Throughput Maximization for Long-Distance Real-Time Data Transmission over Multiple UAVs

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Masanori Horiuchi[1†], Hiroki Nishiyama[2†], Nei Kato[3†],
Fumie Ono[4‡], and Ryu Miura[5‡]
[†]Graduate School of Information Sciences, Tohoku University, Sendai, Japan
[‡]National Institute of Information and Communications Technology (NICT), Tokyo, JAPAN
E-mails:[†] {masanori.horiuchi[1], kato[3]}@it.is.tohoku.ac.jp, hiroki.nishiyama.1983@ieee.org[2],
[‡] {fumie[4], ryu[5]}@nict.go.jp

***Abstract*—Recently, unmanned aerial vehicles (UAVs) have attracted attention as a means to observe a terrain due to their ability to fly above the place to be observed and collect information (e.g., picture, video and sensor data) easily. Moreover, UAVs can transmit data through equipped wireless transceivers. However, because the payload of UAVs is limited, the performance of the transceiver is limited as well. Therefore, UAVs need to cooperate with other UAVs for high speed and long distance data transmission. In this article, we suppose a network model for transmitting in real time observed data in a multihop relay communication; then we take into account parameters related to the observation area (e.g., area size, distance between a base station and observation area) and signal attenuation by obstacles (e.g., buildings, trees). Finally, we propose a way to maximize the network performances affected by those parameters in the network.**

***Index Terms*—Unmanned aerial vehicle (UAV), UAV Networks, Real-time data transmission, Multi-hop communication.**

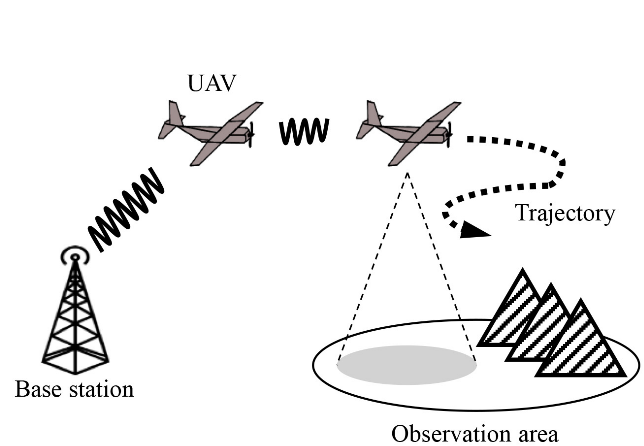

Fig. 1. Overview of observation by UAVs

I. INTRODUCTION

Recently, unmanned aerial vehicles (UAVs) have attracted attention as a means to observe a terrain. Then there are two reasons for this. The first reason is connected to the capabilities of UAVs. UAVs can fly in the sky freely, and carry sensing equipment such as cameras and thermographs. Therefore, by using such equipment, UAVs can effectively collect any information (e.g., picture, video and sensor data) of the ground from the sky. The second reason is the spread of UAVs. UAVs have been originally exploited for surveillance in military. However, they have recently been also used by the industry. Some UAVs in the industry even have a function for control assistance. Therefore, it is easy to control them without special training. Due to the above reasons, anyone can easily obtain and use UAVs for various purposes. This has led to a popularization of UAV-based observation.

We now present the overview of the observation by UAVs. This overview is portrayed in Fig. 1. In UAV-based observation, the observation UAV generally transmits observed data to the base station. Application examples for this are military surveillance, observation of volcanos, creating a map and so forth [1] - [3]. As an example, we consider about confirming the extent of the damage caused by a volcanic eruption or a huge earthquake. At this time, in aircrafts and helicopters on which human beings ride, they cannot approach the volcano and collect any information because it is dangerous for passengers. Also, they need spaces to take off. However, because of a flood or a crack in the ground caused by a huge earthquake, there can be no spaces to take off. Hence, it is difficult for the aircrafts and the helicopters to observe in such situations. On the other hand, UAVs can approach the volcano and collect information, heedless of danger. Moreover, UAVs hardly need spaces to take off. In other words, they can take off both at all places and all times. Hence, unlike aircrafts and helicopters, UAVs can observe in such situations. Also, observation by UAVs can assist rescue operations and prevent secondary disasters thanks to aerial images. Unlike aircrafts and helicopters, UAVs can operate at a low cost. In the observation by aircrafts or helicopters, the cost to collect the aerial images is expensive. However, in the observation by UAVs, the cost can be relatively lower. Thus, in terms of costs, UAV is more suitable for the observation than aircrafts and helicopters.

