An Efficient Utilization of Intermittent Surface-Satellite Optical Links by Using Mass Storage Device Embedded in Satellites

Citation:

Kazuma Kaneko, Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, and Morio Toyoshima, "An Efficient Utilization of Intermittent Surface-Satellite Optical Links by Using Mass Storage Device Embedded in Satellites," Performance Evaluation, vol. 87, pp. 37-46, May 2015.

URL:

http://www.sciencedirect.com/science/article/pii/S016653161500005X

An Efficient Utilization of Intermittent Surface-Satellite Optical Links by Using Mass Storage Device Embedded in Satellites

Kazuma Kaneko[a], Yuichi Kawamoto[a], Hiroki Nishiyama[a], Nei Kato[a], Morio Toyoshima[b]

[a] *Graduate School of Information Sciences, Tohoku University, Sendai, Japan*
[b] *Wireless Network Research Institute, National Institute of Information and Communications Technology (NICT), Tokyo, Japan*

Abstract

Recently, earth observation system by using satellite network have attracted much attention due to their wide coverage and disaster resistance. Although the system is useful for collecting various data, which have an affect on a natural disaster, ecology and so forth, earth observation satellite hardly send the collected observation data to the ground station. This is because that the earth observation satellite need to orbit near surface of the earth to get high-precision data, and it limited the time to that can be used to send the observed data traffic to the ground station. Additionally, the amount of the observed data drastically increase in these days. Thus, we focus on the data relay satellite using optical communication in this network. By relaying observed data to traffic to the relay satellite, which has geostationary orbit, it is possible to increase the chance of sending data for the observation satellite due to the wide coverage of the relay satellite. In addition, laser light that is used in optical communication in satellite network has high frequency and it can deliver large data compared with radio wave. However, laser light is greatly influenced by atmosphere, and optical link capacity between satellite and ground station drastically changes according to weather condition. Therefore, we propose a new data traffic control method to use the network constructed by satellites which has mass storage device effectively according to the condition of optical downlink between satellite and optical ground station. The effectiveness of the proposed method is evaluated with numerical result.

Keywords: Satellite Networks, Optical communication, Mass Storage device, Traffic control

---

Email addresses: `kaneko@it.ecei.tohoku.ac.jp` (Kazuma Kaneko), `youpsan@it.ecei.tohoku.ac.jp` (Yuichi Kawamoto), `bigtree@it.ecei.tohoku.ac.jp` (Hiroki Nishiyama), `kato@it.ecei.tohoku.ac.jp` (Nei Kato), `morio@nict.go.jp` (Morio Toyoshima)

1. Introduction

Recently, it is mentioned that damage caused by extreme weather such as heavy rain and extreme heat pose a serious problem to human societies. Additionally, threat of natural disasters such as earthquake and tsunami is known to greatly affect the life of disaster victims. In order to correctly and promptly predict and deal with these drastic problems, the causes of these problems need to be understood. With the development of satellite networks, it is possible for researchers and others to gain access to the information, such cloud formations that can lead to heavy storm or check the damages caused by natural disaster in order to provide better disaster relief services. Additionally, satellites which are orbiting near surface of the earth are able to observe global environment in detail. One of the earth observation satellites named Advanced Land Observing Satellite (ALOS) is launched in 2006 by Japan Aerospace eXploration Agency (JAXA) and ALOS made a great contribution by checking the damage of the tsunami at East Japan Catastrophic Disaster in March 2011 [1]. While satellites are used for earth observation all over the world, satellites have serious problem in that the amount of time that it can communicate with the ground base station is limited due to the fast orbital speed of the satellites. Although the satellites are able to buffered the data that cannot be sent to the ground base station immediately, it is important to be able to quickly send the data to the ground base station because those data are not useful until they actually reach the ground base station. Due to this reason satellite communication that uses laser light instead of radio wave has attracted much attention because of their feature that is the ability to deliver a large amount of data. Furthermore, it is possible to improve the performance of earth observation satellites downlink by using the concept of data relay satellite. The data relay satellite, which has high altitude and large coverage area makes it possible to extend the time that earth observation satellite can send the observed data traffic to the ground station by relaying the data. In recent years, to realize a more efficient earth observation satellite system, the data relay satellite that use laser light to communicate with other satellites and ground stations is becoming mature enough for practical use. In fact, European Space Agency (ESA) developed Advanced Relay and Technology Mission (ARTEMIS), which is a data relay satellite for optical satellite experiment. However, optical communication has an important problem in that they are easily affected by weather condition. This is because light refract from the edge of different refractive index profile in atmosphere. Therefore, the link condition of the link between satellite and ground station is affected by the weather and unstable due to the laser having to travel through atmosphere. In the case of the earth observation satellite system using the data relay satellite, it is not only optical link between earth observation satellite and ground station but also optical link between the data relay satellite and ground station that is affected by weather condition. Therefore, in this research, we propose the new traffic control method for earth observation satellite system to effectively send the observed data traffic to ground station.

The assumed satellite constellation is presented in Section 2. In addition, the existing research for optical communication are introduced in this section. Section 3 describes our proposed method to effectively send the observed data traffic to the ground station. Section 4 contains an evaluation of the required time which earth observation satellite needs to send all observed data to the ground station in our proposed method. Finally, concluding remarks are provided in Section 5.

