PAPER

Voronoi-Based UAV Flight Method for Non-Uniform User Distribution in Delay-Tolerant Aerial Networks*

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SUMMARY This paper considers an emergency communication system controlling multiple unmanned aerial vehicles (UAVs) in the sky over a large-scale disaster-affected area. This system is based on delay-tolerant networking, and information from ground users is relayed by the UAVs through wireless transmission and the movement of UAVs in a store-and-forward manner. Each UAV moves autonomously according to a predetermined flight method, which uses the positions of other UAVs through communication. In this paper, we propose a new method for UAV flight considering the non-uniformity of user distributions. The method is based on the Voronoi cell using the predicted locations of other UAVs. We evaluate the performance of the proposed method through computer simulations with a non-uniform user distribution generated by a general cluster point process. The simulation results demonstrate the effectiveness of the proposed method.

key words: *unmanned aerial vehicle (UAV), delay-tolerant networking (DTN), delay, Voronoi, user distribution*

1. Introduction

When a large-scale disaster, such as an earthquake or tsunami occurs, communication between rescue teams and affected individuals is necessary to facilitate rescue operations and determine the extent of damage. However, communication may be difficult because of damage to the terrestrial communication systems and very heavy communication demands. In these cases, unmanned aerial vehicles (UAVs) are advantageous. UAVs in the sky have high mobility that is independent of ground conditions. In addition, they provide a high probability of line-of-sight (LoS) links with users on the ground. For these reasons, UAV-based emergency communication systems have attracted much attention [2], [3].

When a sufficient number of UAVs are available over an entire area, the optimal fixed placement of UAVs to provide wireless coverage for ground users can be achieved, although some users may be neglected [4], [5]. However, in an emergency situation, such as a disaster, it is necessary to employ a robust system covering a wide area over time with a limited number of UAVs, where each UAV operates autonomously. In this paper, we consider a delay-tolerant aerial network using UAVs [6]–[8]. In this network, with the use of delay-tolerant networking (DTN) [9], messages, such as damage reports and safety confirmations, are relayed in a store-and-forward manner through wireless transmission and the movement of the UAVs (the number of UAVs is limited). Due to the UAV movement, the message delivery delay from source to destination is much longer than the wireless transmission between UAVs within the communication range. Therefore, the movement of UAVs has a significant impact on reducing the message delivery delay.

In a delay-tolerant aerial network, it is necessary to consider how each UAV moves autonomously and how it selects a destination, which we call a flight method. In a previous study [7], we adopted a random mobility model, such as the random waypoint model [10] as a flight method and also proposed a rebounding flight. In the rebounding flight, when a UAV enters the communication range of another UAV, it selects a random point in the opposite direction of that UAV as its destination. Compared to the random mobility model, which does not use other positions of UAVs, the rebounding flight, which uses another UAV's position, reduces overlap among UAVs and thus improves the message delivery performance. In another study [8], we proposed a Voronoi-based flight method that selects the destination based on the positions of one or more UAVs, some of which are predicted to be out of the communication range. UAVs following these flight methods cover the entire area relatively uniformly over time, which is reasonable because the studies assume that users on the ground are uniformly distributed. However, user distributions are typically uneven, particularly during a disaster, and users are likely to be concentrated in or near predesignated evacuation centers or points of interest that can be known in advance.

Some studies discuss the deployment of UAVs considering the density and distribution of users from different viewpoints [11]–[14]. UAV placement techniques are proposed to maximize the number of covered users in [12] and to minimize battery depletion in UAVs in [11], where the target area is divided into subareas with different user densities or distributions. In [13], a placement method is investigated to maximize the number of covered users subject to the constraint of the minimum data rate for arbitrarily distributed users. In [14], UAV deployment based on user density is proposed to minimize the average distance between users and

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their nearest UAVs. However, these studies mainly discuss UAV deployment and do not address the continuous movement of UAVs with available information through wireless communication within the limited communication range.

In this study, we consider a robust system where each UAV operates autonomously in the absence of terrestrial communication infrastructure or a sufficient number of available UAVs. The objective of this study is to design an autonomous flight method for UAVs considering the non-uniformity of user distributions. To achieve this objective, we expand the Voronoi-based flight method [8] to consider the non-uniformity of users. The contributions of this paper are as follows:

1. We propose a Voronoi-based flight method that incorporates a density function corresponding to the user distribution into the UAV operation of selecting the destination. In this method, the destination is selected based on the Voronoi cell using other UAVs' positions. Either the center of mass (centroid) of the Voronoi cell or a random point inside the cell is used. In addition, we consider two time points at which the destination is changed: after arrival at the destination and after communication with another UAV.
2. We evaluate the performance of the proposed flight method compared to the existing method through computer simulations, where a general cluster point process is used as the user distribution. The simulation results are presented to demonstrate the effectiveness of the proposed method and the impact of the time at which the destination is changed on the performance.

The remainder of this paper is organized as follows. In Sect. 2, the system model for the UAV-based aerial network is presented, while in Sect. 3, the proposed flight method is described. The simulation results are presented in Sect. 4, followed by the conclusions in Sect. 5.