In the following, we focus on the communication performance of UAVs. UAVs can transmit any type of information when they are equipped with a wireless transceiver. Generally speaking, the performance of the wireless transceiver depends on the antenna size. By using a larger antenna, UAVs can transmit data to farther areas or at a higher speed. However, because their payload is limited, the performance of the transceiver is limited too. That is, the high-spec antennas are too large and heavy for UAVs to fly. Therefore, if a single UAV observes and transmits photography data to a base station in real time, the communication range is limited. Due to this, the real-time observation range is limited too. However, usage of multiple UAVs can solve this problem. They can communicate with each other through the equipped wireless transceivers. Such a relationship is called 'UAV network'. One UAV in this network collects observation data and transmits it to another UAV that is closer to a base station. When this UAV receives the data, it transmits it to yet another UAV that is even closer to the base station. By repeating that, it is possible to transmit the data in real time in a long distance. Therefore, the UAV network enables the observation of wide areas in real time. Moreover, using this network, it is possible to transmit the data at a high speed, since transmission speed is strongly tied to transmission distance. We are going to explain this in detail in the latter section. Our research is based on [4]. In [4], users with a smartphone can construct the network on the ground by multihop communication among them. At this time, information in the remote area can be collected by using this network. However, if the large-scale disasters occur, it is difficult to construct the network on the ground. Therefore, in this article, we consider about a UAV network that can be constructed without regard to the condition of the ground.

In this article, we consider a UAV network for observation. In this network, UAVs collect any information in an observation area and transmit it to a base station. At this time, the objective of this network is meeting the demand for a high speed and long distance real-time data transmission. Also, the observation area is designated by an operator. Due to this, the size of the area and the distance between the base station and the area are predetermined. Furthermore, we take into account the existence of obstacles in the area. Finally, in order to clarify the impact of the parameters related to the observation area and attenuation by obstacles, we formulate the network performances and evaluate it.

The remainder of the article is organized as follows. Sec. II presents a survey of the relevant research works in the area of UAVs communication and observation by UAVs. Sec. III portrays an overview of our supposed UAV network. The section also discusses the challenges associated with observation by UAVs. To address these challenges, our proposal is presented in Sec. IV. Evaluation of our proposal is provided in Sec. V. Finally, the article is concluded in Sec. VI.

II. RELATED WORKS

Firstly, we provide a survey of relevant research works in the area of observation by a single UAV. Generally speaking, in the observation by UAVs, they need to quickly transmit detailed information collected from the ground. Therefore, recently, the demand for collecting and transmitting high quality photography data and video data in real time in post-disaster areas has increased. These high quality real-time data are used for creating a 3-dimension map, controlling UAVs manually when UAVs fly out of sight, and so forth. Examples of collecting data through a single UAV is presented in [5] [6]. This collected data was used in creating the 3-dimension map and so forth. However, as it was explained above, the performance of the observation by a single UAV is limited. Therefore, it is necessary to conduct research on the observation of wide areas. In [7], the operational technology developed for the measurement and observation by a single UAV is introduced, particularly for observation activities related to erupting volcanoes. Moreover, a new UAV model was also introduced. In the work in [7], the aim was to improve the loading capacity in order to load the high-spec antennas and observe in wide areas. However, it is difficult to spread the new UAV widely because of the cost to develop and produce it. Therefore, the new UAV cannot be prepared even if the observation is needed in disaster areas as soon as possible. On the other hand, in the observation by multiple UAVs, it is possible for the observation of wide areas to be realized by conventional UAVs. Conventional UAVs can be easily prepared in many different places because their cost is relatively inexpensive. Therefore, in the case of an emergency, they can observe in disaster areas relatively soon.