2. Earth observation using satellite networks and optical communication technologies

In this section, firstly, we introduce a satellite network consisting of satellites constellation. Secondly, we describe optical communication technologies for satellite communications. Finally, we summarize the assumed network which is used in this article.

2.1. Classification of satellites and its feature

Satellites are generally divided into three types, which are Low Earth Orbit satellite (LEO), Medium Earth Orbit satellite (MEO), and Geostationary Earth Orbit satellite (GEO) according to their altitude. LEO satellites have the lowest orbit and MEO satellites are the second lowest one while GEO satellites have the highest orbit. GEO satellites are separated from the Earth's surface by 36,000km, and have tremendously large coverage area [2]. What is special about GEO satellites is that they always cover the same region of the earth, because they orbit at the same speed but against the rotation of Earth. On the other hand, LEO satellite can extend their coverage area to cover a large region of the earth by constructing constellation with a number of LEO satellites. In one example of LEO satellite constellation, Global Precipitation Measurement (GPM), which is intended to collect the data on the distribution of rain on the globe. GPM is organized by various institutes from several countries, and its main satellite was launched on February 2014 [3, 4]. LEO satellites orbit near the Earth's surface with low altitude of around 350km to 1,400km. hence it has to orbit round the earth at high velocity. While the time that LEO satellite can communicate with ground station is strictly limited due to their velocity, LEO satellites can observe the earth in a higher detail when compared with GEO satellites, and this type of satellites are widely used for the earth observation. The data traffic that is not able to be sent to the ground station, is temporally stored in mass storage device embedded on LEO satellite and the satellite wait until when LEO satellite can send that data. Meanwhile, the data relay satellite employ GEO satellite because GEO satellite can always communicate with the same ground station and they can cover a large part of the orbit of the earth observation satellite.

2.2. Optical communication in satellite networks

As previously described, optical communication technology for satellites has been researched all over the world. In Japan, National Institute of Information and Communications Technology (NICT) achieved the world's first optical communication experiment between the GEO satellite of ETS-VI and a Optical Ground Station (OGS) [10, 11, 12]. Moreover, NICT carried out various experiments in cooperation with other institutes, and successfully establish optical link fifteen times out of twenty seven times. JAXA which promotes development of space technology in Japan has performed the laser communication experiment over one hundred times among satellites at Optical Inter-orbit Communications Engineering Test satellite (OICETS) program since 2005. They have succeeded in acquisition and tracking with over 90% probability. ESA has already succeeded in many optical communication experiments [5, 6]. They created the optical experimental satellite, named ARTEMIS. ARTEMIS has already succeeded in establishing optical link between OGS, and successfully communicated with them. Additionally, they can also communicate with airplane using optical link. European Union (EU) plans Global Monitoring of Environment and Security (GMES), which is the space policy to enable to perform environment control and provide useful information about safety [7]. This project use the series of observation satellites, named Sentinel, and European Data Relay Satellite System (EDRS) [8]. When disasters such as earthquake and fire occur, traffic which need to be transmitted to the ground station is expected to be over 6 terabytes per day, thus this satellite plans to use Laser communication Terminal (LCT) developed by Germany's Tesat-Spacecom [9]. NFIRE satellite, which is developed by Aerospace Corporation in America and embedded in LCT performed laser communication experiment with TerraSAR-X satellite which is the earth observation satellite developed by Germany in 2007, and achieved 5.6Gbps data transmission speed. It is said that optical communication in satellite network with bandwidth up to several dozen Gbps can make it possible to effectively send data to ground station. Therefore, in this research, we assume optical links between satellites, and satellite to ground have high capacity (several dozen Gbps). In the next section we describe the assumed scenario for details.

2.3. Assumed scenario and the problem caused by weather condition

In this paper, we assume earth observation satellite network, which is illustrated in Fig. 1. Some earth observation satellites independently observe various location of the earth, and each satellite directly sends the observed data to the same OGS using optical link. Although the time which earth observation satellite can communicate with OGS is strictly limited, the earth observation satellites have optical link between the data relay satellite and they can communicate with the data relay satellite over a wide area. The data relay satellite also has an optical link to OGS and forwards the observed data which is received from earth observation satellite to the ground earth station. In general, the link connecting the satellite and surface has lower capacity than the link existing between satellites because atmosphere deteriorate link capacity. Thus, the link between LEO satellite and the data relay satellite has higher capacity than the link between the data relay satellite and OGS and the link between LEO satellite and OGS. The data that is sent from LEO satellite to the data relay satellite is first saved in mass storage device embedded on the data relay satellite then the

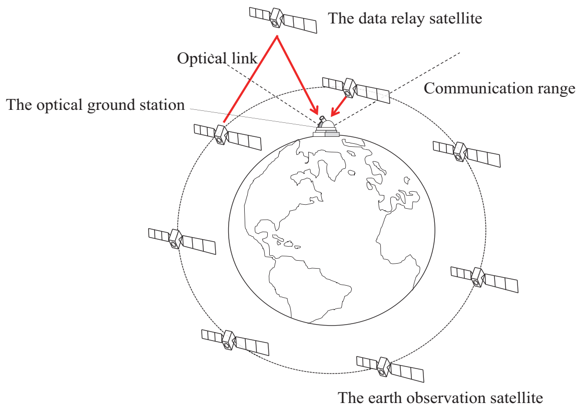


Fig. 1: Optical satellite networks for earth observation.