2. System Model

2.1 Delay-Tolerant Aerial Network Using UAVs

We consider an aerial system where multiple UAVs fly over the target area of interest, as illustrated in Fig. 1. This system delivers messages between arbitrary users on the ground. The entire area is not always within the coverage area of available UAVs, and connections between UAVs are intermittent. With the use of DTN, messages are delivered to users through wireless transmission and UAV movement. As illustrated in Fig. 1, when a ground user is within the coverage area of a UAV, the message is transmitted from the user to the UAV. Then, the message is transmitted wirelessly to another UAV within the communication range. When there are no UAVs within the communication range to transmit the message to, the message is carried by the moving UAV. Subsequently, the message is carried by wireless transmission and UAV movement in the same way. Finally, the destination user receives the message from a UAV that serves that user within its coverage area.

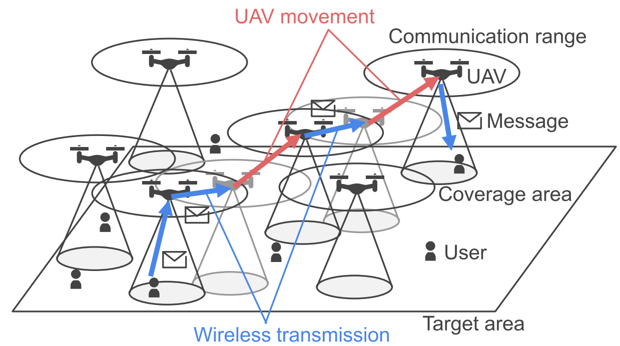


Fig. 1 Delay-tolerant aerial network using UAVs.

We assume that the message is delivered in a non-real-time manner; that is, a certain amount of delay is acceptable. Nevertheless, it is necessary to disseminate information about the damage and safety of the affected areas and individuals as quickly as possible to perform rescue operations and determine the extent of damage. We consider a scenario in which the communication system operates over the entire area despite the limited number of UAVs available during a disaster.

2.2 User Distribution

To reflect the non-uniformity of the user distribution, we consider clustered ground users. Specifically, there are several points where users are clustered in the target area. In practical scenarios, instead of perfect user location information, it is more feasible to obtain partial information, such as the statistical distribution of the users [3]. The cluster point process used as the simulation model is described in Sect. 4.1.

In this study, it is assumed that the distribution of users is available. This distribution can be estimated from the location of evacuation centers and individuals before the disaster and by predicting the flow of individuals after the disaster. Even if the user distribution is initially unknown, it can be estimated as time passes and UAVs fly over the area.

2.3 Channel Model

Air-to-air channels are mainly dominated by LoS components [16]. Thus, the path loss between UAV i and UAV j can be considered the free-space path loss (FSPL), which can be expressed as

$$L_{ij} = 20 \log \left(\frac{4\pi f_0 d_{ij}}{c} \right) \text{ dB}, \tag{1}$$

where f_0 is the carrier frequency of the UAV-to-UAV channel, d_{ij} is the distance between UAV i and UAV j, and c is the speed of light. The received power of UAV j from UAV i is given by

$$P_{ij}^{\mathrm{r}} = P^{\mathrm{t}} - L_{ij} + G^{\mathrm{t}} + G^{\mathrm{r}} \text{ dBm}, \tag{2}$$

where P^{t} denotes the transmit power, and G^{t} and G^{r} denote the antenna gain of the transmitter and receiver, respectively. A UAV can communicate with another UAV when the received power exceeds the minimum received power, $P^{\mathrm{r}}_{\mathrm{min}}$, required for reliable communication.

As a common approach, the air-to-ground channel is modeled by considering the LoS and non-line-of-sight (NLoS) components separately with different occurrence probabilities [17]. NLoS links have higher path loss than LoS links due to shadowing and reflection of signals from buildings. The average path loss for LoS and NLoS links between UAV i and ground user k is expressed as follows [18], [19]:

$$L^{ik}_{\mathrm{LoS}} = 20\log\left(\frac{4\pi f_{\mathrm{c}} d^{ik}}{c}\right) + \eta_{\mathrm{LoS}}\ \mathrm{dB}, \tag{3}$$

$$L^{ik}_{\mathrm{NLoS}} = 20\log\left(\frac{4\pi f_{\mathrm{c}} d^{ik}}{c}\right) + \eta_{\mathrm{NLoS}}\ \mathrm{dB}, \tag{4}$$

respectively, where f_{c} is the carrier frequency of the UAV-to-ground user channel, and d^{ik} is the distance between UAV i and user k. Additionally, η_{LoS} and η_{NLoS} are the average losses other than the FSPL for LoS and NLoS links, respectively, which depend on the type of environment (e.g., rural, urban, dense urban). The probability of having LoS links between a UAV and user is given by [17], [18]:

$$P_{\mathrm{LoS}} = \frac{1}{1 + \alpha \exp\left(-\beta\left(\frac{180}{\pi}\arctan\left(\frac{h}{\sqrt{{d^{ik}}^2 - h^2}}\right) - \alpha\right)\right)}, \tag{5}$$

where α and β are constant values that depend on the environment, and h is the altitude of the UAV. Thus, the average path loss between UAV i and user k is expressed as $L^{ik} = P_{\mathrm{LoS}} L^{ik}_{\mathrm{LoS}} + (1 - P_{\mathrm{LoS}}) L^{ik}_{\mathrm{NLoS}}$. The UAV is equipped with a directional antenna, and the antenna gain of UAV i for user k can be expressed as