Secondly, we provide a survey of relevant research work in the area of UAVs communication and observation by multiple UAVs. In [8], a communication over multiple UAVs is considered. This paper focused on controlling trajectory of UAVs. However, we suppose that the trajectory of observation UAV is not controlled. Monitoring and surveillance by UAV communication networks is presented in [9]. The work in [9] assumed monitoring and surveillance of a specified target in an objective area by multiple UAVs. At this time, the objective area has obstacles. In this network, in order to establish a link between the specified target and the base station, UAVs are located so that they avoid obstacles. Here, the UAV that observes the specified target transmits to the base station through the other UAVs. Then each link always has the required line-of-sight. The supposition of this paper is similar to ours. This is because both we and they deal with multiple UAVs and aim at real-time data transmission. However, the differences between both papers are the size of the objective area, the specified target and the mobility of the observation UAV. The size of the objective area in [9] is still smaller than our supposition. Hence, in [9], the observation UAV hardly moves around. On the other hand, in our supposition, the size of the objective area is so large that the observation UAV has a great range of movement. Also, there is a specified target in [9]. However, in our research, there is no specified target because the objective of our research is the observation all over the objective area. In the case that the specified target is previously known by the operator, the work in [9] is effective. However, in the case that there is no specified target and the UAV observes all over the objective area, our research is effective.

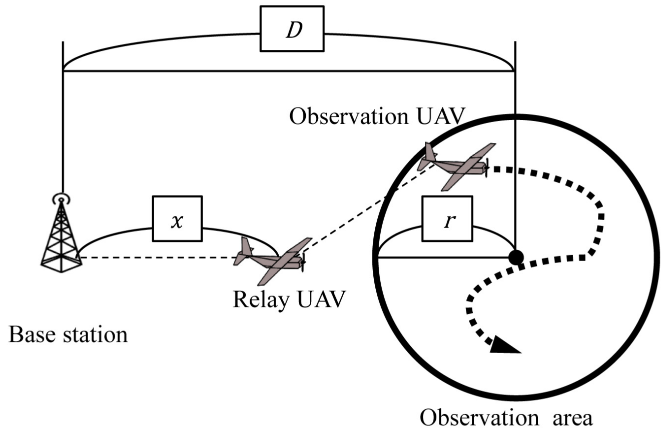

Fig. 2. Supposed UAV network in our research

In these previous researches, most of them focus on the observation by a single UAV without considering multiple UAVs. Therefore, we need to consider the observation by multiple UAVs. In addition, because the demand for the real-time observed data transmission has increased, it is necessary that we take that into account. Also, the observation of wider areas is necessary. Therefore, we conduct research on the real-time observation of wide areas by multiple UAVs. In the following section, we present the supposition in detail.

III. SUPPOSED NETWORK AND CHALLENGES

In this section, we explain about our supposed UAV network. Moreover, we describe the challenges that can occur in the network.

A. Supposed Network

Here, we present the overview of UAVs and UAV networks. In our supposed network, there are a base station, a relay UAV and an observation UAV. Furthermore, the location of the base station is fixed and the observation UAV flies above circular observation area. The interaction of these is portrayed in Fig. 2. In Fig. 2, x denotes the distance between the base station and the location of the relay UAV, D denotes the distance between the base station and the center of the observation area, and r denotes the radius of the area. The observation UAV moves freely in the designated area and continues to collect any information from there. It then transmits the collected data to the base station through the relay UAV in real time. At this time, the collecting data rate is always fixed. Also, to transmit collected information in real time, the throughput must be higher than the data rate. The relay UAV is located between the observation UAV and the base station, fixed in a predetermined location. However, this location is changed again after every specified time period. At this time, the relay UAV is always relocated to an optimal point in terms of performance. The optimal location will be detailed in the following section. In this article, we concentrate on the initial location of the relay UAV. Also, this location is defined as always being outside the observation area. Furthermore, there are constantly obstacles between the relay UAV and the observation UAV. These obstacles attenuate the signal power between them. Therefore, we take into account the attenuation of the transmitted signal power from the observation UAV.