data is sent from the data relay satellite to OGS. In this network, the data relay satellite can communicate with only one earth observation satellite at any given time. This is because that optical link is very limited compared with radio wave link due to directional characteristic of laser light, satellites have to acquire and track other satellite. There are no communication link among earth observation satellites, because it is difficult to establish optical link between one satellite to another satellite and OGS at one time because sensitive acquisition and tracking functionalities are required. Link capacity between earth observation satellite and OGS and link capacity between the data relay satellite and OGS change respectively according to the weather between each satellite and OGS. In such case, the required time, which earth observation satellite needs to send all data to OGS changes depending on the traffic control of earth observation satellite. In the rest of this section, we call LEO satellite as a earth observation satellite and discuss about relationship between the required time which LEO satellite needs to send all data to OGS and traffic control of LEO satellite.

Firstly, we consider the case that LEO satellite is in the communication range of the data relay satellite and out of the communication range of OGS. In the case that the link condition between the data relay satellite and OGS is unfavorable and the predicted link condition between LEO satellite and OGS is favorable, the total time for the LEO satellite to send all observed data to OGS will increase because the LEO satellite has to forward the data to the relay satellite instead of sending those data directly to the OGS. Although LEO satellite can rapidly send observed data to the data relay satellite using optical link among satellites which is not affected by weather condition, the data relay satellite cannot send the observed data to OGS due to unfavorable condition of optical link between the data relay satellite and OGS. Therefore, when the weather among the data relay satellite and OGS is unfavorable, the data, which is sent from LEO satellite to the data relay satellite will stay in mass storage device for a long time due to the unfavorable link condition between the data relay satellite and OGS. As a result, the time it takes for LEO satellite to send all observed data to OGS increases when the observed data is sent to the data relay satellite. In such case, to reduce the required time that LEO satellite needs to send all data to OGS, LEO satellite should keep the data and wait until it can directly send the data to OGS after coming into communication range of OGS. Secondly, we consider the case that LEO satellite is in the communication range of OGS. In this case, LEO satellite can directly send the data to OGS, and LEO satellite does not need to wait for getting into the communication range of OGS. However, when the link between the data relay satellite and OGS is more favorable than the link between LEO satellite and OGS, LEO satellite should send the data to the data relay satellite. In short, LEO satellite has to decide whether or not to send the data to the data relay satellite to decrease the required time which LEO satellite needs to send all data to the OGS in both cases. Therefore traffic control method, which considers the weather condition is needed to decrease the required time which LEO satellite needs to send all data to the OGS. In the next section, we propose such traffic control method, which LEO satellite decide traffic control from the weather condition of each link. The data relay satellite and earth observation satellite also communicate with radio wave in order to get the information about weather.

3. Proposed traffic control method to shorten the required time that LEO satellite needs to send all data to the OGS

In this section, we propose a new traffic control method to effectively send the observed data using the relay satellite in order to decrease the required time, which LEO satellite needs to send all data to the OGS.

3.1. Factors that affect the required time, which LEO satellite needs to send all data to the OGS

In order to shorten the required time it takes for LEO satellite to send all data to the OGS our proposed method decides whether a LEO satellite send to the data relay satellite or keeps the data in its mass storage device according to weather condition. However, LEO satellite should not decide whether or not to send observed data to the data relay satellite only by weather information, because the required time which LEO satellite needs to send all data to OGS is also affected by other factors. Obviously, the remaining time until LEO satellite come into the communication range of OGS makes profound difference. When there is a long period of time until LEO satellite come into the communication range of OGS, LEO satellite should send the data to the data relay satellite because LEO satellite has to wait a long time to send the data directly to OGS. The amount of the data, which the data relay satellite has also affects the time which LEO satellite needs to send all data to OGS. Thus, in our proposal, the LEO satellite calculate the required time to send all data to OGS taking account to these following factors. One is the case that LEO satellite sends the observed data to the data relay satellite, and another is that LEO satellite keep the observed data in storage device. After calculating the required time for both cases, LEO satellite compares these two required time, and decides traffic control such that the required time becomes shorter. To calculate the required time which LEO satellite needs to send all data to OGS, LEO satellite has to estimate the optical link capacity between the data relay satellite and OGS and LEO satellite and OGS from weather information. In the next part, we describe how to estimate optical link capacity from weather information.