$$G^{ik}_{\xi} = \begin{cases} G_{\mathrm{B}}, & 0 \le \phi_{ik} \le \frac{\theta_{\mathrm{B}}}{2}, \\ g(\phi_{ik}), & \text{otherwise,} \end{cases} \tag{6}$$

where $\xi \in \{\mathrm{t}, \mathrm{r}\}$ denotes the transmitter (t) or receiver (r), θ_{B} is the half-power beam width of the directional antenna, G_{B} is the main lobe gain of the antenna and is equal to $\frac{30000}{\theta_{\mathrm{B}}^2}$ [20], and ϕ_{ik} is the angle between the center of the beam direction of UAV i and the direction of user k. We assume that the gain outside the main lobe is negligible, that is, $g(\phi_{ik}(t)) \approx 0$. As with the air-to-air channel model, the communication range between the UAV and ground user can be determined given the minimum received power, $P^{\mathrm{r}}_{\mathrm{min}}$, required for successful transmission.

2.4 Flight Method and Battery Replacement for UAVs

In the network described in Sect. 2.1, the smaller the number of available UAVs, the more the movement of the UAVs affects the message delivery delay. Thus, the flight method of the UAVs is important in reducing the delay. We aim to improve the message delivery performance in terms of the UAV flight method.

The constraints and requirements for UAV operation are described below. As mentioned in Sect. 2.3, each UAV has a limited communication range with other UAVs and a limited coverage area for ground users, and the location information of UAVs out of the communication range is not available to all UAVs. We consider that each UAV operates autonomously with available information from other UAVs in the communication range. The system does not require centralized control and naturally supports an increase or decrease in the number of functioning UAVs in the network due to battery depletion or breakdown. This allows each UAV to join or leave the network at any time and from any location. In addition, each UAV has limited flight duration due to limited battery life. Thus, UAVs must replace their batteries at a battery station before battery depletion. The battery station is provided in the target area. A UAV with a low battery level does not follow the flight method but instead travels to the battery station before its battery is depleted. The UAV exchanges information with other UAVs during movement toward the battery station, except during a certain period of time during battery replacement. After its battery is replaced, the UAV rejoins the network and flies according to the flight method. We assume that the location of the target area and battery station is given in advance and that the location information of each UAV is available to the UAV (e.g., through GPS).

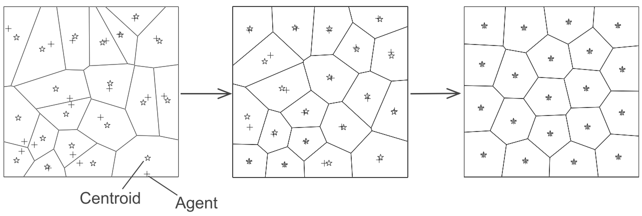
As mentioned in Sect. 1, we proposed flight methods, such as the rebounding flight [7] and Voronoi-based flight [8]. In these flight methods, UAVs move and are distributed somewhat uniformly over time across the entire target area. These studies assumed that users are distributed uniformly on the ground and did not consider non-uniform user distributions. However, users are likely to gather near points of interest, such as designated evacuation centers, which can be predicted or known in advance. In this case, it may be more appropriate for UAVs to move according to the non-uniform distribution of users. It should be noted that moving UAVs also cover areas with low user densities by autonomous operation.

3. Proposed Flight Method

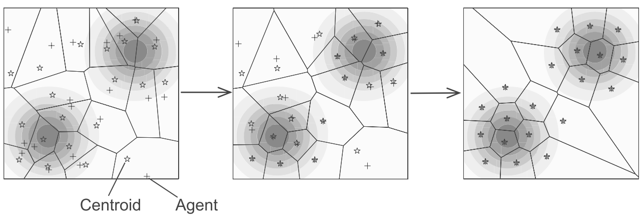
In this section, we propose a flight method considering a non-uniform user distribution.

3.1 Concept of Proposed Flight Method

The proposed flight method is an expansion of the Voronoi-based flight [8] and is based on coverage control [21], which is a method for placing multiple agents to cover as large of an area as possible according to a given distribution. In coverage control, each agent is moved to the center of mass (centroid) of its Voronoi cell while updating its cell and



(a) Without density function.



(b) With density function.

Fig. 2 Examples of coverage control.

centroid as it moves. Each Voronoi cell consists of all points closer to an agent than to any other agent.

Figure 2 presents examples of coverage control. In Fig. 2(a), the distribution density function is not used in the calculation of centroids, in which case the agents eventually result in a uniform arrangement. In contrast, in Fig. 2(b), the density function of a particular distribution represented by the contrast is used. This allows agents to arrange themselves according to the distribution. This method of controlling the placement of agents is the inspiration for controlling the continuous movement of UAVs according to the user distribution. In Fig. 2, it is assumed that each agent can obtain the locations of all other adjacent agents. However, this study assumes that each UAV operates using the location information of other UAVs only within its communication range. We focus on the agent's behavior of moving to the centroid of its Voronoi cell.

The Voronoi-based flight method proposed in [8] considers autonomous UAV operation. However, the destination of each UAV is always the centroid of its Voronoi cell; that is, the destination is constantly updated. This operation results in less UAV movement and is not suitable for a small number of available UAVs. The main differences in UAV operation between this paper and [8] are as follows:

1. This paper incorporates a density function that corresponds to the distribution of ground users into the process of selecting a new destination.
2. This paper considers two time points at which the destination is changed: after arriving at the destination and after communicating with other UAVs.