We now present the communication performance of UAVs. All UAVs in this article are equipped with a wireless transceiver. Besides, they can communicate with each other and the base station. At this time, the link rate between a UAV and the base station or a UAV and another UAV depends on the Shannon - Hartley theorem [10]. A formulation of the theorem is described below:

$$C = B\log_2\left(1+\gamma\right), \quad (1)$$

where C is the link rate and B is the bandwidth in communication. Also, γ stands for signal-noise ratio (SNR). In this article, B is fixed. Therefore, the link rate varies according to SNR. Then the received signal power is set to P_r, where P_r depends on the Friis transmission equation [11]. This equation is below:

$$P_r = \left(\frac{\lambda}{4\pi d}\right)^2 \cdot G_t G_r P_t, \quad (2)$$

where λ is the wavelength in communication, d denotes the transmission distance, G_t and G_r respectively denote antenna gain of transmitter and receiver, and P_t is the transmitted signal power. At this time, SNR is the received signal power divided by the noise power. Therefore, due to Eq. (2), SNR (γ) is defined as following:

$$\gamma = \left(\frac{\lambda}{4\pi d}\right)^2 \cdot \frac{G_t G_r P_t}{N}. \quad (3)$$

In Eq. (3), N is the noise power on a free space. Due to Eq. (3), the link rate is greatly influenced by the transmission distance.

B. Challenge of Supposed Network

In our supposed network, parameters related to the observation area (e.g., the distance between the base station and the observation area, the radius of the observation area) are predetermined. A longer distance between the base station and the observation area means a longer distance for each link. As shown by Eq. (2), this causes the received signal power to decrease. Therefore, due to a decrease in the SNR, the link rate decreases too. That is, the link rate changes in function of the location of the UAVs. Also, setting the radius of the observation area to larger will increase the variation in SNR, since the distance between the observation UAV and the relay UAV changes due to the observation UAV movement. Therefore, the transmittable data rate is dispersed due to this large variation. In this article, we assume that the UAV constantly transmits the observed data in real time. If the data rate is greatly dispersed, it is impossible to transmit the observed data in real time. That is, it is very important to set the parameters related to the observation area because they have a great impact on throughput on end-to-end communication. Moreover, due to signal attenuation caused by obstacles, there is a decrease on the SNR. Hence, the throughput is decreased by obstacles as well as by the longer communication distance, possibly disabling real-time data transmission like the parameters related to the observation area. In the following section, we formulate the upper bound of throughput taking into account the influences of the above.

IV. Proposed Formulation of Throughput and Optimal Location of the Relay UAV in Supposed Network

In this section, we present the modeling of the performance in our supposed UAV network. In the preceding section, we explained about the influences of the parameters related to the observation area and obstacles that exist between the relay UAV and the observation UAV. Therefore, based on that influences, we formulate the upper bound of throughput in the network and the optimal location of the relay UAV.

A. Formulation of Throughput

We propose the formulation of the upper bound of throughput for UAV real-time data transmission. We assume that the observation UAV is at the farthest location from the base station. Due to this, the throughput in the network is the minimum value. Then the throughput expresses the data rate in which the observation UAV can completely transmit the observed data in the environment where SNR varies. Therefore, by obtaining this, we can calculate how much data this network can at least collect from the designated area in a specified time period. Fig. 3 shows the change in link rate between the base station and the relay UAV, and between the relay UAV and the observation UAV when the location of the relay UAV changes. Each link rate is derived from Eqs. (1) and (3). At this time, we define the throughput in the network as the lower value among the two link rates. Therefore, the formula of the upper bound of throughput (T) is below:

$$T = B\log_2\Big(1+\min\big(\gamma_{\mathrm{Relay}},\gamma_{\mathrm{Observer}}\big)\Big), \tag{4}$$

where γ_{Relay} and $\gamma_{Observer}$ respectively denote the signal-noise ratio of the relay UAV and the observation UAV. At this time, each signal-noise ratio is shown below:

$$\gamma_{\mathrm{Relay}} = \left(\frac{\lambda}{4\pi x}\right)^2 \cdot \frac{G_t G_r P_t}{N}, \tag{5}$$

$$\gamma_{\mathrm{Observer}} = \left(\frac{\lambda}{4\pi\big(D+r-x\big)}\right)^2 \cdot \frac{G_t G_r P_t}{N} \cdot \big(1-A\big). \tag{6}$$