3.2. Transition of the weather and link capacity

In this section, we introduce how to estimate the optical link capacity in order to decide traffic control. We consider from the time when the former LEO satellite leaves the communication range of OGS, and we set that time as $t = 0$. In our proposed method, LEO satellite decide every $\mathrm{t_{slot}}$ to whether or not to send the data to the data relay satellite. We define the slot for every $\mathrm{t_{slot}}$ and call first slot from $t = 0$ to $\mathrm{t_{slot}}$. Since LEO satellite has to predict the link capacity in order to calculate the required time that it needs to send all data to OGS, it gets the information on the link conditions for both the link of itself and data relay satellite and the link between the data relay satellite and OGS. Link capacity is defined for every $\mathrm{t_{slot}}$, link capacity between the data relay satellite and OGS at j th slot is BW_j^{GEO}, and link capacity between LEO satellite and OGS at k th slot is bw_k^{LEO}. j represents the number of the slot for the link between the data relay satellite and OGS, hence it begins from first slot. k represents the number of slot for the link between LEO satellite and OGS, it begins from the $(n_{\mathrm{out}} + 1)$ th slot. n_{out} represents the number of slots from the time when the former satellite is out of the communication range of OGS to the time when the LEO satellite get into the communication range of OGS. It is because LEO satellite enable the link between LEO satellite and OGS after the n_{out} th slot. The weather condition of j th slot is $\pi(j)$, BW_j^{GEO} is expressed as follows,

$$BW_j^{\mathrm{GEO}} = \pi(j) \cdot \begin{bmatrix} BW_{\mathrm{sun}} \\ BW_{\mathrm{cloud}} \\ BW_{\mathrm{rain}} \end{bmatrix}, \tag{1}$$

where BW_{sun} is the link capacity when the condition is clear or sunny, BW_{cloud} is link capacity when the condition is cloudy, and BW_{rain} is link capacity of when it is raining. When it is sunny, $\pi(j)$ is $(1, 0, 0)$ and $BW_j^{\mathrm{GEO}} = BW_{\mathrm{sun}}$. $\pi(j) = (0, 1, 0)$ represents cloudy, and $BW_j^{\mathrm{GEO}} = BW_{\mathrm{cloud}}$. $\pi(j) = (0, 0, 1)$ represents rainy, and $BW_j^{\mathrm{GEO}} = BW_{\mathrm{rain}}$. Thus, BW_{j+n}^{GEO} which is the expected link capacity between the data relay satellite and OGS after n th slots from j

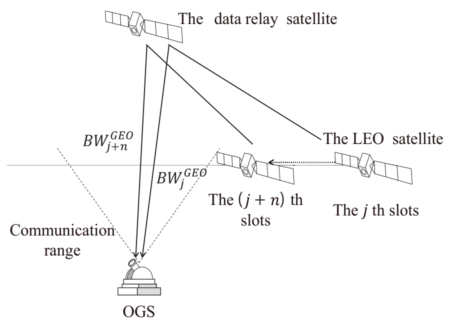


Fig. 2: The relationship between the number of slot and BW_j^{GEO}.

th slot is calculated as follows,

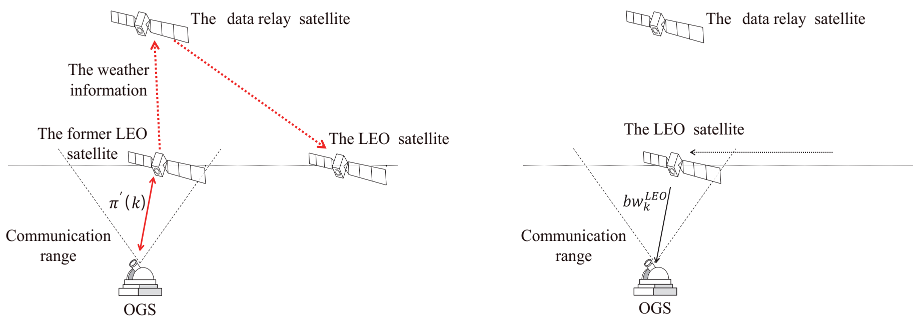
$$BW_{j+n}^{\mathrm{GEO}} = \pi(j+n) \cdot \begin{bmatrix} BW_{\mathrm{sun}} \\ BW_{\mathrm{cloud}} \\ BW_{\mathrm{rain}} \end{bmatrix}. \tag{2}$$

The relationship between the number of slot and BW_j^{GEO} is illustrated in Fig 2. In our proposed method, LEO satellite estimates optical link capacity assuming that the same weather condition will continue for the rest of the slots. When weather condition changes from the previous slot, LEO satellite changes optical link capacity that is used to calculate the required time that all slots follow.

Since positional relationship between the data relay satellite and OGS does not change, slots represent time and the change of weather at the same region for the data relay satellite. By contrast, for LEO satellite slots represents geographical shift of weather because positional relationship between LEO satellite and OGS changes at every moment. LEO satellite gets the information about the link condition between LEO satellite and OGS from former LEO satellite relaying by the data relay satellite at each slots, named $\pi'(k)$ like Fig 3(a). LEO satellite assume that weather will not change from the time the former LEO satellite reach k th slot to the time LEO satellite reach same point and LEO satellite calculate the expected link capacity as follows,

$$bw_k^{\mathrm{LEO}} = \pi'(k) \cdot \begin{bmatrix} BW_{\mathrm{sun}} \\ BW_{\mathrm{cloud}} \\ BW_{\mathrm{rain}} \end{bmatrix}. \tag{3}$$

Fig 3(b) represents the LEO satellite reaches the k th slot. Although $\pi(j)$ update every slots because the data relay satellite can check the weather between the data relay satellite and OGS in every slots, $\pi'(k)$ does not change until LEO satellite reach the same slot where former LEO satellite goes out of communication range. Therefore, LEO satellite has to update BW_j^{GEO} in every



(a) The LEO satellite gets the weather information. (b) The LEO satellite estimates link capacity.