3.2 Operation of Proposed Flight Method

Figure 3 illustrates the main operation of the proposed flight method, which is described as follows. (i) The UAV labeled 1 (UAV 1) exchanges location and destination information with other UAVs within its communication range through wireless links. (ii) UAV 1 computes the Voronoi cell by using the locations of other UAVs, namely, the locations obtained from UAVs within the communication range and those predicted from information obtained in past communications with UAVs now outside the communication range. Then, UAV 1 selects a destination. (iii) UAV 1 moves toward the destination. (iv) After moving, UAV 1 obtains the real-time location information of UAV 3. (v) At this time, UAV 1 computes the Voronoi cell by using not only the location of UAV 3 but also the predicted location of UAV 2, from which UAV 1 obtained location and destination information to predict its real-time location. UAV 1 then selects a new destination. These operations are repeated.

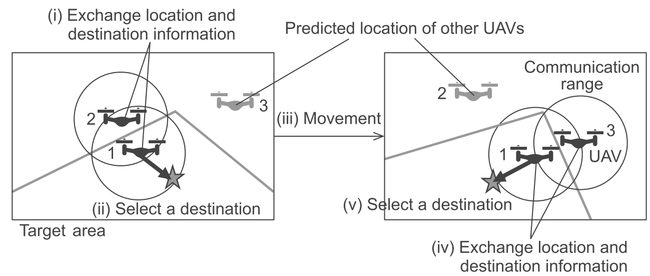


Fig. 3 Main operation of the Voronoi-based flight method.

In Sect. 3.2.1, we describe the location prediction and the resulting weighted Voronoi cell. In Sect. 3.2.2, we explain the method of selecting a new destination, and in Sect. 3.2.3, we consider the time points at which the destination is changed.

3.2.1 Location Prediction and Weighted Voronoi Cell

The accurate real-time location information of other UAVs is available to each UAV only when the UAVs are within communication range. When UAVs are within communication range, they exchange not only messages from ground users but also their real-time location and destination information. A UAV remembers the location and destination information of other UAVs until the next communication to predict the real-time locations of those UAVs. The location prediction assumes that other UAVs are moving toward their destinations at a given speed regardless of where the UAVs are located. Then, the real-time locations of other UAVs are predicted based on the information obtained from past communications. The predicted positions are weighted according to the passage of time to create a Voronoi cell.

Let Q be the target area of a convex polygon, including its interior. Let $p_i \in Q$, $\mathcal{U}_i$, and $\mathcal{W}_i$ be the real-time location of UAV i, the set of predicted locations of other UAVs, and the set of the weights associated with those locations held by UAV i, respectively. The weight associated with the predicted location for UAV j is denoted by $w_j (0 \leq w_j \leq 1)$. The actual real-time locations within the communication range are added to the set of predicted locations, and the weights associated with those locations are initialized to 1.

After the UAV corresponding to the predicted location moves out of the communication range, its weight decreases to 0 as time passes. Once the weight reaches 0, the corresponding predicted location and weight are removed from the set of predicted locations and the set of weights, respectively. The weighted Voronoi cell computed by UAV i with the use of the predicted locations and their weights is defined by

$$V_i = \{q \in Q \mid \|q - p_i\| - s^2 \leq \|q - u_j\| - s^2 w_j^2, \text{ for all corresponding pairs } (u_j, w_j)\text{'s s.t. } u_j \in \mathcal{U}_i, w_j \in \mathcal{W}_i\}, \quad (7)$$

where q represents a point in the target area, $\|\cdot\|$ denotes the Euclidean distance function, and s is a constant with the dimension of the distance in the target area. The larger the value of s, the greater the effect of the weight on the weighted Voronoi cell. The Voronoi cell consists of all points closer to the real-time location of UAV i than to the predicted locations of other UAVs.

3.2.2 Destination Selection

Each UAV uses the weighted Voronoi cell defined by (7) to select its next destination. Two approaches for selecting the destination are considered. Let $\phi(\cdot)$ be a density function that corresponds to the user distribution. This study assumes that the density function is given in advance to all UAVs, regardless of the UAV operation. The first approach is to use the centroid of the Voronoi cell as the destination, as in coverage control. The centroid of the Voronoi cell is given by

$$C_{V_i} = \frac{\int_{V_i} q\phi(q)dq}{\int_{V_i} \phi(q)dq}. \quad (8)$$

In the second approach, each UAV selects a random point inside the Voronoi cell, where each point $p \in V_i$ is selected with the probability $\frac{\phi(p)}{\int_{V_i} \phi(q)dq}$. In other words, a point is randomly selected according to the density function.

The destination in the Voronoi cell is closer to the UAV than any other UAV is. Thus, it is more efficient for the UAV to travel to that destination than other UAVs. The first approach mentioned above focuses on the centroid, whereas the second approach focuses on the Voronoi cell itself. The second approach is considered in this study to examine the effectiveness of using the centroid. Determining whether to use the centroid or a random point is discussed in Sect. 4.2.