In the above equation, A is the attenuation rate. A represents the rate of transmitted signal lost due to obstacles. Fig. 3 shows that maximum throughput is at the intersection of the two link rate curves. Therefore, in the following section, we formulate the location of the relay UAV in order to maximize the throughput.

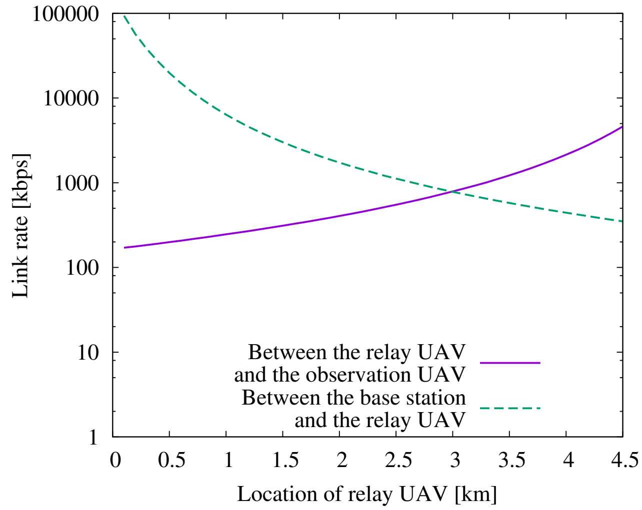

Fig. 3. Influence of the location of the relay UAV in each link rate

B. Formulation of an Optimal Location of the Relay UAV

In this article, an optimal location for the relay UAV is defined as the location that maximizes the upper bound of throughput. The optimal location by that definition is the intersection of the link rate curves in Fig. 3. Therefore, in order to derive the optimal location, we solve the following equation:

$$\begin{aligned} B\log_2\big(1+\gamma_{\mathrm{Relay}}\big) &= B\log_2\big(1+\gamma_{\mathrm{Observer}}\big), && (7)\\ \gamma_{\mathrm{Relay}} &= \gamma_{\mathrm{Observer}}. && (8)\end{aligned}$$

From Eqs. (5), (6) and (8), the optimal location of the relay UAV (X) is below:

$$X = \left(\frac{D+r}{A}\right)\big(1-\sqrt{1-A}\big). \tag{9}$$

Therefore, if the parameters and attenuation rate are known, the optimal location of the relay UAV can maximize the upper bound of throughput. In the supposed network, the relay UAV is constantly located outside the observation area. Hence, a threshold to judge whether the location is outside the observation area or not is necessary. In order to derive the threshold, we solve the equation when the optimal location of the relay UAV corresponds to the boundary of the area.

$$\begin{aligned} D-r &= \left(\frac{D+r}{A}\right)\big(1-\sqrt{1-A}\big),\\ \frac{D}{r} &= 1+\frac{2}{\sqrt{1-A}}. && (10)\end{aligned}$$

The D-to-r ratio shows the balance between the network size and the observation area size. From the right side of Eq. (10), the threshold is derived. If the D-to-r ratio is smaller, the observation area size is relatively larger. At this time, there are cases that the optimal location of the relay UAV is inside the area. However, we assume that the location of the relay UAV is always outside the area. Hence, we should set the D-to-r

TABLE I
EVALUATION ENVIRONMENT

Parameter	Value
Bandwidth (B)	20 MHz
Wavelength (λ)	0.125 m
Transmitted signal power (P_t)	0.25 W
Noise power (N)	1×10^{-10} W
Antenna gain of transmitter (G_t)	1
Antenna gain of receiver (G_r)	1

ratio so that the location is always outside the area. Therefore, in this article, the parameters related to the area are determined so that they exceed the threshold. In the following section, we evaluate the performance in our supposed network.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance that is influenced by the parameters related to the observation area and signal attenuation caused by obstacles when the relay UAV is at the optimal location.