Fig. 3: The LEO satellite estimates link capacity from weather information.

slots from weather information, but LEO satellite can use same value as bw_k^{LEO} by the time when LEO satellite get out of communication range of OGS. The parameter definition is summarized in Table.1.

3.3. Performance comparison between the case of forwarding data to the relay satellite and the case of retaining the data in mass storage device

In this part, we introduce the traffic control procedure of LEO satellite. At first, we consider from the time when former LEO satellite get out of the communication range of OGS to the time when LEO satellite get out the communication range of OGS. We call the amount of the data which LEO satellite has at t is $D(t)$, and the amount of the data which the data relay satellite has at t is $D_{\mathrm{GEO}}(t)$. $D(t)$ is the earth observation data, which LEO satellite collects while orbiting around earth. In this research, we do not consider the increase of the data which LEO satellite collect after the former LEO satellite get out of the range of the OGS and we only focus on the amount of the data which LEO satellite collect by $t = 0$. If $D(t)$ fulfill the following conditional equation,

$$D(t) < \{(\mathrm{n_{out}} - \lfloor t/t_{\mathrm{slot}} \rfloor) \cdot BW_j^{\mathrm{GEO}} \cdot \mathrm{t_{slot}} - \mathrm{D_{GEO}(t)}\}, \tag{4}$$

where $\lfloor t/t_{\mathrm{slot}} \rfloor$ represents the number of the slot at t, LEO satellite sends the data to the data relay satellite. The right side of above conditional equation represents the amount of the data which LEO satellite can send to OGS through the data relay satellite by the time when LEO satellite come into communication range of OGS. Therefore, above conditional equation means that LEO satellite is able to send all data to OGS before LEO satellite come into the communication range of OGS without using the link between LEO satellite and OGS.

The required time to send all data from LEO satellite to OGS by relaying the data to the relay satellite, t_{GEO}, is calculated as belows

Table 1: Parameter definition

$D(t)$	The amount of the data which LEO satellite has at t.
$D_{\text{GEO}}(t)$	The amount of the data which GEO satellite has at t.
t_{slot}	Time interval of one slot.
n_{out}	The number of slots from $t = 0$ to the time when LEO satellite get into communication range of OGS.
n_{in}	The number of slots from the time when LEO satellite get into communication range of OGS to the time when LEO satellite get out communication range of OGS.
BW_j^{GEO}	Expected link capacity between the data relay satellite and OGS at the j th slot.
bw_k^{LEO}	Expected link capacity between LEO satellite and OGS at the k th slot.
$\pi(j)$	The information about the whether between the data relay satellite and OGS at the j th slot.
$\pi'(k)$	The information about the whether between LEO satellite and OGS at the k th slot.
BW_{sun}	Link capacity at clear.
BW_{cloud}	Link capacity at cloudy.
BW_{rain}	Link capacity at rainy.

$$t_{\text{GEO}} = \frac{D(t) + D_{\text{GEO}}(t) - (m - \lfloor t/t_{\text{slot}} \rfloor) \cdot BW_j^{\text{GEO}} \cdot t_{\text{slot}}}{BW_m^{\text{GEO}}} + (m - \lfloor t/t_{\text{slot}} \rfloor) \cdot t_{\text{slot}}, \tag{5}$$

where m represents the number of the slot which LEO satellite can send all data to OGS relaying the data relay satellite, and fulfill under the conditional equation,

$$\{(m - \lfloor t/t_{\text{slot}} \rfloor) \cdot BW_j^{\text{GEO}} \cdot t_{\text{slot}} - D_{\text{GEO}}(t)\} < D(t) < \{(m + 1 - \lfloor t/t_{\text{slot}} \rfloor) \cdot BW_j^{\text{GEO}} \cdot t_{\text{slot}} - D_{\text{GEO}}(t)\}, \tag{6}$$

In the Eq 5, first member of the right side is the required time to send all data, which LEO satellite has from m slot. Second member of the right side represents the time from the slot at t to m th slot.

On the other hand, the required time to send all data that LEO satellite has using only the link between LEO satellite and OGS, t_{LEO}, is calculated as belows,

$$t_{\text{LEO}} = \frac{D(t) - l \cdot bw_k^{\text{LEO}} \cdot \text{t}_{\text{slot}}}{bw_l^{\text{LEO}}} + (l + \text{n}_{\text{out}} - \lfloor \text{t}/\text{t}_{\text{slot}} \rfloor) \cdot \text{t}_{\text{slot}}, \tag{7}$$

where l represents the number of the slot which LEO satellite can send all data to OGS, and fulfill under conditional equation,

$$l \cdot bw_k^{\mathrm{LEO}} \cdot \mathrm{t_{slot}} < D(t) < (l+1) \cdot bw_k^{\mathrm{LEO}} \cdot \mathrm{t_{slot}}. \tag{8}$$