3.2.3 Time Points of Changing Destination

The UAV changes its destination at two time points: (i) after communication with another UAV and (ii) after arriving at the destination. After entering the communication range of another UAV, each UAV updates its Voronoi cell by (7). At this time (i.e., time point (i)), since the information of other UAVs is updated, the destination is also updated using this new information. The more UAVs there are in the area, the more opportunities each UAV has to communicate with those UAVs. Therefore, the destination selection at this time point is considered to be important. Note that when the distance between UAVs are short enough to communicate according to the channel model described in Sect. 2.3, the UAVs will automatically initiate communication. When the distance is continuously short enough to allow communication, the location and destination information of other UAVs and thereby the destination of each UAV will be continuously updated. At time point (ii) (i.e., after arriving at the destination), each UAV must also select the next destination. The fewer UAVs there are, the more likely each UAV is to reach its destination before encountering other UAVs. Thus, the destination selection at this time point plays a significant role in improving the message delivery performance.

4. Simulation Results

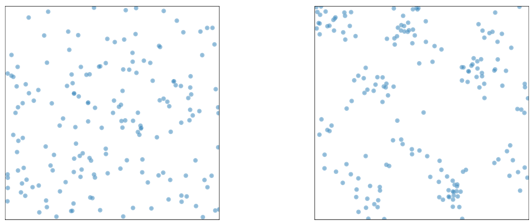
In this section, the message delivery performance of the proposed flight method is evaluated in a delay-tolerant aerial network using UAVs through simulations. The settings are described, followed by results.

4.1 Simulation Model

The parameters used in the simulations are presented in Table 1. The UAVs flew horizontally according to a flight method above the target area, which was a square with a side of 4 km. The simulation time was 3 h. The homogeneous Poisson process (HPP) with density λ_0 and Thomas cluster process (TCP) [22] with parameters λ_T, μ_T, and σ_T were used as the user distributions. In the TCP, virtual parent points were generated according to the HPP with density λ_T, and offspring points were clustered around the parent points. Each parent point was replaced by offspring points, where the number of points followed the Poisson process

Table 1 Simulation settings.

Target area	4 km × 4 km
Simulation time	3 h
HPP parameter, λ_0	10 /km^2
TCP parameters, λ_T, μ_T, σ_T	1 /km^2, 10, (100, 200, 300)
Mean message occurrence interval	10 min/user
Message deadline	60 min
Number of UAVs	5–30
Flight altitude, h	150 m
Transmit power, P^t	17 dBm
Minimum received power, P^r_{min}	−78 dBm
Antenna gain, G^t, G^r	1.2
Half-power beam width, θ_B	140°
Carrier frequencies, f_0, f_c	2.4 GHz, 2 GHz
α, β	9.61, 0.158
η_{LoS}, η_{NLoS}	1 dB, 20 dB
Speed of light, c	3×10^8 m/s
Flight speed	10 m/s
Battery capacity	90 Wh
Battery station location	(2 km, 2 km)
Battery replacement time	3 min
Number of simulations	100



(a) HPP. (b) TCP.

Fig. 4 Examples of user distribution.

with mean μ_T. The offspring points were clustered according to a Gaussian distribution with the parent point as the center and variance σ_T^2. Therefore, the density function was a linear superposition of Gaussian distributions. In the HPP and TCP used in the simulations, the user density was statistically the same at 10 users per km^2, as presented in Table 1. For each user, a message was generated with the destination as a random user following an exponential distribution with a mean occurrence interval of 10 min. Each message was discarded when the time of the message deadline elapsed. The message deadline was set to 1 h. As the performance measure, the delivery delay of a message was defined as the difference between the time the message was generated at the source user to the time it arrived at the destination user.

The flight speed of the UAVs was 10 m/s, and each UAV had a 90-Wh battery. Energy was consumed according to the energy consumption model [23], which depended only on the flight speed of the UAV. In this simulation, the maximum flight time was approximately 40 min. The battery station was located at the center of the target area, and the battery was replaced 3 min after the UAV arrived at the station. During the battery replacement, wireless communication was not performed. The parameters of the channel model described in Sect. 2.3 are presented in Table 1. The communication range between UAVs was approximately 670 m, and the horizontal radius of the coverage area was approximately 290 m. For simplicity, we assumed that the UAV performed wireless communication instantaneously within the communication range. As a DTN routing protocol, epidemic routing [24] was used with an infinite buffer capacity of the UAVs and no hop-count limit for messages. The locations and battery levels of the UAVs were initialized randomly. With the settings described above, the simulation was executed 100 times.

For the parameters of the proposed Voronoi-based flight, s was set to 1000 m, as presented in [8]. In addition, the weight of the predicted location was linearly reduced from the initial value, 1, to 0 over 300 s. Varying these settings can yield better results than those presented below; however, the results do not differ significantly unless extreme values are used. In the proposed method, when the distance between UAVs was continuously short enough to allow the UAVs to communicate, the location and destination information of other UAVs was updated every second, which is related to what mentioned in Sect. 3.2.3. Moreover, the exact density function of an actual user distribution was

Table 2 Flight methods used in the simulation.