A. Evaluation Environment

Parameters are set as shown in Table I. We assume that the UAVs communicate in 2.4 GHz bands. Hence, the wavelength in communication is set to 0.125 m. Furthermore, the bandwidth is set to 20 MHz because of general wireless communication standards such as IEEE 802.11g/n. We assume the usage of non-directional antenna in this evaluation. Hence, G_t and G_r are both set to 1. Also, we assume that the noise power is the signal intensity of the white noise. In this article, the noise power is set to 1×10^{-10}.

In the first part of our evaluation, we pay attention to the influence of the parameters related to the observation area. That is, we change the network size, the sum of the value D and r, and fix the D-to-r ratio and the attenuation rate (A). At this time, the D-to-r ratio is determined so that it exceeds the threshold derived from Eq. (10). Hence, in the first evaluation, we fix the D-to-r ratio to 10 and the attenuation rate to 0.3 and evaluate in each combination of values ($\{D, r\} = \{(3, 0.3), (4, 0.4), (5, 0.5)\}$). At this time, D and r are in kilometer. Based on the above, we evaluate the relationship between the upper bound of throughput and the location of the relay UAV. This is displayed in a graphic chart.

In the second part of our evaluation, we pay attention to the influence of the signal attenuation caused by obstacles. That is, we change the attenuation rate, and fix the network size and the D-to-r ratio. Therefore, in the second evaluation, we fix the D-to-r ratio to 10. Then D is set to 5 km and r is set to 0.5 km. At this time, we evaluate each value of $A(= 0.3, 0.6, 0.9)$. Then we also derive the relationship between the upper bound of throughput and the location of the relay UAV and display it in a graphic chart.

In the third part of our evaluation, we pay attention to the variation of the upper bound of throughput influenced by the network size and the attenuation rate when the relay UAV is at the optimal location. At this time, we consider each combination of the following parameters: ($\{D, r\} = \{(3, 0.3), (4, 0.4), (5, 0.5)\}$, $\{A\} = \{0.3, 0.6, 0.9\}$). Then we display the variation of the upper bound of throughput in a graphic chart.

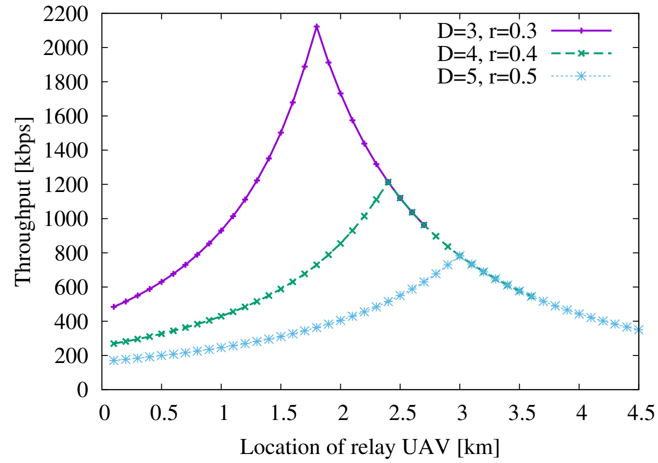

Fig. 4. Influence of the network size in the upper bound of throughput

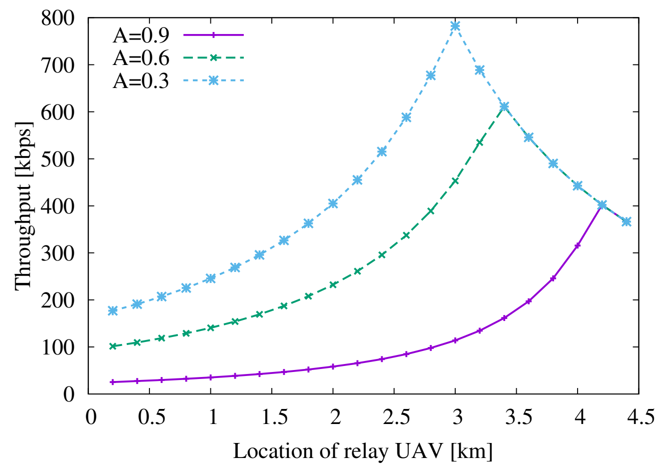

Fig. 5. Influence of the attenuation caused by obstacles in the upper bound of throughput