This equation only apply during the time when LEO satellite is out of the communication range of OGS. In the case that LEO satellite get into the communication range of OGS, these equation change to belows,

$$t_{\mathrm{LEO}} = \frac{D(t) - (l + \mathrm{n_{out}} - \lfloor t/t_{\mathrm{slot}} \rfloor) \cdot bw_k^{\mathrm{LEO}} \cdot \mathrm{t_{slot}}}{bw_l^{\mathrm{LEO}}} + (l + \mathrm{n_{out}} - \lfloor \mathrm{t}/\mathrm{t_{slot}} \rfloor) \cdot \mathrm{t_{slot}}, \tag{9}$$

$$(l - \lfloor t/t_{\mathrm{slot}} \rfloor + \mathrm{n_{out}}) \cdot bw_k^{\mathrm{LEO}} \cdot \mathrm{t_{slot}} < D(t) < (l + 1 - \lfloor t/t_{\mathrm{slot}} \rfloor + \mathrm{n_{out}}) \cdot bw_k^{\mathrm{LEO}} \cdot \mathrm{t_{slot}}. \tag{10}$$

In the Eq 7, and Eq 9 first member of the right side is the required time to send all data which LEO satellite has from l slot. Second member of the right side represents the time from the slot at t to l th slot. When t_{LEO} is smaller than t_{GEO}, LEO satellite should keep the data in its mass storage device and wait to the time when LEO satellite come into the communication range of OGS. Conversely, when t_{LEO} is larger than t_{GEO}, LEO satellite should send the data to the data relay satellite. In our proposed method, LEO satellite compare these two values every slots, and decide whether or not to send the data to the data relay satellite. Once LEO satellite sends the data to the data relay satellite, that data is sent by the data relay satellite to the OGS and is saved in the mass storage device of the satellite. Therefore, if LEO satellite send the data to the data relay satellite, we have to check the time when the data relay satellite needs to send all data to the OGS. Even when the mass storage device embedded on LEO satellite becomes empty, that data may remain in the mass storage device embedded on the data relay satellite.

When $D(t)$ fulfill two conditional equation as follows at same time,

$$\{(\mathrm{n_{in}} + \mathrm{n_{out}} - \lfloor t/t_{\mathrm{slot}} \rfloor) \cdot BW_j^{\mathrm{GEO}} \cdot \mathrm{t_{slot}}\} < D(t), (\mathrm{n_{in}} \cdot bw_k^{\mathrm{LEO}} \cdot \mathrm{t_{slot}}) < D(t), \tag{11}$$

where n_{in} represents the number of slots from the time when LEO satellite get into communication range of OGS to the time when LEO satellite get out communication range of OGS. LEO satellite cannot send all data to OGS using the link between LEO satellite and OGS either using the link between the data relay satellite and OGS , so we do not consider this case.

4. Performance evaluation

In this section, we analyze the performance of the proposed method.

4.1. Parameter settings

The parameter settings are summarized in Table. 2. In this analysis, $D(0)$ varies from 0Gbit to 5000Gbit with a step of 100Gbit, the changes of the time,

Table 2: Parameter settings

$D_{\mathrm{GEO}}(0)$	4.5Tbit
$\mathrm{t}_{\mathrm{slot}}$	120s
$\mathrm{n}_{\mathrm{out}}$	5
n_{in}	5
$\mathrm{BW}_{\mathrm{sun}}$	18Gbps
$\mathrm{BW}_{\mathrm{cloud}}$	10Gbps
$\mathrm{BW}_{\mathrm{rain}}$	0

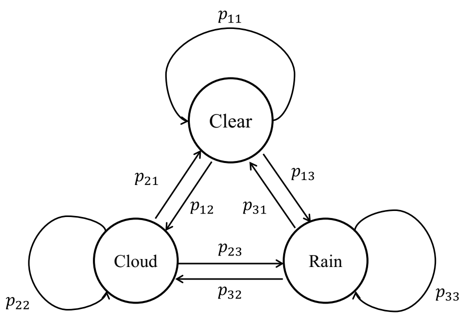


Fig. 4: Weather transition model.

which is required to send all data from LEO satellite to OGS are analyzed. To evaluate this relationship, it reveals the influence of the amount of the observed data that earth observation satellite has to effectiveness of the proposed method. We use a simple method, which LEO satellite sends data to the data relay satellite until getting into communication range of OGS and sends data to the OGS directly in communication range of the OGS as benchmark. We define the time, which required to send all data from LEO satellite to the OGS when applying proposed method as t_{proposed}, and when applying the simple method as t_{simple}. In this analysis, we set $D_{\mathrm{GEO}}(0)$, which is the amount of data which the data relay satellite has at $t = 0$ to 4500Gbit. The time interval of one slot is set to 120 seconds. The number of slots that is outside of the communication range of OGS is set to 5, and inside of communication range of OGS is also set to 5. We suppose that link capacity between satellites and OGS at clear weather is 18Gbps, at cloudy is 10Gbps. In the case of rain, since acquisition and tracking becomes difficult with lower intensity laser, satellite cannot communicate with OGS at all. In this analysis, we suppose the whether changes every $\mathrm{t}_{\mathrm{slot}}$, and following Markov model like Fig 4, which has transition provability matrix expressed as eq 12.