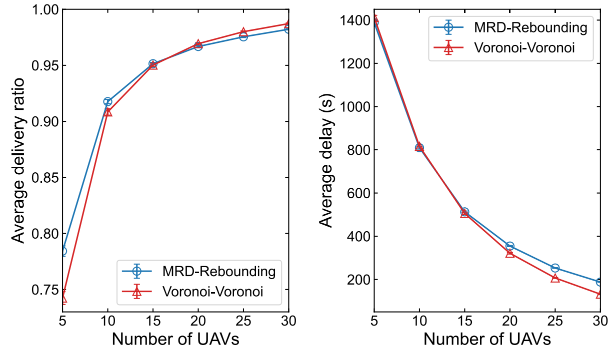
After arrival at destination \ After communication	User distribution **not considered** (Rebounding)	User distribution **considered** (Voronoi)
User distribution **not considered** (MRD)	MRD-Rebounding	MRD-Voronoi Effective for many UAVs
User distribution **considered** (Voronoi)	Voronoi-Rebounding Effective for few UAVs	Voronoi-Voronoi Effective

used in the proposed method. However, the accuracy of the density function is important. Therefore, in the simulation, uncertainties (errors) of the density function were applied to σ_T of the TCP used for the UAV operation to demonstrate the acceptable error range.

For comparison, we considered the destination selection with and without using the Voronoi cell for each time point of changing the destination, as illustrated in Table 2. For the destination selection without using the Voronoi cell, we used the rebounding flight method [7] and modified random direction (MRD) mobility model [15]. In the MRD model, the UAV selects a random direction from all possible directions on the horizontal plane and then selects a random point in that direction. In Table 2, the names of the two methods of selecting the destination are hyphenated, with the first part indicating the method used after the UAV arrives at the destination, and the second part indicating the method used after the UAV communicates with another UAV. There are four patterns: MRD-Rebounding, Voronoi-Rebounding, MRD-Voronoi, and Voronoi-Voronoi. The first pattern does not use the user distribution and was used as a benchmark. The notation "Voronoi" denotes the proposed method, which incorporates the user distribution into the UAV operation. In this method, two options exist: the use of the centroid of the Voronoi cell "(c)" and the use of a random point inside the Voronoi cell "(r)". When these options are not compared, the former option is used without the notation "(c)". In addition, we also considered the proposed Voronoi-based method that does not use the user distribution, that is, $\phi(\cdot) = 1$ in (8). In this case, "(w/o ϕ)" is appended to the method name.

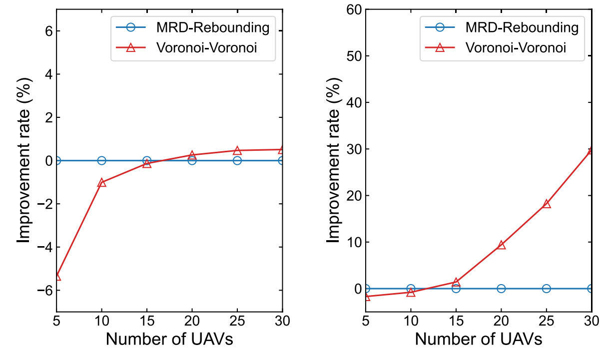
4.2 Message Delivery Performance

First, we compared the methods did and did not consider the user distribution, where the distribution was either uniform or non-uniform. The average delivery ratio and average delivery delay of messages with 95% confidence intervals are presented. The results for the HPP and TCP user distributions are presented in Figs. 5 and 6, respectively. In addition, the improvement rates in the results from those of the benchmark (MRD-Rebounding) are presented in Figs. 7 and 8, for the HPP and TCP cases, respectively. In the HPP case (Figs. 5 and 7), the value of the density function, $\phi(\cdot)$, was a constant (e.g., 1). In this case, the larger the number of UAVs, the higher the delivery ratio and lower the delay of the Voronoi-based method. Even in the case of a uniform user distribution, the use of the Voronoi cell led to better perfor-



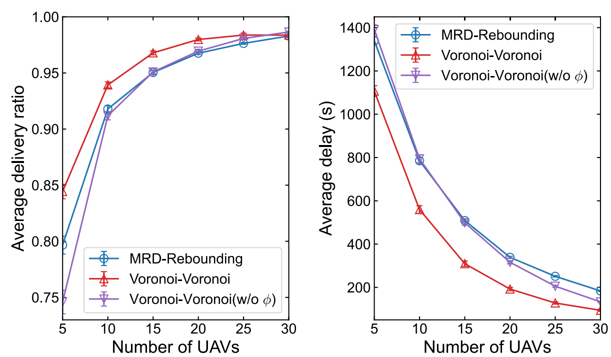
(a) Delivery ratio. (b) Average delay.

Fig. 5 Average message delivery ratio and average delivery delay in the case of HPP.



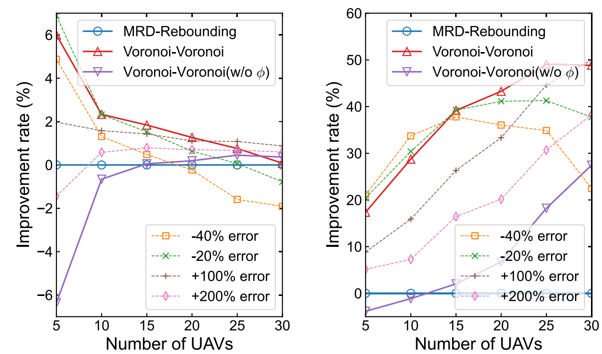
(a) Delivery ratio. (b) Average delay.

Fig. 7 Improvement rate in the case of HPP.



