + p_{L_{R_1+1}}/R_1 + 1$. In other words, the value of Y_{min} becomes larger with the increase of the distance between two layers. In a similar way, the value of Y_{max} becomes smaller with increase of distance between two layers. Therefore, the range of the value of $\sum_{i=1}^{R_1} p_{L_i}/R_1$ narrows with the increase of the distance between two layers.

Eq. 7 is able to be transformed as bellow:

$$\frac{N_{\text{LEO}}}{N_{\text{MEO}}} \cdot Y_{\text{min}} \leq \frac{\sum_{i=1}^{\frac{N_{\text{LEO}}}{N_{\text{MEO}}}\cdot D} p_{L_i}}{D} \leq \frac{N_{\text{LEO}}}{N_{\text{MEO}}} \cdot Y_{\text{max}}. \tag{8}$$

The value of $\sum_{i=1}^{\frac{N_{\text{LEO}}}{N_{\text{MEO}}}\cdot D} p_{L_i}/D$ is equal to the average packet arrival rate of MEO satellite without arriving packet from adjacent MEO satellites. It includes only packets arriving from covering LEO satellites. Hence, if the value of Y_{min} increases and the value of Y_{max} decreases with increase of the distance between two layers, the range of the value of $\sum_{i=1}^{\frac{N_{\text{LEO}}}{N_{\text{MEO}}}\cdot D} p_{L_i}/D$ become smaller. Accordingly, the range of the average packet arrival of MEO satellite narrows. Therefore, the distribution of packet arrival rate of each MEO satellite, λ_{M_j}, becomes almost uniform gradually.

C. Relationship between queuing delay and distribution of packet arrival

We study the change of queuing delay of MEO satellites when the distribution of packet arrival rate becomes almost uniform. In order to consider the relationship between queuing delay and distribution of packet arrival rate simply, we estimate the queuing delays of two situations. First situation is that the packet arrival rates of all MEO satellites are the same. In other words, the distribution of packet arrival rate of MEO satellites is completely uniform. Since all MEO satellites have the same value of the packet arrival rate, we define the λ_{M_j} in that situation as $\lambda_{M_{\text{ave}}}$. Hence, average queuing delay of all MEO satellites in that situation is expressed by using Eq. 4 as following expression. We define the queuing delay as $Delay_{\text{queu1}}$.

$$Delay_{\text{queu1}} = \frac{\lambda_{M_{\text{ave}}}}{\mu - \lambda_{M_{\text{ave}}}} \cdot \frac{1}{\mu}. \tag{9}$$

We assume that two values of packet arrival rate exist as second situation, where a half of all MEO satellites have $(\lambda_{M_{\text{ave}}} - \Delta a)$ and another half MEO satellites have $(\lambda_{M_{\text{ave}}} + \Delta a)$ as satellites packet arrival rates. Δa is random value which expresses the difference between the average packet arrival rate and the value of the average packet arrival rates in second situation. This situation shows that the distribution of average packet arrival rate of MEO satellites is not uniformly. Since the average queuing delay of all MEO satellites in this situation is represented as the average of two satellites having different average packet arrival rate, $(\lambda_{M_{\text{ave}}} - \Delta a)$ and $(\lambda_{M_{\text{ave}}} + \Delta a)$, respectively. It is formulated as $Delay_{\text{queu2}}$ as follows:

$$\begin{aligned} & Delay_{\text{queu2}} \\ = \; & \frac{1}{2} \cdot \left(\frac{\lambda_{M_{\text{ave}}} - \Delta a}{\mu - (\lambda_{M_{\text{ave}}} - \Delta a)} \cdot \frac{1}{\mu} + \frac{\lambda_{M_{\text{ave}}} + \Delta a}{\mu - (\lambda_{M_{\text{ave}}} + \Delta a)} \cdot \frac{1}{\mu} \right) \\ = \; & \frac{\lambda_{M_{\text{ave}}} \cdot (\mu - \lambda_{M_{\text{ave}}}) + (\Delta a)^2}{(\mu - \lambda_{M_{\text{ave}}})^2 - (\Delta a)^2} \cdot \frac{1}{\mu}. \end{aligned} \tag{10}$$

The value of $Delay_{\text{queu2}}$ becomes minimum when the value of Δa equals to zero from above expression, and reaches the same value of $Delay_{\text{queu1}}$. Thus, the value of $Delay_{\text{queu2}}$ is equal to or higher than the value of $Delay_{\text{queu1}}$ at any time. Therefore, the queuing delay of MEO satellites when the distribution of packet arrival rate becomes almost uniform is larger than that of delay when the distribution is ununiform. Though these analyses consider only two situations, the same thing happens in other situations. The closer the distribution of the packet arrival rate to the uniform one, the higher the queuing delay of the MEO satellites.