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} \\ p_{2,1} & p_{2,2} & p_{2,3} \\ p_{3,1} & p_{3,2} & p_{3,3} \end{bmatrix}. \tag{12}$$

Table 3: Probability of first slot.

	Case1	Case2	Case3
Probability of clear at first slot	0.7	0.1	0.2
Probability of cloud at first slot	0.2	0.7	0.1
Probability of rain at first slot	0.1	0.2	0.7

We set transition probability of weather between the data relay satellite and OGS, named P_1, as following matrix,

$$\mathrm{P}_1 = \begin{bmatrix} 0.9 & 0.05 & 0.05 \\ 0.05 & 0.9 & 0.05 \\ 0.05 & 0.05 & 0.9 \end{bmatrix}. \tag{13}$$

P_1 represents the time change of weather between the data relay satellite and OGS. In this analysis since time interval, which weather change is very short, the case which weather does not change is the most likely to occur. In such case, the weather at first slot has a crucial impact to the result. Therefore, in this analysis we analyze three different cases which has another probability of occurrence of weather at first slot summarized in Table. 3. Case1 is the case which clear condition is most likely to occur, Case2 is the probability of cloudy condition is the highest, and Case3 is the case which rainy condition is most likely to occur.

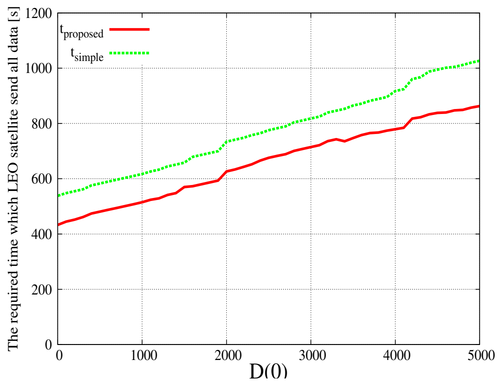
On the other hand, we set transition probability of weather between the earth observation satellite and OGS, named P_2, as following matrix,

$$\mathrm{P}_2 = \begin{bmatrix} 0.6 & 0.3 & 0.1 \\ 0.3 & 0.6 & 0.1 \\ 0.3 & 0.4 & 0.3 \end{bmatrix}. \tag{14}$$

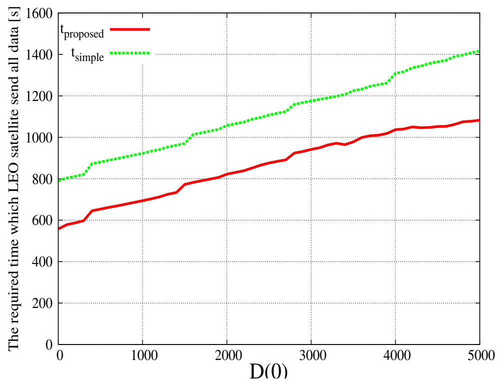
P_2 represents the geographical change of weather between earth observation satellite and OGS. Although time interval is very short, earth observation satellite moves far distance during the time interval. Thus the case which weather does not change is low probability, and the case which weather changes will likely to occur compared with P_1.

4.2. Numerical results

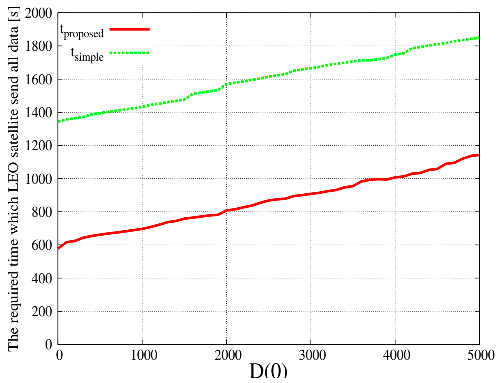
Fig. 5(a) shows the required time to send all the data from earth observation satellite to OGS in the case1. In Fig. 5(a), t_{proposed} is approximately 2 minutes smaller than t_{simple} at any $D(0)$. This result indicates that the proposed method can shorten the required time which earth observation satellite needs to send all data to the OGS. It is because the proposed method select favorable link to send data to the OGS comparing with the simple method. In the simple method, since LEO satellite selects the static link in any case, LEO satellite uses unfavorable link. In addition, it can be said that the amount of the data, which earth



(a) Case1.



(b) Case2.



(c) Case3.

Fig. 5: The required time which LEO satellite send all data to OGS.

observation satellite has do not affect to effectiveness of the proposed method. Fig. 5(b) shows the required time to send all the data from LEO satellite to OGS in the case2. In Fig. 5(b), t_{proposed} is approximately 3 minutes smaller than t_{simple} at any $D(0)$. In case2, the proposed method shows slightly better performance compared with case1. In the case that favorable link is unlikely to appear, it increases that the link between LEO satellite and OGS is unfavorable and the link between the data relay satellite and OGS is favorable. In the simple method, LEO satellite uses unfavorable link between LEO satellite and OGS many times, while the proposed method chooses favorable link between the data relay satellite and OGS. That is why difference in performance between these two method increases. In Fig. 5(c), t_{proposed} is approximately 10 minutes smaller than t_{simple} at any $D(0)$. In case3, difference in performance between these two method becomes larger. This result caused by the increase of the emergence probability of unfavorable link. These three cases indicates that the amount of the data, which earth observation satellite has do not affect to effectiveness of the proposed method. In each cases, we can show effectiveness of the proposed method, and our proposed method can correspond the change of link capacity.