(a) Delivery ratio. (b) Average delay.

Fig. 6 Average message delivery ratio and average delivery delay in the case of TCP, where $\sigma_{\mathrm{T}} = 200$.



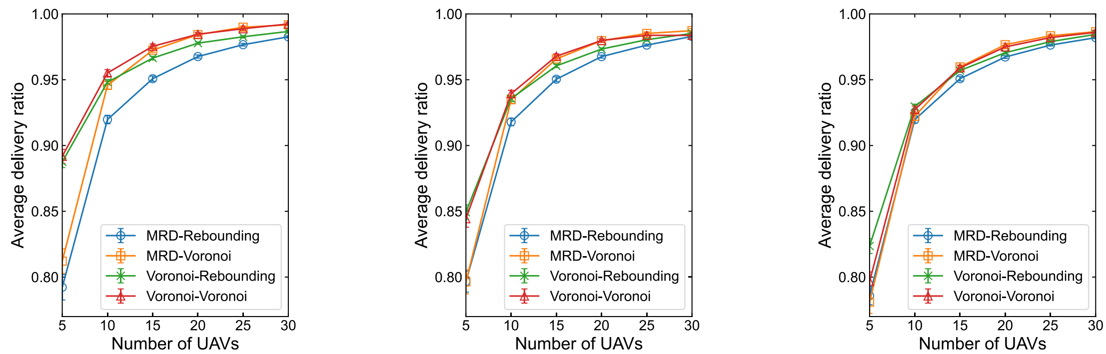
(a) Delivery ratio. (b) Average delay.

Fig. 8 Improvement rate in the case of TCP, where $\sigma_{\mathrm{T}} = 200$.

mance when the number of UAVs was larger, which is consistent with the results reported in [8]. In the TCP case (Figs. 6 and 8), the Voronoi-based method considering the user distribution achieved a higher delivery ratio and lower delay for all number of UAVs than the method that did not consider the user distribution. In other words, the Voronoi-based method reduced the number of UAVs required to achieve a certain delivery ratio or average delay. The consideration of the user distribution resulted in improved message delivery performance. In addition, the Voronoi-based method that did not consider the distribution yielded similar results to those for the HPP case. These results demonstrate the effectiveness of the proposed Voronoi-based method in the case of a non-uniform user distribution.

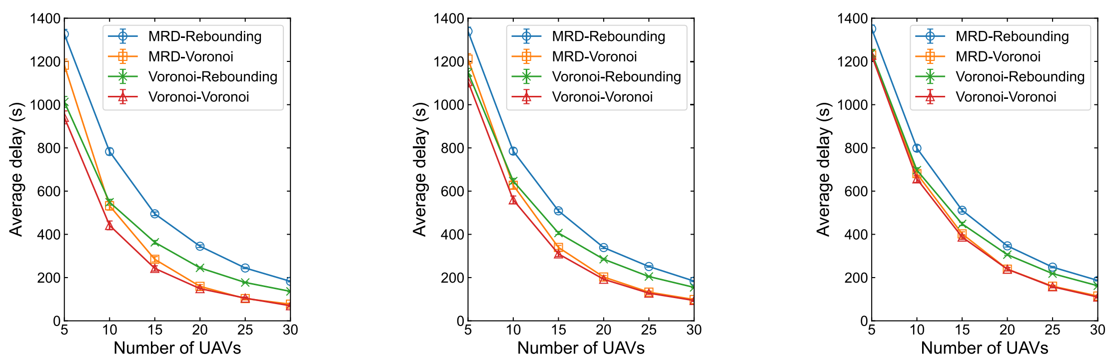
We then examine the impact of the uncertainty in the density function used for the UAV operation on the performance. Figure 8 includes the results where uncertainties (errors) of the density function were applied to σ_T of the TCP. The notation "$\pm X$% error" indicates $\pm X$% relative error of σ_T. From the results, the effectiveness of the proposed method was verified with an error ranging from at least -20% to $+100$% when the number of UAVs was small (less than 20 in the simulations), although the error can degrade the performance. Not shown in this figure, this acceptable error range for outperforming the baseline method for less than 20 UAVs held true for exact σ_T of 100, 200, and 300, of which cases are compared below. It is better to overestimate (rather than underestimate) the variance of the density function in its estimation because positive errors were more tolerable than negative ones. Especially, when the number of UAVs was larger, negative errors resulted in more performance deterioration. We note that there were some parts of performance improvement due to the errors, which indicates that the use of an exact user distribution does not necessarily lead to the best performance, although it led to better performance than the benchmark.

We then compared the destination selection methods and their impact on the two time points at which the destination was changed with varying user heterogeneity. The average message delivery ratio and delivery delay are presented in Figs. 9 and 10, respectively. These results pertain to the TCP case, where σ_{T} was equal to 100, 200, and 300. The smaller the value of σ_{T}, the less uniformly the users were distributed. The effectiveness of the Voronoi-based destination selection was dependent on the number of UAVs. When the Voronoi-based method was not used after reaching the destination (i.e., in the MRD model), the Voronoi-based method after communication with another UAV was more effective when the number of UAVs was large (MRD-Rebounding versus MRD-Voronoi). In contrast, when the Voronoi-based



(a) σ_T = 100. (b) σ_T = 200. (c) σ_T = 300.