From above analyses, it is considered that the distribution of packet arrival rate of MEO satellite reduces with the increase of the distance between two layers, and it causes the decrease of queuing delay. Therefore, the longer the distance between two layers, the smaller the average queuing delay of MEO satellites.

D. Formulating propagation delay

The relationship between satellite altitude and propagation delay is analyzed in this subsection. Propagation delay is calculated from the distance between satellites in MLSNs. When the altitude of satellites changes, the distance between LEO and MEO satellites changes. The distance between their two layers is expressed with their altitudes, h_{LEO} and h_{MEO}, and the elevation angle of antenna from LEO satellites to MEO satellites. Thus, the propagation delay is represented as following expression since it equals to the ratio between distance and the light speed, c.

$$Delay_{\text{prop}} = \frac{d}{c} = \frac{h_{\text{MEO}} - h_{\text{LEO}}}{c \cdot \sin\theta}. \tag{11}$$

Since the value of θ is constant, the propagation delay is proportional to the distance between two layers. Therefore, the longer the distance between two layers, the bigger the average propagation delay between LEO and MEO satellites.

E. Effect of satellite altitude on the transfer delay in MLSNs

From above analyses about the change of queuing delay and propagation delay when satellite altitude varies, the tradeoff relationship between their delays is declared. Thus, because queuing delay decreases and propagation delay increases with the increase of distance between LEO and MEO satellites, the transfer delay which is represented as the sum of queuing delay and propagation delay is considered to be a convex function. Therefore, there is an optimal satellite altitude to minimize the transfer delay. Since queuing delay is determined by the distribution of traffic generated on the ground and the amount of the traffic, it is needed to estimate that kind of information about generated traffic to decide the optimal satellite altitude. From above analyses, we can design the optimal MLSN constellation to minimize the transfer delay in the network.

IV. Simulation

In this section, we verify the relationship between the transfer delay in MLSNs and the satellites altitude. Network Simulator Version 2 (NS-2) is used to evaluate the above relationship.

A. Simulation setup

We assume that the network consists of an MLSN and ground terminals. The MLSN constructs two-layered satellite network with LEO satellites and MEO satellites. The satellites in each layer are connected to others via Inter Satellite Links (ISL), and make mesh type topology. Each layer is also connected via Inter Layer Links (ILL). The bandwidth of these links is set to 5.0Mbps. Additionally, 100 ground terminals are distributed uniformly as source nodes as well as destination nodes. These ground terminals generate traffic flows and send packets to LEO satellites. In order to create a nonuniform distribution traffic, the traffic rate of a ground terminal is set to 8.0Mbps and the remaining ground terminals are set to 0.4Mbps. The traffic flow is modeled as a non-persistent On/Off flow. The On/Off periods of the connections are following the 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 3KB. The traffic generation lasts for 30s. Moreover, we use the Dijkstra Shortest Path algorithm [9] as a routing method in our simulation. In above mentioned network environment, we verify the transfer delay in the network with changing satellites' altitude. In order to vary the distance between two layers, we change MEO satellites altitude between 9000km and 16000km while LEO satellites altitude is set to 780km which is similar to Iridium's altitude.

B. Simulation results

We verify the change of the transfer delay and the existence of the optimal satellite altitude in some constellations. Fig. 3 shows the change of the transfer delay while the number of LEO satellites is set to 66 and the number of MEO satellites varies. In this simulation, we set the number of MEO satellites

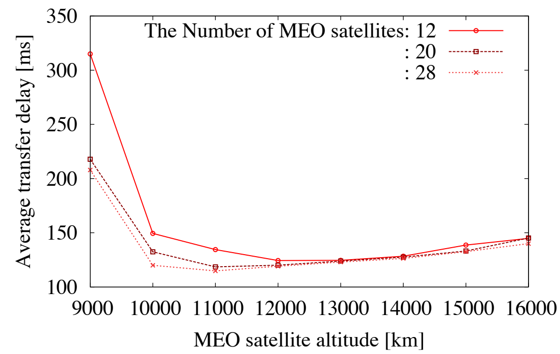


Fig. 3. Transfer delay in different constellation.

to 12, 20, and 28 respectively. From Fig. 3, we can make sure of the existence of an optimal satellite altitude in each constellation. Moreover, it can be seen that large number of MEO satellites permits low altitude of MEO satellites. This is because large number of MEO satellites makes the packets on MEO satellites distribute uniformly and decrease queuing delay at MEO satellites with a shorter distance between two layers.

V. Conclusion

We focused on the effect of the satellite altitude on the delay in MLSNs in this paper. From the analyses of the trade-off relationship between altitude and delay, the existence of an optimal altitude for minimizing the delay in MLSNs is indicated. Additionally, the simulation results verified that the optimal altitude exists and changes when the number of satellites changes.

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