5. Conclusion

In this paper, we focused on earth observation satellite network where each satellite has an optical ground-satellite downlink and mass storage device. With the increasing of demand to utilize the satellite networks for many situations such as disasters, earth observations, the ability to rapidly send data to the ground station is required. Thus, the optical satellite networks having mass storage device are expected as next generation earth observation system due to their many advantages such as large capacity and high speed communication. Furthermore, the data relay satellite is developed in order to cover lack of the communication time between earth observation satellite and optical ground station. However, since the downlink condition of the optical link is dramatically affected by weather condition, it is difficult to utilize optical downlink appropriately. Therefore, we proposed a new traffic control method to effectively send the observed data traffic according to the condition of the optical downlink. The numerical analysis demonstrated that the proposed scheme achieves better performance in transmitting traffic in the network.

[1] M. Shimada, T. Tadono, A. Rosenqvist, Advanced land observing satellite (alos) and monitoring global environmental change, Proceedings of the IEEE 98 (5) (2010) 780–799. doi:10.1109/JPROC.2009.2033724.

[2] J. Evans, Satellite systems for personal communications, IEEE Antennas and Propagation Magazine 39 (3) (1997) 7–20. doi:10.1109/74.598556.

[3] K. Furukawa, M. Kojima, T. Miura, Y. Hyakusoku, H. Kai, T. Ishikiri, T. Iguchi, H. Hanado, K. Nakagawa, M. Okumura, Satellite system test status of the dual-frequency precipitation radar on the global precipitation measurement core spacecraft, in: 2013 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) (2013) 1143–1146. doi:10.1109/IGARSS.2013.6721367.

[4] P. Chambon, R. Roca, I. Jobard, M. Capderou, The sensitivity of tropical rainfall estimation from satellite to the configuration of the microwave imager constellation, IEEE Geoscience and Remote Sensing Letters 10 (5) (2013) 996–1000. doi:10.1109/LGRS.2012.2227668.

[5] E. Leitgeb, P. Brandl, T. Plank, M. Loschnigg, F. Ozek, M. Awan, M. Wittig, Reliable optical wireless links used as feeder links between earth and satellite, in: 2009. ICTON '09. 11th International Conference on Transparent Optical Networks (2009) 1–7. doi:10.1109/ICTON.2009.5184993.

[6] A. W. Jongejans, P. Rinous, A. Roederer, Review of esa mobile antenna developments for satellite communications, in: 1993. AP-S. Digest Antennas and Propagation Society International Symposium 3 (1993) 1838–1841. doi:10.1109/APS.1993.385561.

[7] G. Taini, A. Panetti, F. Spataro, C. Bruno, M. L'Abbate, A. Notarantonio, S. Barrasso, R. Torres, S. Lokas, Sentinel-1 satellite system architecture: Design, performances and operations, in: 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) (2012) 1722–1725. doi:10.1109/IGARSS.2012.6351190.

[8] B. Friedrichs, P. Wertz, Error-control coding and packet processing for broadband relay satellite networks with optical and microwave links, in: 2012 6th Advanced Satellite Multimedia Systems Conference (ASMS) and 12th Signal Processing for Space Communications Workshop (SPSC)(2012) 101–110. doi:10.1109/ASMS-SPSC.2012.6333060.

[9] F. Heine, H. Kampfner, R. Czichy, R. Meyer, M. Lutzer, Optical inter-satellite communication operational, in: 2010 - MILCOM 2010 MILITARY COMMUNICATIONS CONFERENCE (2010) 1583–1587. doi:10.1109/MILCOM.2010.5680175.

[10] M. Toyoshima, K. Takizawa, T. Kuri, W. Klaus, M. Toyoda, H. Kunimori, T. Jono, Y. Takayama, M. Mokuno, K. Arai, Results of ground-to-space optical communications experiments using a low earth orbit satellite, in: Lasers and Electro-Optics Society, 2006. LEOS 2006. 19th Annual Meeting of the IEEE (2006) 80–81. doi:10.1109/LEOS.2006.278846.

[11] S. Yamamoto, E. Okamoto, T. Ikegami, Land mobile satellite propagation measurements in the s-band with non-geostationary ets-vi satellite, in: 1997, IEEE 47th Vehicular Technology Conference 1 (1997) 31–35. doi:10.1109/VETEC.1997.596313.

[12] Y. Yamashita, E. Okamoto, Y. Iwanami, Y. Shoji, M. Toyoshima, Y. Takayama, An efficient ldgm coding scheme for optical satellite-to-ground link based on a new channel model, in: 2010 IEEE Global Telecommunications Conference (GLOBECOM 2010) (2010) 1–6. doi:10.1109/GLOCOM.2010.5683891.