Fig. 9 Average message delivery ratio in the case of TCP with different values of σ_T.



(a) σ_T = 100. (b) σ_T = 200. (c) σ_T = 300.

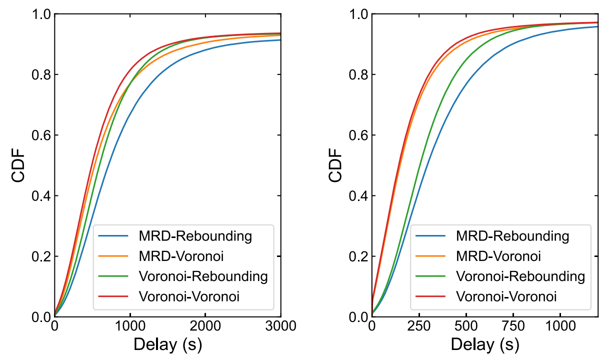
Fig. 10 Average message delivery delay in the case of TCP with different values of σ_T.

method was not used after communication (i.e., in the rebounding flight method), the Voronoi-based destination selection after arriving at the destination was more effective when the number of UAVs was small (MRD-Rebounding versus Voronoi-Rebounding). These results indicate that when there are few UAVs, it is preferable to select the destination based on the user distribution after arriving at the destination. In contrast, when there are many UAVs, it is preferable to select the destination based on the user distribution after communication. This is reasonable because as the number of UAVs increases or decreases, the opportunity for UAVs to communicate with one another increases or decreases, respectively. Furthermore, the proposed method (Voronoi-Voronoi) that uses the Voronoi cell for both time points of changing the destination has the advantages of both methods. That is, it achieves a higher or similar delivery ratio and a lower or similar average delay for all numbers of UAVs compared to the other two Voronoi-based methods (MRD-Voronoi and Voronoi-Rebounding). These results are noted in Table 2.

In addition, as illustrated in Figs. 9 and 10, the proposed Voronoi-based methods that considered the user distribution yielded results that varied greatly depending on the value of σ_T (i.e., the non-uniformity of the user distribution). The proposed methods led to greater performance improvement in the case of a less uniform user distribution.

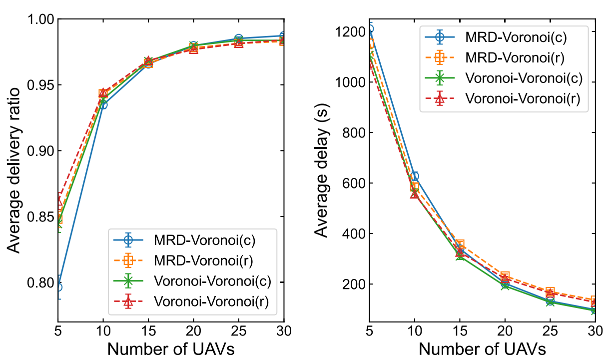
Figure 11 presents the cumulative distribution function (CDF) of the message delivery delay in the TCP case, where $\sigma_T = 200$. The proposed Voronoi-based methods achieved better message delivery performance than the method that did not consider the ground users. In other words, for the proposed methods, the message delivery ratios within a certain delay were higher than those of the benchmark method. Moreover, as illustrated in Figs. 9 and 10, when the number of UAVs was large, the delay performance was improved to a greater extent than when the number of UAVs was small by considering the user distribution at the time of selecting the destination after communication with another UAV.

Finally, for the Voronoi-based method, we compared using the centroid of the Voronoi cell and using a random point inside the cell as a destination. Figure 12 presents this comparison in the case of TCP, where $\sigma_T = 200$. When the number of UAVs was small, it was preferable to use a random point in the Voronoi cell instead of the centroid as the destination to increase the delivery ratio and reduce the average delay. We note that using a random point in the Voronoi cell was more effective than using a completely random point in the entire area. When there were many UAVs and the frequency of communication between UAVs was high, better performance was achieved when the centroid was used rather than a random point as the destination.



(a) 10 UAVs. (b) 20 UAVs.

Fig. 11 CDF of message delivery delay in the case of TCP, where σ_T = 200.



(a) Delivery ratio. (b) Average delay.

Fig. 12 Average message delivery ratio and average delivery delay in the case of TCP, where σ_T = 200, for the comparison of centroid (c) and random point (r).

5. Conclusions

In this paper, we consider a delay-tolerant aerial network using UAVs and propose a Voronoi-based flight method considering the distribution of ground users. In the proposed method, we introduce a density function that corresponds to the user distribution into the operation of selecting the destination. Moreover, we consider the time points at which the destination is changed, that is, after arriving at the destination and after communicating with another UAV. In addition, we consider the case in which the centroid of the Voronoi cell is used as the destination and the case in which a random point in the cell is used as the destination.

A computer simulation is performed using the cluster point process as the user distribution. The simulation results demonstrate that the proposed method improves the message delivery performance in terms of the message delivery ratio and average delay compared to the baseline method, especially in the case of a non-uniform user distribution. Moreover, the improvement is more significant when the user distribution is less uniform. The simulation results also demonstrate that the smaller the number of UAVs, the more the method of selecting the destination after arrival at the destination improves the performance. However, when there is a large number of UAVs, the destination change after communication with another UAV plays a more significant role in improving the message delivery performance, and the method using the centroid instead of a random point in the Voronoi cell leads to better performance.

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