B. Result in Evaluation

Firstly, the evaluation of the influence of the network size is demonstrated in Fig. 4. From Fig. 4, due to an increase in the network size, the throughput decreases as a whole. Moreover, the optimal location of the relay is farther from the base station the larger the network is. This is because the transmission distance is longer since the network size is larger. Also, the optimal location of the relay UAV is always on the curve of the link rate between the base station and the relay UAV. This is because the optimal location is the intersection of the link rate curves and the link rate between the base station and the

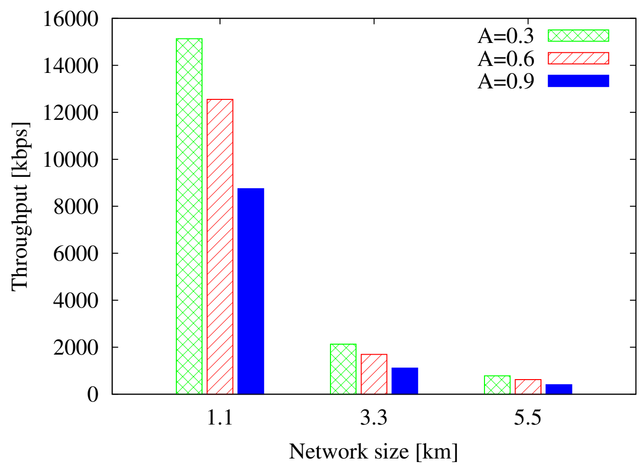

Fig. 6. Influence of variation of both the network size and the attenuation rate in the upper bound of throughput

relay UAV creates a bottleneck in location farther from the base station.

Secondly, the evaluation of the influence of the attenuation rate is demonstrated in Fig. 5. From Fig. 5, due to an increase in the attenuation rate, the throughput also decreases as a whole. In the link between the relay UAV and the observation UAV, the link rate decreases due to the obstacles. Since that creates a bottleneck, the throughput decreases. Then the optimal location of the relay UAV is always on the curve of the link rate between the base station and the relay UAV in the same way as the first evaluation.

Finally, the evaluation of the variation of the upper bound of throughput influenced by the network size and the attenuation rate is demonstrated in Fig. 6. Fig. 6 shows the variation of the theoretical values of the maximum throughput when we change the network size or the attenuation rate. Therefore, if the parameters related to the network size are set and the attenuation rate is cleared, the transmittable data rate in real time is predictable. In other words, if the required data rate in collecting the observed data is decided, the approximate value of the network size is naturally fixed.

VI. CONCLUSION

Recently, UAVs have attracted attention as a means to observe a terrain. This is because it is easy to obtain and control them. Also, UAVs can carry equipment such as cameras and thermographs. In disaster areas, the demand for collecting high quality photography data in real time has increased in order to assist rescue operations and prevent secondary disasters. However, the observation by a single UAV cannot meet this demand. This is because communication range of a single UAV is limited due to limitation of the payload of UAV. This problem can be solved owing to usage of multiple UAVs. Therefore, in this article, we argued about real-time data transmission over a UAV network. Collected data can be transmitted at a high speed and in a long distance through UAV networks. We assumed a network that consisted of a base station, a relay UAV, and an observation UAV and a communication performance of wireless transceivers. Then we indicated the challenges in the supposed network. The challenges were a variation in the throughput caused by influences of the parameters that related to the size of the observation area and signal attenuation by obstacles. In order to evaluate the influences of them, we formulated the upper bound of throughput in the network and the optimal location of the relay UAV that maximize the throughput. Then we evaluated and displayed it in the graphic charts. From these figures, we found the influences of the parameters related to the observation area and the signal attenuation by obstacles in the supposed UAV network.

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